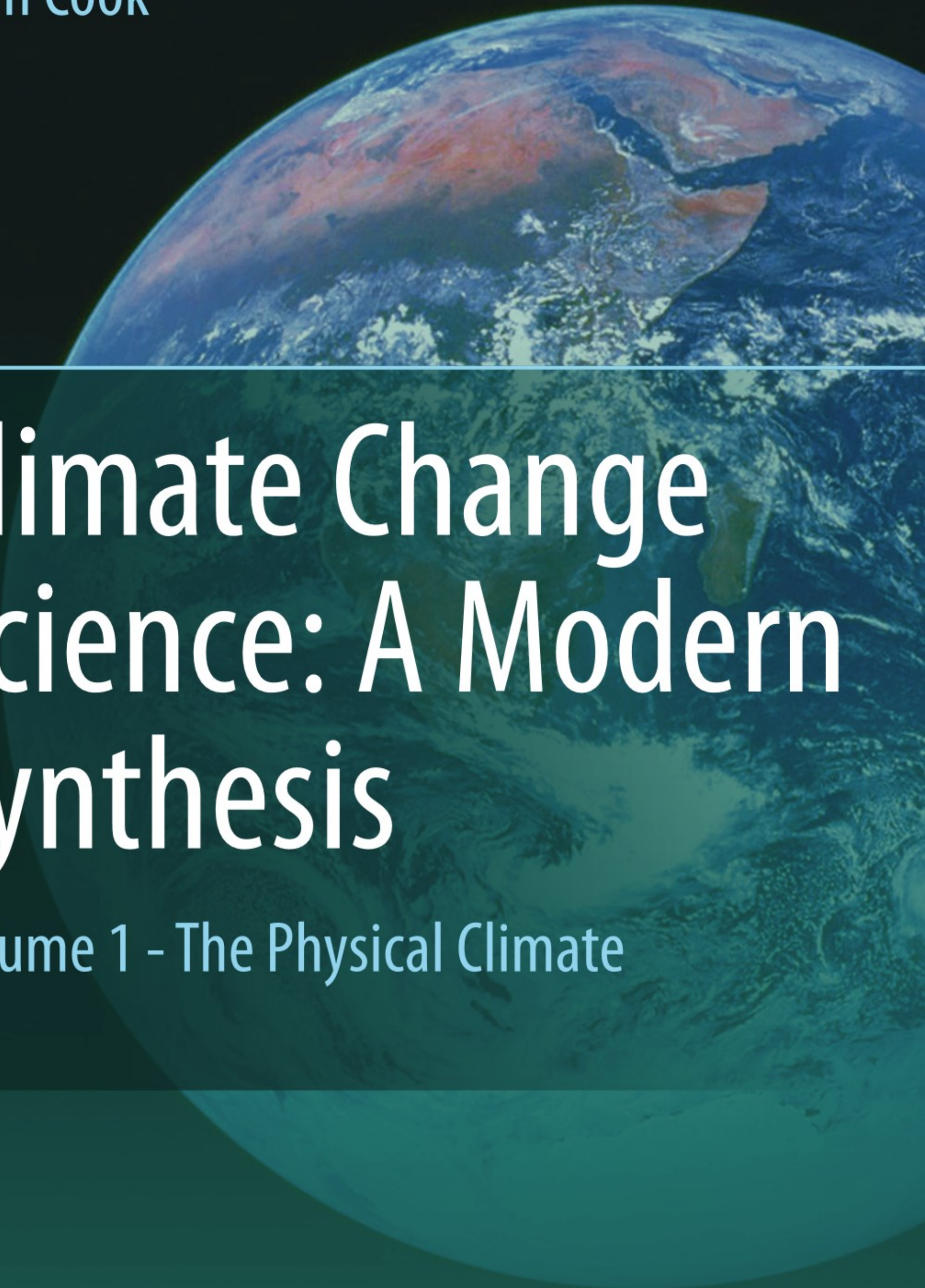
G. Thomas Farmer
John Cook

Climate Change Science: A Modern Synthesis

Volume 1 - The Physical Climate



Springer

Climate Change Science: A Modern Synthesis

PROBABLY THE MOST COPIED
IMAGE OF ALL TIME
TAKEN BY APOLLO 17 ASTRONAUTS ABOUT
MIDWAY
BETWEEN THE MOON AND EARTH
AND THE LAST
TAKEN BY MAN
FROM OUTER SPACE
AS OF
June 2012

G. Thomas Farmer • John Cook

Climate Change Science: A Modern Synthesis

Volume 1 - The Physical Climate

Springer

G. Thomas Farmer
Farmer Enterprises
Las Cruces, NM, USA

John Cook
School of Psychology
The University of Queensland
St Lucia, QLD, Australia

ISBN 978-94-007-5756-1 ISBN 978-94-007-5757-8 (eBook)
DOI 10.1007/978-94-007-5757-8
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2012956285

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

How inappropriate to call this planet Earth
when clearly it is Ocean

Arthur C. Clark

Preface

This textbook, *Climate Change Science: A Modern Synthesis, Volume I: The Physical Climate*, is intended for the introductory college science student who perhaps has not had a science course since secondary or preparatory school. It is also intended to serve as a more advanced textbook for students who have had a basic science course in astronomy, geology, biology, physics, or chemistry and who want to better understand Earth's climate, how Earth's climate has developed, what affects it, and how it may change in the future. However, it presumes no background in any of the sciences. Basic scientific concepts are introduced and explained as they become necessary for understanding the current topic. It constitutes Volume I of a two-textbook treatment of climate change science designed for a 1-year introductory science course. This volume treats the physical aspects of climate change science and is intended for a one-semester or one-quarter introductory science course.

Volume II emphasizes the historical aspects of climate change and Earth science. Each volume is a stand-alone treatment of climate change science, Volume I emphasizing the physical and chemical portions of the science while Volume II emphasizes the evolution and historical aspects of the science. Each volume presents arguments of climate change and global warming skeptics and deniers and the scientific evidence that refutes or supports each argument. The last two chapters in this text discuss denial in the face of overwhelming scientific evidence.

Neither volume assumes a prior college or preparatory course in science or mathematics but they do assume an interest in the world around us. The necessary science is introduced in the context of the evolving subject matter in the text. Mathematics is kept to a minimum in each volume and an understanding of preparatory-school algebra should be sufficient to tackle the mathematics of most climate science concepts contained herein. Additional readings for each chapter contain mathematical material where appropriate.

This volume will also serve as a basic college textbook in beginning Earth science for students who want to understand what modern climate science is all about and whether the Earth is warming to a dangerous level as some say it is. There are others that say that global warming is a "hoax" and questions have been raised about the legitimacy of climate science and those who practice it. Hopefully this book will provide the necessary background for students who want to understand and appreciate the complexities and problems of Earth's climate and climate change science and of those scientists who try to comprehend and explain them. There will be discussions of the legitimate nature of climate science, its current status, some of the problems climate scientists have had to face, and what climate science can contribute to the future of humankind on Planet Earth.

Climate science is far from being a hoax but there are still unanswered questions, as that is the nature of science in general. Climate science would hardly be a science if all questions had already been answered. But climate change science is a legitimate branch of science dealing with an Earth that is being greatly impacted and thus greatly changed by humankind. As in all aspects of science, there is an inherent search for truth. The final two chapters of this text deal with the concepts of denial as it relates to climate science and climate scientists.

Most scientists are well educated and free thinkers who try and keep their minds uncluttered by prejudices; but by human nature this is not always possible to do. However, it is inane to think that the thousands of climate scientists throughout the world have agreed to defraud the public into believing a false claim; that is, that the Earth is warming! The truth is that the Earth *is* warming and the scientists are and have been gathering facts and reporting the truth, or as close to it as they can come. There is no collusion among climate scientists as some have claimed. Those attempting to deny global warming are mainly not climate scientists but are something else; talk-show hosts, weather reporters, right-wing politicians and personalities, anti-science zealots, etc.

This textbook gives the physical evidence for climate change and global warming and is a synthesis of current climate change knowledge. There are parts (Parts IX and X) in this volume that present the ideas of skeptics and deniers and the scientific evidence that either refutes or substantiates their claims. There is also material that concerns the debunking of myths and there are many myths related to science in general and climate change science in particular.

Most scientists are realists and their primary concern is for the best future for humanity on this planet. It is the main reason most of them became scientists. The principal driver of scientific endeavor is to advance human knowledge and to make the Earth a more pleasant place, or at least a better place; a better understood place, for future generations to live. Scientists and others may differ about their definition of "better" but most want to improve the Earth and human society.

Most scientists are excited about their science and they hope to be able to impart that excitement to the students that they teach or for whom they write. Scientists are among the best educated members of society and now is a great time to be a scientist because knowledge is expanding astronomically, in quantum leaps. New knowledge is always exciting in one's major field of interest, but what is being found out today about the Earth and its climate is truly amazing. New satellites are being sent into space and Earth orbit to monitor Earth's climate in ways never before imagined or thought possible. Scientists are learning more and more about the past climates of other planets as well as about that of the Earth. Other space vehicles are exploring other parts of the Universe and man is getting ready to explore other planets.

In the 1960s and 1970s the Earth sciences experienced a change which has been described as a paradigm shift. New information was being acquired from the ocean basins concerning their ages and characteristics and new methods of exploring, sampling, and analyzing were being developed. Scientists had begun to obtain ice cores from Antarctica, Greenland, and some of the glaciers in mountainous areas of the world. Their analysis was beginning to yield important new information about past climate changes; the most recent changes that had taken place on Earth during the past 850,000 years.

Ice cores have taken us back to about 850,000 years ago when the Earth was not so different from what it is now. The continents were approximately where they are today and climate was not too different. But something happened around 700,000 years ago and the Earth cooled to begin cycles of expanding and then retreating of continental-sized ice sheets that covered vast areas of North and South America, Asia and Europe (Eurasia). Ice sheets, including glaciers, also expanded in mountains such as the Alps, Andes, Himalayas, and Rockies. Reasons for these cycles are considered in this text as well as the evidence that allowed scientists to arrive at the conclusion that glacial ice had been much more extensive in the past than it is today. In the span of just a few hundreds of thousands of years, the Earth's climate has undergone radical changes and ice cores have allowed scientists to learn a great deal about the "Ice Age" and its causes. It will be seen that the Earth has experienced several "ice ages" and the latest one is the one about which we know the most.

The major paradigm shift in the Earth sciences has been referred to as Plate Tectonics, which is introduced in this volume but treated extensively in Volume II. It represents a legitimate paradigm shift; but the monumental changes taking place in the knowledge about the Earth involve more than lithospheric plates, their configurations, boundaries, and their motions. The Earth science paradigm shift has broadened and now also involves changes in the interpretation of Earth's climate; the interactions between the atmosphere, biosphere, lithosphere, asthenosphere, and anthrosphere; as well as the evolution of Earth's climate through time, known as paleoclimatology. Scientists' knowledge of climate change science as well as the modern concept of Plate Tectonics constitute paradigm shifts.

If humans can understand climates of the past, perhaps we can better understand what the climate of the future will be and humankind may be able to mitigate some of the problems that are sure to occur in many future scenarios of Planet Earth's climate.

Some scientists will be fortunate enough to influence a few students or colleagues in a positive way. A few will be able to reach many more by publication or performance in the classroom or on the lecture circuit. And a very few will reach the pinnacle of their profession by excelling at every level. This work will attempt to impart some of the writers' excitement about the Earth and its climate to the readers of this text and will hopefully extend their knowledge of Earth and its potential for allowing us to live, work, play, and learn about its many mysteries. Perhaps we can decipher its clues and features, and thereby arrive at solutions to many of its problems.

This book is written for students who are looking to balance their education with a basic science course. And it is also written for the instructors who teach them.

There is enough material here for both as well as for others that want to accept the challenge to gain a better understanding of Earth and its climate.

That the planet is warming is unequivocal. Climate change scientists have gone far beyond the simple concept of global warming and now are attempting to devise ways that humans can cope with ever increasing temperatures and their effects. If scientists can unravel and document the convoluted facts of our world's climate and better understand the ramifications of global warming, the better the chances are that humankind can survive in the years and centuries to come. There is an urgent call for understanding the climate and doing everything possible to mitigate its warming and it is hoped that these texts will help.

Climate change science has become a different branch of science from just climate science, that which has been practiced by climatologists over the years. Climatologists have always been aware that climate can change and can heat up or cool down, usually taking hundreds and possibly thousands of years to make a major change. Scientists and others have known about the most recent ice age for around 200 years or more. We now know about ice ages that took place even further back in time, as far back as 700 million years. Some have said that we are headed for another ice age and perhaps we would be if global warming was not happening. Humans have been adversely affecting Earth's climate for at least 8,000 years, beginning with agriculture and the demise of the hunter-gatherer stage of human history.

Climate change scientists are a relatively new breed of scientist with backgrounds in Earth history, geology, geography, biology, oceanography, astronomy, mathematics, physics, chemistry, engineering, and are able to juggle multitasks at blinding speed thanks mainly to advances in computer science and engineering. Climate science is changing rapidly now and climate change scientists must keep pace with these rapid changes.

Climate change scientists deal with massive amounts of data over relatively long time periods and are able to see significant trends revealed by analyses of these data. The most obvious are the trends in temperatures, changes in sea level, volume changes in glaciers and their waxing and waning, changes in atmospheric and oceanic circulation, configuration of continents and their locations over the Earth's surface, trends in energy amounts received and distributed by Earth processes, etc. Trends are revealed after assembling and analyzing these data with analytical methods developed over many years and agreed to by international groups of scientists. These methods and results are discussed in the pages that follow.

In the last two centuries, humankind has dumped an amazing amount of carbon and carbon dioxide (CO_2) into the atmosphere by the burning fossil fuels. Humans added another 110 billion tons via deforestation and land-use changes. The activities of humankind since the start of the Industrial Revolution in the mid-eighteenth century have had and are still having a tremendous and negative impact on Earth's land, ocean, atmosphere, biota, and human health.

The atmosphere weighs about 5 quadrillion tons, and carbon dioxide, despite human emissions, remains a small component of that. But it grows larger every day. The International Energy Agency (IEA) expects annual global CO_2 emissions from fossil fuels alone to top 40 billion tons added to the atmosphere each year by 2030. It is not that humans will suffocate from the additional CO_2 directly, but that it will cause an increase in Earth's temperature to a degree that will make the planet too hot for humans to live on it or in it. CO_2 is not toxic at levels in the foreseeable future for the atmosphere but its role as a greenhouse gas is a concern at levels seen over the past several decades. This concern is treated in the following pages.

Climate change is real, is being reflected today in major changes in weather patterns throughout the globe, and climate change scientists are working with these changes to find causes and ways to deal with them. Modern citizens of the world need to become better acquainted with the climate changes that are occurring and it is hoped that the words that follow will help.

The Internet has been extensively used in the writing of this work. Websites are listed throughout these texts and contain additional information on the topic under consideration. The authors strongly recommend that these or similar sites be visited for additional information whenever desired or needed. The Internet is an amazing resource for information but it must be used with care and discrimination. There is much misinformation (and disinformation) on the web and one needs to be able to recognize it when found and be able to separate the bad from the good. It is hoped that these texts will aid in this discrimination.

A timeline for some of the major events in the recent development of modern climate change science is given below beginning around 1965 with work by Manabe and Wetherald who built the first comprehensive model of Earth's climate system.

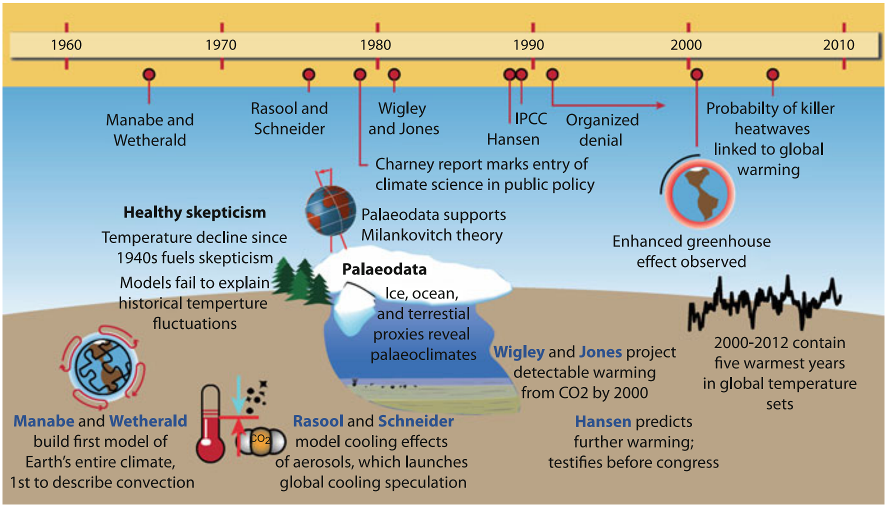


Fig. 1 Timeline for the development of modern climate change science from around 1965 to 2010 (From SkepticalScience.com, viewed 5/11/2012)

The following text is intended to be used in introductory science courses. It introduces concepts common to all the sciences and includes an introduction to the scientific method, some geology, chemistry, physics, and astronomy and other subjects such as statistics, philosophy, and meteorology necessary to understand climate change science.

Volume I of the textbook is divided into Parts I–XI. Each part is listed as follows:

Part I – Scientific Principles and the Scientific Method
Part II – Overview of Climate Change Science
Part III – Earth's Atmosphere
Part IV – The World Ocean and Climate
Part V – Earth's Cryosphere and Recent Climate History
Part VI – Land and Its Climates
Part VII – Climate Models
Part VIII – Climates of the Past (Paleoclimatology)
Part IX – Future Climates and Mitigation
Part X – Understanding Climate Change Denial
Part XI – Specific Declarations Against Climate Science and Climate Scientists

There are also appendices that will serve as reference for parts of the text, a list of abbreviations used in the text, and a glossary of climate change terms.

The book may serve as an introduction to Earth science, climate science, environmental science, geology, and general science students. It may also be used in Advanced Placement courses in the Earth sciences for college preparatory schools. It is a textbook for introductory science students at any level.

The text is written with the basic premise of allowing the instructor maximum flexibility in teaching the introductory science course. It allows the instructor and introductory science student to build on a solid foundation of scientific and introductory information. Some chapters begin with an appropriate quotation relating to that chapter's material. A list of terms and topics ("Things to Know") that the student should keep in mind as the chapter is read follows the quotation or begins the chapter. Some chapters have sections that contain advanced material pertinent to the subject matter of that chapter and the instructor may elect to assign the material or not. The instructor may choose which materials to emphasize in each chapter, change the sequence of material covered in the text, or add additional material. An attempt has been made to have each chapter stand alone and not be dependent on the previous chapter.

The text begins with an introduction to basic scientific principles used in all the sciences, such as the scientific method(s), laws of thermodynamics, the gathering and interpretation of data, a few of the giants of science and their contributions, a few selected climate change scientists and their contributions, Newton's laws of motion, etc.

The introduction is followed by a series of chapters on the major aspects of climate change and its effects and interactions with the atmosphere, the World Ocean, glaciers, and land. Modeling the climate (PART VII, Chap. 18) is a separate chapter as is a section on past climates, and specific arguments of climate change skeptics and deniers.

Terms found in the Glossary or given for emphasis are defined when first introduced.

This volume, *The Physical Climate*, is written with the student's best interest in mind. It is hoped that it has condensed a difficult and multifaceted subject (climate change) and made it a bit easier to understand. The attempt is a synthesis of modern climate change science and the principles used to understand it and it is hoped that the reader will gain a better understanding of the world around us and the need for conservation of its resources.

G. Thomas Farmer
John Cook

Acknowledgements

The current textbook (Volume I) authors have relied heavily on the following individuals, works, and web sites:

- The American Physics Institute web pages by Spencer Weart
- The Intergovernmental Panel on Climate Change (IPCC)
- The United States National Academies of Science (NAS)
- The United States National Research Council (NRC)
- White House Council of Environmental Quality (CEQ)
- SkepticalScience.com
- Science-Skeptic.com
- RealClimate.org
- WhatsUp.com
- U.S. National Aeronautics and Space Administration/Goddard Institute of Space Studies (NASA/GISS)
- U.S. National Aeronautics and Space Administration (NASA) Earth Observations
- U.S. National Oceanic and Atmospheric Administration (NOAA)
- U.S. Environmental Protection Agency (EPA)
- United States Geological Survey (USGS)
- Google.com
- U.S. National Climate Data Center (NCDC)
- U.S. National Weather Service
- U.S. National Environmental Satellite, Data, and Information Service
- U.S. National Oceanic Data Center
- NOAA Office of Atmospheric Research
- U.S. Department of Energy
- U.S. National Regional Center for Atmospheric Research (NCAR)
- Australian Bureau of Meteorology
- U.S. Group for High Resolution Sea Surface Temperatures (GHRSST)
- Henry Pollack, “A World Without Ice”
- Richard Alley, “Earth: The Operator’s Manual”

- Oreskes and Conway, “Merchants of Doubt”
- The American Meteorological Society
- Wikipedia, The Free Encyclopedia
- HotTopic.com
- TheClimateShow.com
- Thomas L. Friedman’s “Hot, Flat, and Crowded”
- Wendy Cook
- Donna Farmer
- Steven Farmer
- William Patrick Roberts

Contents

Part VI Land and Its Climates

Part VII Climate Models

Part VIII Climates of the Past (Paleoclimatology)

Part XI Specific Declarations Against Climate Science and Climate Scientists

Part I
Scientific Principles and the Scientific Method

To a patient scientist, the unfolding greenhouse mystery is far more exciting than the plot of the best mystery novel. But it is slow reading, with new clues sometimes not appearing for several years. Impatience increases when one realizes that it is not the fate of some fictional character, but of our planet and species, which hangs in the balance as the great carbon mystery unfolds at a seemingly glacial pace.

— D. Schindler

Chapter 1
Introduction

1.1 Introduction to Global Warming

Global warming involves a temperature change on planet Earth. The temperature is climbing gradually so that the average person does not feel it. However, there are indirect lines of evidence that the average person can see and feel. Increasing unusual weather patterns reported by the news media nearly every day indicate climate change. More floods in parts of the world and more intense droughts in others indicate climate change. Fires raging in some areas and unusual snowfalls in others indicate climate change. A season of intense tornados and more intense hurricanes indicates more energy in the atmosphere and that is climate change. As the Earth's global temperature increases, rates of evaporation also increase placing more water in the atmosphere. More evaporation dries out the land, soils, forests and takes more water from the ocean. All are signs of a changing climate. A warming Earth is climate change and it is affecting everyday life throughout the globe. Thus 'global warming' is used to refer to Earth's gradually increasing temperature.

1.2 Greenhouse Effect

The greenhouse effect is due to a set of chemicals present in Earth's atmosphere known as greenhouse gases that trap heat close to the planet's surface. As the Sun's rays travel through the atmosphere they are in the form of ultraviolet (UV) rays and visible light that warms the Earth's surface. The warm surface then emits heat that travels from the surface back toward space as infrared (IR) waves and some of it makes its way back to outer space. The rest of it is trapped by greenhouse gases such as water vapor, carbon dioxide, methane, ozone, chlorofluorocarbons, and a

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_1,

few other chemicals and is re-radiated by these chemicals back to the Earth's surface. This keeps the lower part of the atmosphere warm enough for humans to survive. If the greenhouses gases increase in the atmosphere, more of this heat is trapped and the Earth warms; if the greenhouse gases diminish in the atmosphere, less of this heat is trapped and the Earth cools. One of these greenhouse gases, carbon dioxide, is so important in trapping and re-radiating this heat energy that it is known as the Earth's thermostat. Geologists tell us that throughout Earth's history (about 4.5 billion years) there is a direct correlation between carbon dioxide and Earth's temperature. Today's climate scientists tell us that models show the temperature increase with the addition of carbon dioxide; and the models do not show the temperature increase without the increase in carbon dioxide. There are other lines of evidence that point to carbon dioxide as the major cause of the most recent global increase in temperature.

The Earth is hurtling through space in its orbit around the Sun while spinning like a top on its axis of rotation. It would be a frozen lifeless place like our moon or the other planets in our Solar System if not for the thin layer of atmosphere that traps solar energy and insulates the Earth's surface. The way the atmosphere traps solar energy is called the greenhouse effect because it is similar to a greenhouse or an enclosed car heating up in the Sun. In the case of the car, sunlight comes in through a largely transparent window or windshield and is absorbed by whatever it hits, heating up the interior. Some of that heat is trapped inside, because glass lets heat in but doesn't let it out and the inside temperature of the car increases rapidly in the bright sunlight.

In the Earth's atmosphere, sunlight is absorbed by the Earth's surface or rooftops or rocks, and that energy is radiated as heat, infrared energy, back toward space. The Earth's atmosphere absorbs 531 W/m^2 from the Sun plus surface infrared plus thermals plus latent heat, then radiates 333 W/m^2 back to the surface and 199 W/m^2 back to space. Most of the heat that the atmosphere absorbs doesn't make it to space because it gets reradiated back to the Earth's surface by certain gases in the atmosphere, mainly water vapor, carbon dioxide, chlorofluorocarbons, ozone, methane, and a few other gases.

The greenhouse gases consist of more than one atom that are bound together in a way that allows them to vibrate in wavelengths that enable them to capture the infrared radiation on its way back out of the atmosphere. Normally this is a good thing, because without the heat trapped in the atmosphere by these greenhouse gases, planet Earth would be frozen and the temperature would be an uncomfortable −15°C. There would be no life on Earth today as we now know it. Life has evolved under CO_2 levels of approximately 280 ppm.

If extra carbon dioxide that is not part of the natural carbon cycle is added to the atmosphere, then extra heat is trapped that would otherwise escape to space, and the atmosphere gets warmer.

Global warming is an increase in the Earth's overall average temperature, since records have been kept, caused by adding extra carbon dioxide and other greenhouse gases to the atmosphere that absorb and trap heat. The illustration below (Fig. 1.1) shows the result of this trapped heat during the period 1880–2009 as compared to the average global temperature for the period 1961–1990 (stated as a change or an anomaly from the 0 line, either plus or minus in degrees centigrade or Celsius).

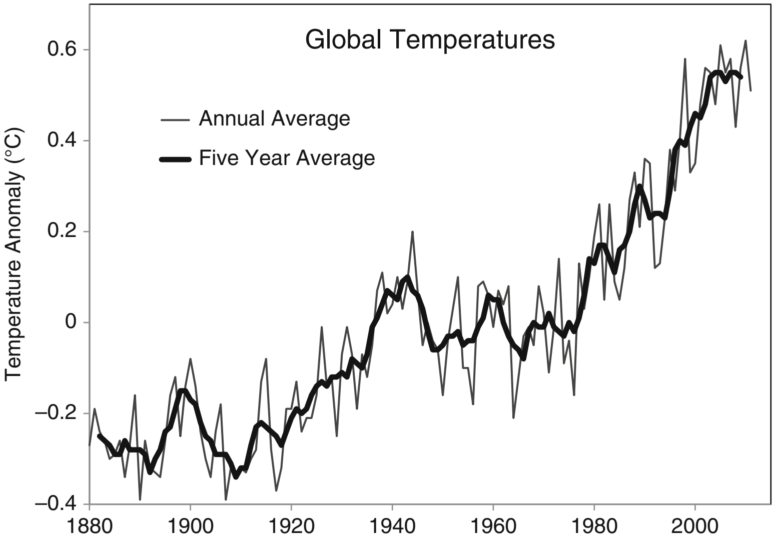


Fig. 1.1 Average global temperature during the period 1880–2009, compiled from various data sources by NASA. The 0-line is the average global temperature for the period 1961–1990. The *smooth curve* is a 5-year average (NASA/GISS, Public Domain)

1.3 Climate Sensitivity

We know that Earth is a sustainer of life because it provides us with an environment that has allowed living organisms, including humans, to evolve and thrive on its surface, in its oceans, and in its air. The atmosphere is the main reason life thrives on the planet, at least for humans. It is the air we breathe. It provides water we drink from precipitation. It provides warmth from sunlight captured by molecules that keep the planet warm enough to grow our food and for us to live. It provides us with something called the “greenhouse effect” that allows us to live on what would be just the third rock from the Sun without it.

How sensitive is Earth’s climate to change? If it is not very sensitive, maybe there is little reason to worry about climate change and global warming. If it is very sensitive, maybe there is every reason to worry. Of course, the sensitivity of the system is also related to feedbacks, such as glacial ice and clouds.

One way to measure the sensitivity of something is to measure how it changes when it is subjected to a known force or a known change in conditions. Put another way, if the climate system is forced to change, how much will it change? So one way to measure sensitivity of Earth’s climate is to measure something that will or is changing it, then measure how much it has changed.

If we could measure the greenhouse gases over an interval of time and determine if they are increasing or decreasing, one part of the climate system would be known and we could measure the temperature over the same interval and that would tell us whether the Earth was being forced to cool or to warm.

If we double CO_2 from its pre-industrial level of 280–560 parts per million (ppm), the temperature caused by the doubling of CO_2 will be between 2 and 4.5°C as determined by the Intergovernmental Panel on Climate Change (IPCC) in 2007 and by a number of independent analyses since. The higher number (4.5°C) is an approximation and is due to the influence of feedbacks on Earth's temperature. The IPCC concluded that the 2°C was conservative, that it was unlikely to be less than 2, and that the most likely value would be an increase of 3°C.

There is a cause for concern with the analysis used above. The increase in carbon dioxide in Earth's atmosphere has not increased in a straight line. Neither has the temperature increased in a straight line. Both rates of increase in the atmosphere have accelerated over time so that the current annual increase in carbon dioxide is around 2 ppm (2 ppm/year). If we double the current amount of carbon dioxide in the atmosphere ($394 \times 2 = 788$) humankind will experience a world that perhaps it has never experienced before. It is dangerous to make predictions, but the situation is not likely to be good.

1.4 Average Global Temperature from 1880 to 2009

The illustration above (Fig. 1.1) is a graph of Earth's global temperature in degrees Celsius from 1880 to 2009. The trend is generally in an upward direction but the light dots indicate the annual variability. The dark line is a 5 year average that smoothes out the annual averages.

1.5 Carbon Dioxide

Carbon dioxide (or CO_2) is the familiar gas that bubbles out of carbonated beverages, and in its solid form, is "dry ice." Carbon dioxide is also a waste product of animal metabolism. Much of the carbon dioxide in the atmosphere is from the burning of fossil fuels. In the carbon cycle, plants take in carbon dioxide and solar energy and they produce oxygen in Earth's atmosphere that we need to live. For most of human civilization, the amount of CO_2 in the atmosphere has been stable at about 280 parts per million (ppm), meaning that out of every million molecules in the air, 280 of them are carbon dioxide. Carbon dioxide is a small fraction of the atmosphere (0.040%), but it's the right amount to absorb just enough heat so that the Earth has the overall average temperature that we and everything else living on the planet have gotten used to. Human civilization has existed in an environment that has had around 280 ppm of carbon dioxide in the atmosphere for thousands of years and it has recently reached over 400 ppm in the Arctic (Fig. 1.2).

The Industrial Revolution began around 1750 when we learned to generate great amounts of electricity and heat needed to build modern civilization by burning coal, oil, and natural gas as fuels for sources of energy. Fossil fuels are the remains of plants and

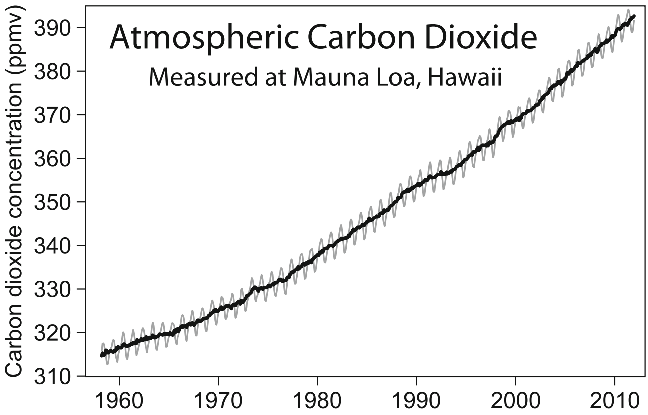


Fig. 1.2 Carbon dioxide concentrations in the atmosphere measured at NOAA's Mauna Loa, Hawaii observatory from 1958 to the present (NOAA, Public Domain)

animals that died and accumulated millions of years ago sinking to the bottom of stagnant water that lacked oxygen necessary to feed the bacteria needed to decompose them. As a result, they became buried under layer upon layer of sediment and compressed into coal or oil. Today we mine coal and drill for oil and then burn them in power plants and cars and airplanes. Fossil fuels are mostly made of carbon, and burning them in oxygen converts them into carbon dioxide that goes up the smoke stack or out the tailpipe and into the atmosphere. This is the extra carbon dioxide beyond the amount we used to have when the carbon cycle was in balance. It is this additional carbon dioxide that is currently causing the Earth to warm. Carbon dioxide doesn't just go away, most of it builds up in the atmosphere and traps more heat and makes the planet warmer. Carbon dioxide stays in the atmosphere for thousands of years. The amount of carbon dioxide in the atmosphere in June of 2012 was 400 ppm and it is increasing at a rate of 2 ppm/year as more and more humans burn more and more fossil fuels. It's astonishing that we can have such a large effect on the whole planet's atmosphere. But it's not so astonishing when you realize that 7 billion humans dump about 30 billion tons of carbon into the atmosphere every year and this amount is rising each year. In 2010, a record 30.6 gigatonnes (Gt) of carbon dioxide poured into Earth's atmosphere, mainly from burning fossil fuel; a rise of 1.6 Gt from 2009, according to estimates from the International Energy Agency (IEA) regarded by many as the gold standard for emissions data.

1.6 Global Warming, Climate, and Weather

Global warming is not about the daily weather, and there's no clear connection between global warming and any single hurricane or snow storm or drought. Adding energy to the whole Earth climate system leads to such things as more frequent severe weather events that on average are stronger and more damaging. One definition of climate by the World Meteorological Organization (WMO) is "weather over a 30-year period or longer." There's a great deal of day-to-day and even year-to-year variability in the weather, and the 0.8°C (or 1.1°F) increase in the average global temperature over decades shown in Fig. 1.1 is a trend that an individual can't detect or feel. However, scientific research brings to bear lots of measurements, data analysis, computer modeling, debate, and discussion among thousands of experts who spend their careers studying these trends in great detail. That's what makes them experts, and why they should be listened to with an open mind.

Global warming is about an overall increase in the amount of energy in the whole Earth climate system caused by an increase in heat-trapping greenhouse gases. The experts are only talking about a few degrees of average temperature increase, which doesn't sound like much, but consider this example. A person's average temperature is 98.6°F. If that person's temperature goes up 1–99.6°F it means a person has a fever and this is reason for concern. Something is causing the fever, either a virus or bacterium and most individuals would want to know its cause and what can be done about it, especially if it lingers. Also, imagine a glass of water and ice cubes in a refrigerator whose temperature is set right at the freezing point of water, 0°C or 32°F. The mixture of ice and water will remain pretty much as it is, but if the temperature is raised by even 1°, the ice cubes will start to melt, and at 2° they will melt faster. Everything was in balance at the old temperature, but at the slightly warmer temperature you eventually end up with all water and no ice, much like what is happening right now to Earth's Arctic sea ice (Fig. 1.2) and mountain glaciers.

1.6.1 Arctic Sea Ice Extent 1979–2005

The Polar Regions of Earth appear to be the most sensitive places on the planet to climate change and global warming. In the illustration below (Fig. 1.3), it can be seen that the north polar region of Earth has lost more than 20% of the Polar Ice Cap since 1979. This loss of Arctic ice is causing unusual weather patterns in the North Atlantic area and possibly influencing oceanic circulation patterns.

1.6.2 Impacts of Global Warming

What happens when the planet gets warmer? More extreme weather, disappearing Arctic ice cap, and receding glaciers throughout most of the world have consequences, such as drowned coastal areas, decline of the polar bears and other Arctic animals, and disappearing, glacier-fed, fresh water supplies for over a billion people. The current rate of sea level rise is 3.2 mm per year (Fig. 1.4), which is cause for concern in low-lying or hurricane-prone coastal areas like Bangladesh, or certain disappearing Pacific islands, or the U.S. Gulf Coast. This will become a national security and military concern when there are millions (perhaps over a billion) of "climate refugees" displaced by rising sea level. They will do what they must to

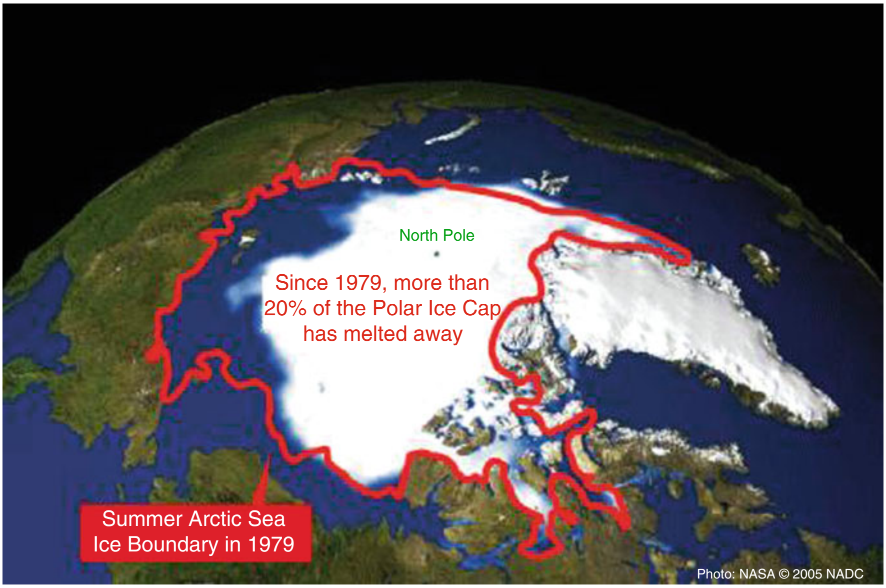


Fig. 1.3 Arctic sea ice is melting away. Actually, ice not only melts but also sublimates passing from the solid state into the atmosphere. The reduction of Arctic sea ice does not raise sea level, just as the reduction of an ice cube in your glass of iced tea doesn't raise the tea level in the glass. Arctic sea ice is frozen ocean water. Since 1979, more than 20% of the polar sea ice cap has disappeared (Source: NASA and the National Snow and Ice Data Center, Public Domain)

survive, as we all would, and they will go inland to China, Australia, the U.S., and elsewhere where they probably won't be welcomed with open arms and invitations to tea. Other consequences of global warming include extended droughts and encroaching deserts, increasing wildfires and insect infestations, and changing rainfall and agricultural patterns. We are seeing some of this already with destructive beetle infestations in the Rocky Mountains and elsewhere in the U.S. and Canada.

The oceans and marine life are doubly affected by global warming; first by an increase in temperature, which intensifies storms such as hurricanes and melts sea ice, and second by increased acidity caused by dissolved CO_2. And these aren't even the worst-case scenarios.

1.7 Timescales, Positive Feedbacks, and Tipping Points

These three factors, timescales, positive feedbacks, and tipping points make confronting global warming both more difficult and more urgent. Natural processes that permanently remove CO_2 from the atmosphere take place on a timescale of decades or longer, so we are already committed to a certain amount of additional

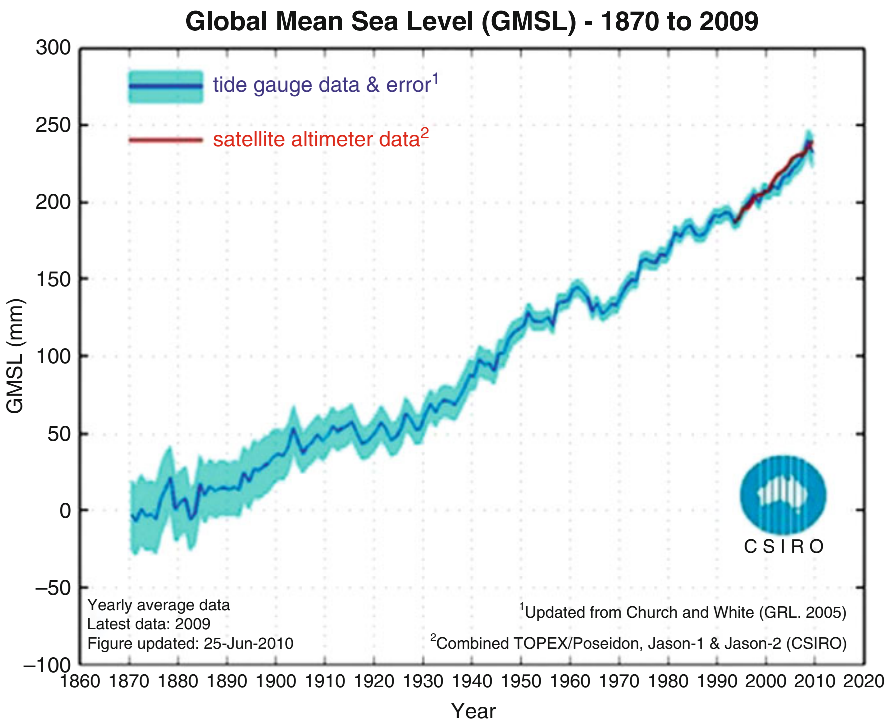


Fig. 1.4 The trend of sea level since 1870 (1870–2009). The *light blue* region is the range of uncertainty in the measurements. Satellite measurements are represented by the *red line* and tide gauge measurements are represented by the *dark blue line*. Sea level has increased about 24 cm (9.4 in.) since 1870. Since 1993, sea level has increased by about 6 cm (2.4 in.) at a fairly constant rate of 3.2 mm per year (Source: CSIRO, the Australian National Scientific Research Organization)

warming even if humans totally stopped burning fossil fuels today. When a system such as Earth's climate system is perturbed from a stable state, "positive feedback" processes can cause the system to move even farther from its previous state, while "negative feedback" processes tend to restore a perturbed system to its previous state. There are several positive feedbacks in the Earth's climate system that could lead to a "tipping point," which is a threshold condition that leads to an irreversible change because once it's done it's done, like pulling the trigger on a loaded weapon with the safety off. There's no way to stop the bullet from its ultimate impact.

One example of a positive feedback in the climate system concerns the decreasing Arctic ice cap shown in Fig. 1.3. Ice is a reflective surface with an albedo of 0.5–0.7, meaning that 50–70% of Sunlight is reflected back toward space and contributes less to global warming. Ocean water is one of the least reflective surfaces with an average albedo of only 0.08 (only 8% reflected, 92% absorbed), so most of the solar energy hitting the ocean participates in global warming. As the size of the Arctic ice cap decreases from melting, a less reflective surface (the ocean) replaces a more reflective surface (the ice), so more solar energy is absorbed and the rate of global warming increases, leading to faster ice cap melting, leading to faster warming.

A second positive feedback in the climate system concerns the thawing of permafrost in northern latitudes. Vast stretches of permafrost contain huge quantities of CO_2 and methane frozen into the soil, which is released into the atmosphere as the permafrost melts, which traps more heat and increases the rate of global warming, which melts more and deeper permafrost, which further increases the rate of global warming, etc. These and other positive feedbacks could lead to a tipping point, where dramatic changes in the Earth System happen quickly and are permanent and irreversible.

1.8 Energy and Climate Policy

Climate science is enormously complex due to the numerous variables yet sufficient progress has been made over the last few decades so that we know the broad outlines of what is needed to avoid the worst consequences of global warming. We need to make major changes in the way we obtain and use energy, and we need to do it soon, or the world will change in ways we won't like and our children and grandchildren will like even less.

Having a specific goal can sometimes motivate progress, and some climate scientists think that we should stabilize the atmospheric CO_2 concentration at no more than 350 ppm. The pre-industrial CO_2 level was 280 ppm, and we're currently at 400 ppm (in June 2012) and increasing at a rate of 2 ppm per year; so we're already above the desired level and rapidly heading in the wrong direction. The target of 350 ppm originated with a paper by NASA climate scientist Dr. James Hansen that reported on an analysis of past climate conditions and their associated CO_2 concentrations. A commonly cited target for policy considerations is to limit global warming to 2°C (3.6°F) from pre-industrial conditions, which gives us a chance to avoid positive feedbacks such as widespread melting of permafrost that could lead to a tipping point. The 2°C limit roughly corresponds to an 80% reduction in CO_2 emissions by the year 2050 if substantial reductions begin immediately. Meeting such targets requires transformational energy policy that establishes clear requirements and a mechanism to meet them, and puts a price on the emission of carbon to drive reductions. Currently there is zero cost for contributing to global warming, so there's no incentive to stop. Nevertheless, taxpayers will continue to pay for the effects of global warming and as time passes the severity of the problem increases and the costs go up.

1.8.1 Energy Choices

Energy choices made today will determine the climate in coming decades. Historically it has been difficult for humans to confront a major problem until some catastrophe occurs. This does not bode well for addressing global warming because we must act far in advance of any catastrophe due to the long timescale for removal of CO_2 from the atmosphere. The solutions are clear; we need to use energy more efficiently, as about half is now wasted by inefficient cars, appliances, buildings, electrical grid, etc., and we need to transition to clean and renewable (non-fossil fuel) sources of energy such as wind, solar, tides, etc. We already know how to do these things. The technologies already exist.

However, the forces opposing change in energy use are formidable, well funded, and very good at deceiving a poorly-informed public about a complex and long-term issue. Coal was cheap for powering the Industrial Revolution and electrifying civilization, but now we know there are long-term global consequences for Earth's future climate. We now know how to make electricity in smarter ways than using fire to boil water to turn a generator. Petroleum is a major contributor to global warming, plus having volatile pricing, environmental damage such as the Gulf oil disaster, leaking pipelines, or tar sands mining; and the loss of life, political destabilization, and enormous expense to taxpayers of protecting oil supplies. Even relatively "clean" natural gas (methane) is not really very clean unless much more is done to prevent leakage of this potent greenhouse gas into the atmosphere at the wellhead and in the pipeline.

Confronting global warming will require a combination of strong legislation crafted by informed and courageous legislators, personal actions to reduce one's own energy use and to support renewable energy, and educating the public about the reality of global warming and what's at stake. One thing that an individual can do is to emphasize the importance of strong clean energy and climate legislation when making political and voting decisions.

For most of us, this issue of global warming is beyond politics; it's about the future of our planet, our offspring and our species. Who to believe about global warming? Consider this simple analogy: if one wants to know how to fix the plumbing, call a plumber, not a climate scientist. If one wants to know if global warming is real and whether or not we should do something about it, ask a climate scientist; not the Coal Lobby, the American Petroleum Institute, some politician, or your local weather TV or radio personality.

1.9 Forcings and Feedbacks

Climate forcing is a change in direction that is caused by an external or internal force operating on Earth's climate system, such as a warming or cooling. If the Sun's energy output changes, it forces a change in Earth's climate. The Sun is the most obvious forcing agent for Earth's climate change but there are others.

Feedbacks supplement forcings. An obvious example of a feedback is glacial ice. If the Earth is cooling and glacial ice on Earth expands, more energy is reflected back to space and the planet cools. If the planet is warming and glacial ice retreats, more energy is absorbed by Earth and less energy is reflected back to space; the Earth warms.

Feedbacks may be positive or negative. A positive feedback enhances a forcing; a negative feedback works against a forcing. The glacial ice feedbacks mentioned above are both positive feedbacks. An example of a negative feedback is if the Earth is warming and thick white cloud cover forces more sunlight to be reflected. It would eventually cause the Earth to slow the warming or cause the Earth to cool.

Being able to determine the evolution of global climate from the end of the Last Glacial Maximum (LGM) approximately 20–18 thousand years ago to the early Holocene 11,700 years ago presents to scientists an unrivaled opportunity for understanding the response of Earth's climate system to external and internal forcings. During this interval of global warming, the decay of ice sheets caused global mean sea level to rise by approximately 80 m; terrestrial and marine ecosystems experienced large disturbances and range shifts; perturbations to the carbon cycle resulted in a net release of the greenhouse gases CO_2 and CH_4 to the atmosphere; and changes in atmosphere and ocean circulation affected the global distribution and fluxes of water and heat.

We will see and study the causes and effects of this evolution of global climate as we proceed in this text.

1.9.1 Earth's Albedo

Albedo is the same as reflectivity and is defined as a substance's ability to reflect light. Glacial ice has a high albedo, ocean water a low albedo. Things with a high albedo, like glacial ice, reflect energy while those with a low albedo absorb energy. A dark landscape like volcanic material absorbs energy while desert sand reflects energy in the form of the Sun's rays that strike them.

1.9.2 Irradiance

Irradiance is the power of electromagnetic radiation (in this case radiation from the Sun) per unit area (radiative flux) incident on a surface. It is expressed in Watts per square meter (W/m^2). Irradiance due to solar radiation is also called insolation.

1.10 Energy Budget

An energy budget for Earth's climate system can be thought of as the amount of energy into the system equals the amount of energy out of the system. If the climate system is in equilibrium, these two are equal (energy out equals energy in). However, the Earth has an atmosphere that absorbs energy in the form of infrared radiation. Energy coming into the atmosphere is in the form of shortwave radiation and energy going out is in the form of longwave radiation. The Earth's atmosphere is transparent to ultraviolet radiation but the gases in the atmosphere (mainly water vapor and carbon dioxide) trap much of the infrared radiation given off by the Earth's surface. This entrapment of energy by atmospheric gases (called greenhouse gases) is what causes the Earth to be able to support life at an average global temperature around 15°C (59°F). Without the atmosphere, Earth's temperature would be about −15°C (5°F), too cold to be comfortable for humans.

1.11 Affected Weather

Climate scientists have been warning since about the mid-1980s that the Earth would warm to the point that it would begin to affect the weather. A warmer atmosphere causes more water to evaporate from the ocean, lakes, streams, and soils. The extra water in the atmosphere will lead to more severe storm activity, including hurricanes and tornadoes, heavier rainfall and flooding in some areas, and dryer deserts in others. We are seeing this today in some weird weather that is becoming the new normal in many areas of the globe.

There are many people who deny that human activity is disrupting our climate but they are a small minority in the general public and nearly non-existent in the climate science community. In 2009, a large number of emails between climate scientists were stolen and released on the Internet, many of them altered or selectively edited. This illegal act has been dubbed "Climategate" and because of its influence in the "debate" about climate change and global warming, warrants further discussion in later chapters.

1.12 Hockey Stick Controversy

The "hockey stick" is a diagram attributed to Michael Mann and colleagues drawn for a paper in 1998 from a variety of sources including proxies from dendrochronology that showed a sharp increase in temperatures during the final years portrayed on the graph (see Fig. 1.5 below). The graph and the research on which it was based were groundbreaking. No one had previously compiled these data and put them together so convincingly.

The Mann, Bradley, and Hughes (MBH) 1988 paper was the first quantitative hemispheric–scale reconstruction going back in time to 1400. It was a landmark paper. In a 1999 paper, the authors extended the reconstruction back to 1000 and it was the later graphic that was prominently featured in the IPCC 2001 AR3 (TAR) Report (see Fig. 1.5).

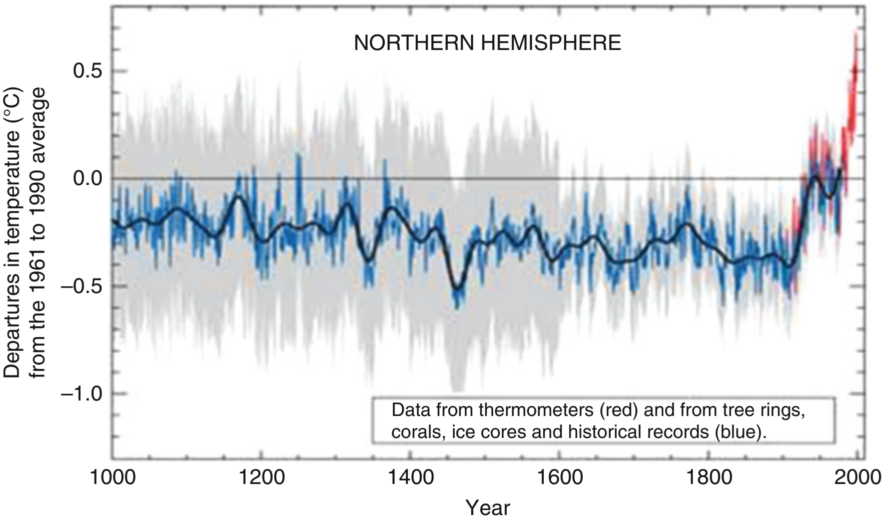


Fig. 1.5 The plot of temperature for the past 1,000 years (the "hockey stick" graph) (Originally published in GRL in 1998 by Michael E. Mann, Raymond S. Bradley, and Malcom K. Hughes and relied upon and republished by the IPCC in their Third Assessment Report (AR3) in 2001)

Much criticism of the graph ensued and it became a favorite of the denialist group, but most subsequent scientific papers supported the basic message of the hockey stick; that the Earth is warming and a great deal of the warming has occurred in the last half of the twentieth century. More than 12 subsequent scientific papers, using various statistical methods and combinations of proxy records, produced reconstructions broadly similar to the original MBH hockey-stick graph, with variations in how flat the pre-twentieth century "shaft" appears. Almost all of them supported the IPCC conclusion that the warmest decade in 1,000 years was probably that at the end of the twentieth century.

The first decade of the twentieth century was even warmer than the last decade of the twentieth century and scientists have seen a leveling off of the rise in temperature in the past several months of the year 2011, which ironically has been attributed to coal-fired power plants in China and India that emit sulphur aerosols that have slowed the warming trend. Of course, this is a temporary situation and not a good environmental one, because the coal-fired power plants are using high-sulphur coal and emitting sulphur into the atmosphere which in turn is causing acid rainfall and adding to ocean acidification.

Actually, the appearance of "climategate" in web searches and the occasional article one hears about or comes across, is a relic or an anachronistic episode still being held on to by skeptics and deniers. In March of 2010, the British House of Commons Science and Technology committee released results of their investigation into the scandal that revealed nothing in the emails conflicted with the scientific consensus that "global warming is happening and that it is induced by human activity."

Additional Readings

Ammann, C., et al. (2007). Solar influence on climate during the past millennium: Results from transient simulations with the NCAR Climate Simulation Model. *Proceedings of the National Academy of Sciences of the United States of America, 104*(10), 3713–3718. doi:10.1073/pnas.0605064103. Bibcode 2007PNAS..104.3713A. PMC 1810336. PMID 17360418.

Henig, J. (2009, December 11). FactCheck: Climategate doesn't refute global warming. *Newsweek*.

Jonsson, P. (2010, July 7). Climate scientists exonerated in 'climategate' but public trust damaged. *Christian Science Monitor*, 2.

Mann, M. E., Bradley, R. S., & Hughes, M. K. (1998). Global-scale temperature patterns and climate forcing over the past six centuries (PDF). *Nature, 392*(6678), 779–787. doi:10.1038/33859. Bibcode 1998Natur.392..779M.

Mann, M. E., Bradley, R. S., & Hughes, M. K. (1999). Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations (PDF). *Geophysical Research Letters, 26*(6), 759–762. doi:10.1029/1999GL900070. Bibcode 1999 GeoRL..26..759M.

Mooney, C., & Kirshenbaum, S. (2010). *Unscientific America: How scientific illiteracy threatens our future*. New York: Basic Books. ISBN 046501917X.

Royal Society. (2005). Joint science academies' statement: Global response to climate change. *Renewable Resources Journal, 23*(3), 19–20.

Ruddiman, W. F. (2005). *Plows, plagues, and petroleum: How humans took control of climate*. Princeton: Princeton University Press. ISBN 0-691-12164-8.

Tollefson, J. (2010, March). Attack sparks memories of McCarthy witch-hunt. *Nature News* (Nature Publishing Group), *464*(149), 149. doi:10.1038/464149a.

Chapter 2
Scientific Principles

Abstract An introduction is given to scientific principles including the laws of thermodynamics and the differences between natural laws, hypotheses, and theories. The concept of geologic time is introduced with examples given of the age of the Earth, the time it takes for climate to change, and examples from the geologic record. Scientific notation is described with examples from very large and very small numbers. Some of the jargon used by climate change scientists is defined. Some early scientists are named from Pliny the Elder to Karl Popper along with their main contributions. Chaos theory is introduced as is the "butterfly effect." The concept of multiple working hypotheses is explained.

Keywords Heat • Thermodynamics • Philosophy • Adiabatic • Feedback • Forcing • Orbital • Tectonic • Entropy • Internet • Climate • Change • Energy • Misinformation • Disinformation • Climategate • Hothouse • Icehouse • Deduction • Induction • Heliocentrism • Hypotheses • Theories • Logarithms • Geologic

Things to Know

The following is a list of things to know from this chapter. It is intended to serve as a guide of emphasis for the student to keep in mind while reading this chapter. It is not intended to be a complete list of "things" in this chapter or on this subject and your instructor may introduce additional topics. Before finishing with this

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_2,

chapter, each of the “Things to Know” should be understood and can be used for review purposes. This list may not include all of the topics and concepts required by your instructor.

Things to Know	
Aristotle	Conservation of Energy
Isaac Newton	W/m^2
Global Warming	Adiabatic Process
Earth’s Energy Imbalance	Richard Feynman
Climate Change	Greenhouse Effect
Joule	Enhanced Greenhouse Effect
Climate Forcing	Climate Feedback
Geologic Time	Watt
Geologic Time Scales	Orbital Events and their Time Span
Tectonic Events	Glacial-Deglacial Events
Historical Events	Age of the Earth
Empiricism	Francis Bacon
Karl Popper	Induction
Deduction	Models and Simulations
T. C. Chamberlin	Laws of Thermodynamics
Natural Science	Scientific Notation
Calculus	Heliocentrism

2.1 Introduction

Scientific principles are those principles that scientists use to conduct scientific work and participate in advancing the knowledge base of humankind. It is not possible to cover all of the principles of science in this volume so only those important to climate change science will be considered here. However, some scientific principles are comprehensive and apply to all scientific studies and these will be briefly considered.

Scientific principles are quite varied. It often depends upon the science as to what principles apply, but there are general principles that all scientists use and those are the ones discussed in these beginning sections of Part I. Without an understanding of the principles of scientific work it is difficult to appreciate what science is all about and the contributions that scientists have made to our way of life and understanding of the world around us.

The concept of the expanse of geologic time is basic to the science of climate change and is presented in this introduction as are the durations of certain climate shifts in the fairly recent and geologic past. The age of the Earth is given as is reference to the geologic time scale. The geologic time scale is shown graphically in an appendix (Appendix I).

The philosophy of science is introduced early in this text beginning with the ancient Greeks and the origin of empirical approaches to science. Major advances in climate and Earth science are introduced with those scientists who first presented them; a few of the individual scientists who made important contributions to learning and to climate science are briefly discussed.

The scientific method is reviewed and examples given as are uses of scientific notation, the difference between hypothesis and theory, and a synopsis of the way science is conducted in the real world. An introduction to global warming and some of the evidence for it is given along with examples.

Denialism is introduced and some of the reasons for it are discussed. Denialism is the tendency to ignore facts when presented with an abundance of them. Denialism in climate science and global warming shares much in common with other proven facts of science, such as the denying of organic evolution.

While there are multiple causes of climate change, the majority of the global warming of the past 50 plus years has been and is being caused by humans burning fossil fuels and cutting down trees and changing the natural landscape. As the reader progresses in this text it will become apparent what the current drivers are that cause the Earth's surface, ocean, and atmosphere to warm, what the causes are, the data supporting them, and what can and should be done about them.

2.2 Internet Searches

A search of the Internet by one of the available search engines such as Google for "scientific principles" will provide one with a list of a variety of subjects. A dictionary of scientific principles, such as the aptly named "*Dictionary of Scientific Principles*" by Stephen Marvin lists over 3,000 principles from mathematics, physics, astronomy, and other subjects including some non-scientific subjects such as philosophy. Only a small number of scientific principles are discussed in this current volume; the scientific principles necessary to lay the foundation for the study of climate change science.

2.3 The Warming Earth: Heat and the Principles of Thermodynamics

As climate is about energy and its transfer throughout the Earth system and heat is energy, the laws of thermodynamics apply. Thermodynamics deals with heat, pressure, work, and volume and these can be applied to gases and the atmosphere is made up mainly of gases. As a matter of fact, the principles of thermodynamics grew out of the development of the steam engine and the principle that pressure is inversely proportional to volume. As pressure increases, volume decreases. When heated, gases expand.

There are three main laws of thermodynamics which were defined first and a fourth law or principle called the Zeroth Law that was defined later. The names First, Second, and Third laws were kept.

The four laws of thermodynamics are discussed in the following sections.

2.3.1 The Zeroth Law of Thermodynamics

The zeroth law states that if two systems are in thermal equilibrium with a third system, they are also in thermal equilibrium with each other.

Although the concept of thermodynamic equilibrium is fundamental to thermodynamics, the need to state it explicitly as a law was not widely perceived until it was stated in the 1930s, long after the first, second, and third laws were already widely understood and recognized. Hence it was numbered the zeroth law. The importance of the law as a foundation to the first through third laws is that it allows the definition of temperature in a non-circular way without reference to entropy.

Entropy is defined by the second law of thermodynamics and has to do with the buildup of energy as work is accomplished. Additional information on entropy may be found at the following web site: http://www.entropylaw.com/entropyenergy.html.

The Zeroth Law is often stated as follows: "If A and C are each in thermal equilibrium with B, A is also in equilibrium with C." If A, B, and C are in thermal equilibrium, then there is no net change of energy. If two objects of different temperature are brought into physical contact, they will eventually reach thermal equilibrium and this is also true for a third object.

There are some thermodynamic processes in which there is no heat transfer. Climate scientists call this type of process an adiabatic process and there are simple equations which relate the pressure and temperature of a gas for an adiabatic process. An adiabatic climatic process involves no heat exchange.

2.3.2 The First Law of Thermodynamics

The first law of thermodynamics distinguishes between two kinds of physical processes, namely energy transfer as work, and energy transfer as heat. Heat is important to climate change science. Energy can be changed from one form to another, but it cannot be created or destroyed. It tells how this shows the existence of a mathematical quantity called the internal energy of a system. The internal energy obeys the principle of conservation of energy but work and heat are not defined as separately conserved quantities. The first law is sometimes called the "conservation of energy law" and can be applied to the Earth's radiation budget.

The energy entering, reflected, absorbed, and emitted by the Earth system are the components of the Earth's radiation budget. Based on the principle of conservation of energy, this radiation budget represents the accounting of the balance between incoming radiation, which is almost entirely solar radiation, and outgoing radiation, which is partly reflected solar radiation and partly radiation emitted from the Earth system, including the atmosphere. A budget that's out of balance can cause the temperature of the atmosphere to increase or decrease and eventually affect Earth's climate. The units of energy employed in measuring this incoming and outgoing radiation are Watts per square meter (W/m^2).

The first law of thermodynamics states that the total amount of energy in the universe is constant. This means that all of the energy has to end up somewhere, either in the original form or in a different from. We can use this knowledge to determine the amount of energy in a system, the amount lost as waste heat, and the efficiency of the system.

2.3.3 The Second Law of Thermodynamics

The second law of thermodynamics distinguishes between reversible and irreversible physical processes. It is sometimes referred to as the "law of entropy." It tells how this shows the existence of a mathematical quantity called the entropy of a system, and thus it expresses the irreversibility of actual physical processes by the statement that the entropy of an isolated macroscopic system never decreases.

The second law of thermodynamics has been stated in many ways. Rudolf Clausius, one of the principal founders of the field of thermodynamics, perhaps said it best, as follows:

> Heat generally cannot flow spontaneously from a material at lower temperature to a material at higher temperature.

The climate change or global warming skeptic tells us that, because the air including greenhouse gases is cooler than the surface of the Earth, it cannot warm the Earth. If it did, that means heat would have to flow from cold to hot, in apparent violation of the second law of thermodynamics.

So have climate scientists made an elementary mistake? No! The skeptic is ignoring the fact that the Earth is being warmed by the Sun, which makes all the difference. Consider the analogy of a blanket covering a human body. The blanket does not produce heat so it is cold when placed against a human body. With time, however, the blanket causes the body to warm because it traps heat given off by the human body. This is similar to the "blanket" provided by the greenhouse gases in the atmosphere holding in heat from the Earth. The heat warms the Earth which has been warmed by the Sun. The greenhouse gases in the atmosphere do re-radiate some heat back to the Earth but the primary heat source is the Sun.

The second law of thermodynamics states that the disorder in the universe always increases. As the disorder in the universe increases, the energy is transformed into less usable forms. Thus, the efficiency of any process will always be less than 100%.

2.3.4 The Third Law of Thermodynamics

The third law of thermodynamics concerns the entropy of a perfect crystal at absolute zero temperature, and implies that it is impossible to cool a system to exactly absolute zero.

The third law of thermodynamics tells us that all molecular movement stops at a temperature we call absolute zero, or 0 K (−273°C). Since temperature is a measure of molecular movement, there can be no temperature lower than absolute zero. At this temperature, a perfect crystal has no disorder.

These laws state that a concentrated energy supply must be used to accomplish useful work. But these four laws are just four of many laws used by scientists to try to understand how the world and the Universe work.

2.4 Climate Scientists

Climate scientists, or climate change scientists, those that we are concerned with here, are those scientists that deal with climate that has changed in the past, is changing today, and will undoubtedly change in the future. Climate change scientists are not the same as climatologists, although some may be climatologists by training, but are scientists that study climate changes over time scales not normally studied by those who have a classical training in climatology. Climate change scientists study climates that have evolved over thousands, millions, tens and hundreds of millions, and billions of years. Climate change scientists may have started their careers as physicists, biologists, geologists, chemists, oceanographers, or one of the other specialties of science. Rarely do they begin their professional careers outside one of the scientific disciplines.

Wikipedia defines climatology as follows:

> Climatology (from Greek κλ μα, *klima*, "place, zone"; and -λογ α, *-logia*) is the study of climate, scientifically defined as weather conditions averaged over a period of time, and is a branch of the atmospheric sciences. Basic knowledge of climate can be used within shorter term weather forecasting using analog techniques such as the El Niño – Southern Oscillation (ENSO), the Madden-Julian Oscillation (MJO), the North Atlantic Oscillation (NAO), the Northern Annular Mode (NAM), the Arctic oscillation (AO), the Northern Pacific (NP) Index, the Pacific Decadal Oscillation (PDO), and the Interdecadal Pacific Oscillation (IPO). Climate models are used for a variety of purposes from study of the dynamics of the weather and climate system to projections of future climate.

Skeptics and deniers of climate change (usually not scientists) are often quoted as stating that climate has changed in the past and is always changing, so the current changes and global warming are natural and mankind has had little to do with it. Hence, nothing can be done about climate change; it's part of a natural cycle. As will be seen in this text, recent and current global warming is not natural and is not part of a natural cycle although natural climate change has happened in the past. There are undeniable human fingerprints on the current warming of the Earth. The most recent warming is being caused largely by the burning of fossil fuels and the process of deforestation, as we will see going forward in this text.

Individual climate scientists, chosen for their major contributions, will be discussed later in this text. Climate change scientists are also climate scientists and their major field of study is climatology. However, in order to understand current climate change and trends and perhaps to be able to forecast the future of climate on Earth, climate change scientists must know more than climatologists have had to know in the past, for new tools have recently become available to them and their interpretation requires knowledge not available to climatologists trained prior to the 1970s.

2.4.1 Scientific Laws and Climate Scientists

Scientific laws or principles that are of interest in this text are those that climate change scientists use to conduct scientific studies, including experiments; to be able to start out right to end up right, to carefully gather data in a prescribed manner, to logically interpret these data, draw valid conclusions, formulate explanatory hypotheses and theories, conduct valid tests and experiments, document and publish the results, and produce new knowledge. Science is all about producing new knowledge.

Non-scientists often see scientists as discovering new things step by step and proceeding or plodding along in a straight line until all the problems of the Universe are solved. It is true that knowledge is cumulative. We know much more about the atom now than we used to know and within the past 100 years or so new subatomic particles have been discovered one after another. But most science does not proceed in a straight line. Often, many new things are discovered at once and some may be totally unexpected. It is the unexpected that makes science so interesting; the "Eureka!" or "Aha!" moment, suddenly realizing one has an entirely new species of fossil or living fish, or equation that nobody has ever seen before. It needs a name and you can name it, thus living forever in the annals of science. This is one of the least important aspects of science but it is difficult to overestimate the thrill of discovery.

The world of science is no different from the world of anything else. It is the same world, with the same problems, the same solutions, the same engineering. It is only mysterious because only relatively few people truly understand it. And this is largely the fault of scientists, those who practice doing science. Mostly scientists have been content to pursue their research and have not been either willing or able to inform the public of its importance or of its methods and successes. As a result, many have a Frankensteinian view of science; of the "mad scientist" in his laboratory with lightning striking all around.

Scientists are beginning to understand that they must communicate more often, more effectively, and with more foresight with the media and the public than in the past and this is especially true for climate change scientists.

Climate is familiar to everyone as weather. Climate has been described as weather over a long period of time usually taken to mean at least 30 years. But it is more than weather. Weather is forecast days and weeks in advance. Climate deals with decades, years, millennia, and millions and billions of years in the past as well as projections of climate into the future.

Although climate change science has established that the Earth is undergoing a warming trend; it is becoming warmer and the number of supporting published scientific papers is growing exponentially, news about this strengthening evidence for global warming is tending to only trickle out to the public in bits and pieces. The individuals representing the news media (radio, television, the blogosphere, newspapers, and magazines) have shown an amazing lack of leadership in reporting the truth about global warming. It's as if there is an attempt by them to present the two sides equally when they are anything but equal. Approximately 97% of climate scientists recognize that the Earth is warming and that global warming is real. There are not two equal sides to the science of climate change just as there are not two equal sides to the sciences of plate tectonics or evolution.

The Earth's climate is changing and the world's population must get the proper information to be able to deal with it. The press and other media must extract the facts concerning global warming and report these to the public; but it is also the climate change scientist that must communicate these changes to the media and the media, in addition to the scientist, must communicate these changes to the public.

In order to understand climate science or any science it is necessary to first understand some basic principles, and these are not difficult. There is no grand mystery about science or scientists. The basic principles of science are those with which most people are familiar; such as logical and critical thought, organization, documentation, the ability to write complete sentences, persistence, patience, and the ability to communicate the results of their science to each other, the media, and the public.

Individual scientists don't work 24 hours a day in a lonely laboratory with a subservient assistant who brings him or her coffee or tea. Scientists today usually work as a team of individuals, some with different backgrounds. For example, a computer programmer may need a piece of information from a chemist in order to write a formula for the climate program that the group is using. Often geologists need information from a physicist or an oceanographer to complete a theory or hypothesis.

Scientists are also humans and go to their homes after the work day and play with their video games, spouses, children, and grandchildren. Most can be said to be "normal" individuals. They participate in their communities, go to sporting events, go camping, help their children and their friends with their school work, judge science fairs, travel to conferences, and in general attempt to enjoy life.

2.5 Scientific Jargon

It is true that each science has its own set of jargon, as does medicine, but once past the jargon almost anyone can become a scientist with the proper education and set of personal values. Most of the jargon of climate science is found in the Glossary that is at the end of the text but like any science there are a few basic terms that must be defined here for the purpose of getting started. A partial list of these terms is given below.

The following definitions are important and necessary when beginning a discussion of climate change science:

- **Joule** – A unit of energy that is defined as the work required to produce one Watt of power for one second, or one "Watt second" (W·s).

- **Watt** – The unit, defined as one joule per second, measures the rate of energy conversion or transfer. In climate science, energy is measured as Watts per square meters (W/m^2).
- **Global climate change** – A forcing of the Earth's climate system to change. The changes are worldwide, not regional or local, and may include a warming or cooling.
- **Global warming** – A heating up of the Earth system either by forcing or by feedbacks, usually in combination. This is occurring worldwide but there may be exceptions locally and regionally.
- **Radiation** – The Sun radiates energy in all directions and that energy striking Earth warms the atmosphere, land, and oceans as shortwave or ultraviolet radiation. Some of the energy that impacts Earth is re-radiated back to space as longwave radiation. Not all of this energy escapes to space and some of it is trapped in the atmosphere by greenhouses gases (GHGs) that re-radiate energy back toward Earth.
- **Ultraviolet (UV) radiation** – Sunlight received by the Earth's atmosphere is in the form of shortwave ultraviolet radiation, visible light, and some other wavelengths.
- **Infrared (IR) radiation** – Heat given off by the Earth is in the form of longwave infrared radiation.
- **Greenhouse effect** – Warming of the lower atmosphere by greenhouse gases that trap energy and re-radiate it back to Earth. Carbon dioxide (CO_2) and water vapor are two of these greenhouse gases. Carbon dioxide consists of one carbon atom with an oxygen atom bonded to each side. When its atoms are bonded tightly together, the carbon dioxide molecule can absorb infrared radiation and the molecule starts to vibrate. The vibrating molecule will emit the radiation again and it is likely to be absorbed by another greenhouse gas molecule, or radiated to outer space, or back to Earth's surface. This absorption-emission-absorption cycle serves to keep heat near the Earth's surface, effectively insulating the surface. The greenhouse effect is that which allows living forms to exist on Earth. A portion of the Sun's radiant energy is reflected back to space by the top of the atmosphere (TOA). The Sun's rays are UV radiation. Some UV radiation is absorbed by the atmosphere, the land, and the ocean. The land and ocean, warmed by the Sun re-radiate heat energy as IR radiation. Without the greenhouse effect, Earth's surface temperature would average at least −15°C based on its size, constitution, and distance from the Sun.
- **Enhanced greenhouse effect** – Increased greenhouse effect causing further warming of the Earth because of the addition of greenhouse gases to the atmosphere by the burning of fossil fuels (coal, petroleum, natural gas) and deforestation. We are now living on an Earth that is experiencing an enhanced greenhouse effect due to human (anthropogenic) activities.
- **Earth system** – The solid Earth, the oceans, the Earth's interior, the gases making up the atmosphere, the Solar System, and any other influences which may affect the Earth. The Earth system includes the whole Earth; past, present and future.

- **Climate forcing** – A natural or anthropogenic (man-made) cause for climate to change. A force that causes climate change. An example of forcing is the amount of radiation given off by the Sun; if the Sun is more active, radiation increases that strikes the Earth, the planet warms; if the Sun's radiation output decreases, the Earth cools. A forcing causes the planet's climate system to build up or lose heat and this is what caused the climate to change.
- **Climate feedback** – A response to a forcing causing an amplification or reduction of the forced climate change. A climate feedback can either be positive or negative. A positive feedback causes a forcing to increase; a negative feedback stops or slows a forcing from increasing; a negative feedback could also cause a forcing to be reversed.

2.6 Communication Between Scientists and the Public

The communication between scientists and the public, especially via the media, is a problem that has proven difficult for scientists in most areas of science.

Most scientists are content to just do science and let others do the communicating. Many large organizations that employ scientists, such as the U.S. National Laboratories and large private companies (e.g., tobacco, chemical, or energy companies) have a public relations department or an organization within the organization that deals with the public. This organizational group usually does not have scientists on its staff and often basic scientific facts and concepts are lost in the communication between the scientist and the public relations group, or between the public relations group and the media, or between the media and the public. The result is miscommunication and the loss of, or the distortion of, basic scientific knowledge. The public is often misinformed.

Misinformation, unintentionally false, may be passed along to the public. And this is unfortunate but is oftentimes corrected. If a journalist makes a mistake, the honest journalist is usually quick to correct it. However, most of the mistaken information passed to the public is disinformation (intentionally false) due to vested interests or ignorance or both. And disinformation is not corrected because it is intentional.

Another situation that has occurred recently (2009 and 2011) is exemplified by emails stolen from a group of climate scientists and selectively edited and forwarded to global warming skeptics and deniers on the Internet. This came to be known as "Climategate." The news media picked up the story and it made headlines all over the world. At least nine independent investigations have been conducted (including one by the U.S. Congress and another by the U.K. House of Commons). Even though all of these investigations determined that the emails didn't change the science that global warming was occurring, the news media largely ignored the facts resulting from the investigations. The corrections were no longer news and many citizens in the general public continue to be misinformed.

2.7 The Concept of Time

Climate change science deals with scientific principles and it also deals with climate change over time. Climate change occurs over decades, years, millennia, and millions of years. Time is something we all experience but it is not something that is easily defined. For our purposes, one way to look at time is to divide time into the past, present, and future. The following are statements that refer to time:

- The U.S. Civil War began in 1865;
- John Q. was born at 5:14 am, November 2, 2000;
- The War of 1812 was fought between the Revolutionary War and World War I;
- The Earth was formed about 4.54 billion years ago;
- Warren C. completed the Boston Marathon in 5 h and 32.5 min;
- Martin's fastball has been clocked at 95.3 miles per hour.
- A Russian satellite will enter Earth's atmosphere on June 10, 2050.

From the above statements it can be seen that some references to time are in absolute time, such as the birth of John Q. and the age of the Earth. Others are in reference to an interval of time, such as Martin's fastball travelling at 95.3 miles per hour. Another statement of time is by reference to other events, such as the War of 1812.

Such statements may be interesting to some but none tells us what time is. A dictionary definition of time is as follows:

> A part of the measuring system used to sequence events, to compare the durations of events and the intervals between them, and to quantify rates of change such as the motion of objects (from Wikipedia, the Free Encyclopedia).

So time is a system devised by humans to measure events, such as the start, duration, prediction, or end of an event or sequence of events.

In order to measure something, one must have a scale, such as a clock or reference point, like the start to a race or the beginning of an event; a week, month, or a year measured on a calendar; or a birth date. It can be stated in a relative sense, such as the U.S. Civil War occurred after the Revolutionary War and before World War One. Or it might be stated as an event beginning on a certain date, hour, minute and second of time. Time may be measured on a relative scale or stated as an absolute time.

Geologic and climatic events take place over a variety of time scales: decades, years, hundreds, thousands, and millions of years. Geologic time is usually expressed in the thousands, millions, or billions of years. The diagram below (Fig. 2.1) shows timelines for historical and climatic events.

The events representing geological time (Fig. 2.2) take place over millions of years (such as tectonic or mountain building episodes), thousands of years (orbital, glacial, interglacial episodes), and human events take place over minutes, hours, days, weeks, decades, centuries, and possibly a couple of thousands of years (such as historical events, like year 01–2012 AD).

Geologic time is measured on a scale that is divided into major events, like the first appearance in the fossil record of trilobites (Cambrian), or the first

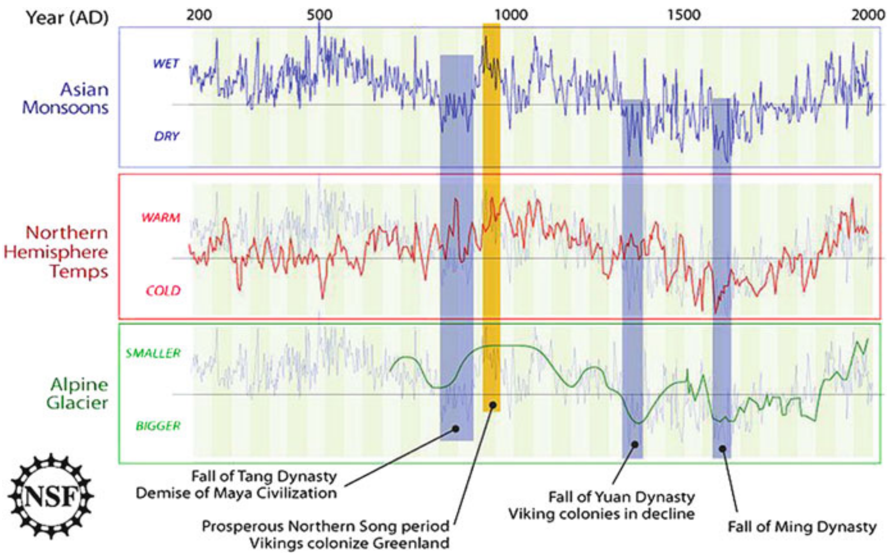


Fig. 2.1 Time scales for different climatic and historic events for the past 2,000 years. *Blue* – Asian monsoons; *Red* – Northern Hemisphere temperatures; *Green* – Alpine glaciers (U.S. National Science Foundation, Public Domain)

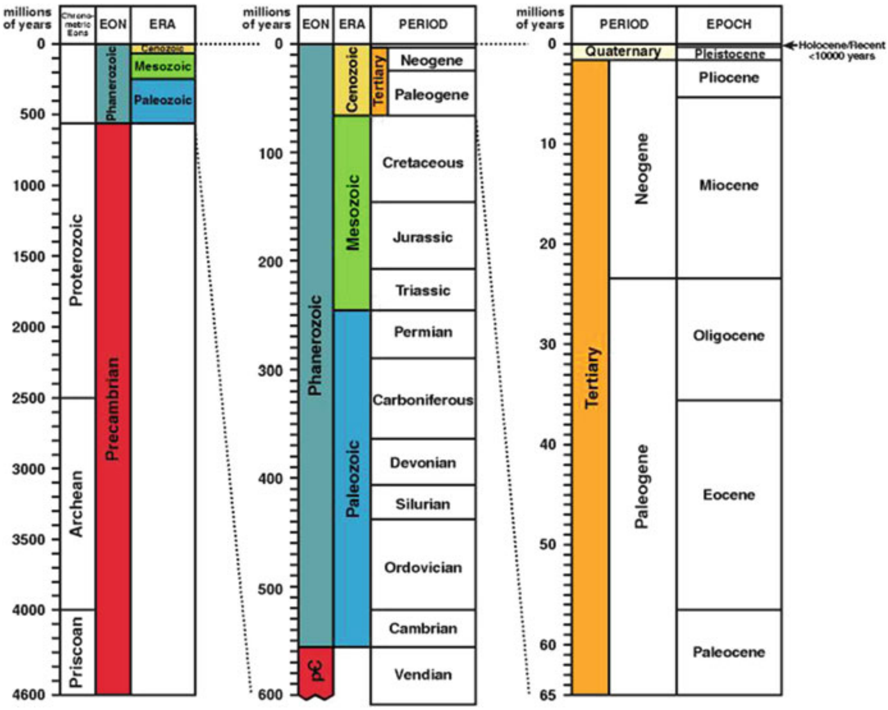


Fig. 2.2 The major divisions of geologic time (From Copyright © 1996–1997 by Andrew MacRae, University of Calgary, Alberta, Canada)

human-like fossils (4.4 million years ago), the extinction of the dinosaurs (the Cretaceous-Tertiary boundary 65.5 million years ago), or the first signs of life in the fossil record (3.5 billion years ago). The geologic time scale is shown diagrammatically in Fig. 2.2 and Appendix I, and it is important that one be familiar with the major subdivisions of geologic time, such as periods and epochs shown in Appendix I as soon as possible. The geologic time scale is used throughout this text and events are given in either absolute time or relative time, or both.

Tectonic (mountain building) events take place over millions of years; orbital events, changes in Earth's orbit, take place over hundreds of thousands of years; glacial-interglacial events take place over thousands of years; and historical events take place over hundreds or thousands of years.

How is time expressed? In a preceding paragraph, Cambrian, 4.4 million, 3.5 billion, and the Cretaceous-Tertiary boundary are all used to express time, either as years ago or by using geologic names such as Cambrian, Cretaceous, and Tertiary. From the geologic column in Fig. 2.2 and Appendix I, it is possible to put both of these means of expressing time into a geological perspective; it is possible to place the above events into a timeframe of geologic time.

Earth is about 4.54 billion years old; this means the Earth originated 4.54 billion years ago or 4,540,000,000 years ago, or 4.54×10^9 years ago. The first 4,000,000,000 (4 billion) years of Earth history, as interpreted by the rocks that were formed during that length of time, does not tell us very much about the events that occurred during that interval. The rocks representing that time interval are just too complex and reworked to reveal much about the time represented. Geologists refer to that length of time as the "Precambrian" or Precambrian time. The Precambrian is not a formal name but refers to a geologic time interval which preceded the Cambrian Period (Fig. 2.2).

Five hundred and forty million years ago or 540,000,000 (540 million) years ago, or 5.4×10^8 years ago, something happened that allowed organisms living then to be able to extract calcium carbonate and silica from sea water to make hard parts. These hard parts are today preserved in rocks of the Earth and allow geologists (and paleontologists) to interpret events surrounding these organisms; how they lived, where they lived, how they died, and how they evolved.

The Earth's climate began to cool about 35 million years ago, 35,000,000 years ago, or 3.5×10^7 years ago and the continent of Antarctica began to ice over (glaciers began to form on the continent). The Earth continued to cool and the planet experienced several ice ages; then it warmed and cooled again and again in cycles.

The last continental glacial advance on Earth reached its maximum extent about 18,000 or 1.8×10^4 years ago and glaciers have been retreating ever since, for the last 18,000 years, with relatively short periods of stoppage and then expansion.

In the last 260 plus years, since the Industrial Revolution, the retreat of Earth's glacial ice has increased due primarily to carbon dioxide emissions and other greenhouse gases from the anthropogenic (humankind's) burning of fossil fuels (coal, petroleum, and natural gas); and it is now happening so rapidly that it has become a problem of global proportions and concern.

2.8 From Hothouse to Icehouse

Climate change has been happening throughout much of Earth's history on scales of decades, hundreds, thousands, millions and billions of years. Temperatures on Earth have gone from "hothouse" to "icehouse" and back again in cycles throughout Earth's history. But the climate changes of the distant past are natural; they have had natural causes that scientists can identify. The most recent climate changes beginning about 10,000 years ago, and especially the last 260 or so years, have been the result of the activities of humankind and their impact on the Earth's climate.

There is abundant evidence that humans are living in a period of Earth history that is unique because of these effects of humankind on the planet. Because of this, the current time is being referred to as the Anthropocene Epoch. The Anthropocene began approximately 8,000 years ago with the advent of agriculture, when humans began to grow food for more and more people; the end of the hunter-gatherer stage of human existence. The impact of agriculture on the atmosphere is, of course, continuing today with agriculture, the burning of fossil fuels, and deforestation and these impacts will continue well into the future. These different impacts that humans are having and have had on Planet Earth will be discussed in later sections of this text.

2.9 Earth's Energy Imbalance

When the amount of energy entering a system equals the energy released by a system, the system is said to be in equilibrium. On planet Earth, if the amount of energy going out of the system equaled the amount of energy that was coming into the system, the system would be in a state of energy equilibrium. Earth currently does not have a condition of energy equilibrium because more energy is coming into the climate system than is being released into space. This energy imbalance is what is causing the Earth to warm.

The amount of energy coming into the Earth's climate system is measured precisely at the top of the atmosphere by satellites. Satellites also precisely measure the amount of energy escaping back into space. The latter is less than the former and this has been measured since the late 1970s when satellites capable of measuring the Earth's energy were placed into Earth orbit.

Earth's energy imbalance is discussed in more detail later in this text.

2.10 An Introduction to Science

Science is the use of natural laws and principles to further the advance of human knowledge. In this respect, science is distinguished from non-science by using natural laws to solve problems and gain understanding. Scientific research and empiricism are basic to expanding human knowledge.

Most of western thought can be traced back to the ancient Greeks where we see the beginnings of attempts to understand the natural world. This period of human history marks the end of the exclusive practice of mysticism to explain natural laws and events.

Modern science is generally traced back to the early modern period during what is known as the Scientific Revolution of the sixteenth and seventeenth centuries. The Scientific Revolution was marked by a new way of studying the natural world, by methodical experimentation and observation aimed at defining "laws of nature."

Examples of the basic sciences are astronomy, biology, chemistry, physics, and geology. Each of these sciences has areas of specialization, such as biology (ecology, genetics), chemistry (organic, inorganic, and analytical), Earth Science (climatology, oceanography), physics (experimental, theoretical), and geology (petrology, mineralogy, paleontology). Each of the sciences is experimental and observational with human knowledge advancing greatly by each one of them. There are also interdisciplinary sciences such as geophysics, biochemistry, etc.

Breakthroughs in biology are such things as mapping the human genome and discovering the structure of DNA. Breakthroughs in chemistry are all around us with new organic compounds and medicines. Breakthroughs in physics are greater understanding of the cosmos and the atom. Breakthroughs in geology have been the concept of plate tectonics and continental drift, and breakthroughs in Earth science are in the areas of climatology and climate change science.

2.10.1 Reasons to Study Science

There are many reasons to study science but perhaps the main one, at least for Earth scientists, is curiosity about the natural world. The answers to questions such as how did the Earth get to where it is today, why are hills and valleys where they are today, how did they get to be that way, where did humans come from? Why do humans exist? All of these questions have answers and scientists are the ones to provide them.

Curiosity drives science and scientific endeavors, or research. Richard Feynman, a physicist and one of the most respected scientists of the twentieth century and one of the scientists at Los Alamos Natural Laboratory who worked on development of the atomic bomb during WWII, described science to his students as follows:

> The principle of science, the definition, almost, is the following: The test of all knowledge is experiment. Experiment is the sole judge of scientific 'truth.' But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment, itself, helps to produce these laws, in the sense that it gives us hints. But also needed is imagination to create from these hints the great generalizations – to guess at the wonderful, simple, but very strange patterns beneath them all, and then to experiment to check again whether we have made the right guess.

Feynman also observed, "…there is an expanding frontier of ignorance…things must be learned only to be unlearned again or, more likely, to be corrected."

2.10.2 The Philosophy of Science

The philosophy of science is simply for one to strive to understand and to hopefully make the world a better place. This is also the philosophy of scientists. Making the Earth a better place to live is not easy and cannot be left only to chance because humans are having an adverse influence on our planet and have been having this kind of influence since at least the beginning of the Industrial Revolution in the mid-eighteenth century. If we accept the concept of the Anthropocene (*anthros*, "human"; *cene*, "new") as a legitimate interval of time, humans have been adversely affecting the planet for the past 10,000 years or before, since the first tree was chopped down or the first man-made fire was started.

Science has caused civilization to advance in many ways and some scientists have become well-known as a result: Galileo (the Earth's place in space relative to the Sun), Albert Einstein (relativity, $E = MC^2$), Charles Darwin (evolution and natural selection), Watson and Crick (DNA), Isaac Newton (basic laws of modern physics), Carl Sagan (astronomy), etc. Earth science has seen some of its scientists become well-known also, such as James Hutton (Uniformitarianism), Harry Hess (seafloor spreading), Michael Mann (the "hockey stick"), Phil Jones (CRU and stolen emails), Richard Alley (Earth: The Operator's Manual), etc. But scientists don't practice science to become well-known, famous, rich, or even notorious. They become scientists to advance knowledge of the world around them; to experiment, to test, and thereby expand the knowledge of the world around us.

Science usually advances in somewhat mysterious ways. A major breakthrough is most often announced to the press or someone wins a Nobel Prize, or someone invents a new device such as the cell phone or a new personal computer, electronic tablet or smart phone. Science advances in fits and starts. But it has made life on the planet much better in many ways. Advances in medical science are usually well publicized as they affect people directly; but so does climate change, even more so than medicine. Global climate change affects everyone on Earth and global climate change may eventually lead to the "four horsemen of the Apocalypse; famine, death, pestilence, and war," and will affect every living creature on Earth that is supported by the atmosphere; but then again it may not.

The second decade of the twenty-first century (2010–2019) is on pace to be the hottest decade ever recorded after the first decade (2000–2009) was the warmest ever recorded even though its rate of temperature rise has tailed off a bit. Introductory science students need to understand that the planet is getting hotter and know what is happening, why, and something about what needs to be and can be done about it, if anything.

Why do we study science and how do we study it? Why is science important? Let's next take a look at what some of the great thinkers of the past have taught us about why science and the acquisition of knowledge are important to mankind.

The basic philosophy of science can be traced from Aristotle through medieval times (500–1450 AD) to the present by discussing some of the different philosophers of science and how their ideas have evolved over time, especially those related to science in general and climate science in particular.

Philosophers of science have mainly been mathematicians due to their perception of the purity of mathematics (e.g., Descartes, Russell). Bacon, Newton, Popper and others, and their ideas, are briefly discussed in the following sections. The "black swan" metaphor is used in discussing empiricism.

The philosophy of science is as old as science itself. Philosophy has been described as "the love of wisdom" and it is difficult to distinguish from science. Science is also the love of wisdom or at least the love of knowing how to obtain the answers to problems. And solving problems and obtaining answers provide wisdom.

As the ancestors of modern man began to wonder about the things around him he began to ask the questions "what" and "why." And he found the answers to them slowly as he became more and more aware of his world as time passed.

The philosophy of science is classified as a subject in philosophy, not in science. Those who practice it for the most part are not scientists, but they have made contributions to how the world views science and scientists so it is pertinent to introduce it here, although others might disagree. "Philosophy of science is about as useful to scientists as ornithology is to birds," according to physicist Richard Feynman. In response to Feynman's quip, some philosophers have pointed out that it is likely that ornithological knowledge would be of great benefit to birds, were it possible for them to possess it.

Most ideas and the beginnings of western thought began with the ancient Greeks. Many ideas can be traced back in time to Aristotle, especially ideas about how knowledge is acquired.

2.10.3 Early History of Science

Science began when humans began to wonder about the world around them. Early humans were most likely terrified by natural events such as high winds, earthquakes, and lightning. Violent storms are today still frightening natural events and may be deadly when they spawn floods, tornadoes, and cyclones. Volcanic eruptions are still awe-inspiring and the early human inhabitants living near them were frightened of them and wondered what was causing them. Their early explanations were fantasy and superstition. They concocted gods and devils to explain the unknown and this may be witnessed today in modern society.

Humankind's curiosity is one of the most basic of human attributes. The need to know how something works and why it works is a basic part of human nature and curiosity fuels the need for humans to try and understand natural systems, such as the climate system. And the climate system is indeed complex and fluid and difficult to understand. But that is reason enough for climate scientists to work at understanding and specialists, such as oceanographers and glaciologists, to try to unravel bits and pieces of it. And climate change scientists use empiricism, induction, and deduction from which to draw their conclusions and to build their models.

Early scientists of note were Greek and Roman; such names as Aristotle, Pliny the Elder, etc. These were supplanted by English, German, and other European scholars after the Dark Ages and the Renaissance, such as Bacon and Newton, and then by more modern scientists.

2.10.4 Aristotle (384–322 BC)

Aristotle was a Greek philosopher whose writings included physics as well as many other subjects (e.g., metaphysics, linguistics, politics, biology, etc.) and is considered one of the founding fathers of Western philosophy. His views went a long way in shaping medieval scholarship and extended into the Renaissance and even today. His scientific views, both in the physical and biological sciences, and his explanation of logic form the basis for much of the later scientific and mathematical works in those fields.

Aristotle's views on logic and religion continue to be read. It is estimated that only about 1/3 of his works have survived but those that have are still being studied. He believed that knowledge was gained by empirical observation and experience.

Our attempt to justify our beliefs logically by giving reasons results in the "regress of reasons." Since any reason can be further challenged, the regress of reasons threatens to be an infinite regress. However, since this is impossible, there must be reasons for which there do not need to be further reasons, i.e., reasons which do not need to be proven. By definition, these are "first principles." The "Problem of First Principles" arises when we ask why such reasons would not need to be proven. Aristotle's answer was that first principles do not need to be proven because they are self-evident, i.e., they are known to be true simply by understanding them and understanding results from observation and experience.

Aristotle's empiricism was that knowledge begins with experience. We get to first principles through induction. But there is no certainty to the generalizations of induction. The "Problem of Induction" is the question 'How do we know when we have examined enough individual cases to make an inductive generalization.' Usually we can't know. Thus, to get from the uncertainty of inductive generalizations to the certainty of self-evident first principles, there must be an intuitive "leap," through what Aristotle calls "Mind." This ties the system together. A deductive system from first principles (like Euclidean geometry) is then what Aristotle calls "knowledge" ("*epistemê*" in Greek or "*scientia"* in Latin).

Aristotle's influence lasted longer in the Roman Catholic Church than it did in the philosophy of science. In the physical sciences, Aristotle's scientific views were supplanted by Newtonian physics.

2.11 Early Scientists

It is difficult to tell who the very first scientist was and it greatly depends on one's definition of scientist. We know that Aristotle's writings show that he used empiricism and deduction. He reasoned very much as scientists do today. But perhaps, and almost certainly, there were intelligent naturalists who reasoned from things that they saw around them and drew conclusions from those observations.

It is most likely that among our very early ancestors there were those that used their minds in a scientific way so it is unimportant to identify the first scientist even if we could; just as it is unimportant to identify the very first human ancestor. Physical anthropologists and human paleontologists might disagree but for our purposes we just need to trace the earlier interests in the natural world and climate change to be able to put our current ideas about climate change in historical perspective.

2.11.1 Pliny the Elder (23 AD–79 AD)

Pliny the Elder was a Roman scholar and naturalist who lost his life in the 79 AD eruption of the volcano Vesuvius, located in the Bay of Naples, Italy, which destroyed the cities of Pompeii and Herculaneum. Pliny was the leading naturalist of his day and wrote numerous volumes on what was then called natural history, including geology, botany, and zoology. He is referred to as Pliny the Elder because his nephew and adopted son, who wrote articles about his life and death, is referred to as Pliny the Younger (63–113 AD).

Pliny the Elder was the author of at least 75 published books, not to mention another 160 volumes of unpublished notebooks. His books included volumes on cavalry tactics, biography, a history of Rome, a study of the Roman campaigns in Germany (20 books), grammar, rhetoric, contemporary history (31 books), and his most famous work, his one surviving book, *Historia Naturalis* (Natural History), published in AD 77. Natural History consists of 37 books including all that the Romans knew about the natural world in the fields of cosmology, astronomy, geography, zoology, botany, mineralogy, medicine, metallurgy, and agriculture.

Pliny the Elder was on a ship in the Bay of Naples when the 79 AD eruption of Vesuvius began and, according to one story, he received a message from a friend who was in the vicinity of the volcano and asked to be rescued. Pliny took a fast boat to shore to rescue his friend and either died naturally on shore or was killed by the toxic gases issuing from the volcanic eruption. Additional information on the life and accomplishments of Pliny the Elder can be found at the following web site: http://www.livius.org/pi-pm/pliny/pliny_e2.html.

2.11.2 Claudius Ptolemy (c. AD 90–c. AD 168)

Claudius Ptolemy (c. AD 90–c. AD 168), was a Roman citizen of Egypt who wrote in Greek. He was a mathematician, astronomer, geographer, astrologer, and poet. He is credited with having written the only surviving comprehensive ancient treatise on astronomy in which he considered the known universe to be geocentric with everything revolving around the Earth. This model became known as the Ptolemaic Hypothesis or Ptolemaic model of the Solar System; that the Sun, Moon, and all the planets revolved around the Earth.

2.11.3 Nicolaus Copernicus (1473–1543)

Nicolaus Copernicus (1473–1543) was a Renaissance astronomer who first proposed that the Earth was not the center of the Universe or the Solar System. He proposed that the Sun was the center of the Solar System and the Earth revolved around it. Such a scheme is called a heliocentric cosmology or heliocentric theory. This concept radically changed the way humankind viewed the Earth and led to the beginning of modern astronomy. The concept began what is sometimes called the Copernican Revolution.

It is impossible to know exactly why Copernicus began to espouse the heliocentric cosmology as his reasons are lost to history. Despite his importance in the history of philosophy, there is a paucity of primary sources on Copernicus. His astronomical writings were few. Therefore, many of the answers to the most interesting questions about Copernicus's ideas and works have been the result of conjecture and inference, and we can only guess why Copernicus adopted the heliocentric system.

2.11.4 Galileo Galilei (1564–1642)

Galileo Galilei (1564–1642) was born in Pisa, Italy but spent most of his life near Florence. He was trained as a mathematician and taught mathematics at the University of Pisa and the University of Padua.

Galileo began to make telescopes after hearing of a similar magnifying device from the Dutch. He ground his own lenses and turned his telescopes to the night sky. It is said that in 2 months (in December and January, 1609), Galileo made more discoveries that changed the world than anyone has ever made before or since. He saw what he believed to be mountains on the Moon, to have proved that the Milky Way was made up of stars, and to have seen four small bodies orbiting Jupiter.

Galileo's observations resulted in his conclusion that the Earth and Moon revolved around the Sun, as Copernicus had theorized before him; that the Earth was in daily motion about its axis and in yearly motion around a stationary Sun. Galileo also discovered Sunspots and reported on these in 1612.

At the time Galileo began his work the Bible was interpreted literally by the Catholic Church and it was believed that the Earth was the center of the Universe. The theory of Claudius Ptolemy (85–165), a Greek astronomer and geographer, was that the Earth was at the center and all heavenly bodies revolved around it. In 1632, Galileo published *Dialogue Concerning the Two Chief Systems of the World – Ptolemaic* *and Copernican*, which favored the Copernican view. Until this publication, Galileo had received little notice from the Church. After its publication, the Inquisition banned its sale and distribution and ordered Galileo to appear before it in Rome. By this time, Galileo was in ill health and could not travel to Rome. He was found guilty in absentia and was condemned to lifelong imprisonment. The sentence in actuality amounted to house arrest and not imprisonment and Galileo continued to write and to have contact with his colleagues.

Galileo used observations (empiricism) to develop his support for the Copernican theory that the Earth revolved around the Sun and not vice versa, and Galileo is given credit for finally proving the Copernican theory.

2.11.5 Francis Bacon (1561–1626)

Francis Bacon (1561–1626) was an English philosopher and scientist and has been called the "father of empiricism" although, as we've seen, that title should be reserved for Aristotle. He established inductive methodologies for scientific work, called the Baconian method (or simply the scientific method). His pre-planned approach to the study of natural science forms the basis for the scientific method used today. To take the place of the established tradition that was in existence during his early life (which has been described as a combination of Scholasticism, humanism, and magic), he proposed an entirely new system based on empirical and inductive principles and the active development of new arts and inventions, a system whose ultimate goal would be the production of practical knowledge for "the use and benefit of men." Bacon spent a great deal of his professional years in politics and rose to become the Lord Chancellor of England. Unfortunately, his political career ended in disgrace in 1621 and he spent the last few years of his life writing about science and philosophy.

2.11.6 Johannes Kepler and Tycho Brahe

Johannes Kepler (1571–1630) was a German mathematician and astronomer and a major figure in the scientific revolution in the seventeenth century. His work and formulation of planetary motion formed the basis for Newton's theory of universal gravitation.

Kepler was familiar with both the Ptolemaic and the Copernican hypotheses of the Earth and Sun and became a strong advocate of the ideas of Copernicus.

He is best known for his laws of planetary motion. His work provided the foundation of Isaac Newton's universal laws of gravitation. Kepler was a student of the Danish nobleman Tycho Brahe (1546–1601). Brahe compiled extensive data on the planet Mars, which would later prove crucial to Kepler in his formulation of the laws of planetary motion because it would be sufficiently precise to demonstrate that the orbit of Mars was not a circle but an ellipse. Brahe was apparently suspicious of Kepler's intellect, fearing that Kepler would outshine him as a scientist, and therefore kept a large portion of his work from Kepler.

2.11.7 Isaac Newton

Isaac Newton (1642–1727) was an English physicist, mathematician, and astronomer who laid the foundation for classical mechanics, the three laws of motion, and universal gravitation. He is considered by many to be "the greatest and most influential scientist who ever lived." He removed the last doubts of heliocentrism and went a long way to advance the Scientific Revolution of the seventeenth century. He built the first reflecting telescope. Newton shares with Gottfried Leibniz the credit for developing differential and integral calculus. We will come back to Isaac Newton again in the following chapter in discussing the laws of motion.

2.12 Empiricism

Empiricism is the idea that knowledge can be derived by careful observation and formulating hypotheses or laws from these observations. The origins of empiricism lie with Aristotle. Aristotle would consult all of the experts and written texts of the time, document and catalog their ideas, observe as much as he could, then derive principles and laws based on all the information he had seen or read. Medicine in ancient Greece was based on Aristotelian empiricism which has had an influence on medicine and science to the present day.

Empiricism emphasizes experience and evidence in the formulation of principles and laws. It is fundamental to the philosophy of science and the scientific method that all hypotheses and theories be tested against observations in the natural world or in the laboratory. Thus, scientific methodology is largely empirical.

There are problems with empiricism that are intuitive. How does one know when enough evidence is acquired to form a conclusion? If one counts all the swans in one area and they are all white, the conclusion based on empiricism is that all swans are white. Then one observes a black swan in another or the same area and the conclusion is shown to be wrong (the "black swan metaphor"). It is often impossible to know all the evidence for a particular conclusion, so scientists resort to statistical analyses and probability theory with large sets of data.

2.13 Inductive Logic

Inductive logic is contrasted with deductive logic. Inductive logic tells one that if a generalization is true, then a conclusion based on the generalization is also true.

In the process of induction, one begins with some facts or observations, and then determines what general conclusion can logically be derived from those facts. One determines what hypothesis or theories could explain the data.

One example often given to illustrate inductive logic is the following: the scientist or philosopher notes the probability of becoming schizophrenic is greatly increased if at least one parent is schizophrenic and from that concludes that schizophrenia is inherited. This is certainly a reasonable hypothesis given the data. However, the induction does not prove that the hypothesis is correct. There are alternate hypotheses that are supported by the data. For example, the behavior of the schizophrenic parent may cause the child to be schizophrenic, not the genetic makeup. What is important in induction is that the hypothesis does offer a logical explanation of the data. To conclude that the parent has no effect on the schizophrenia of the child is not supported given the data and would, therefore, not be a logical conclusion. This leads us to the idea of multiple working hypotheses.

2.14 Multiple Working Hypotheses

Scientists use inductive logic often in research keeping in mind that there may be alternate hypotheses to explain the facts. They must always keep in mind that their main hypothesis may be wrong. As a matter of fact, there is a way of conducting scientific work called the method of multiple working hypotheses first formalized by the geologist T. C. Chamberlin in 1889–1890. As a way of conducting scientific investigations, this is usually the way scientists progress through a research project; always keeping in mind all the possible hypotheses that may explain the data, i.e., multiple working hypotheses.

An example of the use of multiple working hypotheses is given by the problem of the sedimentary rock breccia. Breccia is composed of angular fragments of other rocks, which may be of any kind, naturally cemented together. Breccia may be the result of landslides or avalanches; it may be formed along faults; it may result from the impact of meteorites. When one finds a sample of breccia in the field, all of these possible origins come to mind and they become multiple working hypotheses as to the origin of that particular breccia. The geologist is then ready to seek further information to find the answer to the rock's origin.

Karl Popper (1902–1994), an Austrian-British philosopher of science, rejected the classical empiricism of science and the classical observationalist-inductivist method of science that had grown out of empiricism. His view of theories was that a theory should be considered scientific if and only if it is falsifiable. A search of the Internet will lead to much more information on Karl Popper's ideas on science. Popper is considered one of the most influential of the twentieth century's philosophers of science, but his rejection of empiricism leaves him as not a favorite son of most scientists.

Additional information and examples of inductive logic can be found at the following website: http://plato.stanford.edu/entries/logic-inductive/.

2.15 Deductive Logic

Deductive logic is that used most often in science. Deductive logic begins with a statement, called a *premise*, that is assumed to be true, than determines what else would be true if the premise is true. Using deductive logic, one can provide absolute proof of a conclusion given that the premise is correct. The premise remains unproven and must be accepted on faith for the purpose of exploration or experimentation.

Deduction and induction by themselves are not adequate for a scientific approach. While deduction gives absolute proof, it never makes contact with reality; there is no place for observation or experimentation of the premise, no way to test the validity of the premises. And, while induction is driven by observation, it never approaches actual proof of a theory. The development of the scientific method, over time, has involved a gradual synthesis of these two logical approaches.

Induction is used to formulate an idea or hypothesis which results in the collection of data. After or during the data collection, deduction leads to a conclusion. Either the original idea is right or it is wrong. If the collected data support the original idea, more data are collected or a hypothesis or theory is developed to explain the data. If the data do not support the idea or hypothesis, a new hypothesis is formulated. Many have described the scientific method as being "trial and error." The main intent and hopefully the result of using the scientific method is to minimize the latter (error) and maximize the former (trial).

2.16 Models and Simulations

Models in the context of science are simulations or scaled up or down examples of an actual entity, situation, or perception. One would not build a car, airplane, or spaceship, or even a theory without building a model, if only a mental one. However, in the case of a car, airplane, or spaceship, one would not attempt to build a real one without first building a scale model; and certainly a person would not want to get in it and make it go without having confidence that a model had been used before final construction and all the parts had been checked. Children and some adults have models of cars, trucks, airplanes, helicopters, teddy bears, action figures, etc. and they provide an indication of what the real thing will look like or do.

Models using computers that simulate real-world situations are used often in science, especially in climate change science. Models are used to draw conclusions by scientists every day and they allow scientists to project what may happen well into the future. In climate change science, computer programs that include basic equations of physics and chemistry are used in the process of modeling the climate, which allow climate change scientists to project climate changes into the future and to vary the input and study various scenarios of what might happen in the future.

Models are not only used in science, society, and industry. They are also used in the military. For example, if a general wants his troops to go into battle, it is best to run a model of the terrain and conditions (e.g., weather) expected to be found in the area where the battle is to take place. If the general does not have a model, then the troops may be sent into battle and may be slaughtered. The general would soon be out of troops to die for their country or cause and the battle would be lost, and possibly the war.

Before the advent of computers and computer models, climate scientists and generals ran models in their heads or drew them in their heads or on a chart or table or in the soil. They imagined or drew what the conditions would be like in the future for climate or on the field of battle and relied on these images to decide when to take action and to send troops onto the battlefield. This sometimes worked but often it did not. Although the human brain can run numerous simulations, it can't run millions in a few seconds like a high speed computer. However, models are only as good as the computer programmer and the scientist or general can make them.

Climate models that are used to simulate climate change and project that change into the future are treated in greater detail later in the text.

2.17 The Nature of Science

The early practitioners of science were referred to as natural philosophers and their field of expertise was considered to be natural science. The designation of natural science can be seen today in names such as "Natural Science Museum" and may be used to distinguish the "natural sciences" from the social sciences and "formal sciences" such as mathematics and logic, although the latter are rarely considered sciences. Natural science also includes natural history as in the American Museum of Natural History in New York, NY or the National Museum of Natural History, a part of the Smithsonian complex in Washington, D. C., both in the U.S.

Natural sciences include astronomy, chemistry, physics, geology, Earth science, biology, meteorology, oceanography, materials science, and branches thereof. Climatology and climate change science are also considered natural sciences. The nature of science also deals with the science of nature.

2.18 The Science of Nature

All natural sciences are sciences that study nature. Natural scientists try to determine how the Universe and everything in it works. Astronomers are trying to see farther and farther into the Universe and to explain what is seen there, and this is natural; chemists are performing experiments to try to determine how different substances react with each other and what new substances are produced, many of which are found in nature; physicists are studying the motions of things from subatomic particles to objects in space and the physics and laws of nature; geologists are attempting to decipher all the events of Earth history as can be determined from Earth materials and are also studying rocks, minerals, and gases from other planets, comets and asteroids; Earth scientists are studying all aspects of the Earth; biologists are trying to learn all there is about life; meteorologists are trying to understand and predict weather; oceanographers are unraveling the secrets of the seas; and materials scientists are doing all kinds of things with new and exciting materials, all dealing with the science of nature.

A great many natural events seem to occur without rhyme or reason, as in storms or earthquakes. Many natural systems appear to be in a state of chaos; but what is chaos?

2.19 Chaos Theory

Chaos theory is a branch of mathematics. It is a sub-discipline of mathematics that deals with systems that exhibit chaos but can be made sense of and analyzed mathematically. Some of the complex systems that chaos theory helps us understand are weather, water boiling on a stove, migratory patterns of birds, and how vegetation spreads across a new piece of land. Chaos theory is really about finding the underlying order in apparently random data. Something described as chaotic has numerous variables or moving parts, such as weather or traffic patterns in a large city such as Washington, D.C., London, England, Rome, Italy, or Paris, France.

Chaos theory was introduced by an experiment done in the early 1960s by Edward Lorenz, an American mathematician and meteorologist. In 1960, he was working on the problem of weather prediction. He had a computer set up, with a set of 12 equations to model the weather. It didn't predict the weather itself. However this computer program did theoretically predict what the weather might be. One day in 1961, he wanted to see a particular sequence again. To save time, he started in the middle of the sequence, instead of the beginning. He entered the number off his printout and left to let it run.

When he came back an hour later, the sequence had evolved differently. Instead of the same pattern as before, it diverged from the pattern, ending up wildly different from the original.

Eventually he figured out what had happened. The computer stored the numbers to six decimal places in its memory. To save paper, he only had it print out three decimal places. In the original sequence, the number was .506127, and he had only typed the first three digits, .506.

By all conventional ideas of the time, it should have worked. He should have gotten a sequence very close to the original sequence. A scientist considers him- or herself lucky if (s)he can get measurements with accuracy to three decimal places. Surely the fourth and fifth, impossible to measure using reasonable methods, can't have a huge effect on the outcome of the experiment. Lorenz proved this idea was wrong.

This effect came to be known as the butterfly effect. The amount of difference in the starting points of the two curves is so small that it is comparable to a butterfly flapping its wings and the effects that may ensue.

> The flapping of a single butterfly's wing today produces a tiny change in the state of the atmosphere. Over a period of time, what the atmosphere actually does diverges from what it would have done. So, in a month's time, a tornado that would have devastated the Indonesian coast doesn't happen. Or maybe one that wasn't going to happen does. (From Ian Stewart, *Does God Play Dice? The Mathematics of Chaos*, pg. 141)

This phenomenon, common to chaos theory, is also known as "sensitive dependence on initial conditions." Just a small change in the initial conditions can drastically change the long-term behavior of a system. Such a small amount of difference in a measurement might be considered experimental noise, background noise, or an inaccuracy of the equipment. Such things are impossible to avoid in even the most isolated lab. With a starting number of 2, the final result can be entirely different from the same system with a starting value of 2.000001. It is simply impossible to achieve this level of accuracy – just try and measure something to the nearest one millionth of an inch!

In dealing with very small and very large numbers and a great number of variables, digital computers are essential because they can make extremely fast calculations. This is the reason that chaos theory didn't come about until the advent of the digital computer age and the calculating capabilities of the 1960s.

Additional information on chaos theory may be found at the following web site: http://www.abarim-publications.com/ChaosTheoryIntroduction.html#.TtVP2GMk6nA.

Scientists deal with very large (astronomical) and very small (microns) numbers and they have special ways of managing, using, and referring to them.

2.20 Scientific Notation

Scientific notation is how scientists deal with numbers; scientists deal with very large and very small numbers. For example, light travels at a speed of 300,000,000 m per second.

Written out, that number is three hundred million meters per second. In scientific notation, the speed of light would be written as 3.0×10^8 m/s. That is so much less clutter than writing it all out and when one deals with many large and many small numbers, reducing the clutter is important!

The Earth was formed about 4.54 billion years ago, or 4,540,000,000 years ago. In writing this out, one could say that the Earth began about four (4) billion five hundred forty (540) million years ago, or use scientific notation. Scientific notation allows scientists to use less space and write the number as 4.54×10^9 years ago.

Scientific notation consists of two parts: the first part, 4.54 is the coefficient. The second number is called the base and is always 10. The base number 10 is always written in exponent form, such as in the number 4.54×10^9; the number 9 is referred to as the exponent or the power of 10.

To write scientific notation, for example, 4,540,000,000, the decimal point is placed after the first digit, 4.54 then the zeros are dropped. The coefficient is 4.54. To find the exponent, count the number of places from the decimal point to the end of the number, in this case 9 places (10^9) which is the base. The number 9 is the exponent.

If the number (coefficient) is less than 1, the number is small and the exponent is negative.

For very small numbers, say 0.000001 or a millionth of a second is written as 1×10^{-6}. To find the exponent, count the places after the decimal to the end of the number.

Rules for Multiplication in Scientific Notation:

1. Multiply the coefficients
2. Add the exponents (base 10 remains)

$$\text{Example 1}: (3 \times 10^4)\ (2 \times 10^5) = 6 \times 10^9$$

What happens if the coefficient is more than 10 when using scientific notation?

$$\text{Example 2}: (5 \times 10^3)\ (6 \times 10^3) = 30. \times 10^6$$

While the value is correct it is not correctly written in scientific notation, since the coefficient is not between 1 and 10. One then must move the decimal point over to the left until the coefficient is between 1 and 10. For each place the decimal point moves, the exponent will be raised 1 power of 10.

$$30. \times 10^6 = 3.0 \times 10^7 \text{ in scientific notation.}$$

$$\text{Example 3}: (2.2 \times 10^4)\ (7.1 \times 10^5) = 15.62 \times 10^9 = 1.562 \times 10^{10}$$

$$\text{Example 4}: (7 \times 10^4)\ (5 \times 10^6)\ (3 \times 10^2) = 105. \times 10^{12}$$

In example 4, the decimal must be moved two places over and the exponent is raised by 2. Therefore the value in scientific notation is: 1.05×10^{14}

Rules for Division in Scientific Notation:

1. Divide the coefficients
2. Subtract the exponents (base 10 remains)

$$\text{Example 1}: (6 \times 10^6) / (2 \times 10^3) = 3 \times 10^3$$

What happens if the coefficient is less than 10?

$$\text{Example 2}: (2\times10^7)/(8\times10^3) = 0.25\times10^4$$

While the value is correct it is not correctly written in scientific notation since the coefficient is not between 1 and 10. We must move the decimal point over to the right until the coefficient is between 1 and 10. For each place we move the decimal over the exponent will be lowered 1 power of 10.

$$0.25\times10^4 = 2.5\times10^3 \text{ in scientific notation.}$$

Scientific notation will be used throughout this work when dealing with very large or very small numbers as its practicality can be seen in the above examples.

Logarithms are another way scientists can use to deal with large and small numbers and these are usually taught in courses below the college level; but it should not take long to review. Prior to computers and hand-calculators, logarithms were usually calculated by use of a slide-rule. Logarithms are exponents.

Press coverage of the 2011 earthquakes in Christchurch, New Zealand and Japan, as reports of major earthquakes tend to do, has served as a reminder that many introductory science students have a relatively meager understanding of logarithms. After all, it is not a subject most think about every day or use very often unless one is a scientist or engineer, and most introductory science students are neither.

Both the Richter scale for earthquakes and the pH scale for chemistry are logarithmic and both are used in studying climate change and in other Earth sciences and engineering. A base 10 logarithm (log) is the number, x, so that 10^x gives the number one wants. For example, the log of 100 is 2. This means that $\log(100)=\log(10\times10)=\log(10^2)=2$. Similarly, the log of a million is 6, meaning that $\log(1{,}000{,}000)=\log(10\times10\times10\times10\times10\times10)=\log(10^6)=6$. The log of a number less than 1 is negative. For example, $\log(0.01)=\log(1/100)=\log(1/10^2)=\log(10^{-2})=-2$, compared to 2 for the log of 100.

Before ready access to calculators and computers, logarithms offered a convenient way to multiply large numbers. Now they are mostly used to compare numbers that differ by a very large relative amount.

Generally, if $x=b^y$, then y is the logarithm of x to base b, and is written $\log_b(x)$, so $\log_{10}(1{,}000)=3$.

For example, if we take the population of China (1,340 million), New Zealand (4 million), and India (1,270 million) then it can be hard to make comparisons, since the difference between China and India (70 million) is almost 20 times the population of New Zealand. But if we take the logs of the populations, New Zealand = 6.6, China = 9.13, and India = 9.10. It is now obvious that, relatively speaking, the populations of India and China are about the same while that of New Zealand is very much less.

Earthquakes can range from feeling like the whole Earth is shaking to having the ground shaken like a child with a toy, or to not feeling them at all. So to study and describe earthquakes scientists use the Richter scale. A magnitude 5 earthquake is 1,000 times weaker than a magnitude 8 earthquake because a log difference of 3 means $10^3=10\times10\times10=1{,}000$ difference.

Additional Readings

Ackrill, J. L. (1981). *Aristotle the philosopher*. Oxford/New York: Oxford University Press.

Alley, R. B. (2011). *Earth: The operator's manual*. New York: W. W. Norton and Co.

Barnes, J. (1995). *The Cambridge companion to Aristotle*. Cambridge: Cambridge University Press.

Brody, T. A. (1993). In Luis De La Peña & P. E. Hodgson (Eds.), *The philosophy behind physics*. Berlin: Springer. ISBN 0-387-55914-0.

Godfrey-Smith, P. (2003). *Theory and reality: An introduction to the philosophy of science*. Chicago/London: The University of Chicago Press.

Hansen, J., et al. (2005). Earth's energy imbalance: Confirmation and implications. *Science, 308*, 1431–1435. doi:10.1126/science.1110252.

Krige, J., & Pestre, D. (Eds.). (2003). *Science in the twentieth century*. London: Routledge. ISBN 0-415-28606-9.

Lorenz, E. N. (1963). Deterministic non-periodic flow. *Journal of the Atmospheric Sciences, 20*(2), 130–141. doi:10.1175/1520-0469(1963) 020<0130:DNF>2.0.CO;2.

Smart, J. J. C. (1968). *Between science and philosophy*. New York: Random House.

Smith, J. M., et al. (2005). *Introduction to chemical engineering thermodynamics*. New York: McGraw Hill. OCLC 56491111. ISBN 0-07-310445-0.

van Fraassen, B. C. (2008). *Scientific representation: Paradoxes of perspective*. Oxford: Oxford University Press.

Chapter 3
The Scientific Method and Its Use

Abstract The scientific method is not a linear one-dimensional sequence of events but a three-dimensional approach to solving problems and obtaining answers to questions. A description of the scientific method and examples are given in this chapter. An understanding of the scientific method (or methods) is necessary in order to gain an insight into, and to hopefully gain some appreciation for, what most scientists do and the way they do it, so this chapter deals with the scientific method and how some important scientists have used it to achieve their results. The emphasis is on climate science and climate scientists but other important scientists are mentioned and their results given. Newton's laws of motion are described and their relationship to climate change is given. Continental drift is introduced and related to climates of the past.

Keywords Theories • Hypotheses • Guyots • GISS • Newton • Hess • Tyndall • Wegener • Ussher • Plass • Flemming • Broecker • Callendar • Rahmstorf • DNA • Libby • Sea-floor spreading • Plate tectonics • Hansen • Keeling • Manabe • Franklin • GFDL • Peer review • Continental drift • Arrhenius • Serendipity • Hutton • Uniformitarianism • Darwin • Evolution • Creationism • Fourier • Scientific method • Data • Watson • Crick • Revelle

Things to Know

The following is a list of things to know from this chapter. It is intended, as in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_3,

to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor. This is not intended to be a complete list concerning this subject.

Things to Know	
The scientific method	How are scientific data collected?
Theories	Hypotheses
Peer-review	Alfred Wegener
Alexander Flemming	Newton's laws of motion
Rosalind Franklin	John Tyndall
DNA	Wallace Broecker
Plate Tectonics	Guyots
Arrhenius	Gilbert Plass
Callendar	Willard Libby
International geophysical year	Keeling Curve
Syukuro Manabe	GFDL
James Hansen	GISS
Sea-floor Spreading	Stefan Rahmstorf
Continental drift	*Staphylococcus*

3.1 The Scientific Method

The scientific method is difficult to define because it is more than one method. The best one can do is to illustrate the method used by most scientists by listing the steps taken along with some concrete examples from actual scientific papers.

The scientific method is that method or methods used by scientists to study a scientific problem or to answer a scientific question, draw conclusions, and publish results. What this methodology is, how it is used, and some examples from actual scientific work are given in the following sections. The scientific method actually consists of many methods, as varied as the scientists themselves, and is loosely defined as the way scientists do their work.

The scientific method is not a rigid method or set of methods but it needs to be discussed and understood. It is not possible to understand a science without some understanding of the ways scientists conduct their tasks. The scientific method can be thought of as a series of logical steps; but often it is simply trial and error. However, trial and error without a method takes longer and allows for more mistakes. Scientists try to cut down on mistakes and to make as few as possible.

Scientists are often part of a team that conducts research into an area of study for which they have received funding. Funding for research is often obtained by writing a proposal and receiving a research grant if the proposal is accepted. This is not always the case and was less so in the earlier days of scientific work. In earlier work, especially work done prior to the 1960s, scientists often labored alone on a project that they designed and that they carried out supported by the institution or company for which they worked. Often the institution was a university or government, or an institution supported by a government.

A preliminary look at the scientific method involves at least the following steps:

1. Consider or define a problem;
2. Try to state an explanation for the problem;
3. Determine or deduce a prediction based on the explanation;
4. Perform tests or experiments to see if the explanation is valid.

The four steps above form the basis of the scientific inquiry; they constitute a simple model for the scientific method. One possible sequence is 1, 2, 3, and 4. If 2 is true, what are the consequences? Testing (4) should include considering the opposite of each consequence in order to disprove 2. If 2 can be disproved, then start again with 1.

There must be a fifth step. What good are steps 1 through 4 if no one knows about the results? The fifth step is communication; publication or presentation. The results of scientific research are made known to colleagues by discussion, presentation, publication, or all three; and in the modern world, discussion is largely done by email or in the halls at conferences or the written word. Publication is usually done in peer-reviewed journals or by presentation at a professional conference.

Scientific research is the most important way to determine the causes, trends, and possible solutions to climate change if it is determined that climate change is heading in the wrong direction and will need proper action. Science is an important part of society and the advances made by scientists have been important to human beings' continuance and well-being on Planet Earth.

Scientific discoveries are made by following the logic of the scientific method, and sometimes discoveries are made because of accidents and even stupidity. Serendipity in science is a scientific discovery made by accident and this has played a role in scientific research in the past and will certainly play a role in the future. Hopefully, scientific research will lead to the advancement of human knowledge, which is the primary purpose of conducting scientific research.

Scientific research has already led to many advances beneficial to humans in the medical sciences, such as drug research, and innovations which continue to make life better for humankind; Velcro, solid state electronics, microwave ovens, the personal computer, laptops, ipads, smart phones, etc. are the result of scientific research.

Scientists do their work in many different ways. Some use data they collect themselves; others use data collected by someone else. Some work alone; others work in teams. Most publish their work as soon as possible; others keep their research secret, publishing rarely if at all. Some are brilliant; others are not so smart. Scientists are human; some are even more so than others.

One of the most unusual and enlightening essays about the methods and the way scientists work and think is entitled "*The importance of stupidity in scientific research*." Scientists in general are not stupid. Actually, most of them are quite intelligent. But stupidity often plays a part in the way scientists work. Stupidity in scientific research, which is nothing to be ashamed of, is due to the fact that scientific research is most often into the unknown.

Scientists ask questions and then attempt to find answers to those questions. Some questions do not lead to answers but lead to other questions or to blind alleys, and the scientist has to start over again or change course. Eventually, the scientist will hopefully ask the right question, possibly in collaboration with others, and proceed in the right direction to arrive at the correct answer or answers. Scientists use logic, both inductive and deductive reasoning, and have a set of ethics by which they accomplish their work.

To quote Sherlock Holmes (actually Sir Arthur Conan Doyle, the author), "How many times must I tell you, Watson, when you eliminate all the impossible, what is left, no matter how improbable, must be the truth." And most scientists are interested in obtaining the truth.

The scientific method is that which all reputable scientists follow. It is not a mystery and it is fairly simple but not rigid. It is as varied as the scientists who use it but there are basic parts to it which can be recognized. It is a methodology by which most scientists conduct research and alert fellow scientists (and sometimes the public) to new information.

The scientific method may begin with an idea before any information is collected. It may be the idea that something may exist which has not been thought of before; an original idea, like Albert Einstein's formula for energy and matter, $E = MC^2$, relativity, or plate tectonics, sea-floor spreading, and continental drift; or the origin of species. It is often an idea based on observations; empiricism, such as the movement of stars in the sky or the Earth's place in the Solar System (such as the celestial observations of Copernicus and Galileo, or the configuration of continents on a map).

After an idea is defined or formulated, the scientist begins to collect data, information, or to test, experiment, and make observations. Or the idea may come after the scientist begins to collect data. The collection of data may result in an original idea and this idea then becomes the hypothesis or theory.

An example of the collection of data coming first before the idea is Darwin's theory on the origin of species by means of natural selection. Darwin spent a large part of his life collecting and studying living and fossil organisms. From his observations he formulated his theory on the origin of species.

Hypotheses and theories are usually presented at professional scientific meetings, published in peer-reviewed scientific journals, and discussed with colleagues. This is what is called the peer-review process. This process allows the scientist to receive feedback from peers and to refine their ideas or to change them.

Meetings, journals, and discussions provide feedback and possibly new ideas or information to the scientist. Then the theory is revised if necessary.

It is by this method of logical steps that scientists gain confidence that their theory is correct. Often, new ideas happen by serendipity (by accident or chance), such as in the discovery of a powerful antibiotic. One was discovered by accident and named by a Scottish scientist, Alexander Flemming, who left a Petri dish containing the bacterium *Staphylococcus* sitting uncovered overnight by mistake and discovered an odd-looking substance in the Petri dish the next morning. The substance formed a ring around the *Staphylococcus* and appeared to be impeding the growth of the culture. The substance was named penicillin.

A scientist might be working on formulating a hypothesis or establishing a theory and discover a new line of inquiry by accident or pure luck. This new information may lead to the abandonment of the original hypothesis or may lead to the start of a new one.

Because the scientific process is not rigid, it is subject to abuse. To restrict abuse of the process a code of ethics has been developed among scientists. According to this code, a scientist must give full credit to all other scientists whose work they have used. Data must not be falsified, omitted, or embellished and they must accept responsibility for all their work.

Examples of well-known hypotheses and theories are as follows:

- Nebular hypothesis for Earth's origin and the origin of the Solar System;
- Hypotheses for extinction of life forms;
- Hypotheses of dinosaur origin;
- Theory of dinosaur extinction by means of meteorite impact;
- Theory of gravity;
- Theory of evolution;
- Theory of the Origin of the Universe (the Big Bang Theory);
- Theory of Plate Tectonics.

There are different ways of outlining the basic methods used for scientific research. Scientists and philosophers of science have generally agreed on certain steps that should be taken in all scientific research. These steps and organization of procedures tend to be more characteristic of natural sciences than social sciences, however, but the social scientist also uses them. The cycle of formulating hypotheses, testing, and analyzing the results, and formulating new hypotheses resembles the steps described below.

A more complete list of the essential elements of the scientific method is the following:

1. Characterizations (observations, definitions, and measurements of the subject of inquiry);
2. Hypotheses (theoretical, hypothetical explanations of observations and measurements of the subject);
3. Predictions (reasoning including logical deduction from the data, hypothesis, or theory);
4. Experiments (tests of all of the above);
5. Conclusions;
6. Peer review;
7. Publication.

Each element of a scientific method, if the work is shared, is subject to peer review for possible mistakes, oversights, and enhancements and many iterations of each may be necessary. These activities do not describe all that scientists do but apply mostly to the experimental sciences (e.g., some physics, chemistry, some biology, and some Earth science including climate science). The elements of the scientific method are often taught in classrooms, as they should be for any science class.

Some may question whether climate science is conducted using the scientific method, but it surely is. Climate science only lacks the ability to be able to bring climate inside of the laboratory to conduct experiments, but many experiments related to climate science can, are being, and have been conducted in the laboratory. Examples are as follows:

- Experiments with weak acids which are found in nature and their effects on carbonate (calcite and aragonite, both consisting of $CaCO_3$) dissolution. Carbonates are important constituents of coral reefs, sea shells, sedimentary rocks, cave deposits, and ornamentals and weak acids are present in the environment. For example, every time it rains the CO_2 in the atmosphere combines with H_2O forming H_2CO_3, or carbonic acid. Information gathered from laboratory experiments using carbonic acid and $CaCO_3$ may lead to the protection and preservation of corals in coral reefs and those other things made of calcium carbonate.
- Scientists conduct experiments in the laboratory on the effects of temperature on survival of different species to determine the species' range of tolerance to temperature. They also conduct laboratory experiments with other aspects of the environment to determine limits of tolerance such as atmospheric pressure, various contaminants, and soil conditions for plant species.

There are many experiments that can be done in the laboratory and in the field that relate to climate science. They are being conducted by scientists in laboratories and in fields all over the world.

The scientific method is not a recipe. It requires intelligence, imagination, perseverance and creativity, and some degree of stupidity and accidents from time to time during the scientific process. It is also an ongoing cycle, constantly developing more useful, accurate, and comprehensive models and methods. For example, when Albert Einstein developed the Special and General Theories of Relativity, he did not in any way refute or discount Isaac Newton's laws as set forth in Newton's *Principia* in the seventeenth century. It has been said that if the astronomically large, the infinitely small, and the extremely fast are omitted from Einstein's theories, all phenomena that Newton could not have observed, Newton's equations remain valid. Einstein's theories are expansions and refinements of Newton's theories and they increase our confidence in Newton's work. Ideally, this is the way science should and does work most of the time.

Most nonscientists view science as marching along from step to step and increasing knowledge of the natural world in a linear fashion. Mathematics may work in this way, for example, if a equals b, than c; but science doesn't. A more likely example from science would be if a equals b, than c, d, e, and maybe f.

When advancement in science occurs, scientists try first to evaluate the new information to see if the new advancement is valid. Then they try and use the new information to make further advancements in knowledge by attacking new research problems and trying to find new answers. This is not a linear process as scientists go about their work in different ways and may research a problem with different tools to hopefully arrive at the answer.

A recent (November 2011) example of the scientific method in action comes from work being done at the Large Hadron Collider (LHC) with neutrinos. During a recent test, neutrinos were measured to be traveling faster than the speed of light. The speed of light is thought to be a universal constant and forms the basis of modern physics and Einstein's theories of relativity; in the formula $E = MC^2$, C is the speed of light.

The Large Hadron Collider is a gigantic scientific instrument near Geneva, Switzerland where it spans the border between Switzerland and France about 100 meters underground. It is a particle accelerator used by physicists to study the smallest known particles, the fundamental building blocks of all things. It will revolutionize our understanding, from the minuscule world deep within atoms to the vastness of the Universe. It is in the LHC that neutrinos were said to exceed the speed of light. If this experiment can be duplicated and all the steps conducted adequately documented, Einstein's theory of relativity will collapse.

Scientists in Italy measured the time of passage of neutrinos in the LHC travelling from Switzerland to Italy at a rate faster than the speed of light. Two subsequent measurements have been done at this writing (January 2012), one substantiating the original experiment, the other refuting it. Other experiments are planned which will either refute or substantiate the original result. Neutrinos either travel faster than the speed of light or they do not. Most of the subsequent experiments have shown that neutrinos do not travel faster than the speed of light.

Results such as those with neutrinos at the LHC are often the case with experiments. If the experiment results in a new finding, the experiment must be repeated for confirmation. The results have to be confirmed by additional experiments. If additional experiments are not possible or are not done properly, questions about the results of the original experiment will always remain.

3.2 A Linearized Approach to the Scientific Method

It is a useful exercise to look at a linearized approach to doing scientific research, keeping in mind that this does not represent exactly how most scientific research is done.

A linearized, pragmatic scheme of some of the points above is sometimes offered as a guideline for proceeding with scientific research:

1. Define the question and determine the boundaries;
2. Gather information and resources (observe, count, document);
3. Form a hypothesis;
4. Perform experiments, collect data and document;
5. Analyze the data;
6. Interpret the data and draw conclusions that may serve as a starting point for a new hypothesis;

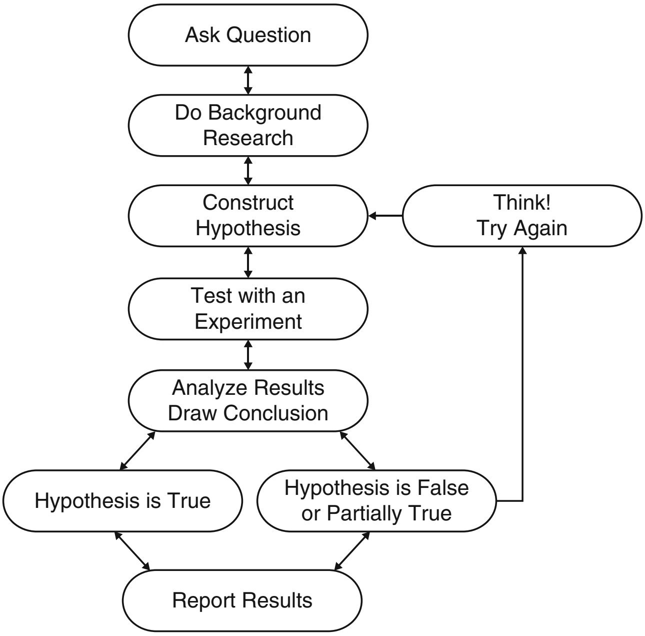


Fig. 3.1 The scientific method's flow of logic (Source: John Cook)

7. Discuss the procedures and results with colleagues;
8. Publish the results;
9. Re-test (frequently done by other scientists).

The iterative cycle inherent in this step-by-step methodology goes from point 3 to 7 back to 3 again. Of course, it is known that scientific thinking (as well as most thought processes) is not, nor should it necessarily be, linear.

While this scheme outlines a typical hypothesis/testing method, it should also be noted that a number of philosophers, historians, and sociologists of science, and scientists claim that such descriptions of the scientific method have little relation to the way science is actually practiced.

The illustration above (Fig. 3.1) is a flow diagram of the thought process often used when conducting a scientific study. A flow of logical thought is essential to a valid scientific study.

Science progresses by argument, skepticism, and debate but it advances through formulating hypotheses clearly and testing them objectively. Testing, experimentation, and objectivity are the keys to science.

In practice, contemporary scientists usually submit their research findings to the scrutiny of their peers, which includes disclosing the methods that they use (and a detailed documentation of those methods), so their results can be checked through replication by other scientists. The insights and research results of individual or teams of scientists are confirmed or rejected in the peer-reviewed literature by the combined efforts of many other scientists.

In conducting scientific research, it is not the belief of the scientists that is important, but rather the results of the testing. Indeed, when Albert Einstein was informed of the publication of a book entitled "100 Authors against Einstein," he is said to have remarked, "If I were wrong, then one would have been enough!" However, that one opposing scientist would have needed proof in the form of reliable data and testable results. And this is also the case for global warming and climate change science. Those that cite 300 or 3,000 or so people signing petitions against global warming are just as important as those who signed the petition about Albert Einstein and relativity; not important at all, as a glance at the names of the dead and irrelevant reveal! Getting people to sign a petition has nothing to do with evidence for or against the science of Earth's climate or anything else, except possibly in a political recall. The scientific evidence speaks for itself and it has spoken literally volumes over the past several decades and centuries. If climate scientists are wrong about global warming, than one proof that the Earth is not warming would be enough.

3.3 Data Collection – Experimentation, Measurement, Observation

Scientists collect information, but it is not collected haphazardly. Data, which are bits (parts) of information, are collected in a certain prescribed manner. Data (yes, the word data is plural; the singular is datum) must always be well documented as they are collected; and subjected to controls on accuracy, quality, and pertinence to the problem that is being considered. In mineral, rock, biota or any other item being collected, the label or documentation is as important as the specimen. Without adequate documentation, the specimen or measurement may be a curiosity but it will have no scientific value.

Climate change data collection involves land, ocean, and atmospheric temperature readings; precipitation changes in regions of the world, wind directions, glacial advances and retreats, sea level lowering or raising worldwide, changes in atmospheric and oceanic currents and their effects, and the long-range trends in these data.

Climate change data are collected according to strict rules of quality assurance (QA) and quality control (QC); often stated together as (QA/QC) so that they can be reproduced according to one part of the scientific method (i.e., reproducibility).

3.4 Ideas, Persistence, Documentation, Testing, Reproducibility, Publication

Scientific work usually begins with an idea, remains current due to scientific persistence and documentation, and ultimately survives due to experimentation, its being tested, and its reproducibility.

An example of a scientific idea is the following: "A map of the world shows that the east coast of South America looks like it could snuggly fit into the west coast of

Fig. 3.2 The continents of South America and Africa and the fit of their coastlines (From http://www.bnvillage.co.uk/black-roots-village/106867-making-connections.html; From NASA, Public Domain)

Africa like pieces of a jigsaw puzzle. Perhaps the two continents were together at one time." This idea was first proposed soon after the first map of the world was made in the 1500s. Figure 3.2 shows the outline of the two Southern Hemisphere continents, South America and Africa, and their "fit" as if they were pieces of a jigsaw puzzle. The first test of this idea came when maps were made of the submerged areas off the coasts of the two continents and geologists saw an even better fit; then the age of the Atlantic Ocean was determined to be younger than originally thought and the theory of Plate Tectonics was born after it was realized that the oceanic crust was being subducted (pulled downward) in the ocean trenches. Of course, it is impossible to reproduce the movement of South America and Africa away from each other, but other evidence clearly shows that they had indeed moved away from each other as new crust was added along what is now the Mid-Atlantic Ridge.

The idea that the continents of Africa and South America were once together was formalized by a German meteorologist and amateur geologist by the name of Alfred Wegener (1880–1930), who in 1912 published a book on continental drift entitled (in English; it was originally published in German) "On the Origin on Continents and Oceans." Wegener had first proposed the idea earlier, but he did not publish it formally until 1912.

Wegener failed to provide a convincing argument because there was no known mechanism for explaining how the continents had drifted apart. His proposed mechanism had to do with the Earth's rotation about its axis and the centrifugal force thus generated, but this was known not to be strong enough to move continents.

Wegener postulated that the continents had drifted apart, from an original landmass he called "Pangaea," due to the centrifugal force caused by the Earth's rotation.

The major question became "How could these large continental masses (Africa and South America) plow through the ocean basins to move to their current locations?" However, the idea of continental drift took root early in the 1900s as some geologists began to see further evidence for the former existence of Pangaea. Soon Earth scientists (mainly geologists) were divided into two camps; "drifters" and "non-drifters": the "drifters" citing abundant evidence from the Southern Hemisphere continents of continental drift and the "non-drifters" arguing that the continents could not have moved over the vast expanses of the ocean basins.

The concept of continental drift persisted throughout the first half of the twentieth century and geologists working in the Southern Hemisphere continents began to find evidence in the rocks and fossils that strongly supported the idea. They were documenting the rocks and fossils from areas that could support the reproducibility of their evidence, but they still could not provide any evidence for a mechanism even though the "drifters" knew that there must be one. Scientists were finding plants and animal fossils in the Southern Hemisphere continents that could not have been dispersed great distances by any known mechanism. There had to be proof that the southern continents were once together.

The hypothesis or theory of continental drift remained in the minds of scientists who were waiting for a mechanism to explain it. What was "continental drift?" Was it a hypothesis or a theory and what is the difference between the two? We need to first define each of them.

3.5 Hypotheses

A hypothesis is usually a precursor to a theory, but not always. In science a hypothesis is conceived either before or after data are collected. By definition, a hypothesis is a proposed possible explanation for a phenomenon or problem. It provides a tentative explanation for a scientific problem that can be tested.

Wegener's idea of drifting continents was a hypothesis which became a theory only after additional information was acquired by geologists working in the Southern Hemisphere continents and it would remain a hypothesis until the theory of plate tectonics was formulated and accepted in the 1960s and early 1970s. But plate tectonics is still a theory although it is well on its way to becoming fact. It is supported by an abundance of facts, as all theories must be.

3.6 Theories

Theories are explanations of phenomena, as opposed to hypotheses which often preclude theories. An example of a theory is evidenced by Newton's theory of gravity, or Darwin's theory of evolution, Albert Einstein's theory of relativity, Harry

Hess' theory of sea-floor spreading. Theories explain a cohesive set of facts. They are not "just a theory" as one former President of the U.S. stated when asked if he believed in evolution. He obviously didn't understand the scientific meaning of theory. Theories are as close to the truth as scientists can often come and are mostly on a par with scientific "laws." Scientific theories are usually more complex than scientific laws but they are essentially the same.

The laws of science are also called physical laws and are considered universal and invariable and are accepted by scientists and the educated public as facts. Many theories are also considered facts, such as the theories of gravity and organic evolution. Examples of scientific laws are Newton's laws of motion.

3.7 Newton's Laws of Motion

Newton's three Laws of Motion are well-known and were first published in 1687 and are stated below. The Newtonian laws of motion are seen in the moving parts of the atmosphere such as high and low pressure systems, wind which is simply moving air, and solid particles and liquids which are carried by wind and currents in the atmosphere.

Newton's First Law of Motion states that in order for the motion of an object to change, a force must act upon it. An object at rest tends to stay at rest until some force causes it to move. An object in motion will continue in motion in a straight line until a force acts upon it to change it from moving in a straight line or stops it from moving.

Newton's Second Law of Motion defines the relationship between acceleration, force, and mass. The acceleration (**a**) of a body is parallel and directly proportional to the net force F and inversely proportional to the mass m, i.e., $F = m\mathbf{a}$.

Newton's Third Law of Motion states that any time a force acts from one object to another, there is equal force acting back on the original object.

There are other physical and chemical laws that govern the behavior of materials on Planet Earth and are treated further and in detail in courses in chemistry and physics.

3.8 The Peer-Review Process

The peer-review process is what is done prior to publication of a scientific paper or legitimate book published by a reputable scientific journal or publisher. It also continues after publication. It is this process that enables a scientist to receive opinions and constructive criticisms from colleagues prior to publication (or before the next edition). Journals and publishers have editors which review and usually send out for review papers and books that are submitted to them.

Reviewers send comments back to the editor who sends them on to the author of the paper or book. Corrections are then made to the written text if the author agrees with the comments and the author then resubmits the material to the editor. If the editor agrees that the material has been improved and it is ready for publication, it is then published.

Editors have the prerogative to refuse to publish material that they think is mistaken, not appropriate, or is irrelevant to the topic at hand. For example, if there is a scientific consensus that CO_2 is a greenhouse gas that causes global warming and a paper is submitted to a professional journal that says the opposite (that CO_2 doesn't cause global warming) and cites no data to substantiate the author's claim, it is most likely that the editor will refuse to publish the paper.

In general, editors are fair-minded and are responsible for the integrity of their product. They do not routinely reject papers or materials that are pertinent and scientifically valid.

3.9 Use of the Scientific Method

The scientific method, and those that have applied it, has resulted in major advances in humankind's understanding of the world around him (or her) and laid the foundation for additional knowledge. Some examples of this use of the scientific method and the resulting understanding are given below.

3.9.1 James Hutton and Uniformitarianism

James Hutton (1726–1797) was a Scotsman farmer and naturalist who is known as the founder of modern geology. Geology forms a large part of Earth and climate change science.

Prior to Hutton's time, Earth history was thought to consist of one catastrophe after another, the most recent being the flood of Noah, or the Noachian Flood. Hutton, being a naturalist, was a keen observer of the world around him and he reasoned that there was not a need for a series of catastrophes to explain the natural world and the history of the Earth; one only had to look at modern processes of erosion and deposition to understand the past history of Earth. These processes could explain how much of Hutton's world could have been formed. All that was needed was a long time. In Hutton's day, the Earth was thought to have been created in a few days and nights and was only a few thousand years old, still old in the minds of most humans.

In the middle of the eighteenth century when Hutton was carefully observing nature, the Earth was believed to be only about 6,000 years old. It was thought that the world had been created on October 22, 4004 BC because that was the date arrived at by an Irish Archbishop by the name of Ussher, whose name still lives in infamy due to his scholarly research on what is often called the "Holy Bible." It seems that Archbishop Ussher had very carefully worked out the genealogies in

Genesis to come up with the absolute date for the Earth's "creation." Fossils were thought to have been placed in the rocks as a result of the "Flood." Others would later say that fossils were placed in rocks to "make atheists of geologists." It is true that many geologists are atheists but surely fossils in rocks are not the cause.

Hutton noted that many rocks were not flat and stacked one upon another as was called for in the "Flood" hypothesis, but at some places, such as at Siccar Point, near Edinburgh, Scotland, vertical layers of grey shale were directly overlain by nearly horizontal layers of red sandstone. Such juxtaposition could only be explained by great Earth movements tilting the shale vertically, then eroding the shale by wind, rain, and sea, and then depositing the red sandstones on top of the eroded surface of the shale.

Hutton, in 1788, presented a paper to the Royal Society of Edinburgh in which he stated that in his studies and observations of the natural world; "The result, therefore, of this physical inquiry is that we find no vestige of a beginning, no prospect of an end." Current Earth scientists and particularly geologists still hold Hutton's view of the Earth.

Hutton had been formally educated in the fields of medicine and chemistry but managed two small family farms while studying natural processes at work on the land. Hutton thought that sediments were deposited by water slowly, then compressed, and turned into rock and that the oldest rocks were made up of "materials furnished from the ruins of former continents." He recognized that this process could be a continuous cycle; when rock is exposed to the atmosphere it decays and erodes. He called this the "great geological cycle" and realized that it had been completed many times. Hutton's approach to the study of Earth and its materials and processes has been called uniformitarianism, which can be simply stated as "the present is the key to the past." The implication of uniformitarianism is that processes now operating on the Earth have been operating throughout Earth history, differing only in their location and intensity.

Hutton's development of uniformitarianism was based on empiricism, carefully observing how things worked in the real world. Geologists today use uniformitarianism to interpret Earth history and climate scientists use a reverse uniformitarianism, stated as "the past is the key to the present." In studying ice and sediment cores, detailed information of the atmospheric conditions of the past gathered from air bubbles in the ice may lead us to a better understanding of the present climate and projections into the future.

3.9.2 Charles Darwin and the Origin of Species

Charles Darwin (1809–1882) was an English naturalist, biologist, and geologist who developed a theory on the origin of species after much time spent observing, collecting, and cataloging fossils, rocks, and animal and plant specimens from around the world. He established that all species on Earth have descended from a common ancestor. He was the originator of the idea of natural selection, that nature gave rise to new species through competition. His theory of natural selection was based on empiricism. In his own words, he attributed his success to "the love of science, unbounded patience in long reflecting over any subject, industry in observing and collecting facts, and a fair share of invention as well as of common sense." This is a fair description of the scientific method as Darwin used it. He also said about himself, "I have steadily endeavoured to keep my mind free so as to give up any hypothesis, however much beloved (and I cannot resist forming one on every subject), as soon as facts are shown to be opposed to it." And this is as it should be for any scientist or science student, or for any person, for that matter. But we see today, especially in politicians, that often they do not have an open mind, and some even debate the presence of mind in some.

Darwin's theory on the origin of species was that a new species would arise by means of natural selection. He explained that the great variety of living and fossil things that he had observed was due to the fact that certain organisms were favored over others for survival; that new species would arise by acts of nature and not by divine creation. Darwin's theory of evolution was put forth in his 1859 book *On the Origin of Species by Means of Natural Selection* which was published in London, England.

The publication of Darwin's book caused a firestorm. The Church (the Roman Catholic Church and the Church of England) immediately condemned it and many religious fundamentalists today still speak out against the theory of evolution; but over 150 years of documentation in science support the theory and it forms the cornerstone of the sciences of biology, geology, and paleontology today.

Charles Darwin was not the first scientist to formulate a theory of evolution but it was the extensive documentation of the facts that the idea was based on that caused it to be accepted almost universally by the scientific community. Without the extensive documentation and the detailed formulation of the theory, Darwin's idea of the origin of species by means of natural selection would not have been as readily accepted.

Darwin's meaning was misrepresented by many after the 1859 publication of the "Origin" and only a careful reading of the book would allow complete understanding of his meaning. Perhaps the phrase, "survival of the fittest" best summarizes Darwin's meaning, but it was not a phrase used by Darwin himself. The phrase was first used by another Englishman, Herbert Spencer.

Darwin's theory of evolution is based on key facts and the inferences drawn from them, which biologist Ernst Mayr summarized as follows (based on facts and inferences):

- Every species is fertile enough that if all offspring survived to reproduce the population would grow (fact).
- Despite periodic fluctuations, populations remain roughly the same size (fact).
- Resources such as food are limited and are relatively stable over time (fact).
- A struggle for survival ensues (inference).
- Individuals in a population vary significantly from one another (fact).
- Much of this variation is inheritable, i.e., genetic (fact).
- Individuals less suited to the environment are less likely to survive and less likely to reproduce; individuals more suited to the environment are more likely

to survive and more likely to reproduce and leave their inheritable traits to future generations, which produces the process of natural selection (inference).
- This slowly effected process results in populations changing to adapt to their environments, and ultimately, these variations accumulate over time to form new species (inference).

Charles Darwin was the naturalist on the ship HMS Beagle, which left England in December of 1831 and returned in October of 1836. This voyage was most likely the most important experience in Darwin's life, as it visited the Cape Verde and other Atlantic islands, then surveyed the South American coasts and islands, including the Galapagos Islands. It then visited Tahiti, New Zealand, Australia, Tasmania and the Azores before returning to England in October of 1836. It is thought that Darwin did not leave England again after 1836. He used information gathered during the voyage of the Beagle to write and publish his books on coral reefs, sexual selection, variation under domestication, botany, geology, a diary of the voyage, and a book entitled *The Descent of Man*.

3.9.3 James Watson and Francis Crick – The Structure of DNA

In 1953 James D. Watson and Francis Crick, using x-ray diffraction data, proposed the spiral staircase structure of DNA (deoxyribonucleic acid). This became known as the double helix for the structure of the DNA molecule. For this work, they were awarded the Nobel Prize in Physiology and Medicine in 1962 which was shared with Maurice Wilkins, a researcher at King's College, London.

James D. Watson (1928–) is an American molecular biologist, geneticist, and zoologist.

Francis Harry Compton Crick (1916–2004) was an English molecular biologist, biophysicist, and neuroscientist and an honorary fellow at the University of Cambridge, U.K. He was a Distinguished Research Professor at the Salk Institute for Biological Studies in La Jolla, CA where he died in 2004.

Watson and Crick's work was founded on earlier work by Linus Pauling and others. As is often the case, major discoveries could not have been made without the work of others. Sir Isaac Newton said that his work was important because he had "stood on the shoulders of giants."

In the early 1950s, the race to discover the structure of DNA was on. At Cambridge University, graduate student Crick and research fellow Watson had become interested, impressed especially by Pauling's work. Meanwhile at King's College in London, Maurice Wilkins (1916–) and Rosalind Franklin were also studying DNA. The Cambridge team's approach was to make physical models to narrow down the possibilities and eventually create an accurate picture of the molecule. The King's team took an experimental approach, looking particularly at x-ray diffraction images of DNA.

In 1951, Watson attended a lecture by Franklin on her work to date. She had found that DNA can exist in two forms, depending on the relative humidity in the surrounding air. This had helped her deduce that the phosphate part of the molecule was on the outside of the structure. Watson returned to Cambridge with a rather muddy recollection of the facts Franklin had presented, though clearly critical of her lecture style and personal appearance. Based on this information, Watson and Crick made a failed model. It caused the head of their unit at the laboratory to tell them to stop DNA research. But the subject kept coming up and they continued to experiment.

Franklin, working mostly alone, found that her x-ray diffractions showed that the "wet" form of DNA (in higher humidity) had all the characteristics of a helix. She suspected that all DNA was helical but did not want to announce this finding until she had sufficient evidence on the other form as well. Wilkins was frustrated. In January, 1953, he showed Franklin's results to Watson, apparently without her knowledge or consent. The x-ray diffraction work showed Watson a distinct double helix.

Watson and Crick took a crucial conceptual step, suggesting the molecule was made of two chains of nucleotides, each in a helix as Franklin had found, but one going up and the other going down.

Watson and Crick showed that each strand of the DNA molecule was a template for the other. During cell division the two strands separate and on each strand a new "other half" is built, just like the one before. This way DNA can reproduce itself without changing its structure, except for occasional errors, or mutations.

The structure so perfectly fit the experimental data that it was almost immediately accepted. The discovery of DNA's structure has been called the most important biological work of the last 100 years, and, some say the field it opened may be the scientific frontier for the next 100. By 1962, when Watson, Crick, and Wilkins won the Nobel Prize for physiology and medicine, Franklin had died. The Nobel Prize only goes to living recipients, and can only be shared among three winners. Crick said that she, if she had lived, would have been honored also for her work. It was actually Franklin's work that led Watson and Crick to their DNA structure, as it was her x-ray crystallography that sealed the deal. Again, empiricism was used with careful observation and the physical building of models to solve the problem of DNA structure.

3.9.4 Harry Hess and Plate Tectonic Theory

The theory of plate tectonics represents a paradigm shift in the Earth sciences. It has caused geologists to view the world and the way it works in an entirely different light.

Harry Hess (1906–1969) was a Professor of Geology at Princeton University and his work set the stage for the later idea of Plate Tectonics. He served in the U.S. Navy in WWII and with the blessing of his crew was able to survey parts of the ocean floor of the Pacific Ocean basin with echo sounding equipment.

Hess formulated a hypothesis about a spreading sea floor in 1959 in an informal manuscript that was widely circulated. It was later published (1962) in a paper entitled "History of Ocean Basins" which was one of the most important and groundbreaking contributions in the development of the theory of Plate Tectonics. Hess built upon the work of an English geologist, Arthur Holmes (1890–1965), who worked in the early to middle parts of the twentieth century.

In Hess' 1962 paper, he described how seafloor spreading worked; molten rock (magma) oozes from the Earth's interior along the mid-oceanic ridges creating new seafloor that spreads away from the active ridge and eventually sinks into the deep ocean trenches.

At the time of Hess' paper, there were certain questions about the seafloor that were still unanswered. It had been discovered that the ocean basins were not as old as they had been thought to be. Geologists had long thought that the ocean basins would yield sediments that would provide evidence for the beginning of time on Earth, the Earth's origin (about 4.54 billion years ago). This was not the case and Hess reasoned that sediment had been accumulating on the ocean floor for only about 300 million years. Hess estimated that it took that long for the ocean floor to move from the mid-ocean ridges to the oceanic trenches near the continents.

Hess' idea received the expected resistance from the scientific community because geologists were still skeptical about a mechanism, although Hess knew that the oldest fossils found at that time on the seafloor were only about 180 million years old. He proposed that the mechanism for sea-floor spreading was new crust formed at the mid-ocean ridges that forced, or pushed, the seafloor to move to the trenches. Many still clung to the belief that continents and ocean basins had been too brittle for them to move great distances as was called for by the sea-floor spreading concept. Earlier ideas on continental drift had the continents plowing through the oceanic crust to their present locations.

Hess was aware that there were limited ways to test his hypothesis, but later geophysical studies confirmed that oceanic crust was disappearing into the Earth's oceanic trenches. Hess, unlike Wegener, lived to see the confirmation of his hypothesis and it resulted in the concept of Plate Tectonics that caused a paradigm shift in the Earth sciences. It caused geologists around the world to look at rocks in an entirely different way than they had before and to analyze their story in an entirely new context.

Hess also discovered hills on the seafloor that had flat tops. These he called guyots, which are flat-topped volcanic hills that were built from the seafloor to the surface of the ocean when they were formed and had their tops cut off (eroded) by wave action. Others were just called seamounts. They then slowly sank below the surface of the sea under their own weight. The geology building at Princeton University is named Guyot Hall in honor of Harry Hess and his ground-breaking research. Hess was a long-time professor at Princeton University.

The relationship of sea-floor spreading to climate change science is further developed in Volume II of this textbook series.

3.9.5 Plate Tectonic Theory

In 1963 it was discovered that there were strips on each side of the mid-oceanic ridges, parallel to the ridges that showed repeated and alternating polarity. Magnetic minerals in the strips, which align themselves with Earth's magnetic field, showed alternating reversals of polarity in the rocks on each side of the mid-ocean ridges; that is, one strip would show the magnetic south end of the magnetic minerals pointing to the North Pole and the adjacent strip showing the reverse (the magnetic north end pointing toward the North Pole), and this alternating sequence was repeated as one went away from the ridge on either side. Each side of the ridge had matching strips of alternating polarity.

Additional studies using age-dating techniques showed that the seafloor became older as one went away from the mid-ocean ridges in either direction, thereby lending further support to Hess' concept of seafloor spreading. If crust was being added at the ridges, it made sense that the younger crust would be near the ridges and therefore, older crust had to be further and further away from the ridges.

The concept that the continents and ocean basins had not always been as they are today was a revolutionary idea to geologists at the time. Geologists tend to be a conservative lot, and it took some time before they became convinced that the Earth's crust was actively engaged in movements that could result in moving whole continents (continental drift).

By the late 1960s enough information had been gathered to propose a theory based on the evidence, and the concept of continental drift would fit nicely into the new theory.

The Plate Tectonic Theory is that the outermost layer of the Earth, the crust, is made up of plates that move relative to each other and have moved relative to each other throughout much of the geologic past. They have probably moved at different rates and perhaps in different directions in the geologic past, but they have wandered or drifted over the face of the Earth to their present positions. Relative movement of these tectonic plates has greatly affected the climate history of Earth and is treated in greater detail in Volume II of this textbook series.

Climate change scientists are those scientists whose contributions are in the realm of climate change. Many of the following scientists have also contributed to other sciences and areas of science, but the emphasis here is on their contributions to climate science and its current implications.

3.9.6 Wallace Broecker and the First Use of the Term Global Warming

Wallace (Wally) Smith Broecker (1931–) is the Newberry Professor in the Department of Earth and Environmental Sciences at Columbia University and a research scientist at Columbia's Lamont-Doherty Earth Observatory. He is widely credited with coining the term "Global Warming." He is also credited with being the originator of the "conveyor belt" concept of oceanic circulation (see Fig. 12.6); a global concept of the oceans acting as a conveyor belt to distribute carbon throughout the World Ocean. He is credited with laying the foundation of carbon cycle science. He has authored over 450 publications in the peer-reviewed literature and is the author of ten (10) books, one of which is *Tracers in the Sea*, which established him as one of the leaders in chemical oceanography. His work with radiocarbon (^{14}C) and tying it to paleoceanography are described as landmarks in the field.

In 1975 in the weekly journal *Science*, Broecker published the first legitimate use of the term "Global Warming" in a peer-reviewed paper entitled "*Climate Change: Are we on the Brink of a Pronounced Global Warming?*" Broecker's paper was written during a brief episode of global cooling in the 1970s, making it even more amazing and prescient.

3.10 Use of the Scientific Method in Climate Change Science

The Earth is warming globally; the temperature of our planet is getting hotter. Global warming is a fact, is unequivocal, and is due mainly to human's burning of fossil fuels for the past few hundred and possibly a few thousand years. Fossil fuels are coal, natural gas, and petroleum. Humans have also been responsible for Earth's warming without realizing it by cutting down trees (deforestation), the making of charcoal, and growing food, especially rice. But the main cause, by far, is the massive burning of fossil fuels since the Industrial Revolution and the mass production of the internal combustion engine that most use as a power source. These advances in the use of power have caused a steady and steadily increasing rise in the concentration of atmospheric carbon dioxide and the Earth continues to warm as a result.

Fossil fuels are composed of hydrocarbons that have been buried in the Earth for millions of years. They form slowly and are not being replaced, and it is getting harder and more expensive to find them and to economically bring them to market. For instance oil, new deposits of which used to be found by drilling on land, now is found by drilling in ocean waters (as in the Gulf of Mexico). The first oil well in the U.S. was in the State of Pennsylvania. The most recent new wells have been drilled off-shore and are being drilled in deeper and deeper waters as new deposits or reservoirs of oil continue to be discovered.

Humans will soon run out of cheap fossil fuels. Fossil fuels have provided humans with a relatively cheap source of power for a long time. At the rate of consumption, we may run out of cheap fossil fuels sooner than later and as we do, they will become more and more expensive to extract, transport, sell, and burn. Many scientists are calling for a policy of leaving the remainder of fossil fuels in the ground before mankind burns all of them. There are at least two reasons for this:

1. Humans may need them later; and
2. Burning them is causing the planet to warm.

It is impossible to know just when the first fire was built with coal, but scientists know early man in Europe was burning coal. It is known that coal was used during the Bronze Age, more than 4,000 years ago. Today (June 2012), coal burning is the greatest source of carbon dioxide (CO_2) in the atmosphere where it stays for a long time (perhaps for thousands of years) and continues to contribute to global warming.

3.10.1 Joseph Fourier and the Greenhouse Effect

Jean Baptiste Joseph Fourier (1768–1830) was a French mathematician and physicist who had studied for the priesthood but never took his vows. Beginning with his work in the 1820s, scientists had understood that gases in the atmosphere might trap heat received from the Sun. Fourier realized that energy in the form of visible light from the Sun easily penetrates the atmosphere to reach the surface and heat it, but heat cannot so easily escape back into space. The air absorbs invisible heat rays (infrared radiation) rising from the surface. The warmed air radiates some of the energy back down to the surface, helping it stay warm. This is the effect that would later be called the "greenhouse effect." The equations and data available to nineteenth-century scientists were too poor to allow an accurate calculation of this effect but Fourier laid the foundation for later physics (e.g., blackbody radiation theory) that showed that a bare, airless Earth at its distance from the Sun should be far colder than it actually is (about 30°C colder).

3.10.2 John Tyndall and Thermal Radiation

John Tyndall (1820–1893) was an Irish physicist, mathematician, and mountaineer who began studying the radiative properties of various gases. He built the first spectrophotometer which he used to measure the absorptive power of gases such as water vapor, carbon dioxide, ozone, and hydrocarbons. He was the first to show the vast differences between gases to absorb and transmit radiant heat.

Tyndall showed that water vapor, carbon dioxide, and ozone were the best absorbers of thermal or heat radiation (not the radiation from atomic and hydrogen bombs, i.e., radioactivity) and they absorb much more strongly than the atmosphere itself. He concluded that water vapor was the strongest absorber of radiant heat and that it is the most important gas in controlling the temperature of the atmosphere. He even speculated on how fluctuations in water vapor and carbon dioxide were related to climate change. Thus, he was many years ahead of his time.

Tyndall became aware that the Earth's climate had changed drastically in the past by observing glaciers in the Alps. He also noted that glaciers had been more extensive in the Earth's past. He is the first scientist known who told his students why the sky is blue. Tyndall suggested that the sky is blue because molecules in the atmosphere preferentially scatter the Sun's blue rays, so that what we see looking up at a cloudless sky is the color blue. This is also true looking at the Earth from outer space; Earth is the blue planet (see frontpiece).

The Sun, stars, Moon, and other planets radiate light which travels to Earth. This light is electromagnetic radiation which travels through space as either waves or photons. Electromagnetic waves are produced by the motion of electrically charged particles. These waves are called electromagnetic radiation because they radiate from electrically charged particles. They travel through outer space as well as through air and other substances.

Electromagnetic radiation, besides acting like waves, acts like a stream of particles that have no mass. The photons with the highest energy correspond to the shortest wavelengths. Electromagnetic radiation travels at the speed of light.

Visible-light waves range in size from 0.4 to 0.7 μm (4,000–7,000 Å), whereas an atom is only a few angstroms in size.

Electromagnetic radiation is discussed in more detail later in this text.

3.10.3 Svante Arrhenius and Carbon Dioxide

Svante Arrhenius (1859–1927) was the first person to investigate what the effect of doubling atmospheric carbon dioxide would have on global climate. Arrhenius was a Swedish scientist and one of the founders of physical chemistry. He was apparently one of the first to discuss quantifying carbon dioxide in the atmosphere. He was the first to predict that emissions of carbon dioxide from the burning of fossil fuels and other combustion processes would cause global warming. Arrhenius stated the following:

> That the atmospheric envelopes limit the heat losses from the planets had been suggested about 1800 by the great French physicist Fourier. His ideas were further developed afterwards by Pouillet and Tyndall. Their theory has been styled the hot-house theory, because they thought that the atmosphere acted after the manner of the glass panes of hot-houses.
>
> If the quantity of carbonic acid in the air should sink to one-half its present percentage, the temperature would fall by about 4°; a diminution to one-quarter would reduce the temperature by 8°. On the other hand, any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4°; and if the carbon dioxide were increased fourfold, the temperature would rise by 8°.

Arrhenius was the first to predict that emissions of carbon dioxide from the burning of fossil fuels and other combustion processes would cause global warming.

In 1903 Arrhenius was awarded the Nobel Prize for Chemistry. His interest in climate science grew out of his interest in the cause or causes of the ice ages. His work laid the foundation for later work in climate change science.

Arrhenius was aware of the works of Fourier, Tyndall, and others before him and in 1895 presented a paper on the influence of carbon dioxide on climate. The article used an energy budget model that was ahead of its time in considering the radiative effects of carbon dioxide and water vapor on the surface temperature of Earth. He performed a series of calculations based on the data available to him on the temperature effects of increasing and decreasing amounts of carbon dioxide in the Earth's atmosphere. His work showed that the Arctic region would experience an increase in temperature of about 8 or 9°C if carbon dioxide increased 2.5–3 times its value (in 1895). Carbon dioxide prior to the Industrial Revolution stood at an estimated 270–280 parts per million (ppm). Today (June 2012), it stands at over 396 ppm.

Arrhenius calculated that in order to get the temperature of the last glacial advance between the 40th and 50th parallels of latitude, the carbon dioxide in the atmosphere would have to decrease between 0.62 and 0.55 of its value in 1895 to lower the temperature 4–5°C.

A few years after Arrhenius published his work, another Swedish scientist, Knut Angström, asked his assistant to measure the passage of infrared radiation through a tube filled with carbon dioxide. The assistant reported that the amount of radiation hardly changed when he reduced the gas by a third. This meant that it took only a trace of the carbon dioxide gas to absorb the radiation. Adding more carbon dioxide made little difference and only a trace of it in the tube was blocking infrared radiation from getting through.

3.10.4 T. C. Chamberlin and the Ice Ages

Thomas Chrowder Chamberlin (1843–1928) was an American geologist who is perhaps best known for his presentation of multiple working hypotheses. He was Head of the Glacial Division of the U.S. Geological Survey, president of the University of Wisconsin (at Madison), founder of the Journal of Geology, organizer of the department of geology at the University of Chicago, and with Forest Ray Moulton, developed a hypothesis of the formation of the Solar System known as the Chamberlin-Moulton planetesimal hypothesis. The planetesimal hypothesis had at its center the idea that smaller objects (planetesimals) collided with each other in the early stages of the Solar System and formed the planets by accretion (growing together and becoming larger).

In 1899, Chamberlin proposed that carbon dioxide in the atmosphere decreased during times of enhanced continental erosion, resulting in glaciation episodes during the last "ice age." Enhanced erosion was due to higher standing mountains (due to mountain-building or orogenies; or plate tectonics) and increased chemical weathering. The oceanic record of strontium isotopes, preserved in marine sediment, supports his suggestion that glacial climates during the Phanerozoic are in part linked to increases in the rate of global chemical erosion relative to outgasing from Earth's interior. Also, the close correlation of the major mountain building episodes of the Late Ordovician and Early Silurian, the Devonian, the Carboniferous and Permian Periods, and the late Cenozoic Era (see Appendix I for geologic Periods, Epochs, and Eras) to times of increased continental erosion and glaciation suggests that Chamberlin's hypothesis of the cause of glacial episodes should be revisited, at least for the earlier glacial episodes prior to the Cenozoic.

Chamberlin formulated his ideas about the ice ages when he worked in the glacial deposits of his native Illinois and Wisconsin. He was responsible for naming the Illinoian (310,000–128,000 years ago) and Wisconsin (35,000–11,800 years ago) glaciations and others of Pleistocene age.

3.10.5 Guy Stewart Callendar and Rising Temperatures

Guy Stewart Calendar (1897–1964) was a British engineer who was the first scientist to study climate change in a systematic way. He was the first to connect rising carbon dioxide concentrations in the atmosphere to the increase in Earth's temperature. He was aware of increasing carbon dioxide in the atmosphere as a result of burning fossil fuels and an increase in atmospheric temperature over the first 40 years of the twentieth century, which he linked empirically. He used the term "enhanced greenhouse effect" to describe what was happening to Earth's climate. The enhanced greenhouse effect is also called the Callendar effect.

Callendar formulated a coherent theory of infrared absorption and emission by trace gases, established the nineteenth-century background concentration of carbon dioxide (290 ppm), and stated that its atmospheric concentration was rising due to human activities, which was causing the Earth's climate to warm.

Callendar's research resulted in fundamental new insights into the spectra of water vapor, carbon dioxide, and ozone at low concentrations and low temperatures in the atmosphere, of critical importance to studies of the Earth's heat budget. He collaborated with a Cambridge physicist on delineating the absorption and emission characteristics of infrared spectra of hydrocarbons and atmospheric trace gases.

Callendar's main scientific contribution was specifically in anthropogenic climate change; the carbon dioxide theory of climate change.

Beginning in 1938, Callendar revived and reformulated the carbon dioxide theory by arguing that rising global temperatures and increased fossil fuel burning were closely linked. Callendar compiled weather data from stations around the world that clearly indicated a global warming trend of about 0.5°C in the early decades of the twentieth century. Callendar established what would become the standard number of 290 parts per million as the nineteenth-century background concentration of carbon dioxide in the atmosphere and documented an increase of 10% in this figure between 1900 and 1935, which closely matched the amount of fuel burned. Callendar pointed out that humans had long been able to intervene in and accelerate natural processes, and that humanity was now intervening heavily in the slow-moving carbon cycle by "throwing some 9,000 tons of carbon dioxide into the air each minute." In an era before computer climate modeling, Callendar compiled all the available information at that time on the detailed infrared absorption and emission spectra of atmospheric trace gases into a coherent picture of interest and relevance to climate scientists. He argued that the rising carbon dioxide content of the atmosphere and the rising temperature were due to human activities, thus establishing the carbon dioxide theory of climate change in its recognizably modern form. He was the first to establish the link between carbon dioxide and Earth's temperature and this is an amazing contribution to climate change science.

3.10.6 Gilbert Plass and Doubling of Carbon Dioxide

Gilbert Norman Plass (1920–2004) was a Canadian physicist who in the 1950s made predictions about the increase in atmospheric carbon dioxide levels in the twentieth century and its effect on the average Earth temperature that closely matches temperature measurements reported half a century later.

Plass worked mainly in the U.S. and worked as a physicist at the Metallurgical Laboratory of the University of Chicago and later at the Johns Hopkins University. He left academia in 1955 and worked for Lockheed Aircraft Corporation, then joined Ford Motor Company in their Aeronutronic division. In 1963 he accepted a position as the first professor of atmospheric and space science at the Southwest Center for Advanced Studies (now the University of Texas at Arlington). In 1968 he became a professor and head of the department of physics at Texas A & M University.

In 1953 as a result of his work on the effects of carbon dioxide from industrial sources as a greenhouse gas, he stated "At its present rate of increase, the carbon dioxide in the atmosphere will raise the Earth's average temperature 1.5 °F every 100 years for centuries to come if man's industrial growth continues, the Earth's climate will continue to grow warmer."

Plass made use of early electronic computers and predicted that a doubling of carbon dioxide would cause a warming of Earth's temperature by 3.6°C. He also predicted that carbon dioxide levels in 2000 would be 30% higher than in 1900 and that the planet would be about 1°C warmer in 2000 than in 1900. Intergovernmental Panel on Climate Change (IPCC) 2007 Fourth Assessment Report estimated a climate sensitivity of 2–4.5°C for a doubling of carbon dioxide, a rise of 37% since pre-industrial times (from about 1750 AD) and a 1900–2000 warming of around 0.7°C.

3.10.7 Hans Suess and Carbon-14 in Carbon Dioxide

Hans Suess (1909–1993) was an Austrian physicist, physical chemist, and geochemist who grew up in Vienna and who had a major role in climate science using radiocarbon (carbon-14, or ^{14}C). In the 1950s, a group at the University of Chicago headed by Willard Libby was using carbon-14 to date ancient materials. These materials were mainly archeological and anthropological, such as pottery and mummies. The Chicago group was also working on the separation and enrichment of isotopes for use in the medical field.

New techniques for isotope separation and enrichment were developed by the Chicago researchers and were used by Suess, who had joined the staff of the U.S. Geological Survey as a geochemist. He later was a founding faculty member of the University of California, Davis. He was responsible for developing radiocarbon dating techniques and contributed to knowledge of the elements and the evolution of the Solar System.

Suess devised a plan to measure carbon isotopes in tree rings. He began to collect old trees with the assistance of staff from the National Park Service and the U.S. Department of Agriculture. Suess' main concern was studying how carbon moved through the environment.

Carbon-14 originates in the upper atmosphere by bombardment of nitrogen by cosmic rays. Carbon-14 has a half-life of around 50,000 years, so the carbon-14 in fossil fuels has largely disappeared, as most fossil fuels are millions of years old.

Suess was the first one to notice that tree rings had less carbon-14 than would have been present in natural carbon tree rings. The carbon in tree rings had to come from the burning of fossil fuels; otherwise there would be more carbon-14 present.

Libby, in the early 1950s, had suggested that perhaps carbon-14 might be used to determine circulation in the deep oceans. The oceans were known to be a sink for carbon (taken up by the oceans) and were known to play a role as a major part of the carbon cycle. Just how carbon was distributed in the oceans was unknown. It was known that carbon dioxide was exchanged between the atmosphere and ocean water at the ocean's surface, but just how or even if this carbon dioxide was mixed in the deeper ocean waters was not known. It seemed certain that the tremendous mass of the oceans would absorb any excess carbon that might come from human activities like the burning of fossil fuels. Suess' measurements of the distribution of carbon ions in the oceans resulted in the prediction that it could take 1,000 years for them to circulate both horizontally and vertically.

There are three isotopes of carbon found in nature, carbon-12 (^{12}C), carbon-13 (^{13}C), and carbon-14 (^{14}C). ^{14}C is radioactive carbon or radiocarbon. ^{12}C and ^{13}C are stable isotopes of carbon and radiocarbon is not measureable after around 50,000 years, so ancient deposits (more than 50,000 years old) contain no measureable amounts of ^{14}C.

Hans Suess' main contribution to climate change science was to determine that oceanic circulation took too long to distribute carbon ions and as a result the oceans would not absorb the amounts of carbon dioxide that mankind was putting into the atmosphere.

3.10.8 Roger Revelle and Ocean Chemistry

Roger Revelle (1909–1991) was a U.S. scientist who made significant contributions to mankind's understanding of the oceans. He was an oceanographer and a major spokesman for science. He was one of the first scientists to recognize the effects of rising levels of atmospheric carbon dioxide on the Earth's surface temperature. He was a long-time member of Scripps Institute of Oceanography and served as its director from 1951 to 1964.

Revelle served on numerous national committees and was chairman of the Panel of Oceanography of the U.S. National Committee on the International Geophysical Year (IGY). During the planning for the IGY, Scripps was named as the principal center in the Atmospheric Carbon Dioxide Program.

Revelle hired Charles David Keeling who joined the Scripps staff to head the IGY program and began measurements of atmospheric carbon dioxide in 1956. Keeling started measurements of CO_2 in Antarctica and at the volcano Mauna Loa, Hawaii. Revelle became interested in the solubility of calcium carbonate and his interest in carbon dioxide in the atmosphere remained for the remainder of his life.

In 1965, Revelle served as a member of the President's Science Advisory Committee on Environmental Pollution. The committee published the first authoritative U.S.

governmental report in which carbon dioxide was officially recognized as a potential global problem.

3.10.9 Charles David Keeling and CO_2

Charles David Keeling (1928–2005) was a U.S. chemist who came to Scripps from California Institute of Technology (Cal Tech) where he had been a postdoctoral fellow in geochemistry. As was seen above, Roger Revelle hired Keeling at Scripps in 1956 to study the geochemistry of carbon and oxygen with an emphasis on the carbon cycle. He was the first scientist to confirm the increase of carbon dioxide in the atmosphere by very precise measurements that produced data which resulted in what is now called the Keeling Curve (Fig. 1.2). Prior to the work of Keeling, no one had quantified that carbon dioxide was steadily increasing in atmospheric concentration and his measurements became a milestone in historical climate change science.

Keeling discovered that the atmosphere breathes in an annual cycle that reflects the influences of photosynthesis, respiration, and atmospheric mixing. Keeling's discovery of the atmospheric background was of great importance, for it motivated his subsequent climatological studies of atmospheric carbon dioxide of the Earth as a whole. By way of example, the discovery of an atmospheric background also eventually motivated global studies by other scientists of additional greenhouse gases such as methane and nitrous oxide and of stratospheric ozone-destroying gases such as chlorofluorocarbons.

Keeling started the observatory on the flanks of Mauna Loa volcano in Hawaii and began his measurement of CO_2 in 1958. He located the observatory up-wind of the volcanic vent. One of the sources of carbon dioxide in the atmosphere is known to be volcanoes, so Keeling had to take care that his CO_2 measurements were not influenced by the gases escaping from the Mauna Loa vent.

Keeling's measurements on Mauna Loa have provided a true measure of the global carbon cycle, an effectively continuous record of the burning of fossil fuel. They also maintain an accuracy and precision that allow scientists to separate fossil fuel emissions from those due to the natural annual cycle of the biosphere, demonstrating a long-term change in the seasonal exchange of CO_2 between the atmosphere, biosphere and ocean.

Mauna Loa is indeed an active volcano and volcanoes release carbon dioxide to the atmosphere; it erupted in 1950, 1975, and 1984. Between eruptions, it emits variable amounts of carbon dioxide (CO_2) and sulfur dioxide (SO_2) from fissures at the summit. The observatory is located on the northern slope of the mountain, 4 miles away from and 2,600 ft lower than the summit, which is 13,675 ft above sea level.

Most of the time, the observatory experiences "baseline" conditions and measures clean air which has been over the Pacific Ocean for days or weeks. Observers know this because the CO_2 analyzer usually gives a very steady reading which varies by less than 3/10 of a part per million (ppm) from hour to hour. These are the conditions used to calculate the averages that go into the graph of atmospheric CO_2 concentrations.

Volcanic CO_2 from the Mauna Loa summit are only detected late at night at times when the regional winds are light and southerly. Under these conditions, a temperature inversion forms above the ground, and the volcanic emissions are trapped near the surface and travel down the side of the mountain slope toward the observatory. When the volcanic emissions arrive at the observatory, the CO_2 analyzer readings increase by several parts per million, and the measured amounts become highly variable for periods of several minutes to a few hours. In the last decade, this has occurred on about 15% of nights between midnight and 6 am.

The carbon dioxide data, measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO_2 in the atmosphere. They were started by Keeling in March of 1958 at a facility now run by the National Oceanic and Atmospheric Administration (NOAA). NOAA started its own CO_2 measurements in May of 1974, and they have run in parallel with those made by Scripps since then. The black curve in the Keeling Curve (Fig. 1.2) represents the seasonally corrected data.

Data are reported as a dry mole fraction defined as the number of molecules of carbon dioxide divided by the number of molecules of dry air multiplied by one million (ppm).

Keeling also noted a seasonal variation in his CO_2 measurements. In the summer months the CO_2 readings would decrease due to plants taking CO_2 out of the atmosphere and using CO_2 in photosynthesis. In winter the CO_2 readings would increase due to plants dying or going dormant and giving up their CO_2 to the atmosphere. This can be seen in the Keeling Curve illustrated in Fig. 1.2.

Keeling's work was motivated by the suggestion, originally made by Svante Arrhenius, that atmospheric carbon dioxide levels might be increasing due to the burning of fossil fuels with potential consequences for global climate. At that time, however, the suggestion was controversial; in part because it was unclear as to what extent the oceans might be buffering the atmospheric CO_2 increase. Within a few years of measurements, the Mauna Loa record had changed the notion of the atmospheric CO_2 increase from a matter of theory to a matter of fact. This was an achievement of tremendous scientific, social, and political importance, and within the scientific community stimulated the involvement of climate researchers such as Syukuro Manabe and others to quantify more precisely the impact of rising CO_2 on global climate. The Mauna Loa record, or Keeling Curve, has become a standard icon symbolizing the impact of humans on the planet.

3.10.10 Syukuro ("Suki") Manabe and Climate Modeling

Syukuro ("Suki") Manabe (1931–) is a meteorologist at the Geophysical Fluid Dynamics Laboratory (GFDL) of NOAA located at Princeton University in the U.S. Shortly after receiving his Ph.D. in meteorology in Japan he emigrated to the

U.S. and began work on some of the earliest attempts to model the atmospheric-oceanic system to be able to solve some of the problems of climate science. In the 1960s, Manabe and his research team developed a radiative-convective model of the atmosphere and modeled greenhouse gases such as water vapor, carbon dioxide, and ozone. This was the beginning of long-term research on climate change and global warming. In the late 1960s he began to develop a general circulation model (GCM) of the atmosphere-ocean-land system.

Suki Manabe pioneered the use of computers to simulate global climate change and natural climate variations.

3.10.11 James Hansen and Temperature Analysis

James Hansen (1941–) is the director of the Goddard Institute of Space Studies (GISS) at Columbia University in New York City, New York and is an adjunct professor in the Department of Earth and Environmental Sciences at Columbia University. He began studying the atmosphere of Venus and later applied his work to the Earth's atmosphere. He developed radiative transfer models to better understand the effects of aerosols and trace gases on Earth's climate. Hansen's development and use of global climate models has contributed to the further understanding of the Earth's climate.

Hansen has become an activist for action to mitigate the effects of climate change, which on a few occasions has led to his arrest. He is particularly active in opposition to coal mining and coal-fired power plants and the contaminants they emit, including carbon dioxide, mercury, arsenic, and others.

In 1987, Hansen and one of his colleagues (S. Lebedeff) devised a method of obtaining a global average temperature. This method continues to be used by GISS and agencies in other countries to arrive at an annual average global temperature. Additional information can be obtained from the following website: http://www.giss.nasa.gov/.

3.10.12 William Ruddiman and Paleoclimate

William F. Ruddiman is a noted paleoclimatologist and a professor emeritus in the Environmental Sciences Department at the University of Virginia. He is perhaps best known for proposing that humans began to affect carbon dioxide and methane concentrations in the atmosphere as early as 10,000 years prior to the present (2012) by deforestation and the beginnings of agriculture. Ruddiman is the author of two books and over 150 scientific papers in peer-reviewed scientific journals. He is a strong proponent of the Anthropocene designation beginning 8,000 years BC when humans began to change the composition of the atmosphere with early agricultural practices.

3.10.13 Gavin Schmidt and GISS

Gavin Schmidt is a climate scientist at the Goddard Institute of Space Studies (GISS) in New York City, NY. He specializes in climate models and is interested in modeling past, present, and future climate. He works on developing and improving coupled climate models and, in particular, is interested in how their results can be compared to paleoclimate data. He has worked on assessing the climate response to multiple forcings, including solar irradiance, atmospheric chemistry, aerosols, and greenhouse gases.

A general outline of one of Gavin Schmidt's recent papers shows the following:

1. Abstract – a synopsis of what is contained in the paper;
2. Introduction – an introduction to the problems to be solved with the work done for the project;
3. Data and Methods – what materials are available for study and how the study was conducted;
4. Results and Conclusions;
5. Appendices;
6. References.

3.10.14 Stefan Rahmstorf, Sea Level and Temperature Rise

A physicist and oceanographer by training, Stefan Rahmstorf has moved from early work in general relativity theory to working on climate issues. He has done research at the New Zealand Oceanographic Institute, at the Institute of Marine Science in Kiel and since 1996 at the Potsdam Institute for Climate Impact Research in Germany (in Potsdam near Berlin, Germany). His work focuses on the role of ocean currents in climate change, past and present. He teaches physics of the oceans as a professor at Potsdam University.

Rahmstorf is a frequent publisher in the area of ocean effects on climate and rising sea level due to melting glaciers. He is a regular contributor to the website RealClimate.com which is highly recommended as a source of updated climate change information.

Additional Readings

Ager, D. (1993). *The new catastrophism: The importance of the rare event in geological history*. Cambridge: Cambridge University Press.

Alley, R. B. (2000). *The two-mile time machine*. Princeton: Princeton University Press.

Appenzeller, T., & Dimick, D. R. (2004, September). The heat is on. *National Geographic*, 12–75.

Badash, L. (2001). Nuclear winter: Scientists in the political arena. *Perspectives in Physics, 3*, 76–105.

Bowen, M. (2008). *Censoring science: Inside the political attack on Dr. James Hansen and the truth of global warming*. New York: Dutton. ISBN 978-0525-95014-1.

Cohen, M., & Ernest, N. (1934). *An introduction to logic and scientific method* (p. 375). New York: Harcourt, Brace, and Company.

Darwin, C. (1859). *On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life* (p. 502). London: John Murray.

Foster, G., & Rahmstorf, S. (2011). Global temperature evolution 1979–2010. *Environmental Research Letters, 6*(2011), 044022 (8 pp). doi:10.1088/1748-9326/6/4/044022.

Hansen, J. E., & Lebedeff, S. (1987). Global trends of measured surface air temperature . *Journal of Geophysical Research*, *92*(D11), 13345–13372. Bibcode 1987JGR....9213345H. doi:10.1029/JD092iD11p13345.

Hansen, J. R., et al. (2002). Global warming continues. *Science, 295*(5553), 275. doi:10.1126/science.295.5553.275c.

Hawking, S. (1996). *The illustrated a brief history of time* (Updated and expanded ed., p. 15). New York: Bantam Books.

Hesketh, I. (2009). *Of apes and ancestors: Evolution, Christianity, and the Oxford debate*. Toronto: University of Toronto Press. ISBN 978-0-8020-9284-7.

Mayr, E. (1982). *The growth of biological thought*. Cambridge: Harvard University Press. ISBN 0-674-36446-5.

Schick, T., & Lewis, V. (2002). *How to think about weird things: Critical thinking for a new age*. Boston: McGraw-Hill Higher Education. ISBN 0-7674-2048-9.

Schmidt, G. A., et al. (2006). Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data. *Journal of Climate, 19*(2), 153–192. Bibcode 2006JCli…19..153S. doi:10.1175/JCLI3612.1.

Part II
Overview of Climate Change Science

Chapter 4
Earth's Energy Budget

Abstract Earth's energy imbalance is the difference between the amount of solar energy absorbed by the Earth and the amount of energy it radiates to space as heat. If the imbalance is positive, more energy coming in than going out, we can expect Earth to become warmer. If the imbalance is negative, then more energy is going out than is being received and the Earth will cool. Earth's energy imbalance is the single most crucial measure of the status of Earth's climate and it defines expectations for future climate change. The Earth's energy budget is explained in this chapter and the fact that Earth retains more of the electromagnetic radiation incident upon it from the Sun than it radiates back to space. The solar constant and aspects of solar electromagnetic radiation and the electromagnetic spectrum are discussed and illustrated. A distinction between weather and climate is made. Calculations of Earth's temperature with and without an atmosphere are completed. Earth's radiation laws are defined. The outgoing spectral radiance at the top of Earth's atmosphere and the absorption at specific frequencies by greenhouse gases are illustrated.

Keywords World Meteorological Organization • Energy • Radiance • Irradiance • Insolation • Photons • Electromagnetic • Spectrum • Kelvin • Heat • Solar constant • Planck • Wien • Nimbus 7 • Stefan-Boltzmann • TOA • Sunspots • UV • IR • Blackbody • Sunspots

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_4,

Things to Know	
The Difference Between Weather and Climate	WMO
TOA	ERM
Photons	6,000 Kelvin
Electromagnetic Radiation	UV
IR	Electromagnetic Spectrum
7,000 ångströms	Heat Energy
Blackbody	Speed of Light
6,000 Kelvin	Irradiance
−19°C	10^{-12} Meter
Insolation	Solar Constant
Visible Light	GSFC
Sunspot Cycles	Wien's Displacement Law
Stefan-Boltzmann Law	ERBS
The Inverse Square Law	1,368 W/m^2
93 Million Miles	Nimbus 7
Indicators of Global Warming	Planck's Law

4.1 Introduction

Climate change science is complex and involves many disciplines. One doesn't need to be an expert in all of them but one does need at least an introductory knowledge and an appreciation of them all. An overview of climate change science includes each of the following:

- Physics of the atmosphere;
- Chemistry of the atmosphere;
- Duration of climatic events;
- The difference between climate and weather;
- Warming of the lower atmosphere (troposphere) and cooling of the upper atmosphere (stratosphere);
- Warming of the World Ocean;
- Warming of the land;
- Melting of sea ice, permafrost, and glaciers;
- Rising concentrations of greenhouse gases in the atmosphere;
- Oceans becoming more acid (acidification);
- Disruption of Earth's weather patterns;
- Animals and plants migrating to higher latitudes and altitudes;
- Rising sea level;
- Diminishing water supplies for millions depending on fresh water from glaciers;
- Encroachment of sea water into fresh water supplies along coastal areas of the world;
- Higher rates of evaporation on land and sea;
- Higher rates of species extinctions;

- Disruption of natural patterns of agricultural growing seasons;
- Disruption of pollination of plants;
- Greater spread of tropical and subtropical diseases;
- Nights warming faster than days;
- Increasing humidity;
- Spring coming earlier and fall later;
- Climate Sensitivity.

All of these topics and more are addressed in the following sections and chapters of this text.

4.2 Weather and Climate

Everyone knows that the climate is always changing! But is it? Or is it weather that is always changing? The climate in southern Florida can be described as tropical and it has been tropical in South Florida for hundreds if not thousands of years. What has the weather been like in South Florida for the past 100 years or so? One can generalize and say that the summers are usually somewhat warmer than the winters but the temperature remains pretty much the same all year long. Every now and then there is a hurricane to disrupt the weather but there are no long-lasting climatic effects from hurricanes. Certainly there is much destruction but the climate soon returns to normal. So maybe the climate is not always changing; maybe it's the weather that changes all the time. Weather and climate are certainly two different things.

Climate in an area has been defined as weather over a long period of time, usually taken to be at least 30 years, according to the World Meteorological Organization (WMO). Weather is what happens today, tomorrow, or predicted for the next week or 10 days. Weather has been defined as the state of the atmosphere at any given time.

Weather is not climate and it is necessary to make that distinction before we consider climate change trends. We cannot speak in terms of global weather, but we can speak in terms of global climate. And the global climate is getting warmer throughout most of the world.

4.3 Solar and Heat Energy

Heat is energy and the majority of Earth's energy comes from the Sun. Some of the solar energy is directly reflected back to space by the top of Earth's atmosphere (TOA), by clouds, by solid particles in the Earth's atmosphere (aerosols), by glaciers, by oceans, and by the solid Earth itself. Solar energy leaves the Sun as electromagnetic radiation (EMR), travels through space, and impinges upon the Earth.

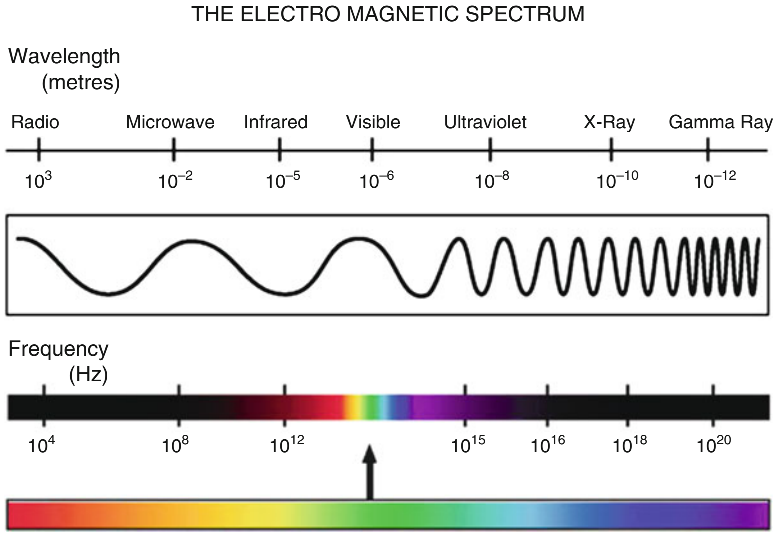


Fig.4.1 The electromagnetic spectrum (From http://www.scienceprog.com/wp-content/uploads/2009/05/electromagnetic_spectrum.jpg)

EMR is a form of energy emitted and absorbed by charged particles, which exhibits wave-like behavior as it travels through space.

The electromagnetic spectrum consists of wavelengths of light varying from long wavelengths (low energy) to very short wavelengths (high energy). The length of a wave is measured from crest to crest or from trough to trough (Fig. 4.1). Light is a type of radiation and behaves as waves of light and as particles of light (photons). Visible light is part of the radiation that comes from the Sun, light bulbs, fires, and other forms of illumination. Visible-light waves range in size from 0.4 to 0.7 µm (4,000–7,000Å), whereas an atom is only a few ångströms in size.

The electromagnetic spectrum and the different wavelengths are shown in Fig. 4.1.

Electromagnetic waves are produced by the motion of electrically charged particles. These waves are also called "electromagnetic radiation" because they radiate from electrically charged particles. They travel through empty space as well as through air and other substances.

Electromagnetic radiation, besides acting like waves, also acts like a stream or packet of particles (photons) that have no mass. The photons with the highest energy correspond to the shortest wavelengths. Electromagnetic radiation travels at the speed of light which is thought to be a universal constant and is on the order of 3×10^8 m/s or 300,000,000 m/s.

Light produces heat, as one can attest who has ever touched an incandescent light bulb after it has given off light for any length of time. The most common light sources are thermal (heat); a body at a given temperature emits a characteristic spectrum of what is referred to in physics as blackbody radiation. Examples include Sunlight (the radiation emitted by the Sun at around 6,000K). About 40% of Sunlight is visible and is the main source of Earth's heat. Other heat sources are from Earth's interior and incandescent light bulbs and glowing solid particles in flames.

A blackbody is an object that absorbs all the incident radiation that hits it. It in turn radiates heat depending on the temperature of the object.

The peak of the blackbody spectrum is in the infrared for relatively cool objects like human beings. As the temperature increases, the peak shifts to shorter wavelengths, producing first a red glow, then a white one, and finally a blue color as the peak moves out of the visible part of the spectrum and into the ultraviolet. These colors can be seen when metal is heated to "red hot" or "white hot." Blue thermal emission is not often seen.

Over time, the amount of incoming solar radiation (short-wave or ultraviolet) absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation (heat energy or infrared radiation). About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface, by evapo-transpiration, and by longwave radiation that is absorbed by clouds and greenhouse gases. Some of this longwave energy escapes back into space.

The greenhouse gases in the atmosphere radiate longwave energy back to Earth as well as out to space. Certain gases in the atmosphere trap the longwave radiation and re-radiate it back to the Earth's surface. This re-radiation of heat energy is what allows Earth's near-surface temperature to be about 30°C warmer than it would be without the greenhouse gases and these gases have allowed life on Earth to develop over time and thrive. Earth would be a very uncomfortable place at an average global temperature of −15 to −19°C.

4.4 Earth's Radiation Laws

The vast majority of the energy driving Earth systems is solar radiation. Energy from the Sun drives almost every known physical, chemical, and biological cycle on Earth's surface. Beneath the surface, energy derived from the Earth's interior drives volcanoes, fumaroles and geysers, and drives plates and causes continents to drift, but most energy and its results at and near the Earth's surface are radiated from the Sun.

The average properties of the Sun's electromagnetic radiation interacting with matter are given in a simple set of rules called radiation laws. These laws apply when the radiating body is what is referred to as a blackbody radiator (Fig. 4.4).

In order to determine the effects of solar radiation on the Earth, it is first necessary to determine the amount of solar radiation reaching the atmosphere and surface of the Earth. There are three terms which are often used by atmospheric and climate change scientists when dealing with solar radiation impacting Earth, as follows:

- **Irradiance** – The amount of electromagnetic energy incident on a surface per unit time per unit area. In the past this quantity has often been referred to as "flux." When measuring solar irradiance (via satellite), scientists are measuring the amount of electromagnetic energy incident on a surface perpendicular to the incoming radiation at the top of the Earth's atmosphere, not the output at the solar surface. Total solar irradiance (TSI) is the amount of solar radiative energy incident on the Earth's upper atmosphere.

- **Solar Constant** – The solar constant is the amount of energy received at the top of the Earth's atmosphere on a surface oriented perpendicular to the Sun's rays (at the mean distance of the Earth from the Sun). The generally accepted solar constant of 1,368 W/m^2 is a yearly average measured by satellite.
- **Insolation** – In general, solar radiation received at the Earth's surface (**In_Sol_Ation**; from **in**cident **sol**ar radi**ation**). The rate at which direct solar radiation is incident upon a unit horizontal surface at any point on or above the Earth's surface.

The main problem with determining the Earth's surface temperature with calculations made for the top of the atmosphere (TOA) is that up to 70% of incoming radiation can be blocked by gases in the atmosphere and by clouds. Scientists usually estimate the amount of energy actually reaching the surface and this estimate is plugged into climate models.

It must also be assumed that the surface receiving the radiation is perpendicular to the incoming radiation. This is a problem due to the Earth's rotation, its axial tilt (obliquity), the latitude and orientation of the surface relative to the solar radiation, and the season of the year.

All of these factors change the angle of the surface receiving the radiation, which changes the intensity of the energy received.

Assuming that the radiation emission of the Sun is constant is also a problem because this value fluctuates with cycles in solar activity. The Sun has recently (as of June 2012) come out of a long period described as a solar minimum which is a period of reduced solar activity. NASA satellites have measured incoming radiation since 1978 and have recorded changes in solar irradiance (Fig. 4.2). This data can be accessed on the Internet from the Goddard Space Flight Center (GSFC): http://www.nasa.gov/centers/goddard/home/index.html.

Energy from the Sun arrives at Earth as electromagnetic waves, or as an electromagnetic spectrum. Electromagnetic waves travel at the speed of light and consist of the entire range of frequencies and wavelengths at which electromagnetic waves can travel from the smallest (a single atom) to the largest (theoretical infinity).

The energy emitted from the Sun is electromagnetic energy. The amount of energy can be expressed by the units of Planck's Law. Planck's Law describes the electromagnetic radiation emitted from a blackbody at absolute temperature T and written as follows:

$$E_\lambda = a / [\lambda^5 \{e^{(b/\lambda T)} - 1\}] \tag{4.1}$$

Where $\mathbf{E_\lambda}$ = the amount of energy (Wm^2 μm^{-1}) emitted at wave length λ (μm) by a body at temperature T (in units Kelvin) with ***a*** and *b* as constants.

The wavelength emitted from an object depends on the temperature of the object. This wave length can be calculated according to Wien's Law when the temperature of the object is known. This is also referred to as Wien's Displacement Law.

The wavelength distribution of thermal radiation from a blackbody at any temperature has essentially the same shape as the distribution at any other temperature,

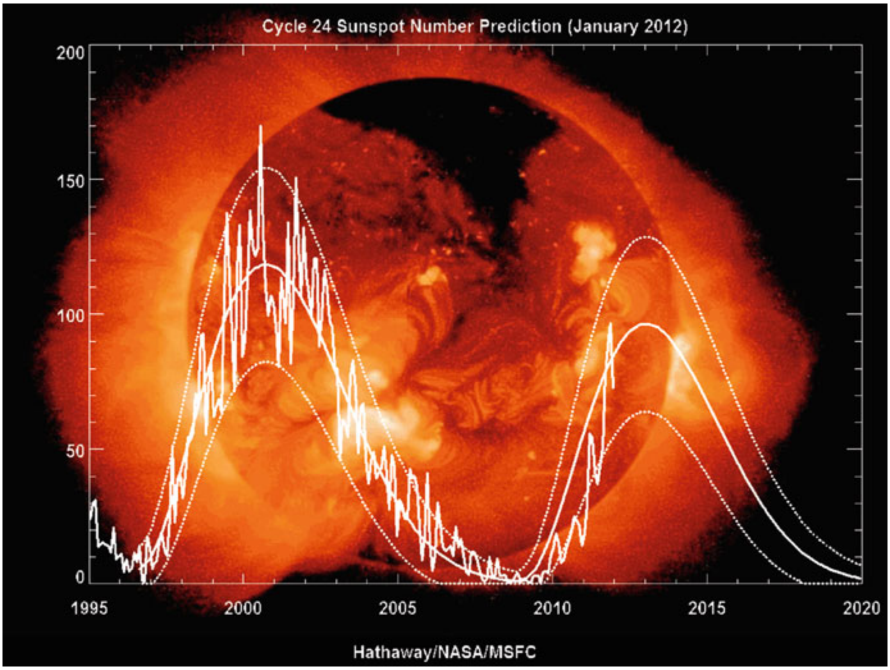


Fig. 4.2 The Sunspot cycle from 1995 to 2020. The *jagged curve* traces actual Sunspot counts. *Smooth curves* are fits to the data and one forecaster's predictions of future activity (Credit: David Hathaway, NASA/MSFC; From http://science.nasa.gov/science-news/science-at-nasa/2009/01apr_deepsolarminimum/; Public Domain)

except that each wavelength is displaced on the graph. This is the reason it is called Wien's Displacement Law.

By differentiating Eq. 4.1 (Planck's Law), it is possible to determine the wavelength of maximum radiation emission from the Sun using Wien's Law:

$$\lambda_{maximum} = 2897 / T$$

$\lambda_{\mathrm{maximum}}$ = the peak wavelength of energy in micrometers
T = Temperature of the object radiating energy.
2897 = Wien's Displacement Law Constant

Using Wien's Law, the peak wavelength of radiation emitted from an object is inversely proportional to the temperature of that object. The radiation output of an object can be calculated using the Stefan-Boltzmann Law when the temperature is known. The Stefan-Boltzmann Law states that the total energy radiated per unit surface area of a blackbody per unit of time is directly proportional to the fourth power of the blackbody's thermodynamic temperature T (also called the absolute temperature). The Stefan-Boltzmann Law is written as follows:

$$E = l\,\sigma\,T^4$$

E = Surface irradiance of the object
l = Emissivity of the object
σ = Stefan-Boltzmann Constant (5.67×10^{-8} W/m^{2}K^4)
T = Temperature of the object

The Inverse Square Law is used to calculate the decrease in radiation intensity due to an increase in distance from the radiation source. The Inverse Square Law is written as follows:

$$\mathbf{I = E\left(4\pi \times R^2\right)/\left(4\pi \times r^2\right)}$$

I = Irradiance at the surface of the outer sphere
E = Irradiance at the surface of the object (the Sun)
$4\pi \times R^2$ = Surface area of the object
$4\pi \times r^2$ = Surface area of the outer sphere

In order to be able to calculate the solar constant the following equation is used:

$$\mathbf{So = E\,(Sun) \times (R\,(Sun)\,/\,r)^2}$$

So = Solar Constant
E = Surface irradiance of the Sun
R = 6.96×10^5 km = Radius of the Sun
r = 1.5×10^8 km = Average Sun – Earthdistance

The solar radiation reaching the Earth's surface can be found with the following equation:

$$\mathbf{I = S\cos Z}$$

I = Insolation
S ~ 1,000 W/m^2 (clear day solar insolation on a surface perpendicular to incoming solar radiation. This varys a great deal due to atmospheric variables).
Z = Zenith Angle (Zenith Angle is the angle from the point directly overhead to the Sun's position in the sky. The angle is dependent on latitude, solar declination angle, and the time of day).

$$\mathbf{Z = \cos^{-1}(\sin\phi\sin\delta + \cos\phi\cos\delta\cos H)}$$

φ = Latitude
H = Hour Angle = 15° × (Time – 12) (Angle of radiation due to time of day. Time is given in solar time as the hour of the day from midnight)
δ = Solar declination angle

Solar declinations can be found for each hemisphere on NASA's websites such as the following for the Northern Hemisphere: http://edmall.gsfc.nasa.gov/inv99Project.Site/Pages/science-briefs/ed-stickler/ed-irradiance.html.

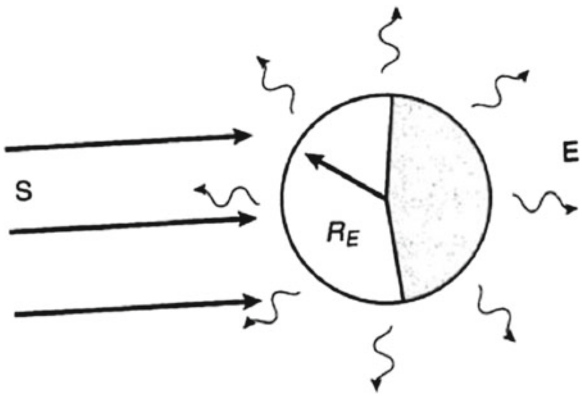
In addition to making calculations for solar irradiation based upon physics concepts, the public can access and analyze solar irradiance data that is collected by orbiting satellites and ground-based pyranometers (a pyranometers is an instrument for measuring solar radiation). Satellite irradiance data is available from 1978 to the present on the Internet. The irradiance data has been collected by the following NASA satellites:

- Nimbus 7 (Earth Radiation Budget) 1978–1993;
- Solar Maximum Mission: Active Cavity Radiometer Irradiance Monitor I (ACRIM I) 1980–1989;
- Earth Radiation Budget Satellite (ERBS) Solar Monitor Measurements 1984–1996;
- Upper Atmosphere Research Satellite (UARS) ACRIM II Measurements 1991–1997.

Data and further information related to these satellites and others are available to the public through the NASA Goddard Space Flight Center Data Archive Center: http://daac.gsfc.nasa.gov/.

A few simple calculations will illustrate the effect that the physics of the atmosphere has on Earth's surface temperature as shown by the following steps:

Step 1 – Assume that the Earth has no atmosphere. Calculate the average global surface temperature.



To calculate the Earth's average surface temperature, you can use the Stefan-Boltzman Law for a blackbody.

$$E = \sigma T^4$$

where the Stefan-Boltzman constant, $\sigma = 5.67 * 10^{-8} \dfrac{Watts}{m^2 * K^4}$

In this equation, E is the rate of incident solar irradiance, which can be taken to be about 1,368 W per square meter (as an average measured by satellites).

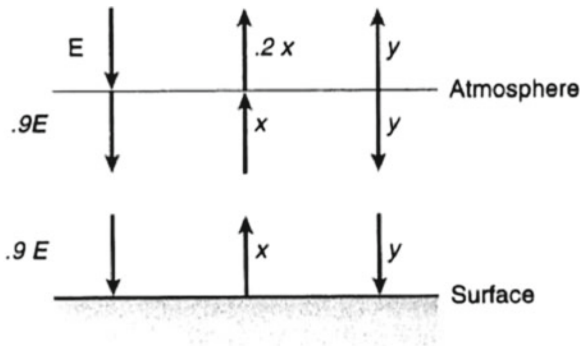
Solving for temperature:

$$T = \left(\frac{E}{\sigma}\right)^{1/4} = \left(\frac{1{,}360\,\frac{Watts}{m^2}}{5.67 * 10^{-8}\,\frac{Watts}{m^2 * K^4}}\right)^{1/4} = 254.5\,\mathrm{K} = -19\,^{\circ}\mathrm{C}$$

Step 2 – Next add in the atmosphere. Recalculate the average global surface temperature.

For this calculation, the atmosphere can be regarded as a thin layer with an absorptivity of 0.1 for solar radiation and 0.8 for infrared radiation. Let x equal the irradiance of the earth's surface and y the irradiance (both upward and downward) of the atmosphere. E is the irradiance entering the earth-atmosphere system from space averaged over the globe (E = 342 W/m^2) (solar constant = 1,368/4 = 342 W/m^2).

At the Earth's surface, a radiation balance requires that:



Doing a radiation balance for the surface and the atmosphere, e.g., energy into the surface equals energy out of the surface and energy into the atmosphere equals energy out of the atmosphere gives you the following equations, respectively:

$$0.9E + y = xE + x = 0.9E + 2y + 0.2x$$

Solving these equations simultaneously reveals that x = 377 W/m^2 and y = 163 W/m^2.

Again, by using the Stefen-Boltzman Law, you can now calculate the temperature of the surface of the earth.

$$T = \left(\frac{E}{\sigma}\right)^{1/4} = \left(\frac{x}{\sigma}\right)^{1/4} = \left(\frac{163\,\frac{Watts}{m^2}}{5.67 * 10^{-8}\,\frac{Watts}{m^2 * K^4}}\right)^{1/4} = 286\,\mathrm{K} = 13\,^{\circ}\mathrm{C}$$

You can see that with an atmosphere, the average surface temperature of the earth is actually 13°C. Taking it one additional step, you can calculate the increase in absorptivity that would be needed to increase the global average surface temperature by 1°C. Using the equations above, you can see that the increase would only need to be about 0.02.

No matter how you decide to describe it, through hands on experiments and measurements, or through the calculations, climate change is happening and the global climate is very sensitive to change. The sooner we all accept it, the sooner we can start working together to both reduce our emissions and adapt to the changes that are already happening.

The problem presented above is adapted from Wallace and Hobbs, 1977 as it was stated by Scott McNally, in *Scientific American*, February 16, 2012 (used with permission).

4.5 Earth's Energy Imbalance

If the Earth emitted the same amount of energy as it was receiving, it would be in energy equilibrium or balance. But there is more energy coming into the Earth system than is going out, so the system compensates by warming. It has to warm because of the energy imbalance. Prior to the Industrial Revolution the atmospheric concentration of carbon dioxide had been stable for hundreds of years and the Earth's temperature had had normal fluctuations due to a balance of energy received with energy emitted by the Earth.

The Sun is ultimately responsible for virtually all energy that reaches the Earth's surface. Direct overhead Sunlight, as measured by satellite, at the top of the atmosphere provides 1,368 W/m^2; however, much of the Sunlight is reflected off the top of the atmosphere so that the light which is absorbed at any typical location is an annual average of ~342 W/m^2. If this were the total heat received at the surface, then, neglecting changes in albedo (Earth's reflectivity), the Earth's surface would be expected to have an average temperature of −19°C. Instead, the Earth's atmosphere recycles heat coming from the surface and delivers an additional 324 W/m^2, which results in an average surface temperature of roughly plus 15°C. This is the greenhouse effect which keeps the Earth's surface habitable for living organisms.

The total solar energy is determined by the temperature of the Sun's visible surface, or photosphere, which is about 6,000°K (Kelvin). Like the Sun, the Earth emits an amount of energy determined by the temperature of Earth's lower atmosphere, the troposphere, which is about 255°K (or about −18°C). But this in turn is determined by Earth's need to balance the incoming solar energy which it absorbs, by emitting an equal amount of energy back to space, in order to remain in equilibrium.

The troposphere not only radiates out to space, but also radiates downward to the surface, and that "back-radiation" from the atmosphere adds to the fraction of solar energy which penetrates to the surface, to heat the surface to about 288° K (or about +15°C). The figure below shows how Earth's energy balance is achieved for a

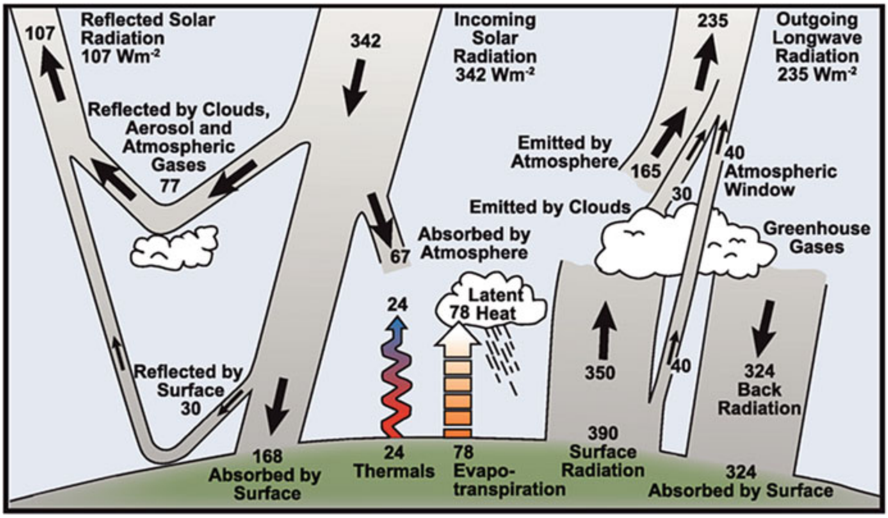


Fig. 4.3 Estimate of the Earth's annual and global average energy balance (from IPCC AR4 2007)

typical square meter at the **t**op of the atmosphere (TOA) and how it depends on the solar constant of about 1,368 W/m^2 divided by 4 (because Earth's cross section which absorbs the solar energy is 1/4 of its emitting surface area) as well as the Earth-atmosphere albedo, which is the fraction of solar energy reflected by a combination of the land, ice and especially clouds which compose the Earth-atmosphere system. (1,368 W/m^2 divided by 4 equals 342 W/m^2).

Incoming solar radiation is 342 W/m^2 at the top of the atmosphere (TOA) and if Earth was in energy balance, 342 W/m^2 would also be outgoing. The majority of incoming solar radiation is shortwave ultraviolet radiation. The outgoing radiation is longwave infrared radiation. In Fig. 4.3 above, 324 W/m^2 are reflected back to Earth by greenhouse gases and absorbed by Earth's surface and 235 W/m^2 are emitted back to outer space (Fig. 4.3).

Although the Earth and Sun behave approximately as black bodies, this is not the case for the gases that make up the Earth's atmosphere. Certain atmospheric gases absorb radiation at some wavelengths but allow radiation at other wavelengths to pass through. Black bodies are objects that absorb all electromagnetic radiation impinging upon them and radiate amounts depending on their temperature.

Absorption of energy by a particular gas occurs when the frequency of the electromagnetic radiation is similar to that of the molecular vibrational frequency of the gas in question. The atmosphere is mostly transparent in the visible part of the spectrum but significant absorption occurs of ultraviolet radiation (incoming shortwave solar radiation) by ozone and absorption of infrared radiation (longwave outgoing terrestrial radiation) by water vapor, carbon dioxide and other trace gases.

The absorption of terrestrial infrared radiation is particularly important to the energy budget of the Earth's atmosphere. Such absorption by the trace gases heats the atmosphere, stimulating it to emit more longwave radiation. Some of this is released into space while the rest is re-radiated back to Earth. The net effect of this is that the Earth stores more energy near its surface than it would if there was no atmosphere, consequently the temperature is higher by about 33 K (+15°C).

This process is popularly known as the greenhouse effect as was defined earlier in this text. Glass in a greenhouse is transparent to solar radiation, but opaque to terrestrial infrared radiation. The glass acts like some of the atmospheric gases and absorbs the outgoing energy. Much of this energy is then re-emitted back into the greenhouse causing the temperature inside to rise. In reality, a greenhouse is warmer than its surroundings principally because of the shelter it offers rather than because of any radiative considerations. Nevertheless, the term has stuck largely as a result of media reporting and the analogy is useful.

Consequently, the gases in the atmosphere which absorb the outgoing infrared radiation are known as greenhouse gases and include carbon dioxide, water vapor, nitrous oxide, methane, and ozone. All the greenhouse gases have molecules whose vibrational frequency lies in the infrared part of the spectrum. Despite the considerable absorption by these greenhouse gases, there is an atmospheric window through which terrestrial infrared radiation can pass. This occurs at about 8–13 μm, and its gradual closing is one of the effects of anthropogenic emissions of greenhouse gases. As this window closes the Earth's temperature will rise even more rapidly than it is rising at present.

Energy arriving at the top of the atmosphere starts an energy cascade involving numerous energy transformations. On entering the atmosphere, some of the solar shortwave radiation is absorbed by gases in the atmosphere (e.g., carbon dioxide, water vapor), some is scattered, some is absorbed by the Earth's surface and some is reflected directly back into space by either clouds or the surface itself. The amount of shortwave radiation reflected depends on a factor known as the albedo (or reflectivity). Albedo varies according to the surface. Ice and certain clouds have a high albedo (0.6, or 60% to 0.9, or 90%) while the oceans generally have a low albedo (0.1, or 10%). For the whole Earth this averages at about 0.30, meaning that 30% of the incoming solar radiation is reflected.

Of the terrestrial longwave radiation re-emitted from the Earth's surface, most is re-absorbed by the greenhouse gases and only a little escapes directly through the atmospheric window. Long-wave radiation re-emitted from the atmosphere (greenhouse gases, clouds) is either returned to the Earth's surface or released into space. The net result of this greenhouse effect is to increase the amount of energy stored near the Earth's surface, with a consequent increase in temperature. There are also additional heat fluxes associated with evaporation and transpiration which balance the energy fluxes into and out of all parts of the Earth-atmosphere system.

A blackbody is an object which absorbs all radiation falling upon it and does not reflect any, but will emit radiation as it is heated. As the blackbody is heated, it will emit radiation according to Plank's Law. All radiation emitted by a blackbody is due to its temperature; the higher the temperature, the more radiation that will be emitted.

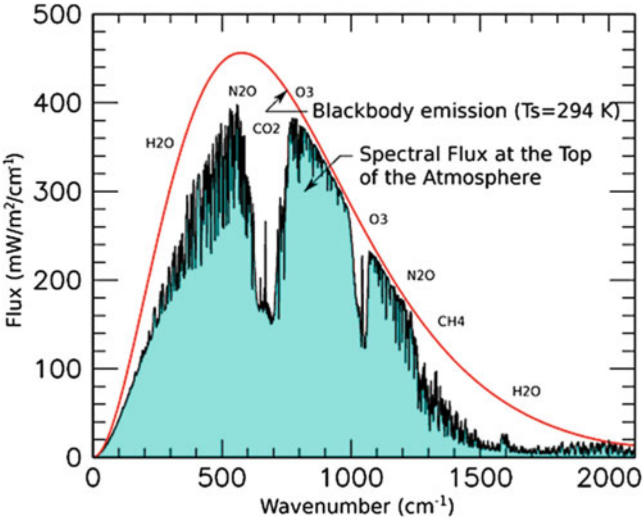


Fig. 4.4 Outgoing spectral radiance at the top of Earth's atmosphere showing the absorption at specific frequencies and the principle absorber. For comparison, the *red curve* shows the flux from a classic "blackbody" at 294 °K (≈31°C≈69.5°F) (NASA/GISS, Public Domain)

The figure above (Fig. 4.4) shows two curves, one from a classical blackbody and the other looking down at the atmosphere from outer space. The red curve is radiation of a blackbody at Ts = 294 K. The black curve is spectral flux at the top of the atmosphere. The large reduction in flux is at the wavelengths absorbed by carbon dioxide (CO_2).

Solar radiation is emitted uniformly in all directions. After travelling 93 million miles only a tiny fraction of the energy emitted by the Sun toward the Earth is intercepted by the Earth. Therefore, the energy flux arriving at the top of the Earth's atmosphere is many orders of magnitude smaller than that leaving the Sun. The latest satellite measurements indicate a value of 1,368 W/m^2 for the energy received at the top of the atmosphere on a surface perpendicular to the solar beam. This is known as the solar constant, which is a misnomer as the "solar constant" varies with the amount of energy produced by the Sun and this varies over time. It has been found to vary in an 11-year sunspot cycle but this is also variable.

Additional Readings

Archer, D. (2005). Fate of fossil fuel CO_2 in geologic time. *Journal of Geophysical Research, 110*, C09S05. doi:10.1029/2004JC002625.

Beerling, D. (2009). Methane and the CH_4-related greenhouse effect over the past 400 million years. *American Journal of Science, 309*, 97–113.

Beltrami, H. (2002). Continental heat gain in the global climate system. *Geophysical Research Letters, 29*, 1167. doi:10.1029/2001GL014310.

Hansen, J., Rossow, W., & Fung, I. (Eds.). (1993): *Long-term monitoring of global climate forcings and feedbacks* (NASA Conf. Publ. 3234). New York: Goddard Institute for Space Studies.

Hansen, J., et al. (2011). Earth's energy imbalance and implications. *Atmospheric Chemistry and Physics, 11*, 13421–13449. doi:10.5194/acp-11-13421-2011.

Hansen, J., et al. (2012). *Perceptions of climate change: The new climate dice* [WWW document], URL http://www.columbia.edu/~jeh1/mailings/2012/20120105_PerceptionsAndDice.pdf

Intergovernmental Panel on Climate Change (IPCC). (2007). In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Climate change 2007: The physical science basis*. New York: Cambridge University Press, 996 pp.

Mishchenko, M. I., et al. (2007). Accurate monitoring of terrestrial aerosols and total solar irradiance: Introducing the Glory mission. *Bulletin of the American Meteorological Society, 88*, 677–691. doi:10.1175/BAMS-88-5-677.

Chapter 5
Climate Change Trends

Abstract Global warming started when humans began altering the chemistry of the atmosphere by agricultural practices about 10,000 years ago and was exacerbated by the beginning of the Industrial Revolution due to the increased burning of coal as a cheap source of energy. As a result of these factors, and the mass production of the internal combustion engine, greenhouse gases have been building up in the atmosphere for the past 10,000 years. There are certain observable trends that are and have been taking place, especially during the latter half of the twentieth century and into the twenty-first. Among these are rising temperatures over land and sea, receding glaciers and rising sea level. Other climate change trends are listed and further discussed in this chapter. Different temperature scales used in climate science are Celsius, Fahrenheit, and Kelvin. The features of temperature graphs are explained and examples given. A typical meteorological station is described and illustrated. Sources of temperature data are discussed as well as potential problems with the data. The BEST study, their reasons, and their results are explained as are methane clathrates and climate change perturbations and attribution.

Keywords Celsius • El Niño • Centigrade • Pyranometer • GISS • ENSO • BEST • NCDC • Climate change • Trends • Kelvin • Fahrenheit • Absolute zero • UAH • RSS • Extinctions • Tropospheric warming • Stratospheric cooling • Perturbations • NOAA • Rocketsondes • Arctic ice • Proxies • Arctic warming • SSTs • Permafrost • Meteorological station • Methane • Clathrates • Radiosondes • Attribution • Forcings • Feedbacks • Temperature

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_5,

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the “Things to Know” should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
Climate Change Trends	Temperature Scales
Attribution	BEST
Forcings	Tropospheric warming
El Niño	NCDC
Feedbacks	Kelvin
Arctic Ice	Climate perturbations
Absolute zero	Stratospheric cooling
Sea-surface temperatures	NOAA
Radiosondes	Animal and plant extinctions
Methane Clathrates	RSS
Land-based meteorological station	Permafrost
Proxy	Pyranometer

5.1 Climate Change Trends

How do we know the climate is changing and the Earth is warming? The list of reasons given below shows some of the main reasons that we know but there are others that will be discussed later in this text. The most obvious indicators that the Earth is warming are the following:

1. Increased humidity in the atmosphere;
2. Increased evaporation of ocean and fresh water and moisture from soils;
3. Increasing frequency and intensity of storms and unusual weather patterns;
4. Melting glaciers;
5. Melting permafrost and release of methane to the atmosphere;
6. Decreasing snow cover in winter;
7. Temperature increases over land and sea;
8. Temperature increases in boreholes;
9. Increase in ocean heat content;
10. Increasing air temperatures in the lower atmosphere (troposphere);
11. Increasing temperature of the upper crust of the solid Earth;
12. Cooling of the stratosphere;
13. Plants and animals shifting to higher latitudes and altitudes;
14. Sea level rising;
15. Ice sheets, glaciers, and sea ice melting;

16. Spring coming earlier and fall later in the year;
17. Ocean acidification; ocean waters are becoming more acidic;
18. Nights warming more rapidly than days;
19. Outbreaks of pest infestations earlier each year;
20. Increase of animal and plant species extinction.

5.2 Rising Temperatures

Are temperatures rising all over the Earth? And if so, how do we know? How fast are temperatures rising, if they are rising, and why?

Temperature records tell us that some places on Earth are getting warmer while others are getting colder depending on the season of the year and local factors. But how do we know that the Earth as a whole is growing warmer, cooler, or staying the same? How do we arrive at a global average temperature for the Earth? If we could calculate an annual global temperature for a series of years we could see if the Earth is warming, cooling, or staying the same over a certain period of time, and this has been done by scientists at NASA's Goddard Institute of Space Studies (GISS) as well as by others.

To obtain the annual average temperature for the Earth, it seems that all scientists would need to do is add all of the temperature readings from the Earth and divide by the number of readings. That procedure would give scientists a number but it would not be an accurate or meaningful number. Some of the reasons why that number would not be accurate are as follows:

- Most of the readings would be from the Northern Hemisphere because most of the land and the people with thermometers are in the Northern Hemisphere, so the average would not be a world-wide average;
- Some of the readings would be from different seasons of the year and one season may be represented by more readings than another season;
- Some of the readings would be from nighttime, others from daytime and there could be more of one than the other;
- Some readings would be from old weather stations located near vents or surrounded by asphalt or city buildings (the heat-island effect) and this would increase the average temperature;
- Temperature readings from one station may be reporting more temperature readings than other stations.

Fortunately, a method for calculating the Earth's global average temperature was devised by scientists at NASA's Goddard Institute of Space Studies (GISS) in the 1970s which will be described later in this text after we first look at different ways to measure temperature; and the different temperature scales that are used internationally to record and refer to temperatures.

A recent (2011) paper published in *Environmental Research Letters* extracted the human-caused global warming signal from the global surface temperature and lower atmosphere (troposphere) temperature data. In order to accomplish this, the authors filtered out the effects of solar activity, the El Niño Southern Oscillation (ENSO), and the volcanic activity from the data. The result of this study confirmed the warming trend presented by earlier workers.

5.2.1 Temperature Scales

To be able to measure and to report temperature readings in a meaningful way, universal temperature scales have been devised. The most commonly used scales are Fahrenheit (°F) and Celsius (°C) but there are other temperature scales used for different purposes. The Kelvin (K) scale is also used in climate science but Celsius (the same as Centigrade) is used most often as can be seen in the majority of the graphs present in this text. The following illustrations (Fig. 5.1 and Table 5.1) compare the three most commonly used temperature scales used in climate change science.

Some baseline temperatures in the three most commonly used temperature scales are shown below in Fig. 5.1.

The following equations allow conversion between the Celsius and Fahrenheit temperature scales:

$$\text{Temperature Celsius } (T_c) = 0.55\,(T_f - 32)$$

$$\text{Temperature Fahrenheit } (T_f) = 1.8T_c + 32$$

A Celsius to Fahrenheit and *vice versa* conversion program can be found at the following web site: http://www.wbuf.noaa.gov/tempfc.htm. By entering the temperature in either Celsius or Fahrenheit, the equivalent temperature in the other scale is automatically shown.

The Kelvin scale has no degrees but is simply divided into units Kelvin (1 unit K equals 1 degree Celsius or Centigrade). The lowest point on the Kelvin scale is absolute zero, the point at which matter becomes stationary (subatomic particles become frozen). Absolute zero Kelvin is equivalent to −273°C. Thus, 0°C is 273 K. Each degree on the Celsius scale is +273 K. Thus, 10°C is 283 K. The Kelvin scale is stated without degrees and is reported with just a number. There are no minus numbers to the Kelvin scale and nothing has ever been reduced in temperature to zero K.

5.2.2 Temperatures Shown by Graphs

Temperatures shown by plotting annual global temperatures against time are shown in the illustration Fig. 1.1 in the Introduction. It is possible in this way to show temperature trends through time and visually determine that the Earth is warming, cooling, or staying about the same.

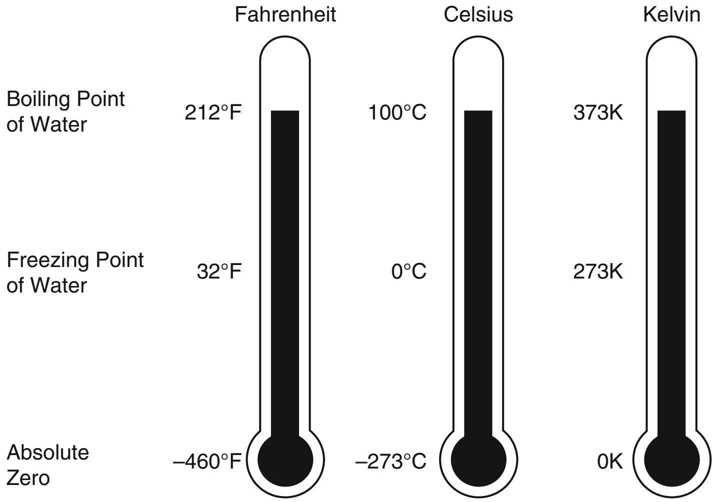


Fig. 5.1 Celsius, Fahrenheit, and Kelvin temperature scales. The Celsius scale is also called the centigrade temperature scale, and is the scale based on 0 for the freezing point of water and 100 for the boiling point of water. Invented in 1742 by the Swedish astronomer Anders Celsius, it is sometimes called the centigrade scale because of the 100-degree interval between the defined points. The following formula can be used to convert a temperature from its representation on the Fahrenheit (F) scale to the Celsius (C) value: $C = 5/9(F - 32)$. The Celsius scale is in general use wherever metric units have become accepted, and it is used in scientific work everywhere (Redrawn from website cfbt-us.com with permission from Ed Hartin)

Table 5.1 Scales commonly used when discussing temperature, Fahrenheit, Kelvin, and Celsius

Commonly used temperature scales			
Temperature	Kelvin	Degree Celsius	Degree Fahrenheit
Symbol	K	°C	°F
Boiling point of water	373.15	100	212
Melting point of ice	273.15	0	32
Absolute zero	0.	–273.15	–459.67

Temperatures in the graphs shown in this text are given in degrees Celsius (°C) unless otherwise stated. They are also given as temperature anomalies which are temperatures as compared to an average global temperature for a stated interval of time (as the global average for the temperatures during the period 1951–1980 in Fig. 1.1). By using this method of referring to temperature it can be easily seen that Earth's temperature is warming, cooling, or staying the same for a given unit of time.

Let's look at what can be gleaned from Fig. 1.1. There are two axes to the graph: the x-axis along the bottom giving the number of years from 1880 to 2000 and beyond. The vertical or y-axis is stated as the temperature anomaly and given in °C. The 0° position on the y-axis represents the average temperature for the period

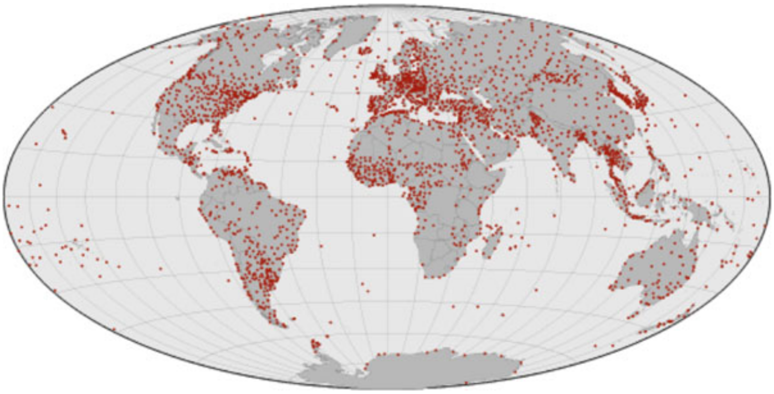


Fig. 5.2 Weather stations (*red dots*) are scattered unevenly across the globe. They are especially sparse in Africa and over the oceans. Before scientists could be confident in global temperature records, they needed to demonstrate that widely spaced observations captured global temperature trends accurately (NASA map by Robert Simmon, based on data from the National Climatic Data Center, Public Domain)

1951–1980, as stated in the caption, and all temperatures on the graph are plotted with reference to the 0° point, either positive (above) or negative (below) 0°.

There is a series of black squares along the x-axis connected by a thin black line and identified in the graph as the annual mean. There is a red line bisecting the black line identified as the 5-year running mean and as expected the two lines are roughly parallel. As can be seen in the graph (Fig. 1.1), there was a slight cooling beginning around 1880 until 1890, then a slight warming followed by a cooling until around 1910, then a gradual and pretty consistent warming until about 1940, then a slight cooling through the 1970s, and then an almost constant warming until the present time (beyond 2000; the last number on the x-axis).

The black squares in Fig. 1.1 are annual means and the red line is a 5-year running mean. Note the green vertical bars which represent uncertainty; their length indicates the degree of uncertainty. The green bars become shorter as the temperature plot approaches the present reflecting greater confidence in temperature measurements as instrumentation and quality control improve.

The method of calculating a global average temperature was originally devised with the understanding that the sample of temperature readings was heavily biased toward the Northern Hemisphere.

Absolute estimates of global average surface temperature are difficult to compile for several reasons. Some regions have few temperature measurement stations, such as the Sahara Desert and Antarctica, and interpolation must be made over large, data-sparse regions. The distribution of weather stations over the Earth's surface is represented by the illustration above (Fig. 5.2).

By stating the temperatures as anomalies and as a temperature index, confusion with raw temperature data is avoided. Skeptics disagree with the method of average temperature methodology. Often the disagreement is due to simple denial of the warming

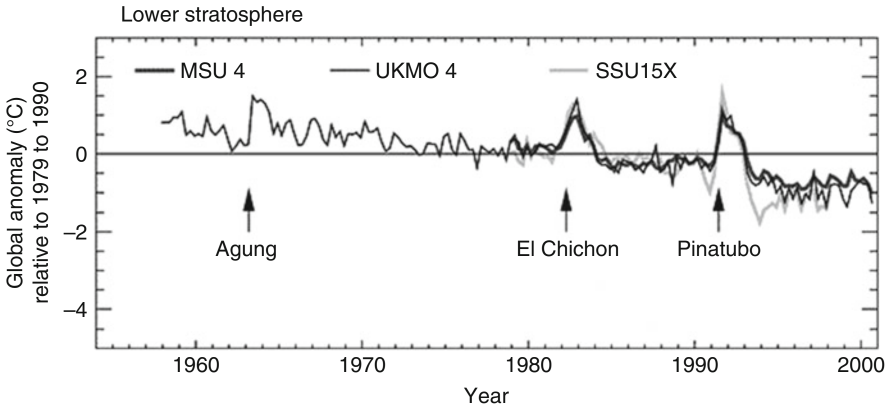


Fig. 5.3 Microwave sounding unit (MSU) lower troposphere and lower stratosphere 1979–2010 temperature trend (°C/decade) and 12 months running mean global temperature time series with respect to 1979–1998 (From Wikipedia, Giorgiogp2, GNU Free Documentation license)

trend that is evident in plots of the temperature record. It is also sometimes due to a lack of understanding of how the data are used to derive an annual average temperature.

5.2.3 Rising Land and Sea Temperatures

Land temperatures are derived mainly from weather stations located throughout the world on land. Areas with the greatest populations have the most weather stations and as most of the land and population areas of the world are located in the Northern Hemisphere, most of the weather stations are also located in the Northern Hemisphere. Records show that both land and sea are warming.

5.2.4 Tropospheric Warming and Stratospheric Cooling

Tropospheric and stratospheric temperatures are central to the problem of greenhouse warming because General Circulation Models (GCMs) predict that temperature changes with enhanced concentrations of greenhouse gases will have a characteristic profile in these layers, with warming in the mid- and lower troposphere and cooling in much of the stratosphere. The cooler stratospheric temperatures would be an expected consequence of the increased trapping of terrestrial radiation in the troposphere.

The illustration above (Fig. 5.3) shows the cooling of the lower stratosphere during the latter part of the twentieth century as directly measured by satellites and weather balloons.

If the stratosphere is cooling, the Sun could not be causing the Earth's global warming. If it was the Sun, the atmosphere would be heating throughout and the stratosphere would be warming as well.

It is harder to measure temperature in the stratosphere than in the troposphere where in the latter there is a network of measurement stations. Stratospheric temperature measurements do exist. They have been made using weather balloons, radiosondes, microwave sounding units (MSUs), rocketsondes (an instrument carried aloft by a rocket), LIDAR (light detection and ranging), and satellites (Fig. 5.3).

5.3 Sources of Uncertainty with Temperature Data

Despite all the attempts to formalize, convert, assimilate, analyse, and reduce the temperature data, problems will always remain, and it is important to be aware of them as discussed in the following sections. Uncertainty is part of science and a good scientist always remains sceptical until experiments and tests have been verified; and this is certainly the case with temperature data.

There are, however, problems inherent in collecting any data from natural systems for any purpose. These problems may be due to any one or all of the following for any natural data set:

- Missing components or errors in the data;
- "Noise" in the data associated with biased or incomplete observations;
- Random sampling error and biases (non-representativeness) in a sample.

There are statistical and other methods of dealing with most of the uncertainty.

The key to understanding global climate change is to first understand what global climate is, and how it operates. It is a complex system involving many variables in time (temporal) and space (spatial) and there are additional sources of uncertainty as follows:

- Ambiguously defined concepts and terminology;
- Inappropriate spatial or temporal units;
- Inappropriateness of or lack of confidence in underlying assumptions;
- Uncertainty due to projections of human behaviour (e.g., future consumption patterns, or technological change), which is distinct from uncertainty due to "natural" sources (e.g., climate sensitivity, chaos).

The global climate system is the result of links and interactions between the atmosphere, oceans, glaciers, living organisms, Earth history, and the solid Earth. Only by considering the climate system in these relationships is it possible to understand the cycles of energy in the atmosphere, an understanding which is required to investigate the causes (and effects) of climatic change.

Because of the convergence of individual elements that make up the climate system, it is appropriate to divide a treatment of the system into separate sections; each section dealing with a different component. This will begin with the atmosphere and its energy budget or energy cycle, the balance of which ultimately controls the global climate. Following this, the other components of the climate system (the oceans and hydrosphere, cryosphere, biosphere, and geosphere) will be introduced showing how each influences the Earth's energy budget and global climate.

5.4 Climate Construction from Instrumental Data

In order to understand the climate and to gain insight into how it is changing and what may be causing the changes, it is necessary to gather the most accurate data available. The following sections will treat the methods and discuss the accuracy and problems with these data.

The basic elements of climate are temperature, rainfall, humidity, and wind over decades, centuries, thousands, and millions of years. There are instruments to measure these climate elements at present. The thermometer is used today to measure temperature and was developed in the 1600s. To measure climate in the past before instruments were devised, however, proxies (substitutes) must be used. Proxies are indirect ways or substitutes used to measure climate elements prior to the development of instrumentation.

5.5 Measurement of Temperature

The global temperature is determined by data reduction after millions of temperature data points have been assembled. This is a monumental task that is only possible because of increasing computer capability and the dedication of thousands of individuals all over the world.

For temperature records before the advent of the thermometer in the seventeenth century, temperature data must be acquired using proxies. Some of the proxies used for temperature in the distant past are geochemical, such as oxygen and carbon ratios that will be discussed later in the text. Other proxies are derived from such things as tree-rings, stalactites and other cave deposits, ice cores, sediment cores from lakes and the ocean, shells of sea creatures, and boreholes into the solid Earth.

Arctic temperatures in the 1990s reached their warmest level of any decade in at least 2,000 years, research published September 4, 2009 in *Science*, indicates. The study, which incorporates geologic records and computer simulations, provides new evidence that the Arctic would be cooling if not for greenhouse gas emissions that are overpowering natural climate patterns.

The similarity of characteristics among the different paleoclimate (proxy) reconstructions provides confidence in the following important conclusions:

- Dramatic global warming has occurred since the nineteenth century.
- The recent record of warm temperatures in the last 15 years is the warmest on Earth in at least the last 1,000 years, and possibly in the last 2,000 years or further back in Earth's history.
- Temperature proxies (substitutes) are perhaps the best evidence for reconstructing the past history of the planet's climate.

Climate proxies are discussed further in the chapter on paleoclimates.

5.5.1 Global Temperature from Meteorological Stations

The temperature graph given in Fig. 1.1 is a graph of readings taken from meteorological stations worldwide from 1880 to 2010. These are from stations located on land and sea and indicate the warming of the atmosphere just above the surface of the Earth.

A typical land-based meteorological station consists of the following:

- A wind gauge or vane;
- A Sunshine recorder;
- A pyranometer (an instrument for measuring insolation);
- A rain gauge;
- A snow gauge;
- An anemometer (an instrument that measures wind speed);
- A temperature recorder shielded by a cover or shelter.

Global land temperatures are reported by a variety of agencies. Those in the United States, and used worldwide, are reported by the U.S. National Climate Data Center (NCDC), a portion of the National Oceanographic and Atmospheric Administration (NOAA), and NASA's Goddard Institute of Space Studies (GISS). These reports are based on the Global Historical Climate Network (GHCN version 3 data). The Global Historical Climatology Network (GHCN) is a database widely used by climate scientists for temperature, precipitation and pressure records managed by the NCDC, Arizona State University, and the Carbon Dioxide Information Analysis Center. Other reporting centers are the U.K.'s Hadley Centre and the Climate Research Unit at the University of East Anglia.

Most of the land records used in calculating the global averages comes from weather stations but some comes from boreholes drilled into the Earth. The latter have only century resolution, at best.

The global land surface temperature was the warmest on record for March 2011, 3.3°F above the twentieth century mean of 40.8°F, for a global average temperature of 44.1°F for March 2011. Temperatures more than 8°F above average covered much of the Asian continent. Two months after the greatest January snow cover extent on record on the Eurasian continent, the unusually warm temperatures led to rapid snow melt, and the March 2011 snow cover extent on the Eurasian continent was the lowest on record.

5.6 The Berkeley Earth Surface Temperature (BEST) Study

The Berkeley Earth Surface Temperature (BEST) study set out to develop a new method of obtaining a land surface average temperature and compare it with existing studies that have been done by U.S. and U.K. Governmental agencies. The study was led by a University of California (Berkeley) physicist who was described as a climate change/global warming skeptic prior to the study.

The BEST study used over 39,000 unique stations which are more than five times the 7,280 stations found in the Global Historical Climatology Network Monthly data set (GHCN-M). Some of the final results of the study are shown in Fig. 5.4.

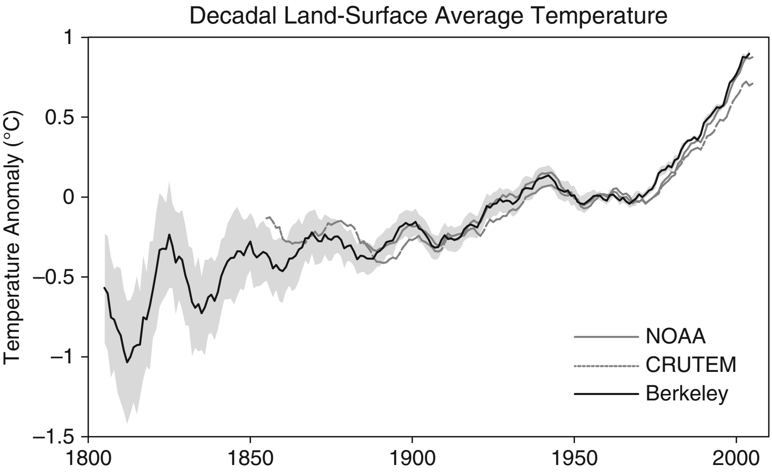


Fig. 5.4 Results of the BEST study. Temperature records constructed by NASA/GISS, NOAA, HadCRU, and UC Berkeley, the latter conducted by a team of University of California Berkeley researchers, has investigated 1.6 billion meteorological records. The data come from 5 times as many stations as in the previous studies. The researchers find exactly the same quantitative results for global temperature rise. The above graph shows the decadal land-surface average temperature using a 10-year moving average of surface temperatures over land. Anomalies are relative to the Jan 1950–December 1979 mean. The *grey band* indicates 95% statistical and spatial uncertainty interval (Based on data from http://www.berkeleyearth.org/analysis)

The Berkeley Earth Surface Temperature Study has created a preliminary merged data set by combining 1.6 billion temperature reports from 15 preexisting data archives.

The BEST study addressed scientific concerns raised by skeptics and deniers including urban heat island effect, poor station quality, and the risk of data selection bias. The BEST group concluded that the warming trend is real, that over the past 50 years the land surface has warmed by 0.911°C, and their results mirror those obtained from earlier studies carried out by the U.S. National Oceanic and Atmospheric Administration (NOAA), the U.K.'s Hadley Centre, NASA's GISS Surface Temperature Analysis, and the Climatic Research Unit (CRU) at the University of East Anglia in the U.K. The BEST study also found that the urban heat island effect and poor station quality did not bias the results obtained from these earlier studies.

5.7 Land Temperatures from Boreholes

A global temperature reconstruction using temperatures measured from boreholes was begun and has been maintained by the Geothermal Laboratory at the University of Michigan (also maintained at the NCDC). In the UM study, underground temperature measurements were examined from a database of over 350 boreholes in eastern North America, Central Europe, Southern Africa and Australia (There are 116 sites in eastern North America, 98 in central Europe, 86 in southern Africa, and 58 in Australia). Using this approach, scientists found that the twentieth century was

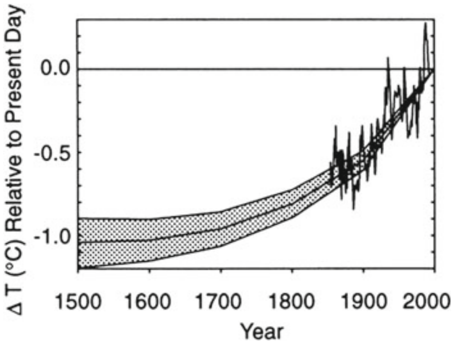


Fig. 5.5 Composite surface temperature change over the past five centuries, relative to the present, as determined from geothermal data. *Shaded areas* represent ±1 standard error about the mean history. Superimposed is a smoothed (5-year running average) SAT instrumental record (10) representing a composite of the same regions as the geothermal data. Because the SAT series is referenced to the mean anomaly over the interval from 1961 to 1990 and because the geothermal result is referenced to the present, we have shifted the SAT series downward by 0.2°C to enable a visual comparison of the trends by a direct overlay (Modified from Pollard 2005; http://www.ncdc.noaa.gov/paleo/paleo.html, Public Domain)

the warmest of the past five centuries, thus confirming the results of surface temperature studies.

The geophysical methods used to generate borehole temperature reconstructions do not permit annual or decadal resolution, but only the century-scale trend in temperatures over the last several centuries. Nonetheless, this record, totally independent of data and methods used in other studies, shows that the Earth has been warming dramatically for some time.

A composite temperature history for 358 borehole sites obtained by University of Michigan scientists from all over the world indicates that the present-day mean temperature of these sites is about 1.0°C warmer, on average, than five centuries ago. The change of temperature in the twentieth century alone has been about 0.5° and equals the cumulative change that is inferred for the previous four centuries. The temperature of the twentieth century appears to be warmer than the mean temperature of any of the previous four centuries. The composite meteorological record for the sites, where available, displays similar trends in the time interval of overlap (Fig. 5.5).

More information on land temperatures from boreholes can be found at the following web site: http://www.ncdc.noaa.gov/paleo/paleo.html.

5.8 Rising Sea Temperatures

Sea water responds more slowly to temperature changes than does air or land and the World Ocean is the greatest reservoir of heat on the planet. Global warming caused by human activities that emit heat-trapping carbon dioxide has raised the average global air temperature by about 1°F over the past century. In the oceans, this

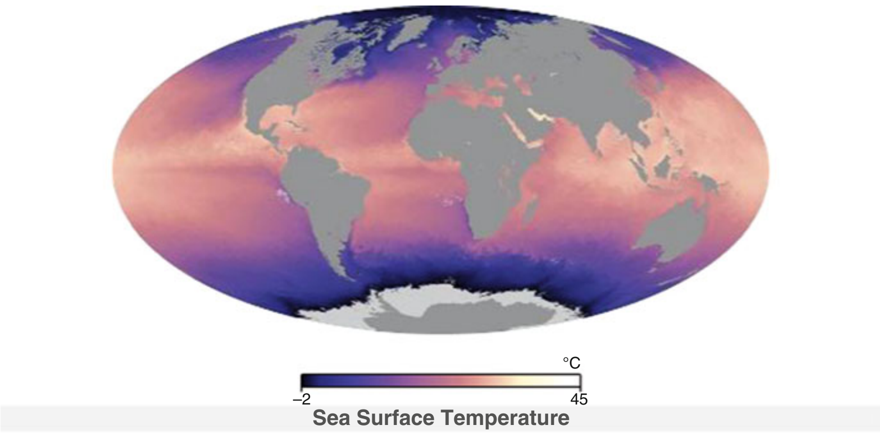


Fig. 5.6 Sea surface temperature distribution throughout the globe (From http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=MYD28M, Public Domain)

change has only been about 0.18°F. This warming has occurred from the surface to a depth of about 2,300 ft (700 m), where most marine life exists.

The ocean has an important role in climate variability and change. The ocean's heat capacity is about 1,000 times larger than that of the atmosphere, and the oceans net heat uptake since 1960 is around 20 times greater than that of the atmosphere. This large amount of heat, which has been mainly stored in the upper layers of the ocean, plays a crucial role in climate change, in particular variations on seasonal to decadal time scales. As the ocean warms it also causes sea level to rise due to thermal expansion and if ocean waters continue to warm there are severe consequences for the world's food chain.

5.8.1 Relative Distribution of Sea-Surface Temperatures (SSTs)

The current relative distribution of sea-surface temperatures is shown in Fig. 5.6. Sea surface temperatures across the globe have a large influence on climate and weather patterns. For example, every 3–7 years a wide swath of the Pacific Ocean along the Equator warms by 2–3 °C. This warming is a hallmark of the climate pattern of El Niño, which changes rainfall patterns around the globe, causing heavy rainfall in the southeastern United States and severe drought in Australia, Indonesia, and southern Asia. On a smaller scale, ocean temperatures influence the development of tropical cyclones (hurricanes and typhoons), which draw energy from warm ocean waters to form and intensify. There is a direct relationship between the strength of the El Niño and the number of storms and storm intensities.

The sea surface temperature map shown in Fig. 5.6 is based on observations by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite. The satellite measures the temperature of the top millimeter of the ocean surface. In this map, the coolest waters appear in blue (approximately −2°C or

28.4°F), and the warmest temperatures appear in pink-yellow (45 °C or 113 °F). Land masses and the large area of sea ice around Antarctica appear in shades of gray, indicating no data were collected.

The most obvious pattern shown in a time series (which can be downloaded from the NASA web site for their Earth Observatory information at http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=MYD28M), is the year-round difference in sea surface temperatures between Equatorial regions and the poles. Various warm and cool currents stand out even in monthly averages of sea surface temperature. A band of warm waters flows up the East Coast of the United States and then across the North Atlantic – the well-known Gulf Stream.

Although short-lived weather events that influence ocean temperature are often hidden in monthly averages, a few events do show up. For example, in December 2003, strong winds blew southwest from the Gulf of Mexico over Central America toward the Pacific Ocean, driving warm surface waters away from the coast and allowing cold water from deeper in the ocean to rise up to the surface. These winds are a recurring phenomenon in the area in winter; they are known as Tehuano winds.

5.8.2 Ocean Heat Content

Approximately 93.4% of the Earth's heat buildup has gone into the World Ocean. How does the ocean gain heat? Climate scientists and oceanographers like to think of the ocean as having a "skin" which is the upper few millimeters to a few meters of the ocean. The "skin" is warmed by sunlight and the heat begins to move downward to deeper ocean waters. Therefore, as stated by the Second Law of Thermodynamics, as sunlight continues to heat the ocean surface, heat moves into the atmosphere if the latter is cooler, down into the deeper ocean water which is also cooler, and is dispersed in all directions by ocean currents.

It has been documented that warmer waters in the Southern Ocean (around Antarctica) are melting glacial ice from the west coast of Antarctica. The warming waters of the Southern Ocean are melting ice from the west Antarctic ice shelves. As these ice shelves melt, additional ice moves from the continent to replace them as ice shelves and this leads to additional sea level rise.

The illustration below (Fig. 5.7) shows the increasing heat content in the first 700 m of ocean waters from the 1950s through 2009. It is in the first 700 m of the World Ocean where most oceanic life exists. There is little doubt where most of Earth's heat buildup is occurring; it is occurring in the World Ocean.

5.9 Melting Ice

The majority of ice is found in nature as glaciers, ice sheets, sea ice, permafrost, and on the bottom of the ocean in methane clathrates. It is also found on lakes and streams during colder parts of the year in mid-latitudes and higher elevations, as

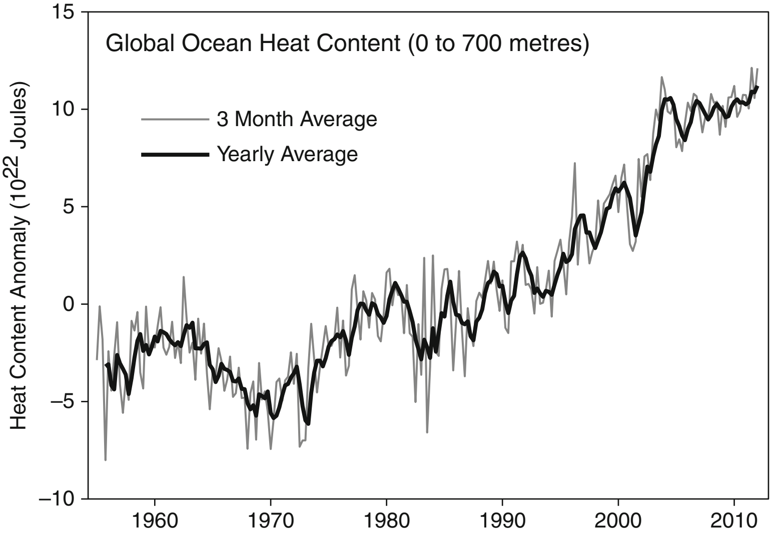


Fig. 5.7 Global ocean heat content (From http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/; updated from Levitus et al. 2009, Public Domain)

icebergs in the ocean, and as ice shelves and ice caps. Most of this ice is melting, some more rapidly than others. Ice may even be expanding due to local conditions in some locations and in different times of the year but the diminishing trend of ice on Earth is apparent.

There has been debate over the glaciers in the Himalayan Mountains since an error was discovered in the thousands of pages of the IPCC AR4 report of 2007. The report stated that the Himalayan glaciers were disappearing at a faster rate than was actually happening. This error was corrected by the IPCC but some critics have not given up on their attacks of the 2007 report. The Himalayan glaciers are receding in their lower reaches but some may actually be gaining ice at higher elevations. Those in the highest elevations will take much more warming to recede as temperatures at higher elevations are lower and the majority of precipitation falls as snow.

The IPC AR4 2007 report consisted of four major sections with numerous supplementary reports. These sections are as follows:

- Contribution of Working Group I (WGI): *Climate Change 2007: The Physical Science Basis*.
- Contribution of Working Group II (WGII): *Climate Change 2007: Impacts, Adaptation and Vulnerability*.
- Contribution of Working Group III (WGIII): *Climate Change 2007: Mitigation of Climate Change*.
- Contribution of Working Groups I, II, and III: *The Synthesis Report* (SYR).

The IPCC AR4 2007 report, *Climate Change 2007: The Physical Science Basis*, assessed current scientific knowledge of "the natural and human drivers of climate

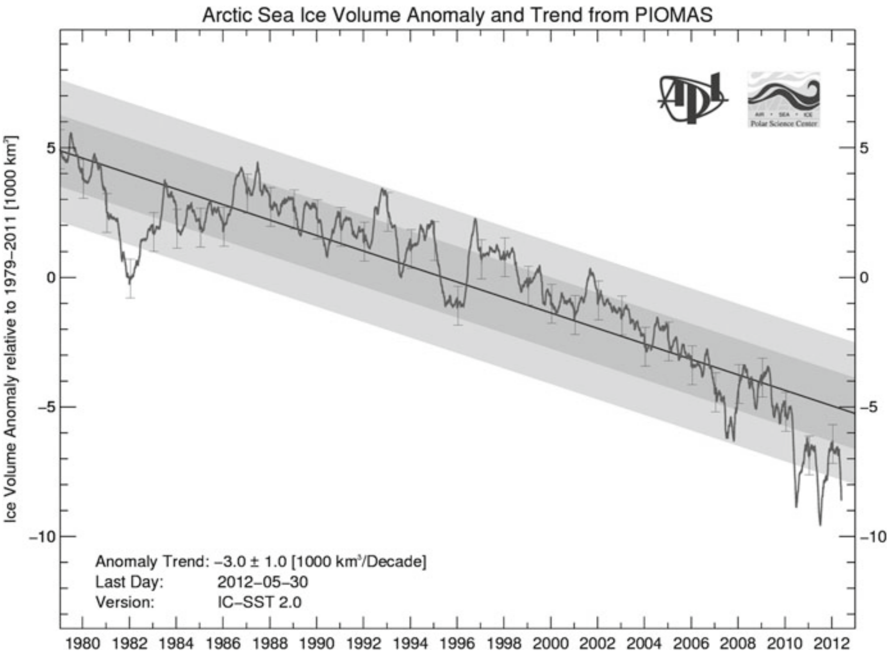


Fig. 5.8 Arctic sea ice volume anomaly from Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) updated once a month. Daily Sea Ice volume anomalies for each day are computed relative to the 1979–2010 average for that day of the year. The trend for the period 1979-present is shown in blue. *Shaded areas* show one and two standard deviations from the trend. *Error bars* indicate the uncertainty of the monthly anomaly plotted once per year (From Polar Science Center, http://psc.apl.washington.edu/wordpress/, viewed 12/28/2011; work supported by U.S. Public funds, Public Domain)

change" as well as observed changes in climate. It looked at the ability of science to attribute changes to different causes, and made projections of future climate change.

The *Physical Science Basis* was produced by 676 authors (152 lead authors, 26 review editors, and 498 contributing authors) from 40 countries, and then reviewed by over 625 expert reviewers. More than 6,000 peer-reviewed publications were cited. It is amazing that only two mistakes have been found.

Before being approved, the summary was reviewed line by line by representatives of 113 governments during the 10th session of WGI, in January to February 2007.

Further discussion of the reports can be found throughout t his text.

The illustration above (Fig. 5.8) shows the decline in Arctic sea ice volume since 1979 through 11-30-2011.

Arctic ice has undergone a steady decline in extent while Antarctic sea ice has apparently increased. Does this mean that the Antarctic is cooling thereby forming new sea ice? Not necessarily, because sea ice is frozen water and its extent may be deceptive. It is possible to have global warming and expanding sea ice if the volume of ice throughout the globe is decreasing. Extent is not necessarily related to volume. New ice may be forming on the ocean surface while old ice is being reduced in volume, as is happening in both the Arctic and Antarctic.

Arctic sea ice thickness comparisons over time are given in a fairly recent study. This study examined sea ice thickness records from submarines and ICESat (NASA's Ice, Cloud and Elevation satellite) observations from 1958 to 2008 (ICESat's laser altimeter). Examining 42 years of submarine records (1958–2000), and 5 years of ICESat records (2003–2008), scientists determined that mean Arctic sea ice thickness declined from 3.64 m in 1980 to 1.89 m in 2008, a decline of 1.75 m.

Another recent study (February 2012) shows that the oldest and thickest Arctic sea ice is disappearing at a faster rate than the younger and thinner ice at the edges of the ice cap. The rapid disappearance of older ice makes the Arctic Ocean's sea ice cap more vulnerable to further decline.

The thickest "multi-year" ice survives through two or more summers, while young, seasonal ice forms over a winter and typically melts just as quickly as it formed. Scientists also describe a third category; "perennial" ice is all ice cover that has survived at least one summer. All multi-year ice is perennial ice, but not all perennial ice is multi-year ice.

5.9.1 Permafrost, Methane, and Clathrates

Vast areas of higher latitudes and high altitudes have permanently frozen ground or permafrost. In such areas, the upper few inches of permafrost melt during the warmer seasons of the year and the resulting layer is called the active zone. The active zone causes problems with buildings, roads, and other human-made structures in regions of permafrost.

Permafrost traps a huge quantity of methane (CH_4) in the frozen soils. The methane forms as a product of bacterial activity and is released upon thawing. Methane releases have been occurring recently and there are eyewitness reports from permafrost areas of the world, especially on the North Slope of Alaska and off the coast of Siberia, of methane bubbling up through sea water and lakes.

The Arctic Ocean is underlain by vast deposits of methane in the form of methane clathrates (Fig. 5.9). As the Arctic is warming faster than the rest of the world, it is only a matter of time before this methane is released to the atmosphere. The majority of the methane accumulated in what is now shallow ocean water during the last glacial maximum (LGM) about 18,000 years ago during the low stand of sea level. As these massive sheets of ice receded, sea level rose and these areas have become the world's shallow seas bordering the continents today (see Fig. 5.9).

Before the coastal areas of the world became completely drowned by rising sea level during the melting of the last continental glaciation, they were salt or tidal marshes in which anaerobic (oxygen-free) bacteria were breaking down complex hydrocarbons to methane. In dry conditions there is plenty of atmospheric oxygen, and so aerobic bacteria which produce carbon dioxide (CO_2) are preferred. But in wet areas such as

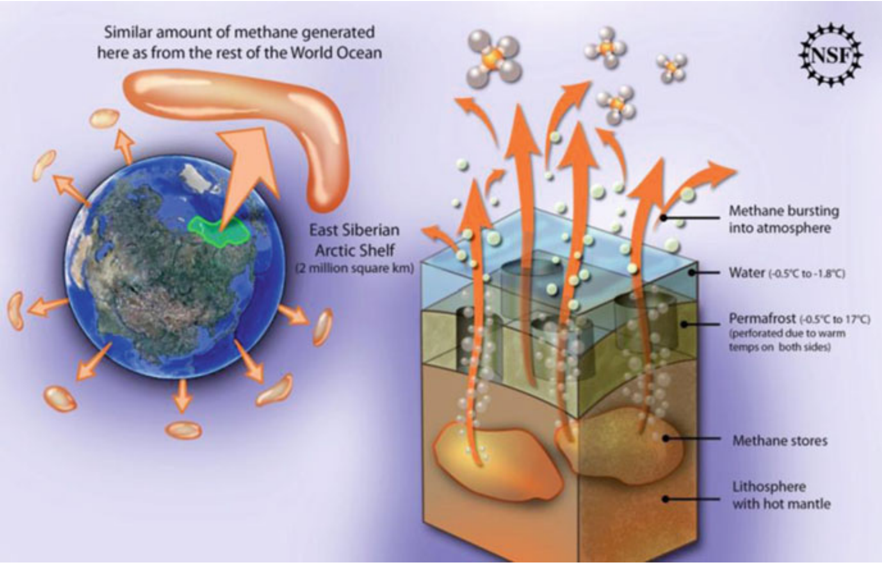


Fig. 5.9 Methane clathrates in the shallow Arctic ocean (National Science Foundation, Public Domain, from (http://www.theresilientearth.com/?q=content/arctic-armageddon-or-methane-madness)

swamps, wetlands and in parts of the ocean, there is not enough oxygen so complex hydrocarbons get broken down to methane by anaerobic bacteria. Some of this methane gets trapped and some makes its way into the atmosphere where it is gradually broken down to CO_2 and water (H_2O) vapor in a series of chemical reactions.

5.9.2 Methane Clathrates

Clathrates are a type of compound structure that consists of a cage of molecules that can trap gases, such as methane, in a solid form (Fig. 5.10).

For methane, the most important cage is one that is made of water molecules, and so is erroneously described sometimes as a hydrate. Some key facts about clathrates make them particularly interesting to climatologists and climate change scientists. First, they may make up a significant portion of total fossil carbon reserves. Current best estimates suggest that maybe 500–2,000 gigatonnes (1 gigatonne = 1 billion tonnes) of carbon may be stored as methane clathrates (5–20% of total estimated reserves). Some estimates are as high as 10,000 gigatonnes. They occur mainly on the continental shelf where the water is relatively cold; there is sufficient pressure and enough organic material to keep the methane-producing bacteria active. Most importantly, clathrates can be explosively unstable if the temperature increases or the pressure decreases which can happen as a function of climate change (warming),

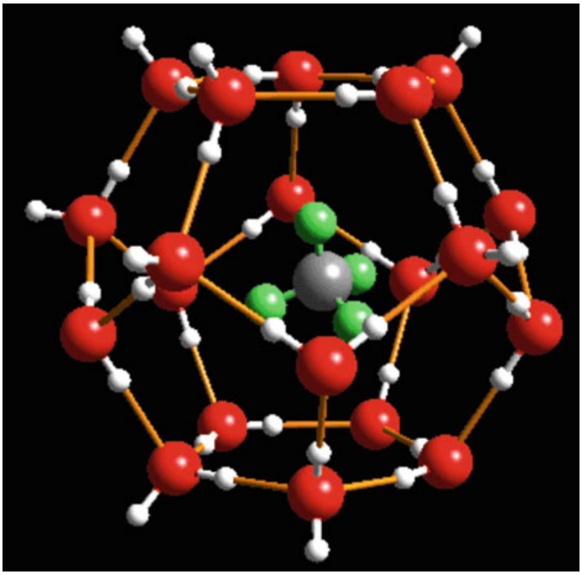


Fig. 5.10 A model of a methane clathrate showing the cage of H_2O molecules trapping a methane molecule (From http://peggy.uni-mki.gwdg.de/docs/kuhs/clathrate_hydrates.html; **No source information given on web site**. Permission granted by Dr. Werner Kuhs from which the figure is taken)

tectonic uplift, or undersea landslides. A release of methane from clathrates has already begun in shallow waters of the Arctic where methane has been seen as bubbles issuing from lakes and shallow continental shelf areas and near disturbed areas of the Gulf of Mexico, as in the case of the BP oil well blowout in 2010.

There is an imminent danger of additional methane being released from shallow Arctic waters in the near future as oil and natural gas drilling platforms are in progress toward the Arctic as this is being written in June 2012. There are predictions of new reserves of significant quantity to be found off the northern coasts of Alaska, Canada, and Siberia and the real possibility of environmental disasters as new fields are opened in this pristine and fragile area around the North Pole.

5.10 Rising Sea Level

Sea level has been rising over most of the globe since at least 1870. This rise in sea level is not due to the same factors in all places, however. In some areas, the land is sinking which appears to accentuate the rise in sea level. In other areas, land is rising which appears to lessen the rise in sea level. The illustration below (Fig. 5.11) shows the global mean sea level rise from both tide gauges and satellite altimeter measurements. Global sea level actually was lowered during 2011 due to an unusually strong El Niño that increased precipitation over land and caused major flooding in several parts of the world (especially in Australia and Pakistan). There was so much water removed from the World Ocean due to the strong El Niño that sea level worldwide was lowered. However, as can be seen in Fig. 5.11, sea level has begun to rise again.

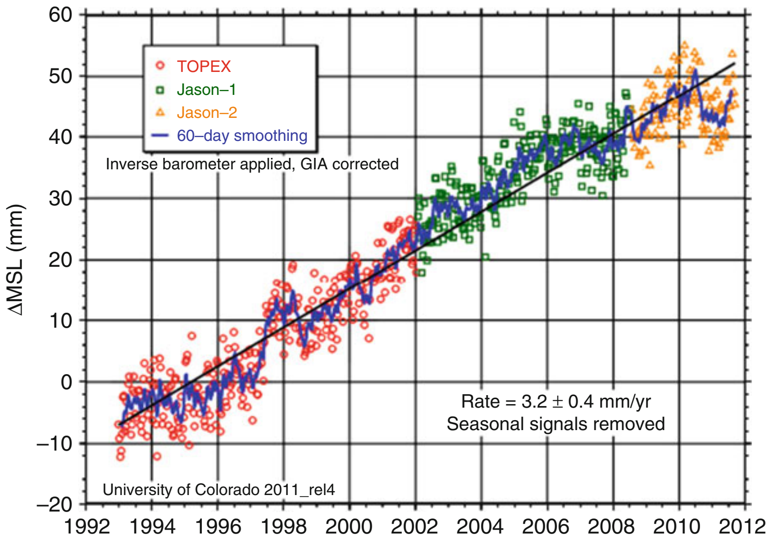


Fig. 5.11 Global mean sea level (GMSL) from 1992 through 2011 (From http://sealevel.colorado.edu/; This work was funded by NASA under a OSTM/Jason science investigation. Public Domain)

5.11 Migration of Plants and Animals

Plants and animals are migrating to higher latitudes and altitudes. A recent (2011) study reported in the journal *Science*, which examined roughly 2,000 species, found plants and animals are moving 15 ft per day or about a mile per year away from the Equator at a rate much faster than in previous decades. Species migrated more rapidly from areas most heavily impacted by climate change. Distributions of species have recently shifted to higher elevations at a median rate of 11.0 m per decade, and to higher latitudes at a median rate of 16.9 km per decade.

As the Earth continues to warm, animals and plants continue to migrate. Biologists are concerned that some species will not be able to migrate fast enough, and of course some cannot physically migrate, and whole species will eventually become extinct as rising temperatures exceed their limits of tolerance.

5.12 Species Extinctions

Human beings are currently causing the greatest mass extinction of species since the extinction of the dinosaurs 65 million years ago. If present trends continue it has been estimated that up to one half of all species currently living on Earth will be extinct in less than 100 years as a result of habitat destruction, pollution, invasive species, and climate change. The extinctions have already begun. Vertebrate species fell by nearly one third between 1970 and 2006, natural habitats are in decline, genetic diversity of crops is falling and 60 breeds of livestock have become extinct since 2000.

In 2010, the United Nations reported that biodiversity on Earth was in trouble; that species were becoming extinct at a rate never before seen in human history. Many of these extinctions, including plants and animals, are occurring in the World Ocean including many organisms that are integral parts of the food chain.

5.13 Human Health Effects of Rising Temperatures

Global warming is already having harmful effects on human health. Climate change poses a serious threat to human health. The World Health Organization (WHO) estimates that since 2000 one million people have been killed directly or indirectly because of our warming planet. This is not including death from air pollution, which kills 800,000 people each year and is expected to worsen with global warming.

As the Earth's temperature increases the seasons are changing especially in the mid-latitudes; spring is coming earlier and fall later almost every year. This increases the growing season for plants increasing the pollen counts in the atmosphere and causing more allergic reactions in humans. Allergic reactions can often lead to respiratory infections and death especially in the very young and very old.

As the climate continues to warm, water and food borne diseases are an increasing problem for human health and the forecast is not good for each of the following:

- According to the U.S. Center for Disease Control (CDC), food borne diseases are responsible for about 76 million cases of illness, with 325,000 hospitalizations and 5,000 deaths in the U.S. every year. Water borne diseases are responsible for about nine million cases of illness every year in the U.S.
- The following diseases can all be transmitted by water and food contamination: *E. coli*, typhoid, hepatitis A, dysentery, cryptosporidiosis, polio, giardia, cholera, and botulism.
- Water treatment facilities have difficulty removing many water borne diseases from drinking water, including cryptosporidiosis and giardia. Contaminated drinking water caused a cryptosporidiosis outbreak where 403,000 people became ill in Madison, Wisconsin in 1993. A CDC report estimated the outbreak cost $96.2 million: $31.7 million in medical costs and $64.6 million in productivity losses.
- Diarrhea, caused mainly by food and water borne diseases, is the second leading cause of death in young children. According to the CDC each year an estimated four billion cases of diarrhea cause two million deaths.

How climate change can increase water and food borne diseases:

- Increase in temperature causes more occurrence/survival of bacteria, toxic algae, and other contamination in food and water. Also, according to the IPCC climate change is already reducing the amount of high quality freshwater and this situation is expected to worsen. People will be forced to use poorer quality water sources, leading to increased disease.

- The major pathogens that cause acute gastroenteritis multiply faster in warmer conditions. According to a study on climate change impacts on the U.S., this is predicted to impact lakes and increase the number of recreational water borne disease outbreaks.
- Climate change is predicted to cause more extreme flooding and storms, which are known to lead to contaminated water supplies. Heavy rainfall can cause sewer/storm water systems to overflow, releasing raw (untreated) sewerage into local water sources.
- The WHO reported that in 2000 climate change was responsible for approximately 2.4% of worldwide diarrhea. In 2030, warmer temperatures and more severe rainfall and flooding will cause up to a 10% higher risk of diarrhea in some areas.
- According to the IPCC, the distribution and activity of flies, cockroaches, and rodents could change in response to climatic changes. These species are carriers of food-borne pathogens and are considered to be major hygienic pests in the domestic environment.

5.14 Attribution

Attribution is assigning a cause to a result and in climate science as well as in other sciences this may be difficult to do. However, in some cases such as global warming, sometimes it is possible to eliminate natural causes and be left with only human (anthropogenic) causes to explain the result.

In the recent past, variations in the Sun's energy output have regulated the Earth's temperature to a great degree. Scientists know that the Sun today is warmer than the Sun of billions of years ago. So can the recent warming on Earth be attributed to the Sun? According to some deniers and skeptics, the answer is yes. However, scientific facts tell us just the opposite: no! As a matter of fact, since the 1970s to 2011 and into 2012, the Sun has been in a deep stage of its solar minimum phase. In other words, the Sun has been producing less energy while the Earth has been warming (Fig. 5.12).

As can be seen in Fig. 5.12, there was a fairly good correlation between solar activity and the Earth's temperature until around 1980, then the two began to diverge, and they have been diverging until fairly recently.

If the Sun is not causing the Earth to warm, what is causing global warming? What other things could cause the Earth to warm? Let's look at some other possibilities:

- The Earth may be moving closer to the Sun in its orbit;
- The Sun may be moving closer to the Earth;
- The Earth may be heating up from the inside;
- Another star, like the Sun, may be moving closer to Earth;

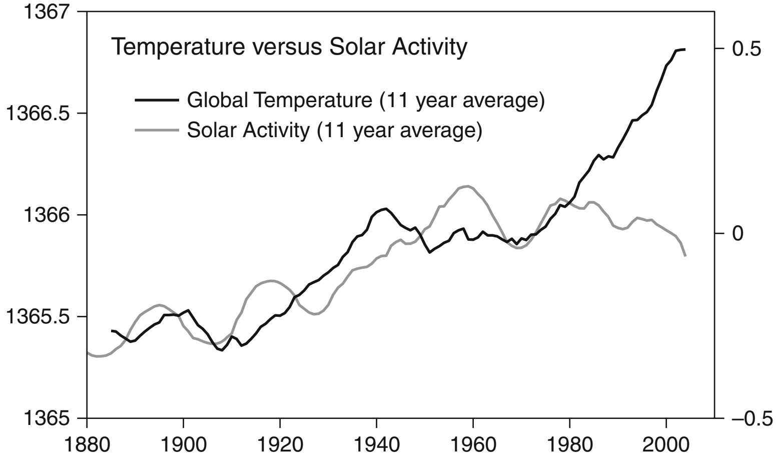


Fig. 5.12 Global temperature (*dark line*, NASA GISS) and Total solar irradiance (*lighter line*, 1880–1978 from Solanki); 1979–2009 from Physikalisch-Meteorologisches Observatorium Davos (PMOD). (From SkepticalScience.com, redrawn by John Cook)

- The temperature record may be unreliable;
- Something in the atmosphere may be holding more heat close to the Earth rather than letting it escape into space.

Astronomers tell us that the orbits of Earth and the other planets in the Solar System have very stable and predictable orbits and these have not deviated substantially in recorded history. So the Earth is not moving closer to the Sun and the Sun is not moving closer to the Earth.

Geologists and geophysicists tell us that although the Earth has a great deal of internal heat that this heat is not expanding outward. So the Earth's surface and lower atmosphere are not heating up from the inside.

No star is moving closer to Earth and if it were it would be so far away at present to have no effect on the Earth's temperature.

Is there something in the atmosphere that may act to contain heat and possibly re-radiate heat back to the Earth's surface? Remember the greenhouse effect from Chap. 2? It is now time for some chemistry as it is chemicals that cause the greenhouse effect.

5.15 Greenhouse Gases

There are chemicals in Earth's atmosphere that are greenhouse gases (GHGs) that trap heat and allow the Earth to support life. The main GHGs are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Other minor greenhouse gases are such things as chlorofluorocarbons (CFCs) and a few others. Their increasing concentrations in the atmosphere are shown in Fig. 5.13.

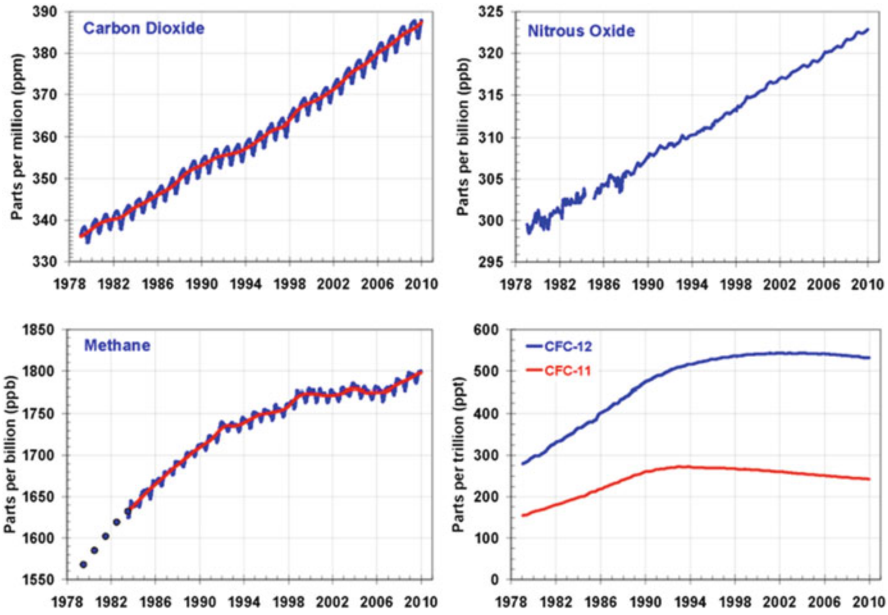


Fig. 5.13 Greenhouse gases increasing in the atmosphere since 1978 (From NOAA http://www.esrl.noaa.gov/gmd/aggi/, Public Domain)

Carbon dioxide, nitrous oxide, and methane appear to have been steadily increasing while the CFCs appear to be leveling off or slightly decreasing in Earth's atmosphere (Fig. 5.13). Greenhouse gases appear to be good candidates for causing global warming and they will be treated separately in a later chapter (Chap. 9).

The observed patterns of warming, including greater warming over land than over the ocean, and their changes over time, are simulated only by models that include anthropogenic forcing. No coupled global climate model that has used natural forcing only has reproduced the continental mean warming trends in individual continents (except Antarctica) over the second half of the twentieth century.

The illustration below (Fig. 5.14) shows time series of global mean near-surface air temperature anomalies in observations and simulations by using a Canadian computer model (CanESM2). In Fig. 5.14a all of the observations and simulations are graphed together from 1850 to 2011. In the illustration, black lines show observed global mean annual temperature from HadCRUT3, and thin colored lines show global mean temperature from five-member ensembles of CanESM2 forced with (a) anthropogenic and natural forcings (ALL), (b) natural forcings only (NAT), (c) greenhouse gases only (GHG), and (d) aerosols only (AER). All anomalies are calculated relative to the period 1851–1900, and ensemble means are shown by thick colored lines in the figure.

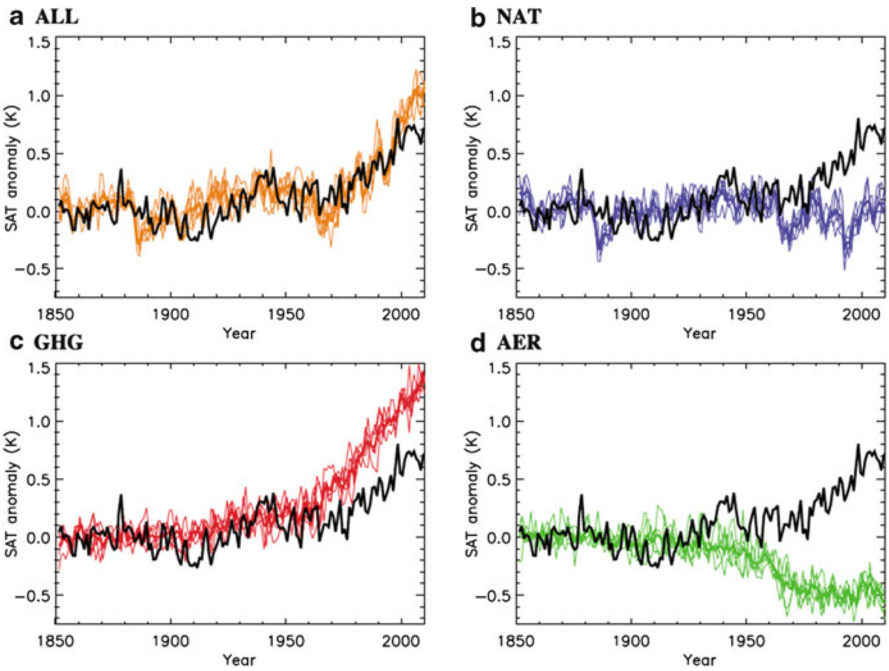


Fig. 5.14 Time series of global mean near-surface air temperature anomalies in observations and simulations of CanESM2. *Black lines* show observed global mean annual mean temperature from HadCRUT3, and *thin coloured lines* show global mean temperature from five-member ensembles of CanESM2 forced with (**a**) anthropogenic and natural forcings (ALL), (**b**) natural forcings only (NAT), (**c**) greenhouse gases only (GHG), and (**d**) aerosols only (AER). All anomalies are calculated relative to the period 1851–1900, and ensemble means are shown by *thick coloured lines* (From SkepticalScience.com, viewed 1/14/2012; data from Gillett et al. 2012)

5.16 Human Fingerprints on Global Warming

There are specific human fingerprints on the current warming of the planet. The human fingerprints point directly to humankind as the source for the vast majority of the global warming that has occurred during the latter half of the twentieth century and into the twenty-first.

5.16.1 Earth's Cooling Upper Atmosphere

As more heat is added to the lower atmosphere (the troposphere), less heat escapes to warm the upper atmosphere (the stratosphere) and the upper atmosphere cools. This has been measured by satellites and weather balloons (radiosondes). If the Sun was the cause of global warming, the upper atmosphere would also be warming.

5.16.2 Rising Tropopause

As the troposphere warms the air expands and the top of the troposphere (the tropopause) rises. Scientists have found that the tropopause from 1979 to 1999 had risen by about 200 m. The rising tropopause is caused by the increasing heat of the troposphere.

5.16.3 Less Heat Escaping to Space

Satellites measure less heat escaping to space at the particular wavelengths that CO_2 absorbs heat, thus finding "direct experimental evidence for a significant increase in the Earth's greenhouse effect." Skeptics and deniers of global warming say that there is no evidence that CO_2 is causing global warming. This empirical fact proves that CO_2 is causing global warming.

5.16.4 Nights Warming Faster than Days

If an increased greenhouse effect is causing global warming, we should see certain patterns in the warming. For example, the planet should warm faster at night than during the day. This is indeed being observed.

5.16.5 Winter Warming Faster than Summer

Temperatures from both Northern and Southern Hemispheres show winters warming faster than summer based on both land and sea records and satellite records.

5.16.6 More Fossil Fuel Carbon in Coral

The most common carbon isotope is carbon-12 (^{12}C) which is found in roughly 99% of the carbon dioxide in the atmosphere. The slightly heavier carbon-13 (^{13}C) makes up most of the rest. Plants prefer carbon-12 over carbon-13. This means the ratio of carbon-13 to carbon-12 is less in plants than it is in the atmosphere. As fossil fuels originally come from plants, it means when we burn fossil fuels, we're releasing more ^{12}C into the atmosphere. If fossil fuel burning is responsible for the rise in atmospheric CO_2 levels, we should be seeing the ratio of ^{13}C to ^{12}C decrease. This decrease in the ratio is exactly what is being recorded.

5.16.7 Shrinking Upper Atmosphere

The thermosphere and ionosphere are shrinking as measured by satellites. The ionosphere is expected to cool and contract in response to greenhouse warming. This has been observed by satellites.

5.16.8 Less Oxygen in the Atmosphere

Oxygen levels are falling in line with the amount of carbon dioxide rising, just as one would expect from fossil fuel burning which takes oxygen out of the air to create carbon dioxide.

5.16.9 More Fossil Fuel Carbon in the Atmosphere

See "More Fossil Fuel Carbon in Coral" above.

5.16.10 More Heat Returning to Earth

Less heat is escaping to space; so where is it going? It is being reflected back to the Earth's surface. Surface measurements confirm this, observing more downward infrared radiation. A closer look at the downward radiation finds more heat returning at CO_2 wavelengths, leading to the conclusion that "this experimental data should effectively end the argument by skeptics that no experimental evidence exists for the connection between greenhouse gas increases in the atmosphere and global warming."

5.16.11 Pattern of Ocean Warming

Ocean heat content has increased significantly over the past 40 years. In fact, approximately 93% of the total heating of the Earth system over that period has gone into warming the oceans. Barnett et al. (2005) investigated the cause of this warming signal, and concluded as follows:

> "[The increase in ocean heat content] cannot be explained by natural internal climate variability or solar and volcanic forcing, but is well simulated by two anthropogenically forced climate models. We conclude that it is of human origin, a conclusion robust to observational sampling and model differences. Changes in advection combine with surface forcing to give the overall warming pattern. The implications of this study suggest that society needs to seriously consider model predictions of future climate change".

Humans are currently emitting several billion tonnes (1 billion tonnes is a gigatonne, a tonne is equal to a metric ton which is a unit of weight equal to 1,000 kg, or 2,204.6 lb) of CO_2 into the atmosphere every year. Of course, it could be a coincidence that CO_2 levels are increasing so sharply at the same time as the Earth's temperature is rising so let's look at more evidence that humans are responsible for the rise in CO_2 levels and global warming. Correlation does not mean cause and effect but in science, when several independent lines of evidence point to the same conclusion, scientists may draw conclusions with a great deal of certainty.

When measuring the type of carbon accumulating in the atmosphere, we see more of the type of carbon that comes from fossil fuels. Carbon from fossil fuels has no carbon-14, radioactive carbon or radiocarbon. Radiocarbon has a half-life of 5,700 years and very little if any is remaining in fossil fuels because most fossil fuels are millions of years old.

Scientists know how much carbon-14 is in the atmosphere relative to non-radioactive carbon. As the ratio of carbon-14 to non-radioactive carbon decreases, the indication is that non-radioactive carbon is being released. The main source of this release is the burning of fossil fuels.

Human fingerprints are indicated by measurements of oxygen in the atmosphere. Oxygen levels are falling in line with the amount of carbon dioxide rising, just as one would expect from fossil fuel burning which removes oxygen from the atmosphere to create carbon dioxide. For every atom of carbon in the molecule of carbon dioxide, there are two oxygen atoms.

Further independent evidence that humans are raising CO_2 levels comes from measurements of carbon found in coral records going back several centuries. These coral skeletons show a recent sharp rise in the type of carbon that comes from fossil fuels.

We know humans are raising CO_2 levels because of the type of carbon being released and because we are able to measure it directly. Also, satellites measure less heat escaping out to space at the particular wavelengths that CO_2 absorbs heat, thus finding "direct experimental evidence for a significant increase in the Earth's greenhouse effect."

If less heat is escaping to space, where is it going? It is being reflected back to the Earth's surface. Surface measurements confirm this, observing more downward infrared radiation. A closer look at the downward radiation finds more heat returning at CO_2 wavelengths leading to the conclusion that "this experimental data should effectively end the argument by skeptics that no experimental evidence exists for the connection between greenhouse gas increases in the atmosphere and global warming."

If an increased greenhouse effect is causing global warming, we should see certain patterns in the warming. For example, the planet should warm faster at night than during the day. This is indeed being observed.

Another distinctive pattern of greenhouse warming is cooling in the upper atmosphere, otherwise known as the stratosphere. This is exactly what's happening.

With the lower atmosphere (the troposphere) warming and the upper atmosphere (the stratosphere) cooling, another consequence is the boundary between the troposphere and stratosphere, otherwise known as the tropopause, should rise as a consequence of greenhouse warming. This has been observed.

An even higher layer of the atmosphere, the ionosphere, is expected to cool and contract in response to greenhouse warming. This has been observed by satellites.

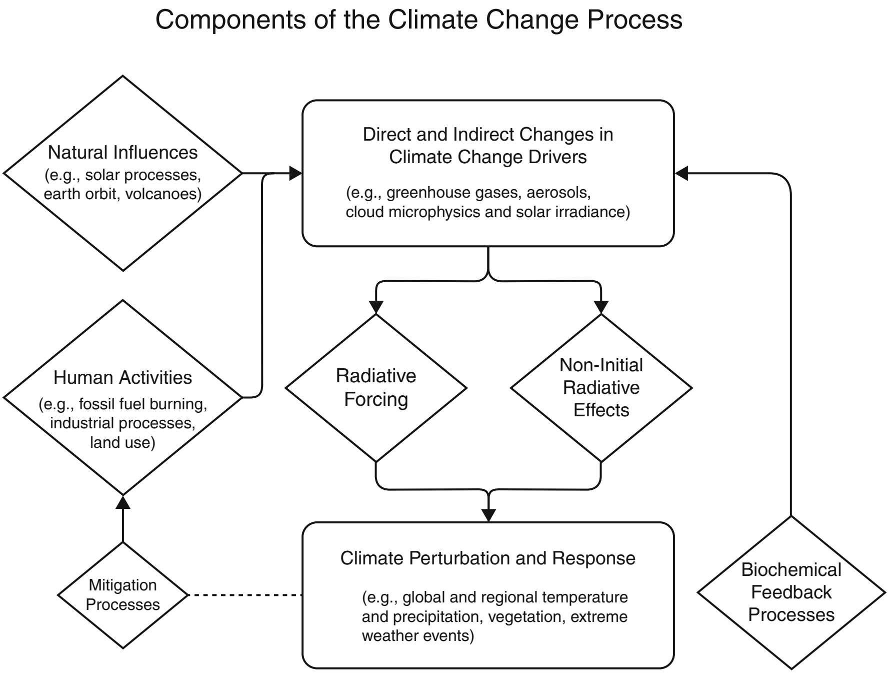


Fig. 5.15 Components of the climate change process (Redrawn from IPCC, AR4, 2007 by John Cook)

Science proceeds by gathering evidence. It isn't a house of cards, ready to topple if you remove one line of evidence. Instead, it's like a complex puzzle. As the body of evidence builds, we get a clearer picture of what's driving our climate. We now have many lines of evidence all pointing to a single, consistent answer.

The main cause of global warming is increasing carbon dioxide levels from fossil fuel burning. Nothing else makes sense or fits all the facts; and this conclusion is backed by numerous lines of evidence.

Earth's climate is changing. Some of this change is gradual and cannot be detected on a day-to-day basis, such as the global increase in temperature or the gradual melting of glacial ice and rising sea level. Other climate changes are more obvious, such as changing weather patterns, more severe and more frequent storms, or longer hot spells or cold periods. And climate change will become even more obvious in the future as weather patterns continue to change.

5.17 Components of the Climate Change Process

Components of the climate change process are shown in the illustration above (Fig. 5.15). When the drivers of climate are forced in one direction, the climate changes in that direction. For example, when volcanoes erupt violently they emit tremendous amounts of solid particles into the atmosphere and these particles block out some of the Sun's rays which causes the Earth to cool. The cooling is said to be a perturbation, which is a response to a forcing and is a result of natural forcing of the climate in the direction of global cooling.

The greatest driver or forcing of Earth's climate has been the amount of sunlight received by the Earth. There is a direct effect on the climate if less sunlight falls on the Earth; the Earth cools. If a greater amount of sunlight impacts the Earth, the Earth warms. So there is a direct effect on the climate by the total amount of sunlight received by the Earth. This is called a radiative forcing due to the fact that the energy causing the climate to change radiates from the Sun. An example of a non-radiative forcing is the cooling caused by violent volcanic eruptions or warming by changes in land use.

Forcings cause the climate to change and a climate change may initiate a feedback that causes the forcing to increase in intensity or decrease and possibly reverse a forcing. These are called positive and negative feedbacks, respectively.

5.18 Other Effects of Global Warming

Global warming, the most obvious climate change happening now, is causing more evaporation to occur from the ocean and soils. This evaporation increases the moisture content of the Earth's atmosphere and dries out the land and vegetation. This moisture must fall to Earth somewhere and it is being measured in increasing rainfall (and snowfall) in some areas. This increased precipitation leads to flooding in some land areas, the breaching of dams and levees, and more natural disasters than before the warming occurred. The drying out of land and vegetation results in more wildfires especially in areas that have experienced long periods of drought.

Some areas that were having normal precipitation are now experiencing less precipitation. More precipitation is falling in some areas and less in other areas. The southwestern U.S. is experiencing a double impact from the changing climate as it is becoming dryer due to the loss of soil moisture and hotter due to a warming climate.

Climate change and global warming are causing more evaporation to occur over the oceans and that results in greater cloud formation. There is more heat energy in the atmosphere available to storm systems and this extra energy causes storms to become more frequent and more intense. It is fairly certain that hurricane Katrina that struck the Gulf Coast of the United States in 2005 was as strong as it was because of the increased temperature of waters in the Gulf of Mexico.

In some areas there is more snowfall in higher elevations and latitudes and more rainfall in lower elevations and latitudes. These are general trends and there are local and regional exceptions, but the general trends are what interest climate change scientists the most.

The most abundant and effective greenhouse gas is water vapor, but it does not stay in the atmosphere for long periods of time. It is flushed out of the atmosphere and falls to Earth as precipitation. Some of the other gases, such as carbon dioxide, remain in the atmosphere for much longer periods of time, possibly thousands of years.

The most important of the greenhouse gases for trapping heat in the atmosphere over long time periods and warming the Earth is carbon dioxide, as we will see in a later chapter. Carbon dioxide is well-mixed in the atmosphere and its molecular structure is such that it both absorbs and re-radiates heat that it traps from the infrared energy given off by the Earth. The carbon dioxide molecules in the atmosphere re-radiate this heat energy in all directions, some to outer space, some to adjacent molecules, and some back to the Earth's surface. The physics of this re-radiation has been known since the 1800s.

5.19 Forcings and Feedbacks in the Climate System

There are factors which cause the Earth's climate system to change, as we have seen. These factors are called forcings because they force a change in Earth's climate. Other factors enhance or retard forcings; these are feedbacks. Both forcings and feedbacks are discussed below.

5.19.1 Forcings

When something forces the Earth's climate to change direction, such as warming or cooling, it is called a forcing. Forcings which directly affect the climate, that is, push it in a certain direction, are:

- Changes in the amount of energy radiated by the Sun. If the Sun produces less energy, it forces the Earth to cool; if it produces more energy, it forces the Earth to warm. The Sun has been in a minimal state for the past several decades until recently (October 2011). During Solar Maximum, huge sunspots and intense solar flares are a daily occurrence. Auroras appear in Florida. Radiation storms knock out satellites. Radio blackouts frustrate ham radio operators. The last such episode took place in the years around 2000–2001. During Solar Minimum, the opposite occurs. Solar flares are almost nonexistent while whole weeks go by without a single, tiny sunspot to break the monotony of the blank sun. This is what we are experiencing now. If the orbital parameters of Earth change, the climate is forced to change. For example, if Earth moves closer to the Sun in its orbit, the Earth warms; if it's orbit moves further away from the Sun, the Earth cools;
- If mountains are uplifted and Earth's plates move, the Earth's atmospheric and oceanic circulation patterns change and the cliate changes. This changes the pace of weathering (the breakdown of rocks) which also increases as mountains are uplifted and more rocks are exposed. Weathering takes carbon dioxide out of the atmosphere as the rocks break down and the Earth cools. There is more carbon dioxide stored in rocks of the Earth's crust than anywhere else;
- Increasing greenhouse gases (GHGs) in the atmosphere trap heat to warm the Earth. If these gases increase in concentration in the atmosphere, the Earth warms. If they decrease in concentration the Earth cools.

5.19.2 Positive and Negative Forcing and Their Effects

Anything that causes a climate change is called a forcing. One may think of it as something that is forcing the climate to change. There are forcing agents (such as an increase or decrease in sunlight hitting the Earth) and forcing effects (such as a warming or cooling of the Earth). Forcings may either be positive or negative (Fig. 5.16). Figure 5.16a shows the cumulative positive greenhouse gases forcing agents from 1950 through 2004. Figure 5.16b shows the cumulative negative forcing agents over the same time period.

Forcings may occur suddenly or over a few hundred or hundreds of thousands of years. A near collision with another planet in the early development of Earth may have forced the Earth to gain an axial tilt. This would have happened suddenly and the result of the axial tilt is the seasonal changes which occur in middle latitudes each year (summer, winter, fall, and spring).

Figure 5.17 is a diagrammatic representation of the Earth's climate system from pole (on the left side) to Equator (on the right side) showing interactions between the Sun's energy, the atmosphere, oceans, ice sheet, vegetation, back radiation, weathering, greenhouse gases, volcanoes, wind, precipitation, river runoff, etc.

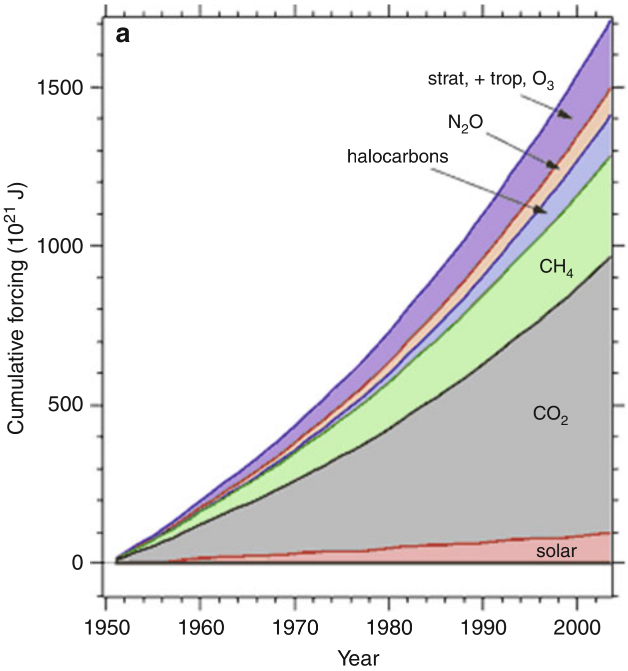
5.19.3 Feedbacks

Forcings cause changes in the climate system and feedbacks either enhance a forcing (positive feedback) or dampen or reverse a forcing (negative feedback).

Feedbacks may also be a forcing. For example, a greenhouse gas may be a forcing when it increases in the atmosphere to the extent that it forces the climate to change. Carbon dioxide has built up in the atmosphere since the Industrial Revolution, the mass production of the internal combustion engine, and because of other human activities. As this concentration increased, it forced the Earth's climate to begin to warm after the Earth's temperature had been relatively stable for thousands of years. After the initial forced warming, carbon dioxide continues to build in the atmosphere and has become a positive feedback as well as a positive forcing. A positive forcing is defined as one which causes warming. A negative forcing is defined as one which causes cooling.

Oceans cover about 71% of Earth's surface area and are a significant part of the climate system. Sea water absorbs energy from both the Sun and the Earth's interior. Colder sea water absorbs CO_2 from the atmosphere and warm sea water releases it to the atmosphere (a carbon source). As ocean waters warm, they will change from a carbon dioxide sink to become a source and release CO_2 to the atmosphere in greater quantities than the world has ever known.

Feedbacks are secondary effects on the climate system (see Fig. 5.18). For example, if there is more melting of glacial and sea ice, there is more land and darker ocean to absorb energy from the Sun, less Sunlight is reflected back to space by the ice, and the Earth warms.



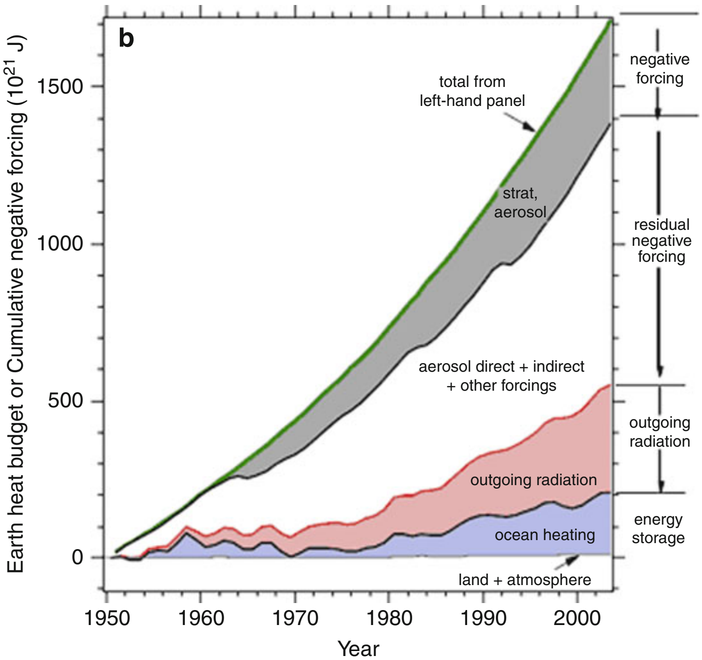


Fig. 5.16 (**a**) Cumulative energy budget for the Earth since 1950, showing mostly positive and mostly long-lived forcing agents from 1950 through 2004 (From Murphy et al. 2009). (**b**) Cumulative negative forcings such as stratospheric aerosols, direct and indirect aerosol forcing, increased outgoing radiation from a warming Earth, and the amount remaining to heat the Earth (From Murphy et al. 2009)

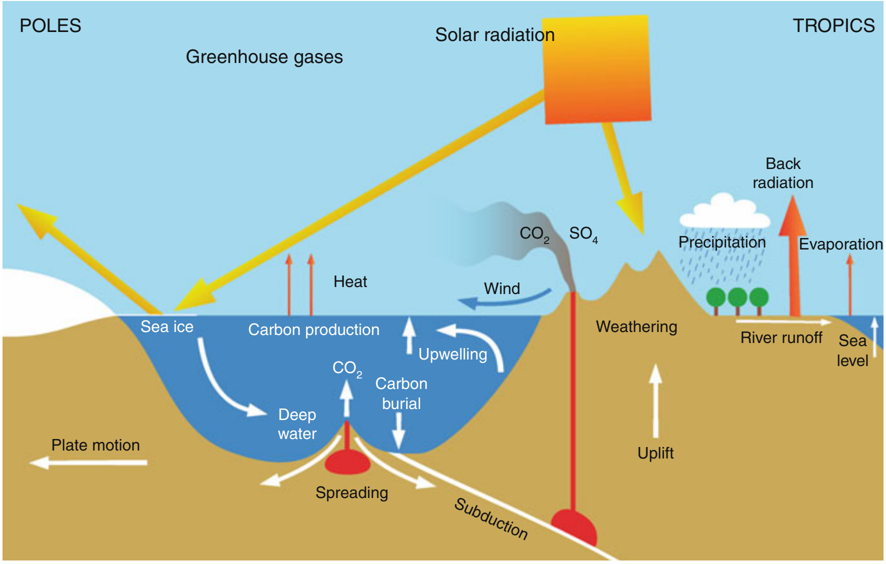


Fig. 5.17 The major components of the climate system. H_2O_v is water vapor (Source: John Cook Redrawn from Ruddiman 2001)

Feedbacks are either positive or negative. A positive feedback continues a forcing direction. If the climate is warming and a part of the climate system causes additional warming, the feedback is positive as in the case of the melting ice. If the climate is warming and a part of the climate system slows, stops, or reverses the warming, the feedback is negative. If glaciers begin to grow again and sea ice expands and more sunlight is reflected back to space and the Earth cools, the feedback is negative.

Energy from Earth's interior (either generated by radioactive decay or remnant heat from the Earth's early molten state) reaches the surface from volcanic activity on the sea floor and on land. This is the energy that causes volcanoes to form and drives the Earth's crustal plates and it is this energy that causes the plates to move and continents to drift.

Energy from the Sun retained by Earth's atmosphere is distributed throughout the Earth system; it has been described as a "cascade" of energy throughout the system. This energy results in plants producing oxygen, sugars, water, and more plant material by photosynthesis as plants grow.

5.20 Climate Sensitivity

Climate sensitivity is usually expressed as the Earth's temperature that would be expected as a result of a doubling of CO_2 but we know that climate is sensitive to more things than just CO_2, such as all forcings. The IPCC AR4 2007 defines

Fig. 5.18 The difference between the amounts of sunlight Greenland reflects in the summer of 2011 versus the average percent it reflected between 2000 and 2006. Virtually the entire ice sheet shows some change, with some areas reflecting close to 20% less light than a decade ago. The map is based on observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on NASA's Terra and Aqua satellites (NASA, Public Domain)

climate sensitivity as follows: "The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is defined as the equilibrium global average surface warming following a doubling of CO_2 concentration. Progress since the TAR enables an assessment that climate sensitivity is likely to be in the range of 2–4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C (Fig. 5.19). Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values."

Although we know that Earth's climate is sensitive to forcings, the IPCC's definition of climate sensitivity is accepted by most climate scientists.

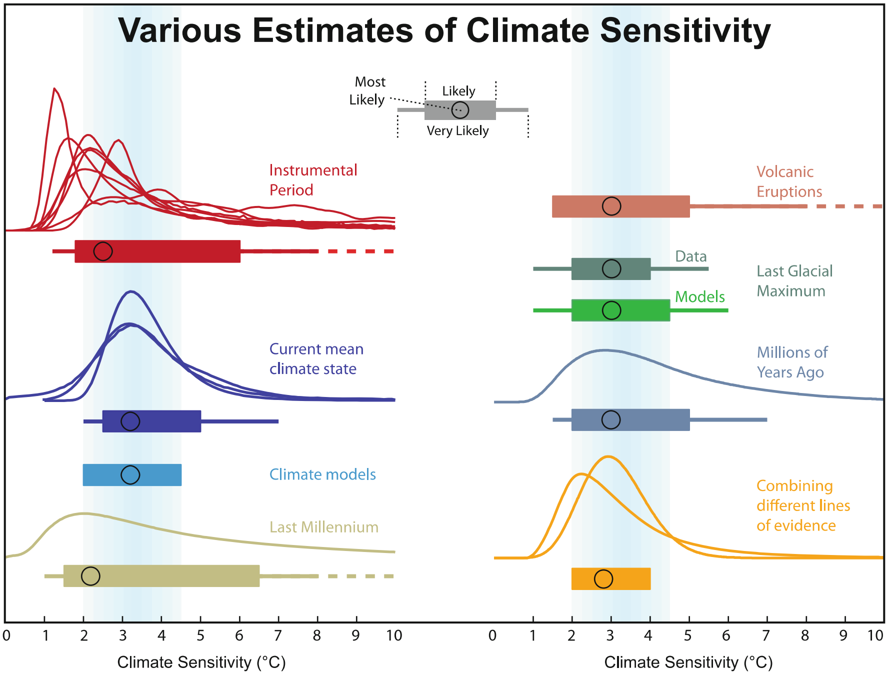


Fig. 5.19 Distributions and ranges for climate sensitivity from different lines of evidence. The *circle* indicates the most likely value. The *thin colored bars* indicate very likely value (more than 90% probability). The *thicker colored bars* indicate likely values (more than 66% probability). *Dashed lines* indicate no robust constraint on an upper bound. The IPCC likely range (2–4.5°C) and most likely value (3°C) are indicated by the vertical *grey bar* and *black line*, respectively (Adapted from Knutti and Hegerl 2008) (From SkepticalScience.com))

Additional Readings

Ammann, C., et al. (2007). Solar influence on climate during the past millennium: Results from transient simulations with the NCAR Climate Simulation Model (PDF). *Proceedings of the National Academy of Sciences of the United States of America, 104*(10), 3713–3718.

IPCC AR4 SYR. (2007). Core Writing Team, Pachauri, R. K. & Reisinger, A. (Eds.), *Climate change 2007: Synthesis report, Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC. ISBN 92-9169-122-4

IPCC AR4 WG1. (2007). Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., & Miller, H. L. (Eds.), *Climate change 2007: The physical science basis, Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. ISBN 978-0-521-88009-1 (pb: 978-0-521-70596-7)

Keppler, F., et al. (2006, January 18). *Global warming – The blame is not with the plants*. Max Planck Society, Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany.

McKibben, B. (2011). *The global warming reader*. New York: OR Books. ISBN 978-1-935928-36-2.

Pollack, H. (2009). *A world without ice*. New York: Avery, A Member of Penguin Books, Ltd. ISBN 978-1-58333-357-0.

Revkin, A. C. (2005, November 5). Rise in gases unmatched by a history in ancient ice. *The New York Times*.

Ruddiman, W. F. (2005, August 1). *Plows, plagues, and petroleum: How humans took control of climate*. Princeton: Princeton University Press. ISBN 0-691-12164-8.

Ruddiman, W. F. (2008). *Earth's climate: Past and future* (2nd ed.). New York: W. H. Freeman and Company.

Walter, K. M., et al. (2006). Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. *Nature, 443*(7107), 71–75. Bibcode 2006Natur.443…71W. PMID 16957728. doi:10.1038/nature05040.

Chapter 6
Earth's Surface Temperature

Abstract The Earth is getting warmer and the surface temperature reflects the warming trend. Temperature records are kept and analyzed by several government agencies throughout the world among which are the Goddard Institute of Space Studies in the U. S., the Climate Research Unit in the U. K., the Japan Meteorological Association, and others. Tipping points beyond which nothing can be done to reverse them are discussed. Work by the U.K.'s Met Office and the Climate Research Unit of the University of East Anglia was one of the first to report global warming. James Hansen of GISS reported on their studies and appeared before a committee of the U. S. congress advocating that action be taken to slow or stop warming that was occurring due to greenhouse gases. Scenarios A, B, and C were described by Hansen. Hansen and Lebedeff's paper defining a method of determining a global average temperature is described as is the current method of determination.

Keywords Phil Jones • James Hansen • A1F1 • Temperatures • Land • IPCC • CRU • El Niño-La Niña • NCDC • TAR • GHGs • GISTEMP • CDAT • Public domain • Assurance • Quality • Muller • Anomalies • SSTs • Willett • Anomalies • Köppen • Callendar • Budyko

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know"

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_6,

should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to know	
SSTs	Land temperatures
Richard Muller	IMO
Temperature anomalies	A1F1
El Niño-La Niña Cycle	0.8°C
ICOADS	AOGCMs
ERSST	Global mean surface air temperature
IS92a	NASA/GISS
NOAA/NCDC	1951–1980
IPCC	Urban island effect
BEST study	TAR
Temperature index	Hansen and Lebedeff
Base period	Hadley centre
Quality control	Sea-level rise
1,200 km	0.4°C
SRES	Temperature index
MOHC	Quality assurance
A1T	Tipping point, tipping level, point of no return
GFDL	Buoys
A1 scenario	CRU
A2 scenario	B1 scenario
B2 scenario	

6.1 Introduction

This chapter is concerned with the Earth's surface temperature. The surface temperature was introduced in a previous chapter (Chap. 4) but in this chapter we will consider how temperature records are kept, reduced, analyzed, and how an annual average temperature can be determined.

The initial methodology for obtaining an average global temperature was produced in the 1970s by James Hansen and colleagues at NASA/GISS and formalized in a 1981 paper by Hansen and Lebedeff. This is the same methodology that is used today, with updates, to arrive at a global average temperature.

Determination of the Earth's average surface temperature grew out of work by American, British, Russian, and Japanese scientists working independently. In 1982, Phil Jones and colleagues of the U. K.'s Climate Research Unit (CRU) of the University of East Anglia issued the following statement: "We have produced, using objective techniques, a long-term series of average Northern Hemisphere temperatures." This statement by Jones and his colleagues began what is today CRU's methodology to produce the average annual global temperature of the Earth but it is biased toward the non-Arctic Northern Hemisphere.

The CRU team joined forces with scientists at the U. K. Meteorological Office Hadley Centre (MOHC), who were refining estimates of observed changes in sea-surface temperature (SST). This partnership led to the development of the Hadley Centre/CRU observational record of combined changes in SST and land-surface temperature (HadCRUT) and formed the basis for a global average temperature.

Groups at the NASA/Goddard Institute for Space Studies in New York (GISS) and at the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) in North Carolina independently attempted to reproduce the HadCRUT results. Although all three teams used raw temperature measurements from similar (but non-identical) sets of observing stations, they made different choices in the treatment of these raw measurements and the calculation of area averages. In spite of these differences, the GISS and NCDC analyses confirmed the "warming Earth" findings of the CRU and MOHC scientists; that during the latter half of the twentieth century, Earth's temperature had been rising sharply.

If any single event can be said to have put climate change on the world's policy radar, it was the testimony of NASA scientist James Hansen before Senator Tim Wirth's committee in Congress on June 23, 1988. This event was widely reported by the press and Dr. Hansen became the "face" of global warming and the object of scorn by climate change and global warming skeptics and deniers who were supported mainly by the oil and gas segment of society. Later chapters of this text will introduce the deniers and skeptics and their reasons.

In Hansen's testimony, he used three different scenarios; A, B, and C. They consisted of hypothesized future concentrations of the main greenhouse gases CO_2, CH_4, CFCs, etc., together with a few scattered volcanic eruptions. The details varied for each scenario, but the net effect of all the changes was that Scenario A assumed exponential growth in greenhouse gas forcings, Scenario B was roughly a linear increase in forcings, and Scenario C was similar to B, but had close to constant forcings from 2000 onwards. Scenario B and C had a large volcanic eruption in 1995. Essentially, a high, middle and low estimate were chosen to bracket the set of possibilities. Hansen specifically stated that he thought the middle scenario (B) the "most plausible."

These experiments were started from a control run of the GISS model with 1959 conditions and used observed greenhouse gas forcings up until 1984, and subsequent projections. The results are shown in the illustration below (Fig. 6.1).

The Hansen scenario closest to the observations since 1984 is clearly Scenario B.

Recently (2011) a group of scientists (the Berkeley Earth Surface Temperature or BEST study) led by a well-known climate skeptic and Professor of Physics at the University of California, Berkeley, Dr. Richard Muller, conducted a comprehensive review of methodology used to determine the annual average global temperature of the Earth and found after developing their own methodology, that their results agreed with previous methods used by others and that the annual global land temperature was rising, especially during the latter half of the twentieth century and

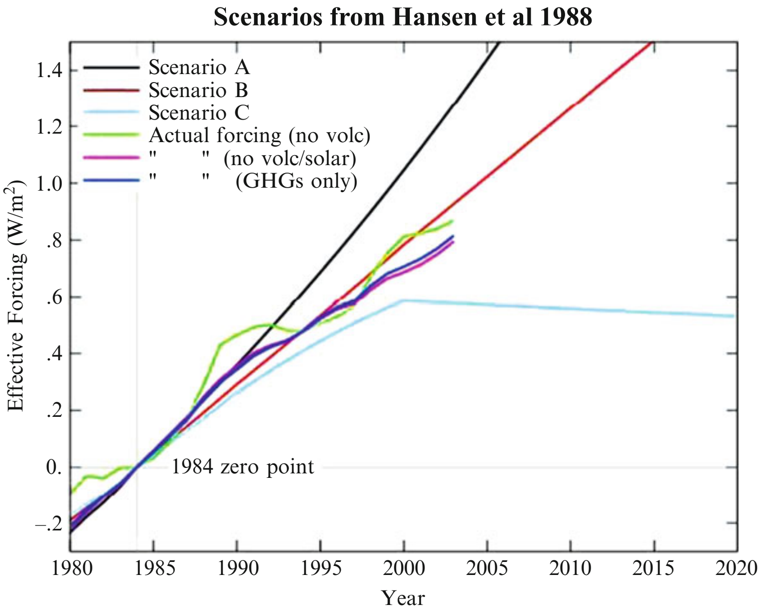


Fig. 6.1 Scenarios presented to the United States Congress in 1998 by James Hansen of NASA/GISS (From RealClimate.com, viewed 1/20/2012. Scenarios from Hansen et al. 1988)

into the twenty-first century. Global warming is real, as climate scientists have been telling the world since at least the 1970s.

6.2 Tipping Points

A tipping point has been taken to mean that a point has been reached beyond which nothing can be done to stop it. Hansen of NASA/GISS talks about tipping levels and points of no return instead of tipping points.

The tipping level is the level of greenhouse gases that will lead to large, undesirable, even disastrous, effects. The Earth has reached the tipping level for several important effects. That is why, according to Hansen, we must go back in CO_2 amounts at least to 350 ppm and possibly lower (in June 2012 the CO_2 level was 396 and 400 ppm in the Arctic).

The point of no return is when the dynamics of the process take over and the process, such as disappearing ice, is out of control and nothing can be done to stop it; an example is an ice sheet or glacier disintegrating because of positive feedback and warming that is already in the pipeline. Unfortunately, Arctic summer sea ice has reached the point where it will disappear within the next few decades. Arctic sea ice has reached its tipping point and it will disappear no matter what humans do to try and save it. Arctic sea ice is at the point of no return and will undoubtedly have severe effects on global weather patterns, especially in the Northern Hemisphere, when all of it disappears.

6.3 Temperature Records

The adequacy and reliability of temperature data and the method of computing the annual average temperature of the Earth have been questioned since the first annual average temperature was calculated. The calculation of an annual average temperature must be done according to very stringent rules agreed upon by international groups of climate scientists and published in the peer-reviewed literature for others to replicate and substantiate. This was done initially by Hansen and his co-workers at NASA/GISS. Their methodology has been vindicated by Professor Muller and his Berkeley team.

There are three well-known reconstructions of monthly global mean surface temperature from instrumental data: NASA's GISTEMP analysis, the CRUTEM analysis (from the University of East Anglia's Climate Research Unit), and an analysis by NOAA's National Climatic Data Center (NCDC). These three analyses of global temperature data are almost identical. The main deficiency is in the CRUTEM's data which does not include sufficient polar data and therefore has a definite warming bias. Now there is a fourth, the BEST team's analysis.

All four analyses use data from the Global Historical Climatology Network (GHCN) and all four give a land-station only reconstruction and, except for the BEST study, a combined land-ocean reconstruction that includes sea surface temperature measurements. The GHCN collects data from more than 40,000 stations that are distributed on all continents and is the largest collection of daily climatological data in the world. The total of 1.4 billion data values includes 250 million values each for maximum and minimum temperatures, 500 million precipitation totals, and 200 million observations each for snowfall and snow depth. Station records, some of which extend back to the nineteenth century, are updated daily where possible and are usually available 1–2 days after the date and time of the observation. All records are subjected to intense quality control and quality assurance checks.

All temperature data are available to the public and analyses have been done independently by many scientists. Their results are identical to those by the entities given above if objective methods of analysis are used with the proper QA/QC for each step.

In addition to the above data collecting and analysis organizations, there is also the European Centre for Medium-Range Weather Forecasts (ECMWF) that collects temperature and other weather-related data and several other European organizations which collect temperature data.

University of Alabama, Huntsville (UAH) and Remote Sensing Systems (RSS) perform analyses from satellite data. The Japan Meteorological Association (JMA) also performs analyses of temperature data as do other agencies around the world. Each agency reports similar trends in temperature that tell us that the global temperature of planet Earth is rising.

6.4 Data Reduction

Because of the massive amounts of temperature and other climate-related data available from around the world, data reduction is necessary. Data reduction cannot be random, however, and must follow guidelines agreed upon by international bodies. Data reduction is defined as the transformation of numerical or alphabetical digital information derived empirically or experimentally into a corrected, ordered, and simplified form. When the information is derived from instrument readings, there may be a conversion from analog to digital form. However, most data today is in digital form; it has been acquired or converted, analyzed and reported digitally.

Data reduction has two meanings: (1) Data reduction by decreasing the dimensionality (exploratory multivariate statistics), and (2) Data reduction by unbiased decreasing of the sample size (exploratory graphics). Sometimes plotting an extremely large data set can obscure an existing pattern. When one has a very large data file, it can be useful to plot only a subset of the data so that the pattern is not hidden by the number of point markers.

These definitions of "data reduction" are both statistical definitions and can be found in many textbooks on basic statistics or at the following website: http://www.statsoft.com/textbook/statistics-glossary/d/?button=0#DataReduction.

6.5 Data Analysis

With massive amounts of data, even with data reduction, there are still massive amounts of temperature data to sort through. Basic statistical techniques are used to analyze these data. Maxima and minima with arithmetic means and standard deviations are used along with tests of significance of the data. Tests of correlation and quality of these data are performed.

The analysis method documented by Hansen and Lebedeff in 1981 showed that the correlation of temperature change was reasonably strong for stations separated by up to 1,200 km, especially at middle and high latitudes. This is the model used by GISS for today's analysis of climate data, with numerous updates as data analysis progresses.

6.6 Climate Data Analysis Tools (CDAT)

Lawrence Livermore National Laboratory has developed a software package which is used specifically for climate data analysis called CDAT (Climate Data Analysis Tools). This software package is:

- Developed at the Program for Climate Model Diagnosis and Intercomparison (PCMDI);
- Designed for climate science data;
- Analysis, conversion, sub-setting and array operations;
- Visualization system (VCS, Xmgrace, VTK);

- Graphical User Interface (VCDAT);
- XML representation (CDML) for datasets;
- Integrated with other packages (like LAS and OPeNDAP);
- Open-source and free.

CDAT is public domain software and is available for download at the following web site: http://www2-pcmdi.llnl.gov/cdat.

Other software packages for data analysis are available online and are in the public domain and can be downloaded.

6.7 Data Reporting

Data reporting is essential for informing the scientific community and the general public about what Earth's climate is doing; whether the Earth is warming or cooling, where the storms are most likely to increase along with their intensity, where will desertification most likely occur, etc. These questions are often answered through the use of climate models (see Chap. 18).

Reports of data analysis results are usually published in major peer-reviewed scientific journals, such as *Nature*, *Science*, *Journal of Climatology*, etc., either online, in hard copy, or both and are stored at major archival sites and available at their individual websites.

6.8 Average Land Temperatures

By the 1970s it became obvious that a method was needed to arrive at an average annual temperature for the Earth in order to compare the yearly average temperature with average temperatures from other years. Only in this way could a trend or trends be calculated to determine whether the Earth was cooling, warming, or staying the same from year to year.

Hansen and colleagues in 1981 showed that, contrary to impressions from northern latitudes which indicated a slight cooling, global cooling after 1940 was small, and there was actually net global warming of about 0.4°C between the 1880s and 1970s. The methods used by the scientists at GISS can be found and downloaded at the following website: http://data.giss.nasa.gov/gistemp/.

6.9 History of the Development of the Global Average Temperature

The analysis method developed by GISS scientists obtained quantitative estimates of the error in annual and 5-year mean temperature change by sampling at station locations that allowed a relatively complete data set which was shown to have realistic space (spatial) and time (temporal) variability.

They derived an error estimate that only addressed error due to incomplete spatial coverage of measurements. As there are other potential sources of error, such as urban warming near meteorological stations, etc., many other methods have been used to verify the approximate magnitude of inferred global warming, the latest of which is the very comprehensive methodology developed by the Berkeley Earth Surface Temperature study (BEST) that was discussed in Chap. 4. These methods include inference of surface temperature change from vertical temperature profiles in the ground (boreholes) at many sites around the world, rate of glacier retreat at many locations, and studies by several groups of the effect of urban and other local human influences on the global temperature record. All of these yield consistent estimates of the approximate magnitude of global warming, which now stands at about twice the magnitude that GISS reported in 1981, or about 0.8°C. The BEST study concluded that the warming has been on the order of 0.91°C since the 1950s.

Further affirmation of the reality of the warming is its spatial distribution, which has the largest values at locations remote from any local human influence, with a global pattern consistent with that expected for response to global climate forcings; larger in the Northern Hemisphere than the Southern Hemisphere, larger at high latitudes than low latitudes, and larger over land than over ocean.

Some improvements in the original analysis were made including use of satellite-observed night lights to determine which stations are located in urban and near-urban areas, the long-term trends of those stations being adjusted to agree with long-term trends of nearby rural stations.

6.10 Current Analysis Method

The temperature analysis used today uses satellite observed nightlights to identify measurement stations located in extreme darkness and adjusts temperature trends of urban and near-urban stations for non-climatic factors, verifying that urban effects on analyzed global change are small. Alternative choices for the ocean data are tested.

The GISS scientists showed that global temperature is sensitive to estimated temperature change in Polar Regions, where observations are limited. They suggested use of 12-month (n × 12) running mean temperature to fully remove the annual cycle and improve information content in temperature graphs. They concluded that global temperature continued to rise rapidly in the past decade, despite large year-to-year fluctuations associated with the El Niño-La Niña cycle of tropical ocean temperature, discussed later in Chap. 13. Record high global temperature during the period with instrumental data was reached in 2010. The current analysis is now based on the adjusted GHCN v3 data for the data over land and on NOAA/NCDC's ERSST for data over the oceans.

The temperature analysis is limited to the period since 1880 because of poor spatial coverage of stations and decreasing data quality prior to that time. Meteorological station data provide a useful indication of temperature change in the Northern Hemisphere extra-tropics for a few decades prior to 1880, and there are a small number of station records that extend back to previous centuries. However, GISS scientists think that analyses for these earlier years need to be carried out on a station by station basis with an attempt to discern the method and reliability of measurements at each station. Global studies of still earlier times depend upon incorporation of proxy (substitute) measures of temperature change.

The Intergovernmental Panel on Climate Change (IPCC AR4 2007) issued the following statement:

"*The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agriculture.*" The report goes on to note that these findings come with a *"very high confidence rate that the globally averaged net effect of human activities since 1750 has been one of warming. Warming of the climate system is unequivocal as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.*"

The IPCC's conclusion that "global warming is unequivocal" and there is a very high rate of confidence that it is the result of human activities since 1750 (or the start of the Industrial Revolution) is hardly in doubt.

All temperature analyses indicate that during the last two decades (1990–1999 and 2000–2009, as of June 2012), globally averaged land temperatures have been higher than in any two decades in the past 150 years. Over the past 100 years (since 1912), a global temperature increase of 0.45°C per 100 years has been observed. Since the interpretation of the rise in temperature is a key issue for global warming, the accuracy of the data needs to be carefully considered. A number of potential problems may have affected the land temperature record, as follows:

- Spatial coverage of the data is incomplete (as it always will be; it is impossible to ever have complete coverage unless it is by more than one satellite) and varies considerably;
- Satellite instruments decay; as one satellite instrument decays, another is sent up to replace it and there is always a question if the new data is the same as the old data; there are statistical methods which are used to test the two data sets;
- Changes have occurred in the observing schedules and practices;
- Changes have occurred in the exposure of thermometers;
- Recording stations have changed their locations;
- Changes in the environment, especially urbanization, have taken place around many recording stations (this is the "heat island effect").

The potential problems with temperature data given above have been largely accounted for in the data sets used for annual, decadal, and monthly figures as the BEST results substantiated.

The oceans comprise about 71% of the Earth's surface. Obviously, a compilation of global temperature variations must include ocean surface temperatures as well as readings from land stations. Scientists have created historical analyses of global sea surface temperatures (SSTs) which are derived mostly from observations taken by commercial ships and the latest information from Argo floats.

6.11 Temperature Anomalies

Temperature data are reported as anomalies compared to a zero degree (0°) standard that is the average temperature for a range of years (as stated in Fig. 2.1 as 1951–1980). Temperatures are given as annual arithmetic means either above or below the standard for that graph. In Fig. 2.1, annual means (averages) are along the solid black line with a 5-year running mean indicated by the black line.

Temperature anomaly refers to the deviation from the average of global temperature. The term "temperature anomaly" means a departure from a reference value or long-term average temperature; the departure from a norm. A positive anomaly indicates that the observed temperature was warmer than the reference value, while a negative anomaly indicates that the observed temperature was cooler than the reference value. The reference value is the average or value of the arithmetic mean from a given period of time such as the mean temperature from 1991 to 2000.

The global temperature is calculated using anomalies because they give a more accurate picture of temperature change than actual raw temperature readings. When calculating an average temperature for a region, factors like station location or elevation affect the data, but when looking at the difference from the average for that same location, those factors are less critical. For example, while the actual temperature on a hilltop will be different than in a nearby valley on a given day or month, stations in both places will show a similar trend in temperature when you calculate the change in temperature compared to the average for that station. The change is what is important, not the raw temperatures.

Using anomalies also helps minimize problems when stations are added to or removed from the monitoring network.

In mountainous areas, most observations come from the inhabited valleys, so the effect of elevation on a region's average temperature must be considered as well. For example, a summer month over an area may be cooler than average, both at a mountain top and in a nearby valley, but the absolute temperatures will be quite different at the two locations. The use of anomalies in this case will show that temperatures for both locations were below average.

Using reference values computed on smaller, more local, scales over the same time period establishes a baseline from which anomalies are calculated. This effectively normalizes the data so they can be compared and combined to more accurately represent temperature patterns with respect to what is normal for different places within a region.

For these reasons, large-area summaries incorporate anomalies, not the temperature itself. Anomalies more accurately describe climate variability over larger areas than absolute temperatures do, and they give a frame of reference that allows more meaningful comparisons between locations and more accurate calculations of temperature trends. The Fig. 2.1 shows temperatures as anomalies. The temperature index is simply the method of stating the temperatures as temperature anomalies instead of actual raw temperatures.

Combined land and ocean temperatures have increased rather differently in the two hemispheres. A rapid increase in the Northern Hemisphere temperature during the 1920s and 1930s contrasts with a more gradual increase in the Southern Hemisphere. Both hemispheres had relatively stable temperatures from the 1940s to the 1970s, although there is some evidence of cooling in the Northern Hemisphere during the 1960s and 1970s. Since the 1960s in the Southern Hemisphere but after 1975 in the Northern Hemisphere, temperatures have risen sharply.

While globally-averaged records offer a means of assessing climate change, it is important to recognize that they represent an over-simplification. Significant latitudinal and regional differences in the extent and timing of warming exist. In addition, winter temperatures and night-time minimums may have risen more than summer temperatures and day-time maximums.

One of the most important factors in climate change science, of course, is global temperature. Temperature is recorded in most parts of the world by weather stations, buoys, satellites, ships, balloons, and rockets. Global temperature records go back to the written record of mankind, before the invention of the thermometer, but these earlier records are, of course, anecdotal.

The U.S. National Aeronautics and Space Administration (NASA) and the U.S. National Oceanic and Atmospheric Administration (NOAA) both released their final evaluations of global temperatures in 2011 on January 20th, 2012. They provide two of the longest-standing and most reliable annual evaluations of the climate, using data from the Goddard Institute for Space Studies (GISS) and National Climatic Data Center (NCDC).

While there are always going to be slight differences (because they use slightly different methodologies and instruments for collecting the data), their trends, as well as those from other notable temperature databases, line up closely. The graph below (Fig. 6.2) is a graph constructed in 2010 of global temperature anomalies from these databases (as well as a few others) since 1890, to give a graphic example of their correlation.

Instrumental observations over the past 160 years or so show that temperatures at the Earth's surface have risen globally, with important regional variations. For the global average, warming in the last Century has occurred in two phases, from the 1910s to the 1940s (0.35°C), and more strongly from the 1970s to the present (0.55°C), a total of 0.90°C. An increasing rate of warming has taken place over the last 25 years, and 12 of the 13 warmest years on record have occurred in the past 13 years (including 2010, which is tied with 2005 as the warmest year on record). Above the surface, global observations since the late 1950s show that the troposphere (from the Earth's surface up to an altitude of about 10 km) has warmed at a slightly greater rate than the surface, while the stratosphere (from an altitude of about 10–30 km) has cooled markedly since 1979. This is in accord with physical expectations and most model results if the warming is caused by the greenhouse effect. The stratosphere cools due to heat being trapped nearer the surface.

Confirmation of global warming comes from warming of the land and oceans, destruction of coral reefs (often referred to as bleaching), rising sea levels, glaciers melting, sea ice retreating and disappearing in the Arctic, diminished snow cover in the Northern Hemisphere, the increasing extinction of species, the melting of permafrost, and the migration of flora and fauna to areas that are warming; that is, to

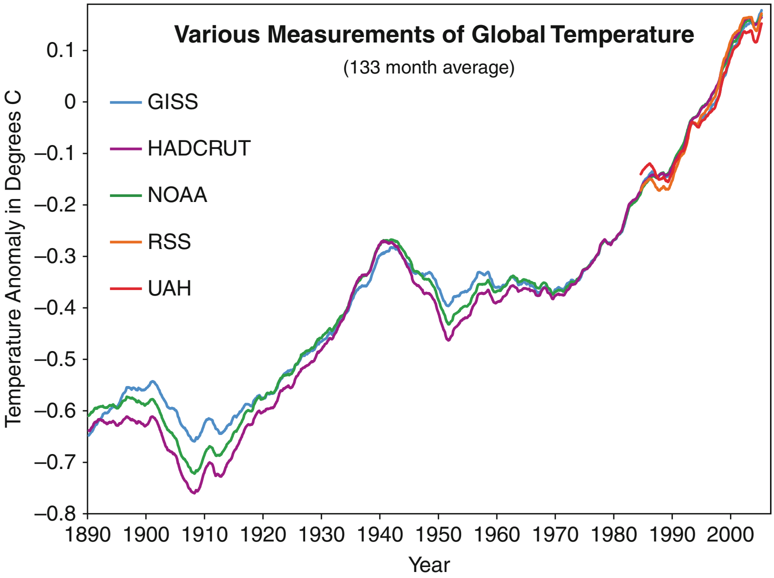


Fig. 6.2 Temperature anomalies in degrees Celsius from 1890 to 2010. *GISS* Goddard Institute of Space Studies, *HADCRUT* Hadley Centre Climate Research Unit Temperature, *NOAA* National Oceanographic and Atmospheric Administration, *RSS* Remote Sensing Systems, *UAH* University of Alabama at Huntsville (From SkepticalScience.com, viewed 1/21/2012)

higher altitudes and higher latitudes. Global warming is causing an increase in species extinction in those organisms that cannot migrate, migrate fast enough, or adapt. There is some concern that the Earth may be experiencing the start of the sixth great mass extinction that the planet has undergone since life began.

There is no single thermometer for measuring the global temperature. Instead, individual measurements are taken multiple times every day at several thousand stations over the land areas of the world and are combined with thousands more measurements of sea surface temperature taken from buoys and ships moving over the oceans to produce an estimate of global average temperature every month.

Scientists have to work with data they acquire, observe, or have collected from the past and analyze those data for accuracy with the best tools available to them; then make decisions as to whether to use those data or not depending on their accuracy. This is why levels of uncertainty are given in the majority of figures representing past temperature data.

Prior to the development of instruments to record temperatures, the written word was used to reveal the weather and temperature. It was "unusually cold in London this winter" or "unusually warm." Shortly after the invention of the thermometer in the early 1600s, efforts to quantify and record the temperature began. The first meteorological network was formed in northern Italy in 1653 and reports of temperature observations were published in the earliest scientific journals. By the latter part of the nineteenth century, systematic observations of the temperature and weather were being made in almost all inhabited areas of the world. International coordination of meteorological observations from ships began in 1853.

The International Meteorological Organization (IMO) was formed in 1873. Its successor, the World Meteorological Organization (WMO), works to promote, maintain, and distribute standardized meteorological observations. Even today, with uniform observations, there are still four major obstacles to turning instrumental observations into accurate global time series for temperature:

1. Access to the data in usable format. Much of the earlier data were not in a standard format and they had to be standardized;
2. Quality control to remove or edit erroneous data points. This is done to ensure and increase accuracy;
3. Quality assurance. Homogeneity assessments and adjustments where necessary to ensure the fidelity of the data; and
4. Area-averaging in the presence of substantial gaps.

Much has been made recently of the effect of El Niño and La Niña on climate models and global temperature calculations. The illustration below (Fig. 6.3) correlates global temperature and the El Niño – La Niña index. It also shows the three major volcanic eruptions of the later twentieth century (since 1960) and their effect on the global temperature. Large volcanic eruptions that cause volcanic particles to stay in the atmosphere have a cooling effect which may last about 2 years.

As the majority of land on Earth is located in the Northern Hemisphere, earlier temperature records are more abundant and complete from this part of the globe than from the Southern Hemisphere. More recent temperature data show more global coverage. The illustration below (Fig. 6.4) shows the change in climate forcing from 1978 to 2008 in the Northern Hemisphere.

One consequence of working only with temperature change is that analysis does not produce estimates of absolute temperature. For those who require an absolute global mean temperature, NASA/GISS scientists have estimated the 1951–1980 global mean surface air temperature as 14°C with uncertainty several tenths of a degree Celsius. That value was obtained by using a global climate model to fill in temperatures at grid points without observations, but it is consistent with results based on observational data. Different kinds of climate models are discussed in Chap. 18.

NASA/GISS scientists found that the correlation of neighboring station temperature records had no significant dependence on direction between the stations. They also examined the sensitivity of analysed global temperature to the chosen limit for station radius of influence (1,200 km). The global mean temperature anomaly was insensitive to this choice for the range from 250 to 2,000 km. The main effect is to make the global temperature anomaly map smoother as the radius of influence increases. However, global maps of temperature anomalies using a small radius of influence are useful for detecting stations with a temperature record that is inconsistent with stations in neighbouring regions.

The standard GISS analysis interpolates among station measurements and extrapolates anomalies as far as 1,200 km into regions without measurement stations as described by Hansen and Lebedeff. Resulting regions with defined temperature

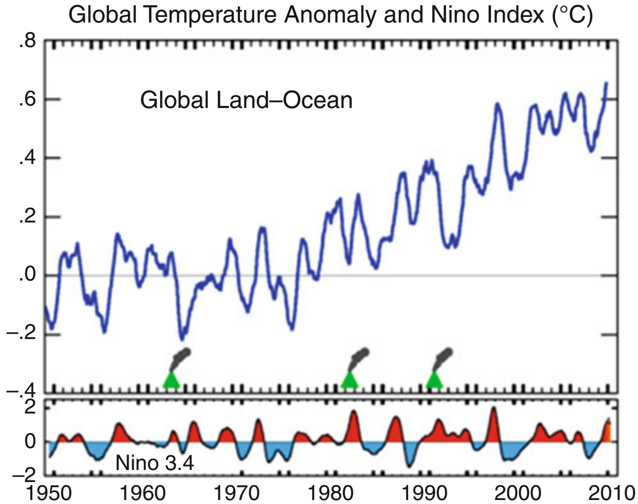


Fig. 6.3 *Blue curve*: 12-month running-mean global temperature. Note correlation with Niño index (*red*=El Niño, *blue*=La Niña). Large volcanoes (*green*) have a cooling effect for ~2 years (NASA/GISS, Public Domain)

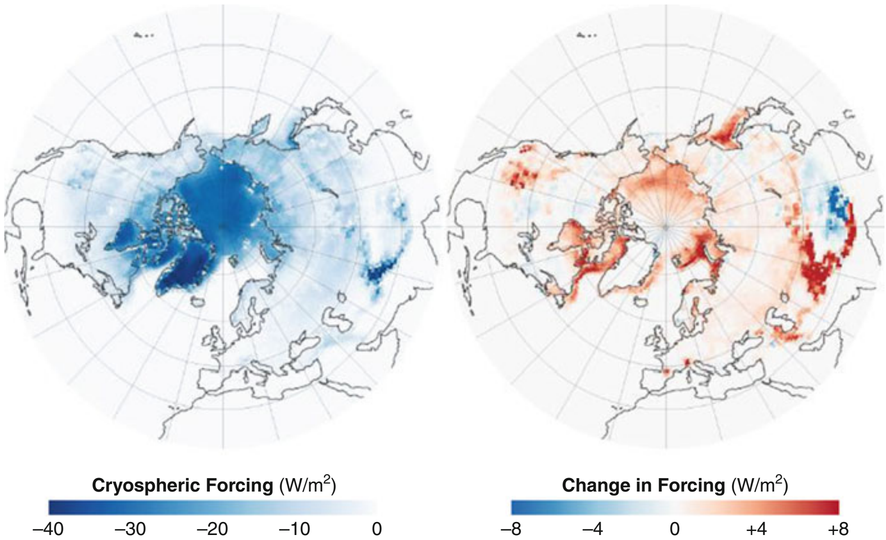


Fig. 6.4 The change in climate forcing in the Northern Hemisphere. The *left image* shows how much energy the Northern Hemisphere's snow and ice reflected on average between 1979 and 2008. *Dark blue* indicates more reflected energy, in Watts per square meter (W m^{-2}), and thus more cooling. The Greenland ice sheet reflects more energy than any other single location in the Northern Hemisphere. The second-largest contributor to cooling is the cap of sea ice over the Arctic Ocean. The *right image* shows how the energy being reflected from the cryosphere has changed between 1979 and 2008. When snow and ice disappear, they are replaced by dark land or ocean, both of which absorb more energy than ice. The image shows that the Northern Hemisphere is absorbing more energy, particularly along the outer edges of the Arctic Ocean, where sea ice has disappeared, and in the mountains of Central Asia (NASA, Public Domain)

anomalies are used to calculate a temperature anomaly history for large latitude zones. Early versions of the GISS analysis method calculated the global temperature anomaly time series as the average for these several latitude zones, with each zone weighted by the area with defined temperature anomaly. That definition can result in the global temperature anomaly differing from the average anomaly for the two hemispheres by as much as several hundredths of a degree during the early decades (1880–1920) when spatial coverage was especially poor.

6.12 History of Temperature Recordings

Temperature records taken at the Earth's surface are critical to the interpretation of climate change. Do these records indicate the Earth is cooling, getting hotter, or staying steady? Do more recordings of temperature allow more accurate calculations of an annual global temperature?

A brief history of temperature recordings that are used for temperature trends is discussed below.

Wladimir Köppen, a German climatologist**,** was the first scientist (in 1881) to overcome many of the obstacles in gathering temperature data in an effort to study the effect of changes in Sunspots. Köppen considered examination of the annual mean temperature to be an adequate technique for quality control of far distant stations. Using data from more than 100 stations, Köppen averaged annual observations into several major latitude belts and then area-averaged these into a near-global temperature time series.

Guy Stewart Callendar (1938), an English engineer and inventor, produced the next global temperature time series expressly to investigate the influence of CO_2 on temperature. Callendar examined about 200 station records. Only a small portion of them were deemed defective. After removing two Arctic stations because he had no compensating stations from the Antarctic region, he created a global average using data from 147 stations.

Most of Callendar's data came from World Weather Records (WWR). Initiated by a resolution at the 1923 IMO Conference, WWR was a monumental international undertaking producing a 1,196-page volume of monthly temperature, precipitation, and pressure data from hundreds of stations around the world, some with data starting in the early 1800s. In the early 1960s, scientists had these data digitized at the U. S.'s National Climatic Data Center (NCDC). The WWR project continues today under the auspices of the WMO with the digital publication of decadal updates to the climate records for thousands of stations worldwide.

H.C. Willett (1950) also used WWR as the main source of data for 129 stations that were used to create a global temperature time series going back to 1845. While the resolution that initiated WWR called for the publication of long and homogeneous records, Willett took this one step further by carefully selecting a subset of stations with as continuous and homogeneous a record as possible from the most recent update of WWR, which included data through 1940. To avoid over-weighting certain areas such as Europe, only one record, the "best" available, was included from each 10° latitude and longitude square. Station monthly data were averaged into 5-year periods and then converted to anomalies with respect to the 5-year period 1935–1939. Each station's anomaly was given equal weight to create the global time series.

Callendar created a new near-global temperature time series in 1961 and cited Willett as a guide for some of his improvements. Callendar evaluated 600 stations with about three-quarters of them passing his quality checks. At the time unknown to Callendar, a former student of Willett, Mitchell in 1963 had created his own updated global temperature time series using slightly fewer than 200 stations and averaging the data into latitude bands.

Meanwhile, research in Russia was proceeding with a very different method to produce large-scale time series. Mikhail Budyko used smoothed, hand-drawn maps of monthly temperature anomalies as a starting point. While restricted to analysis of the Northern Hemisphere, this map-based approach not only allowed the inclusion of an increasing number of stations over time (e.g., 246 in 1881, 753 in 1913, 976 in 1940 and about 2,000 in 1960) but also the utilization of data over the oceans.

A great deal of effort has been spent increasing the number of stations and digitizing historical station data as well as addressing the continuing problem of acquiring up-to-date data; there can be a long lag-time between making an observation and the data getting into global data sets. During the 1970s and 1980s, several teams produced global temperature time series. Advances especially worth noting during this period include the extended spatial interpolation and station averaging technique of GISS scientists and the Hadley Centre's CRU's painstaking assessment of homogeneity and adjustments to account for discontinuities in the record of each of the thousands of stations in a global data set. Since then, global and national data sets have been rigorously adjusted for homogeneity using a variety of statistical approaches.

6.13 Sea Surface Temperatures (SSTs)

As the importance of ocean data became increasingly recognized, a major effort was initiated to seek out, digitize, and initiate quality control of historical archives of ocean data. This work has since grown into the International Comprehensive Ocean–atmosphere Data Set (ICOADS), which has coordinated the acquisition, digitization and synthesis of data ranging from transmissions by Japanese merchant ships to the logbooks of South African whaling boats. The amount of sea surface temperature (SST) and related data acquired continue to grow as more data points are added throughout the World Ocean.

The U.S. National Oceanic and Atmospheric Administration maintains a National Data Buoy Center (NDBC) web page (http://www.ndbc.noaa.gov/). Part of NDBC is the Argo global float array coupled with the Jason satellite altimeter system. Together the Argo and Jason data sets will be assimilated into computer models developed by the Global Ocean Data Assimilation Experiment (GODAE) that will allow a test of scientists' ability to forecast ocean climate.

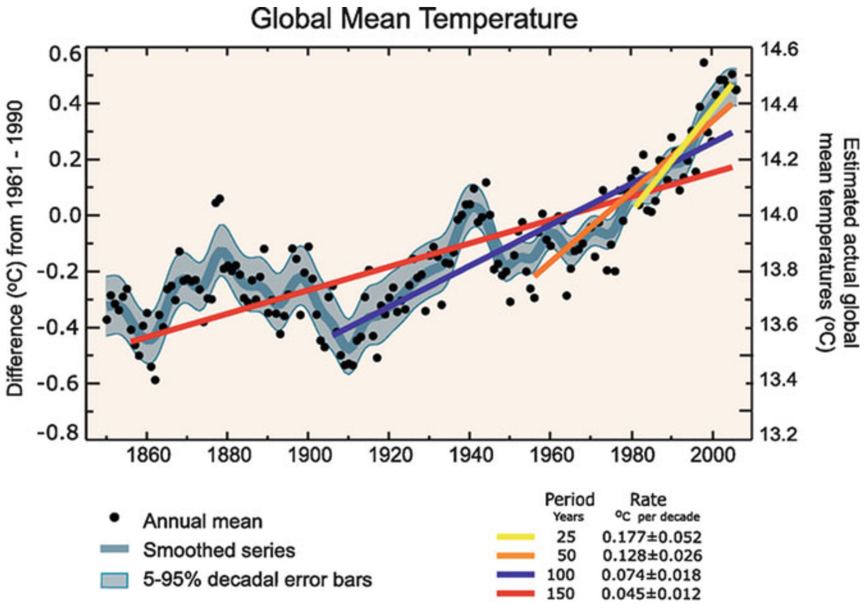
ICOADS offers surface marine data spanning the past three centuries, and simple gridded monthly summary products for 2° latitude by 2° longitude boxes back to 1,800 (and 1° by 1° boxes since 1960); these data and products are distributed worldwide. As it contains observations from many different observing systems encompassing the evolution of measurement technology over hundreds of years, ICOADS is probably the most complete and heterogeneous collection of surface marine data in existence.

As fundamental as the basic data work of ICOADS is, there have been two other major advances in SST data. The first was adjusting the early observations to make them comparable to current observations. Prior to 1940, the majority of SST observations were made from ships by hauling a bucket on deck filled with surface water and placing a thermometer in it. This is no longer done, but the older data had to be revised.

Most of the ship observations are taken in narrow shipping lanes, so the second advance has been increasing global coverage in a variety of ways. Direct improvement of coverage has been achieved by the internationally coordinated placement of drifting and moored buoys. The buoys began to be numerous enough to make significant contributions to SST analyses in the mid-1980s and have subsequently increased to more than 1,000 buoys transmitting data at any one time. Since 1982, satellite data, anchored to *in situ* observations, have contributed to near-global coverage on land and sea. In addition, several different approaches have been used to interpolate and combine land and ocean observations into the current global temperature time series. To place the current instrumental observations into a longer historical context requires the use of proxy data (proxy data in this case is data that are derived from methods other than direct recordings or observations of temperature such as annual tree-rings, ice cores, radiometrics, and isotope ratios). The U.S. NOAA maintains the SST records; and these may be found at the NOAA web site: http://www.noaa.gov.

Despite the fact that many recent observations are digitized and automatic, the vast majority of data that go into global surface temperature calculations (over 400 million individual readings of thermometers at land stations and over 140 million individual *in situ* SST observations) have depended on the dedication of tens of thousands of individuals for well over a century. Climate science owes a great debt to the work of these individual weather station observers who record temperatures, as well as to international organizations such as the IMO, WMO, and the Global Climate Observing System (GCOS), which encourage the taking and sharing of high-quality meteorological observations. They are too often ignored and not given the credit they so richly deserve.

The illustration below (Fig. 6.5) shows estimated mean temperatures from 1850 to 2005 in the top graph and the bottom maps show the temperature distribution on the Earth's surface (left) and in the troposphere (right). The troposphere temperatures are measured by satellite and range from the surface to an altitude of an average of 10 km.



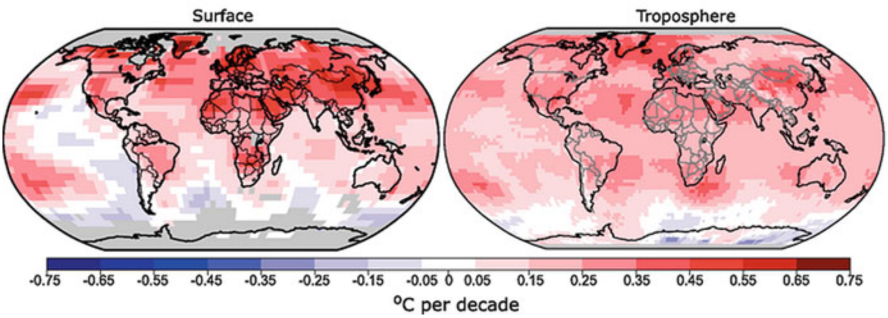


Fig. 6.5 (*Top*) Annual global mean observed temperatures (*black dots*) along with simple fits to the data. The *left hand axis* shows anomalies relative to the 1961–1990 average and the *right hand axis* shows the estimated actual temperature (°C). Linear trend fits to the last 25 (*yellow*), 50 (*orange*), 100 (*purple*) and 150 years (*red*) are shown, and correspond to 1981–2005, 1956–2005, 1906–2005, and 1856–2005, respectively. Note that for shorter recent periods, the slope is greater, indicating accelerated warming. The *blue curve* is a smoothed depiction to capture the decadal variations. To give an idea of whether the fluctuations are meaningful, decadal 5–95% (*light grey*) error ranges about that line are given (accordingly, annual values do exceed those limits). Results from climate models driven by estimated radiative forcings for the twentieth century suggest that there was little change prior to about 1915, and that a substantial fraction of the early twentieth-century change was contributed by naturally occurring influences including solar radiation changes, volcanism and natural variability. From about 1940 to 1970 the increasing industrialization following World War II increased pollution in the Northern Hemisphere, contributing to cooling, and increases in carbon dioxide and other greenhouse gases dominate the observed warming after the mid-1970s. (*Bottom*) Patterns of linear global temperature trends from 1979 to 2005 estimated at the surface (*left*), and for the troposphere (*right*) from the surface to about 10 km altitude, from satellite records. *Grey areas* indicate incomplete data. Note the more spatially uniform warming in the satellite tropospheric record while the surface temperature changes more clearly relate to land and ocean (IPCC AR4, 2007)

6.14 Projections of Future Temperatures

Climate change scientists use climate models with different scenarios to try and project future climates. Scientists do not predict future climates but use historical data and models to project climate scenarios into the future. Historical data are used in history matching (or hindcasting) because if a model can be used to match the climate events of the past it may be used to project events into the future, such as temperature increases.

The two illustrations below show results of models from the IPCC Third Assessment Report (IPCC AR3 or TAR, 2001) (Fig. 6.6), and those from the IPCC Fourth Assessment Report (IPCC AR4, 2007) (Fig. 6.7). The IPCC provides temperature "projections" as part of their assessment reports. These projections are based on scenarios using various amounts of CO_2 to drive global circulation models (GCMs). These projections are not predictions. The IPCC does not make predictions. Scientists may try and predict the weather but not the climate.

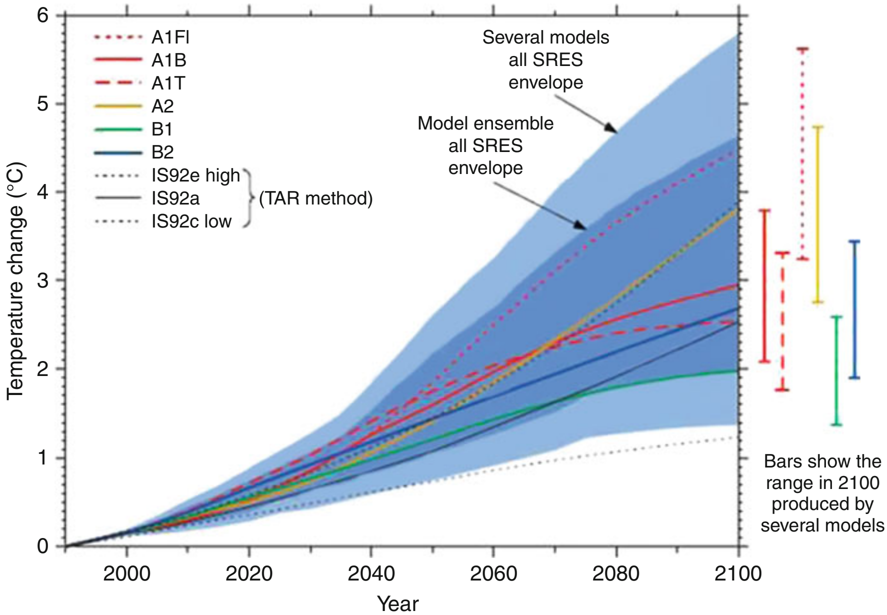


Fig. 6.6 This figure shows Figure 9.14 from the IPCC Third Assessment Report (TAR). It shows temperature projections to 2100: "results are relative to 1990 and shown for 1990–2100. Future changes for the six illustrative Special Report on Emission Scenarios (SRES) using a simple climate model tuned to seven Atmospheric-Ocean General Circulation Models (AOGCMs). Also for comparison, following the same method, results are shown for IS92a (from the TAR). The *dark blue* shading represents the envelope of the full set of 35 SRES scenarios using the simple model ensemble mean results. The *light blue* envelope is based on the Geophysical Fluid Dynamics Laboratory (USA) (GFDL_R15_a) and DOE PCM parameter settings. The *bars* show the range of simple model results in 2100 for the AOGCM model tunings" (From IPCC AR3, 2001)

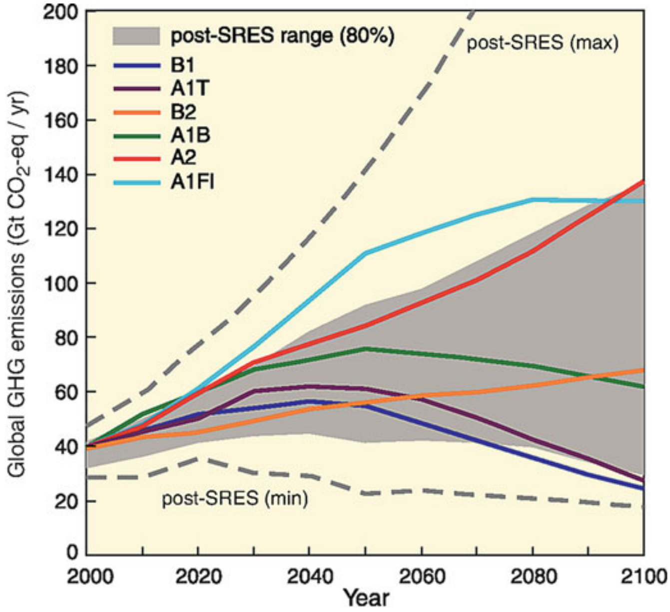


Fig. 6.7 Global GHG emissions (in $GtCO_2$-eq per year) in the absence of additional climate policies: six illustrative SRES marker scenarios (*coloured lines*) and 80th percentile range of recent scenarios published since SRES (post-SRES) (*gray shaded area*). *Dashed lines* show the full range of post-SRES scenarios. The emissions include CO_2, CH_4, N_2O and F-gases {WGIII 1.3, 3.2, Figure SPM.4}

6.15 The IPCC Special Report on Emission Scenarios (SRES), 2007

Descriptions of the IPCC Emission Scenarios as stated in their Emissions Report (SRES, 2007) A1, A2, B1 and B2 are given below.

A1. The A1 scenario describes a future world of very rapid economic growth, global population that peaks in mid-Century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 scenario describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions

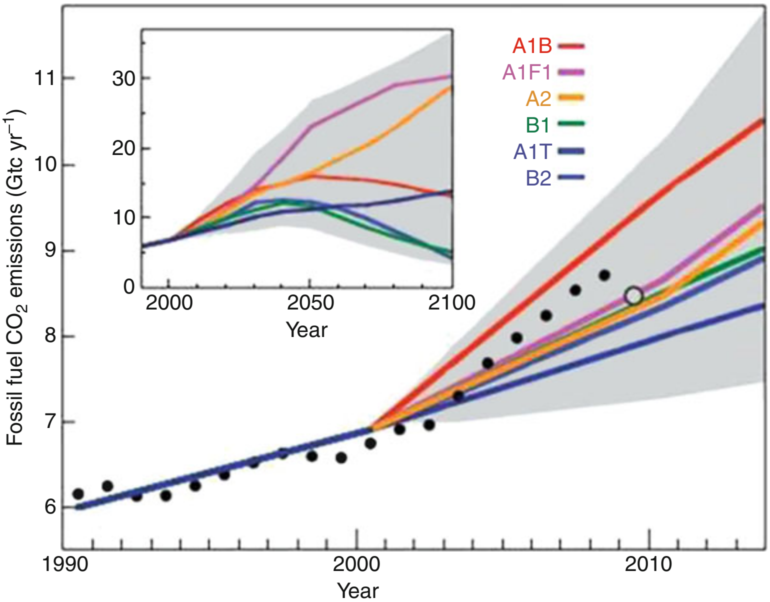


Fig. 6.8 Fossil Fuel CO_2 emissions. The graph shows that estimates of annual industrial CO_2 emissions in gigatonnes of carbon per year (Gt $year^{-1}$) for 1990–2008 (*black circles*) and for 2009 (*open circle*) fall within the range of IPCC scenarios (*grey shaded area*) and of the six IPCC illustrative marker scenarios (*colored lines*). The *inset* shows these scenarios to the year 2100. At the *top* is a fossil fuel intensive scenario (Manning et al., Nature Geoscience 3, 376–377 (2010) doi: 10.1038/ngeo880)

converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other scenarios.

B1. The B1 scenario describes a convergent world with the same global population that peaks in mid-Century and declines thereafter, as in the A1 scenario, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 scenario describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 scenarios. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

The illustration above (Fig. 6.6) shows temperature projections to 2100 with the scenarios from the IPCC Third Assessment Report.

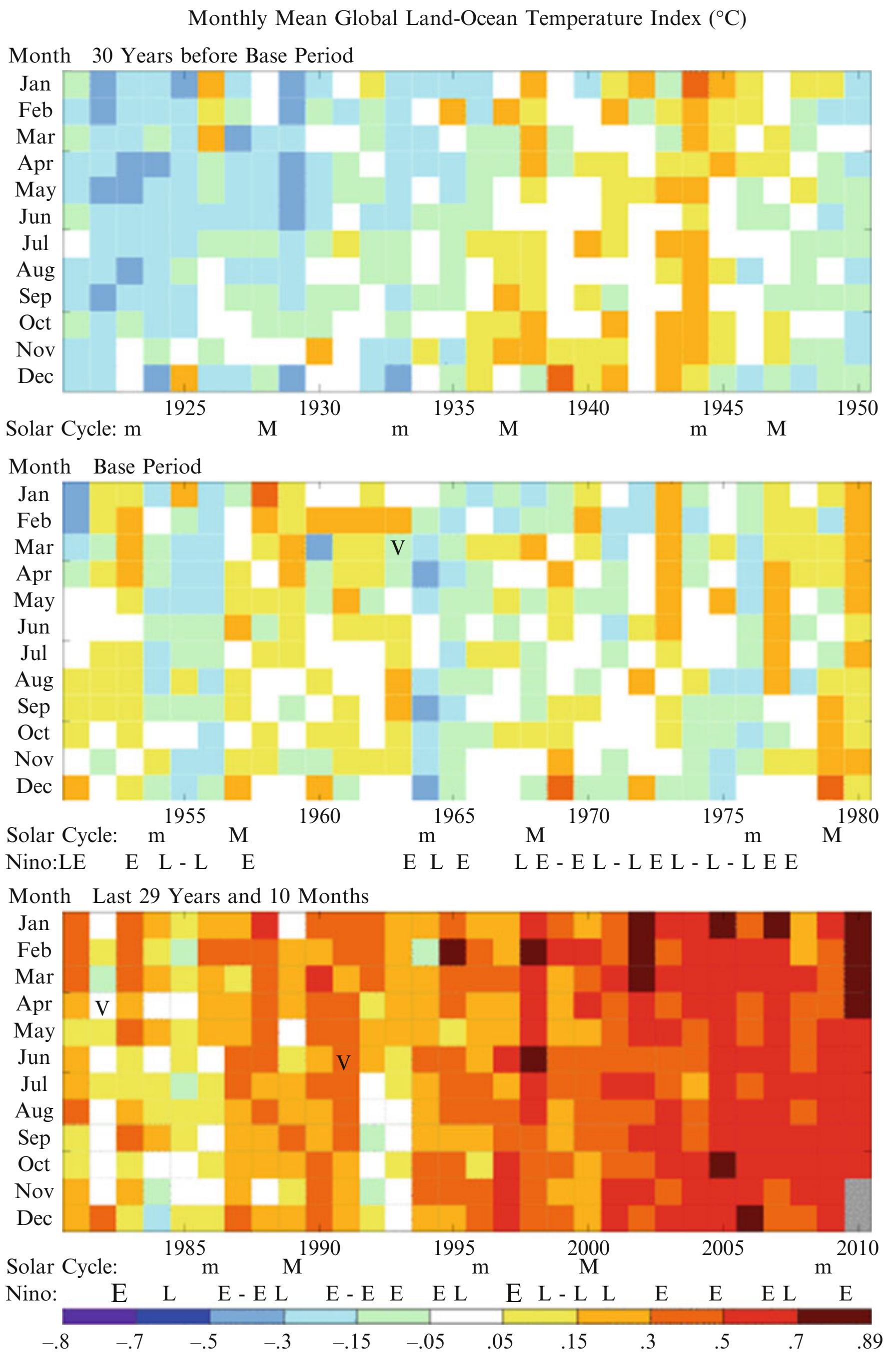


Fig. 6.9 Monthly mean global land-ocean temperature index (°C); (*Top Panel*) 30 years prior to the Base Period. (*Middle Panel*) The Base Period. (*Bottom Panel*) Past 30 years (1980–2010) (NASA/GISS, Public Domain)

The illustration above (Fig. 6.7) shows global greenhouse gas emissions according to the IPCC AR4 scenarios in gigatonnes of carbon dioxide equivalent per year (Gt $CO_{2\text{-eq}}$ year^{-1}).

The illustration above (Fig. 6.8) shows fossil fuel CO_2 emissions. The graph shows that estimates of annual industrial CO_2 emissions in gigatonnes of carbon per year (Gt year^{-1}) for 1990–2008 (black circles) and for 2009 (open circle) fall within the range of IPCC scenarios (grey shaded area) and of the six IPCC illustrative marker scenarios (colored lines).

The illustration above (Fig. 6.9) shows temperature changes plotted monthly starting in 1920 through October 2010 and color-coded according to the temperature scale along the base of the figure. The temperature increases over this time period are striking.

Additional Readings

Bradley, R. S., et al. (2003). The climate of the last millennium. In K. Alverson, R. S. Bradley, & T. F. Pedersen (Eds.), *Paleoclimate, global change and the future* (pp. 105–141). Berlin: Springer.

Hansen, J. (2011). Earth's energy imbalance and implications. *Atmospheric Chemistry and Physics, 11*, 13421–13449. doi:10.5194/acp-11-13421-2011.

Hansen, J., Rossow, W., & Fung, I. (Eds.). (1993). *Long-term monitoring of global climate forcings and feedbacks* (NASA conference publication, 3234). New York: Goddard Institute for Space Studies.

Hansen, J., et al. (2008). Target atmospheric CO_2: Where should humanity aim? *Open Atmospheric Science Journal, 2*, 217–231. doi:10.2174/1874282300802010217.

IPCCTAR WG1 (2001). Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., Johnson, C. A. (Eds.), *Climate change 2001: The scientific basis*, *contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press, ISBN 0-521-80767-0 (pb: 0-521-01495-6).

Le Treut, H., et al. (2007). Historical overview of climate change. In *Climate change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge/New York: Cambridge University Press.

Chapter 7
Climate Change Science as Earth Science

Abstract Climate change science is a part of Earth science. One cannot study the Earth and not study climate; and climate is changing throughout the globe. Weather is also changing and the study of weather is also part of Earth science. The faint early Sun paradox is discussed and some of the early evidence from the geologic past is presented. The four premises of the Gaia hypothesis or theory are given and reasons are stated for and against the hypothesis or theory. The Great Oxygenation Event is introduced with the role of cyanobacteria in the early Earth atmosphere. There are different kinds of ways to conduct scientific work and these are discussed. Examples of good science, bad science, and non-science are given. Different scales and their importance are discussed. Fractals are introduced.

Keywords Fractals • Cyanobacteria • Scale • Ethics • Gaia • Earth • Cryptovolcanic • Oxygenation • Bolides • Meteor crater • Sagan • Quadrangle • Lovelock • Lindzen • Parsec • Paradox • Gigaannum • Uniformitarianism • ZAMS • Geologic • Time • Thermostat • Ethics

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_7,

Things to know	
Earth systems	Cyanobacteria
El Chichón	ZAMS
Meteorology	Gaia hypothesis and its four main premises
The great oxygenation event	Cryptovolcanic structures
O_3	Meteor Crater, AZ
H_2CO_3	Bolides
Gigaannum	James lovelock
Uniformitarianism	Richard Lindzen
Good science examples	Gigaparsec
Bad science examples	Carl Sagan
Light year	LIA
N_2	El Niño
78.1%	Non-Science
1:24,000	Parsec
Richard Muller	7.5 min quadrangles
MWP	

7.1 Introduction

Earth science includes all of Earth's systems and their interrelationships including weather and climate. It includes the atmosphere, oceans, land, the biota, their history, and how they have evolved over time to their current status. These systems are not separate entities but are one system that has evolved together over time, are physically and chemically interrelated, and should be thought of as one system. They are treated separately as we go along because one thinks about them separately. For example, the atmosphere, oceans, continents, land, soils, biota, and their histories are discussed separately in the sections that follow and these separate areas of Earth science should be familiar to all. Climate change science is an integral part of Earth science as are climatology and meteorology (the science of weather).

Later sections of this Introduction include the concept of scale, an introduction to climate change and global warming, Earth history and climate change.

The effect of mankind's activities on Planet Earth has become a topic of importance during the last several decades of the twentieth century and into the twenty-first as there is no question that man's activities have had and are having a profound and deleterious effect on the environmental health of the planet. This is a major theme throughout both volumes of this text.

7.2 Climate Science as Earth Science

Climate is a definite part of the Earth and as such should be included in Earth science studies. Earth science has not included a lot of basic climate science in the past but hopefully will emphasize it more in the future as concerns about Earth's climate become greater. Climate science is becoming more important as temperatures continue to rise and the consequences of global warming become more apparent. Already Earth is experiencing major shifts in weather patterns, a rising sea level with profound coastal effects, and a disruption of fresh water supplies in various parts of the world.

Classical Earth science has emphasized the solid Earth; minerals, rocks, soils, ocean basins, the Earth's interior, shorelines, and glaciers with a smattering of meteorology and climatology. Earth science of the future will have to address climate change in greater detail.

Earth science also includes the history of the Earth and geologic time. The second volume in this textbook series emphasizes the historical aspects of Earth's climate.

7.3 The Faint Young Sun Paradox

Astronomers have concluded, by studying stars throughout the visible Universe, that the Sun has gained in its capacity to emit energy from its inception to the present. This increase in energy has resulted from the Sun's ability to fuse hydrogen to form helium which causes the Sun to expand and grow brighter with time, thus producing more energy (as heat) over time from formation of the Solar System 4.5 billion years ago to the present. Using models of the Sun's activity, astronomers have estimated that the Sun was 25–30% weaker 4.5 billion years ago than it is now.

If the Sun was 25–30% weaker than it is now and slowly built up to its present strength, was the Earth completely frozen during its early history? There is some evidence of a "Snowball Earth" early in its history but there is also evidence of living organisms in shallow marine waters at about 3.5 billion years ago. There is also abundant evidence of running water (not frozen) early in its history and this has led Earth scientists to a mystery called the Faint Early Sun Paradox.

The Faint Early Sun Paradox is a paradox because we know that a slight cooling of the Earth would cause all water on Earth to freeze despite the warming caused by greenhouse gases. If the Sun early in Earth's history was only 25–30% of what it is today there would not have been any running water; yet we have evidence of running water early in Earth's history and geologists tell us that the Earth was not frozen for the first three billion years or so.

The answer to this paradox is contained in the explanation that something kept the early Earth warm despite the weak Sun. But if that something was at work keeping the Earth warm while the Sun's output continued to increase, the Earth at present would be too hot to sustain life.

The problem of the faint early Sun has been around for many years, and these are some of the facts and ideas: astronomers presume that the Sun started its life on the zero-age main sequence (ZAMS) with essentially the same mass that it has today, given the low flux of the solar wind, and we presume that our understanding of the physics of the Sun at that stage is reasonably good. Evolutionary models of the ZAMS Sun then predict that it had about 70% of its current luminosity.

That low luminosity is a problem when combined with what we know about the early atmosphere of the Earth because if the Earth's surface were to become covered in ice then the albedo would be high enough to prevent the young planet from recovering or warming and the ice melting. One solution to this problem is to provide the early Earth with a reducing atmosphere that leads to a strong greenhouse effect with a high concentration of CO_2, keeping the surface fairly warm, or at least non-frozen. We know that one source of CO_2 is volcanoes, although it is a minor source today. Volcanic activity almost certainly was more abundant during the early development of the Earth.

Geologists know that the early Earth had liquid water on its surface, and astrogeologists know that the young Mars did as well. Of course both planets may have had greenhouse atmospheres, but perhaps our understanding of the ZAMS Sun is incomplete. The Faint Young Sun Paradox remains a problem that scientists are continuing to study. The answer probably lies in the Earth having an early greenhouse gas atmosphere with the concentration of carbon dioxide being many times higher than it is today.

7.4 The Gaia Hypothesis

The Gaia Hypothesis (or Theory) was proposed in the 1970s by two scientists (James Lovelock and Lynn Margulis) who proposed that the Earth's climate was controlled by the organisms that were a part of it. According to the hypothesis or theory, organisms control Earth's climate and benefit from the Earth for the good of the organisms. This is a view which contrasts with Darwin's concept, and that of most scientists, that organisms evolve by means of natural selection. The founders of the Gaia Hypothesis accept natural selection, but there are differences in the way it is interpreted.

The Gaia Hypothesis or Theory asserts that living organisms and their inorganic surroundings have evolved together as a single living system that greatly affects the chemistry and conditions of Earth's surface. Some scientists believe that this "Gaian system" self-regulates global temperature, atmospheric content, ocean salinity, and other factors in an "automatic" manner. Earth's living system appears to keep conditions on our planet just right for life to persist. The Gaia Theory has already inspired ideas and practical applications for economic systems, policy, scientific inquiry, and other valuable work. The future holds more of the same.

According to the Gaia Hypothesis, organisms unconsciously regulate Earth's climate for their own benefit. This hypothesis creates the view that evolution has occurred for the benefit of Earth's life forms. There is little scientific evidence that supports this view.

The Gaia Hypothesis has four main premises or propositions:

1. All life on Earth is carbon based, therefore life regulates the carbon cycle;
2. Plants perform photosynthesis removing carbon dioxide from the atmosphere and thereby storing it in soils or in the oceans;

3. Precipitation results in the formation of carbonic acid (H_2CO_3) which causes increased chemical weathering and transportation of carbon into the oceans where it is used by organisms to build their hard parts from $CaCO_3$.
4. That Earth is alive.

The Gaia theory holds that the Earth is a living entity. However, Earth has no parents, no DNA, and cannot reproduce, criteria most scientists think are necessary attributes for life.

In the Gaia Hypothesis, life evolved on Earth for the purpose of regulating its climate. There are others that think that life on Earth has no purpose. Additional information on the Gaia Hypothesis (or Gaia Theory) may be found on the Internet and a search engine (e.g., Google) will reveal numerous sites.

7.5 Introduction to Life Science

Living organisms constitute the biosphere which is part of the Earth and therefore a part of Earth science. The biosphere depends on climate for its existence and variety and interacts with Earth's climate in various ways. It is an integral part of the carbon cycle and is a producer of fossil fuels, the burning of which releases greenhouse gases into the atmosphere.

Life on Earth has made major advances over time, first developing the ability to replicate itself, or reproduce. This happened relatively early in Earth's history and by 3.5 billion years ago, photosynthesis by cyanobacteria caused oxygen to increase in the atmosphere. Algal reef-like organisms first appeared in the fossil record about this time. Cyanobacteria have also been called blue-green algae but cyanobacteria are bacteria and not algae.

By 2.4 billion years (or 2.4 Ga for Gigaannum), there was free oxygen in the atmosphere which began to increase. This happened gradually over time but is referred to as the Great Oxygenation Event (GOE) with a date of 2.4 billion years ago. There were certainly pockets of oxygen in the primitive oceans that most likely preceded the GOE. A recent study from MIT (August 2011) cites evidence that oxygen was present in the early ocean as early as 2.7 Ga, 300 million years prior to the GOE, but it took time for the free oxygen to accumulate.

A basic concept for climate change science is that of geologic time. Geologic time is a special way of looking at time because it refers to vast, long intervals of time or a long time ago compared to human time. Humans think of time in terms of seconds, minutes, hours, a lifetime, a generation, a millennium, etc. But geologic time is on the order of thousands and millions to billions of years and entails a means of looking at time and the events of Earth's past in the proper context.

Climate has existed on Earth since the current atmosphere was formed, shortly after the Earth was formed and cooled from a molten state. This was about 4,540,000,000 years ago, as was discussed earlier; a very long time ago, indeed. Geologic time and its subdivisions are given in Appendix I. Readers of this text should pay particular attention to the subdivisions of geologic time in Appendix I as it is basic to discussions throughout the text. Eventually it will be necessary to commit the geologic time scale to memory, especially in reading the second part of this textbook series.

7.6 Introduction to the Atmosphere

The atmosphere is the gaseous envelop that surrounds the Earth. It consists of solids and liquids too but it consists mainly of gases. It is a dynamic system; the atmosphere is the most unstable and rapidly changing part of the complex climate system. Its composition, which has changed with the evolution of the Earth, is of central importance to the problem of global warming.

The Earth's dry atmosphere is composed mainly of nitrogen (N_2, 78.1%), oxygen (O_2, 20.9%), and argon (Ar, 0.93%). These gases have only limited interaction with the incoming solar radiation and they do not interact with the infrared radiation emitted by the Earth. However there are a number of trace gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3), which do absorb and emit infrared radiation. These are the so called greenhouse gases, with a total volume in dry air of less than 0.1%, play an essential role in the Earth's energy budget. They trap heat in the lower part of the atmosphere, near the Earth's surface and have been largely responsible for the Earth's most recent global warming.

The temperature of the air near the surface has been measured by land, sea, and satellite instruments very accurately since the 1970s and fairly accurately since the late nineteenth century (black curve in graph A, Fig. 7.1). Four main influences are known, and combining these gives a good match to the observations (orange curve in A, Fig. 7.1). The known influences are:

- Irregular "El Niño" fluctuations in the upwelling of deep cold waters in the tropical Pacific Ocean, which cool or warm the air for a few years (purple curve in B in Fig. 7.1);
- Sulfate and ash particles emitted in volcanic eruptions, such as El Chichón in 1982 and Pinatubo in 1991, which bring temporary cooling (blue curve);
- A quasi-regular cycle in the Sun's activity that changes the radiation received at Earth (green curve); and
- Human ("anthropogenic") changes, primarily emission of carbon dioxide from fossil fuels, but also other greenhouse gases and pollution such as smoke, and land-use changes such as deforestation (red curve).

Theorists can calculate the actual influence of each factor, but only approximately. The global heating since the 1970s can be explained only by humanity's greenhouse gas emissions. Note, for example, how the temperature trend in the first decade of the twenty-first century was generally flat because an upward push by anthropogenic forces was temporarily offset by a downward pull as solar activity decreased and the oceans absorbed more heat than usual from the atmosphere (sea water temperatures in fact continued to rise).

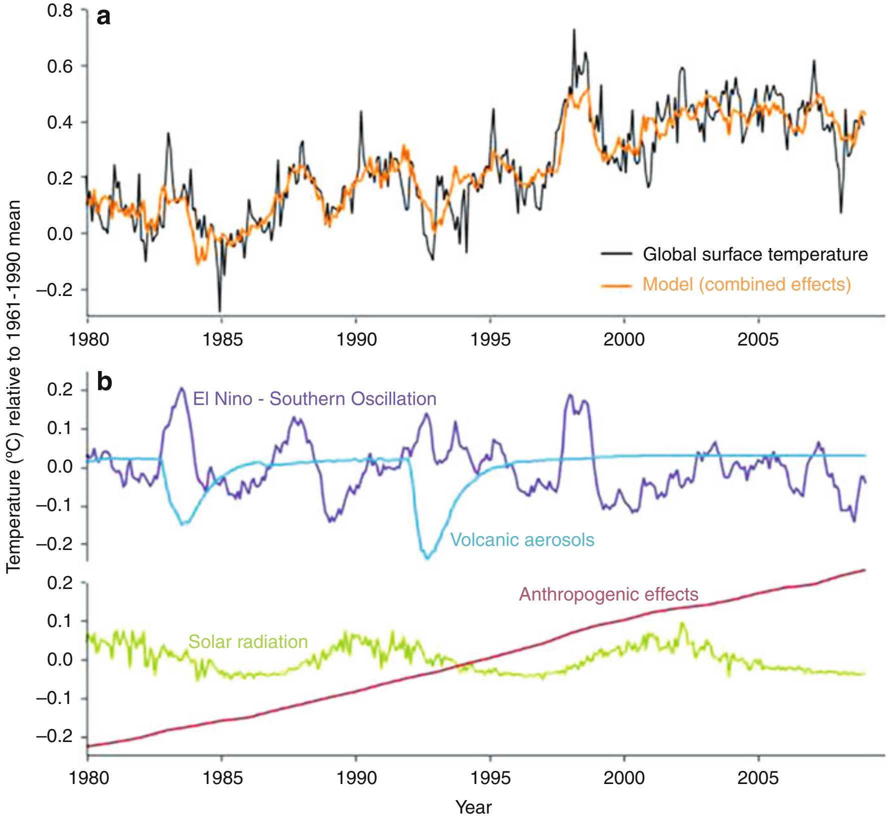


Fig. 7.1 (**a**) Observed monthly mean global temperatures (*black*) and an empirical model (*orange*) that combines four different influences. (**b**) Individual contributions of these influences, namely ENSO (*purple*), volcanic aerosols (*blue*), solar irradiance (*green*) and anthropogenic effects (*red*). Together the four influences explain 76% (r2) of the variance in the global temperature observations (Adapted from Lean and Rind 2009)

7.7 Open System Science

Some Earth Science textbooks have considered the Earth to be a closed system. One recent (January 2010) online Earth Science site showed a picture of Earth with the statement that everything that was shown was part of a closed system. Spectacular evidence that the Earth is not a closed system can be found in many places on Earth and in Earth history, perhaps none so spectacular as Meteor Crater, AZ (Fig. 7.2). Bolides are large extraterrestrial bodies that impact Earth as did the one which formed Meteor Crater, AZ and the even larger one which many believe caused the extinction of the dinosaurs about 65 million years ago (Ma) and struck in the area of the Yucatán Peninsula.

Many structures have been found around the world, throughout the Earth's surface, some of which have been called "cryptovolcanic" structures because of their nearly circular outline, that are now believed to represent past bolide impact structures.

Fig. 7.2 Meteor Crater, AZ (From http://www.ucar.edu/communications/quarterly/winter0708/meteor.jsp), (original photo by John Sheldon)

Their origin as bolide impact structures can be confirmed by "shock structures" formed only by sudden massive impacts such as high-impact SiO_2 and some cone-in-cone structures.

7.8 Uniformitarianism and Climate Change Science

Uniformitarianism is the basic tenant used in the interpretation of Earth history; "the present is the key to the past." It was uniformitarianism that first led humans to realize that the Earth had experienced extensive glaciations in the fairly recent geologic past. Explorers in the Alps had recognized glacial features down valley in valleys that still contained glaciers and they realized that glaciers had once been more extensive. They began to study modern glaciers and were then better able to understand where ancient glaciers had been in the past.

Climate change science has reversed the principle of uniformitarianism somewhat. By studying the past history of the atmosphere that is recorded in gas bubbles preserved in glaciers, it is possible to better understand the relationship of certain atmospheric constituents and their effects on Earth's temperature, and to use this information to project into the future as to what may happen to Earth's temperature if these particular constituents continue to rise in atmospheric concentrations. In this case, the "past is the key to the future."

7.9 Recent Climate Data and Future Projections

Recent data from ice cores have shown a direct correlation between concentrations of greenhouse gases and Earth temperature. As the concentration of greenhouse gases increase, Earth temperatures increase. As the concentration of greenhouse gases decrease, Earth temperatures decrease. It appears that greenhouse gases represent the thermostat that regulates Earth's temperature.

Many skeptics have pointed to the fact that temperatures increase before greenhouse gases increase, so how can greenhouse gases regulate temperature? As the Earth's global temperature warms, the majority of heat and greenhouse gases are stored in the oceans. At a certain temperature, greenhouse gases are released from storage in ocean water and permafrost that increase the Earth's temperature. The Earth's temperature and greenhouse gases appear to work in tandem.

7.10 Components of the Climate Change System

The major components of the current climate change system are:

- The Earth's rapidly rising temperature on a global scale;
- The atmosphere;
- Warming land at Earth's surface;
- Warming oceans;
- Melting of permafrost and glacial ice;
- Rising sea level;
- Ocean acidification;
- Migration and extinction of living organisms;
- The World Ocean's interaction with the atmosphere and the interchange of greenhouse gases, especially CO_2;
- Solar irradiance;
- The burning of fossil fuels;
- Volcanic emissions of solids; and
- Milankovitch cycles.

Each of these topics has a history and will be treated in later chapters of this text.

7.11 Good Science, Bad Science, and Non-Science

Good science is done by scientists with a set of ethics and a scientific method that guide them. Scientists are engaged in finding answers to problems and follow a scientific method or a logical system of action to find an honest scientific answer. Honest scientific answers are the product of good science.

The products of good science stand the test of time. They are arrived at by actions (a scientific method) that can be reproduced. The method or methods employed are well documented so that they can be reproduced time and time again, if necessary.

An important distinction to make clear when science is being discussed is the difference between fact and opinion. Fact, in a scientific context, is a generally accepted reality (but still open to scientific inquiry). Hypotheses and theories are generally based on objective inferences, unlike opinions, which are generally based on subjective influences or intuition. And sometimes it is difficult to distinguish fact from opinion. This may be especially true in the realm of climate science as it seems that everyone has an opinion concerning climate. However opinions are not science.

For example, a statement such as “It was certainly cold last winter so the Earth cannot be warming” is certainly an opinion. A statement such as “The Earth’s temperature has increased 0.911 °C since 1950” could best be called a fact, given supporting evidence. Statements such as “the Earth orbits the Sun,” or “evolution occurs over time,” or “gravity exists” are all today considered to be both facts and theories (and could possibly turn out to be wrong if new evidence comes to light that contradicts them).

Opinions are neither fact nor theory; they are not officially the domain of science (but don’t think that scientists don’t have opinions; scientists are also human, and opinions often help guide their research). Thus, science cannot directly address such issues as whether God exists or whether people are good or bad but scientists can discuss good and bad science and give examples of each.

7.12 Examples of Good Science

In *The Demon-Haunted World* (p. 261), Carl Sagan, the great science popularizer, wrote:

> Science is different from many another human enterprise – not, of course, in its practitioners being influenced by the culture they grew up in, nor in sometimes being right and sometimes wrong (which are common to every human activity), but in its passion for framing testable hypotheses, in its search for definitive experiments that confirm or deny ideas, in the vigor of its substantive debate, and in its willingness to abandon ideas that have been found wanting. If we were not aware of our own limitations, though, if we were not seeking further data, if we were unwilling to perform controlled experiments, if we did not respect the evidence, we would have very little leverage in our quest for the truth. Through opportunism and timidity we might then be buffeted by every ideological breeze, with nothing of lasting value to hang onto.

Good science may be exemplified by the Berkeley Earth Surface Temperature (BEST) study completed to date (February 2012) by a team led by the climate change skeptic and recent climate change convert, Richard Muller. By definition, all scientists are skeptics as this is the nature of science, as we’ve seen. Scientists are supposed to be objective and to view things critically, so skepticism is a valid approach to science.

Muller and his team set out to document temperature data of land areas throughout the world and report the data no matter what the result. Partial funding for this study came from some of the supporters of climate change deniers, namely the billionaire Koch brothers, Charles and David Koch.

The Berkeley Earth Surface Temperature team includes statisticians, physicists, climate experts and others with experience analyzing large and complex data sets.

The BEST study's aim is to resolve current criticism of the former temperature analyses by government agencies and others, and to prepare an open record that allows rapid response to further criticism or suggestions. The results will include not only the best estimate for the global temperature change, but estimates of the uncertainties in the record.

The Berkeley Earth Surface Temperature study is using over 39,000 unique stations, which is more than five times the 7,280 stations found in the Global Historical Climatology Network Monthly data set (GHCN-M) used by previous studies. The study provides an open platform for further analysis by publishing their complete data and software code. The initial data release is now available and the analysis supports the previous studies that the Earth is warming.

The BEST study has been criticized by one of its co-authors (Judith Curry) because it did not include ocean SSTs. However, it was more comprehensive than previous studies over land had been.

7.13 Examples of Bad Science

Bad science is often scientific work that does not follow a scientific method. Bad science produces misinformation (unintentional) and disinformation (intentional). There are numerous examples in the literature, peer reviewed and non-peer reviewed, especially from tobacco advocates, acid rain, and climate change deniers.

The tobacco industry actually hired scientists (and probably still does) to try and prove that smoking is not harmful to one's health. However, there is overwhelming evidence that all forms of tobacco harm one's health. The same can be said of global warming. Global warming, as revealed by climate change science, is also hazardous to the health of life on Earth.

A professor at M.I.T. and climate change skeptic, Richard Lindzen, published the following statement in the non-peer reviewed literature: "Climate is always changing. We have had ice ages and warmer periods when alligators were found in Spitsbergen. Ice ages have occurred in a 100 thousand year cycle for the last 700 thousand years, and there have been previous periods that appear to have been warmer than the present despite CO_2 levels being lower than they are now. More recently, we have had the medieval warm period and the little ice age. During the latter, alpine glaciers advanced to the chagrin of overrun villages. Since the beginning of the nineteenth century these glaciers have been retreating. Frankly, we don't fully understand either the advance or the retreat."

Lindzen's statement quoted above contains several misstatements: Climate is not always changing. Weather is always changing. Climate has changed in the past, slowly and over decades and millennia, and often correlated with changes in greenhouse gases. Lindzen's key word is "always." How long is always? Climate changes when it's forced to change. When our planet suffers an energy imbalance and gains or loses heat, global temperature changes.

The planet has been hotter in the past but ice cores tell us that these climate changes have been directly related to greenhouse gases, at least for the past 850,000 years.

The Medieval Warm Period (MWP) and the Little Ice Age (LIA) were most likely not global in extent and the Medieval Warm Period was not warmer than the present as claimed by some skeptics, Lindzen among them. Despite substantial uncertainties, especially for the period prior to 1600 when data are scarce, the warmest period of the last 2,000 years prior to the twentieth century very likely occurred between 950 and 1100, but temperatures were probably between 0.1 and 0.2°C below the 1961–1990 mean and significantly below the level shown by instrumental data after 1980. The heterogeneous nature of climate during the Medieval Warm Period is illustrated by the wide spread of values exhibited by the individual records. Warmth in some regions appears to have matched or exceeded recent levels of warmth in these regions, but globally the Medieval Warm Period was cooler than recent global temperatures.

Ice core records currently analyzed go back at least 850,000 years and they show a relationship between Earth's temperature and greenhouse gases. When the temperature is high the greenhouse gases are also high. Deep-sea sediment cores give an even longer temperature record and combined with other lines of evidence, such as geochemical modeling, show an even longer relationship between greenhouse gases and Earth's temperature.

7.14 Examples of Non-Science

A brief example of non-science is the unpublished hypothesis and the "sound bite." Wild, controversial hypotheses (often in the form of "sound bites") are readily accepted by the unknowing public. An example of a sound bite is the following statement publically uttered by non-scientists Senator Inhofe of Oklahoma and former Senator Santorum of Pennsylvania (both non-scientists) and perhaps others: "Global warming is a hoax." For ideas to become accepted in the scientific community, they must be published, undergoing the process of peer review by reputable scientists, to separate the good science from the bad science and the non-science. Even then some not-so-good science still finds its way into the literature in peer-reviewed publications, so scientists and others must think critically when reviewing other scientists' work. The same can be said of everyone in examining what they read and hear about climate science or about science in general.

Often bad science and non-science statements and works appear in the peer-reviewed literature in selected journals or in books that are published by "think tanks" or periodicals that have financial backers who have a preconceived agenda such as the Heartland Institute, the Cato Institute, and the George C. Marshall Institute. These three, and there are many others, have financial backing from the chemical, tobacco, and energy companies and have a few scientists or pseudoscientists on staff who say what they are told to say.

7.15 Ethics in Science

Anyone dealing with research in science is expected to be ethical, but how does one become ethical? Ethics is a system of moral principles which govern appropriate conduct. So ethics and morals are synonyms. An ethical person is also a moral person.

Ethics in science is like ethics in everything else. There is an ethical way of conducting oneself and most people and scientists are ethical. There are checks and balances in scientific endeavors that usually ensure that most scientists are ethical, at least those that publish in the peer reviewed literature or that are in the public eye. One major aspect of these checks and balances is the peer-review process. As a researcher, a scientist prepares a report stating the methods used, the data gathered, how the data were gathered, and the conclusions drawn. The report is then either published in a journal, book, or presented at a scientific conference, as is mentioned above, and peers are all too anxious to provide the scientist with feedback.

There are examples of unethical scientists, however, and this is of course true in climate science, or any other aspect of science, as well as in other professional lines of work. Climate science as a separate branch of science is relatively young compared to the natural sciences (biology, geology) or the physical sciences (physics, chemistry, physical geology). Climate science is difficult to fit into a category because it consists of many sciences and other fields, such as physics, mathematics, chemistry, biology, meteorology, geology, oceanography, economics, sociology, political science, computer science, and climatology. It is literally a potpourri of all the different sciences. And it is a relatively new science as a separate entity because mankind did not care so much about climate until temperature, recorded over a relatively long period of time, began to show a sharp rise as shown in the plots in this text. These plots of temperature against time suddenly began to get people's attention in the late twentieth and early twenty-first centuries and climate became more important than it had been. Prior to this fairly recent interest, climate was somewhere one went to for retirement or recreation. But we know that climate is a long-term trend, decades or millennia in duration, and just a few recordings or changes in the weather are not relevant. Trends are what allow scientists to see what is happening to our climate and allow them to project those trends into the future.

There is an ethical question that scientists and politicians must eventually face. Studies show that the most carbon dioxide producing countries are the ones least affected by global warming.

The question then becomes: "How does one motivate the countries that emit the most carbon dioxide to slow or stop their emissions if they are the least affected?"

There is no ready answer to this question. The international community of states recognizing the facts provided by climate science will be the ones to enforce emission standards.

7.16 The Concept of Scale in Earth and Climate Change Science

Scale is an important concept to grasp in both science and the humanities. Artists who paint must be aware of the scale of their painting, whether painting a landscape or a flower. Historians must be aware of the scale of events. Scientists, architects, and engineers use scale in their drawings and calculations. Looking at a globe requires a scale different from examining plans for a house or other buildings and there are different kinds of scales. Different temperature scales were discussed in previous chapters and there are many other kinds of scale. One definition of scale may be as follows: a linear or curved surface with calibrated numerical markings against which a pointer moves; the number nearest the pointer indicates the value of something measured. Or a scale may be a device used to measure something's or somebody's weight, or height. So there are different kinds of scales; for temperature, for rainfall, for relative humidity, for maps, and for climate.

The climate of an area may be given by using scales such as the average temperature of the area, or the number of consecutive sunny days; or the average snowfall in centimeters, feet, or inches; or by using such terms as tropical, polar, etc.

Time scales may vary for the history of individual planets in the Solar System, as illustrated in the figure below (Fig. 7.3). Time scales differ for the Earth (top), Mars (middle) and the Moon (bottom).

A more detailed geologic time scale for Earth is given in Appendix I.

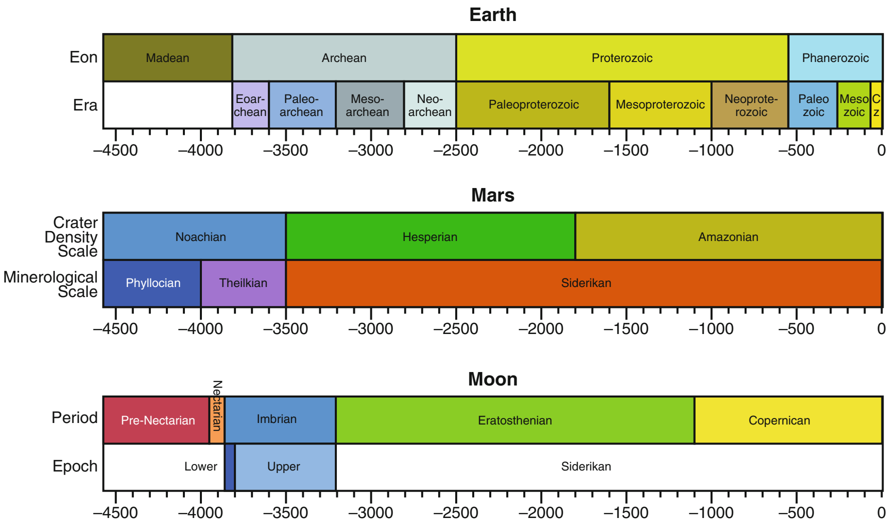


Fig. 7.3 Time scales devised for the Earth (*top*), Mars (*middle*) and the Earth's Moon (*bottom*). Solar system origin is to the *left* and the present is to the *right* (From http://pweb.jps.net/~tgangale/mars/mst/GeologicTimeScales.htm, released to the Public Domain by Thomas Gangale)

7.17 Map Scales

Scales used on maps vary depending on the area being represented by the map. For the whole Earth, scales must be small as compared to a local map, whose scale must be large to show the detail required. If the scale of a map is stated as a ratio or a fraction, the larger the whole number, the larger the scale. For example, a scale expressed as a fraction of 1/1,000 or 1:1,000 is larger than a scale of 1/64,000 or 1:64,000.

The U.S. Geological Survey (USGS) publishes maps at various scales. The scale used for most U.S. topographic maps expressed as a ratio is 1:24,000. USGS maps at this scale cover an area measuring 7.5 min of latitude and 7.5 min of longitude and are commonly called 7.5-min quadrangle maps. Map coverage for most of the United States has been completed at this scale, except for Puerto Rico, which is mapped at 1:20,000 and 1:30,000, and for a few States that have been mapped at 1:25,000. Most of Alaska has been mapped at 1:63,360, with some populated areas also mapped at 1:24,000 and 1:25,000. These map scales, expressed as ratios or fractions, mean 1 in. on the map equals 24,000 in. on the ground (1:24,000) or 1 in. on the map equals 25,000 in. on the ground (1:25,000) or 1 ft on the map equals 25,000 ft on the ground.

The scale of a map showing the whole Earth, such as the one in Fig. 7.4 below is a very small scale. Maps are described as small scale, typically for world maps

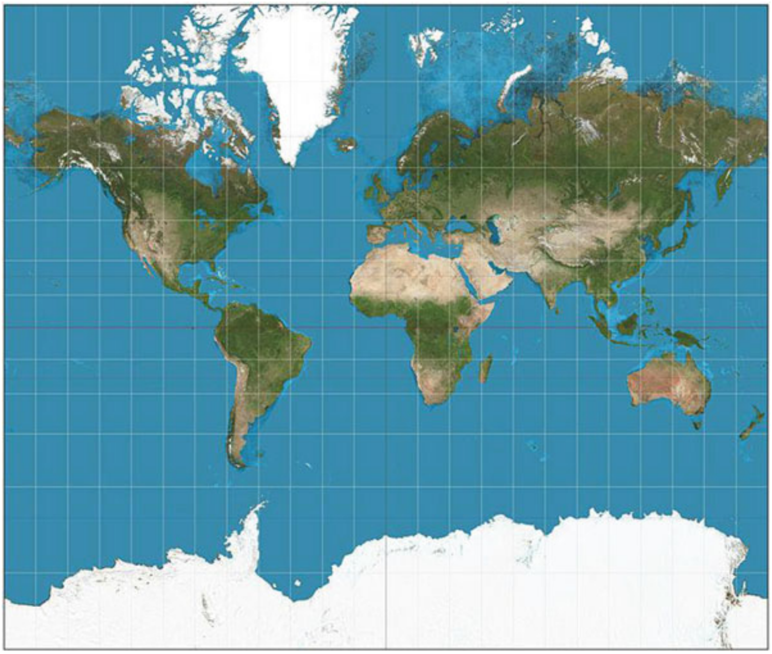


Fig. 7.4 A small-scaled map of the Earth represented by a Mercator projection, greatly exaggerating the sizes of land areas in polar regions (From Wikipedia, CC Attribution-Share Alike 3.0 Unported License, by Strebe)

or large regional maps, showing large areas of land on a small space; or large scale, showing smaller areas in more detail, typically for county maps or town plans. The town plan might be on a scale of 1/10,000 and the world map might be on a scale of 1/100,000,000. There is no hard and fast dividing line between "small" and "large" scales.

7.18 Fractals

Scale may be illustrated by the use of fractals. A fractal is a rough or fragmented geometric shape that can be split into parts, each of which is a reduced-size copy of the whole (see Fig. 7.5).

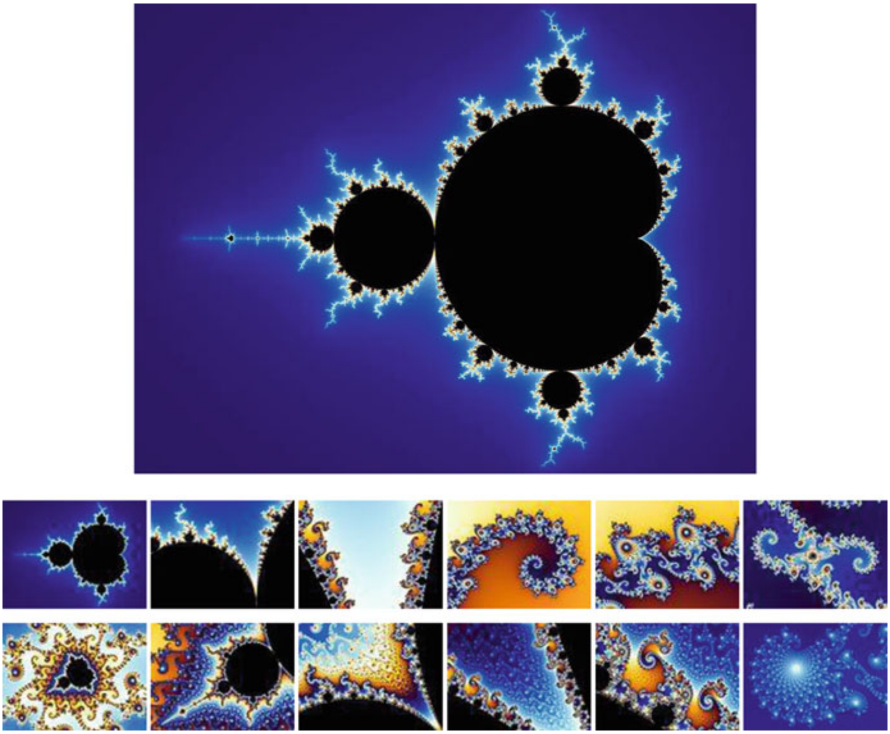


Fig. 7.5 The Mandelbrot set is a well-known example of fractals. Study the set from *left* to *right* (Created by Wolfgang Beyer with the program Ultra Fractal 3. From Wikipedia, GNU Free Documentation License, Version 1.2 or any later version published by the Free Software Foundation; with no Invariant Sections, no Front-Cover Texts, and no Back-Cover Texts. A copy of the license is included in the section entitled GNU Free Documentation License)

7.19 Graph Scales

Graphs that are used in this text consist of x- and y-axes and the scales vary depending on what is being shown or graphed. Generally, the y-axis shows the temperature in degrees Celsius and the x-axis shows the years or time. The shape of the graph can be greatly changed depending upon the scales used.

7.20 Time Scales

A time scale defines units of time ranging from the smallest fraction to vast intervals of geologic and cosmic time scales.

7.21 Earth Scales

Earth scales are those that are most familiar to us such as the metric and English scales of measurement and length. Time scales originally based on day and night and smaller and larger times such as days, weeks, months, years, decades, etc. And geologic time scales such as millennia, millions, and billions of years.

The geologic time scale can be found in Appendix I.

7.22 Planetary Scales

Planetary scales have to do mainly with distances from the Sun, sizes of the individual planets, their relative sizes, etc. Planetary scales are illustrated by Fig. 7.6 which shows the size scale of the planets.

7.23 Cosmic Scales

Much of our knowledge of our own galaxy, the Milky Way, comes from studying other galaxies. There are estimated to be 100 billion other galaxies in the universe. Some are larger than the Milky Way, most are smaller.

Measurements between and within galaxies require a different scale based on light years (one light year) is a unit of length and is expressed as the distance that light travels in one Julian year. Light travels in a vacuum at a speed of 3×10^8 meters/second (m/s). Astronomers prefer to use the parsec unit of measurement.

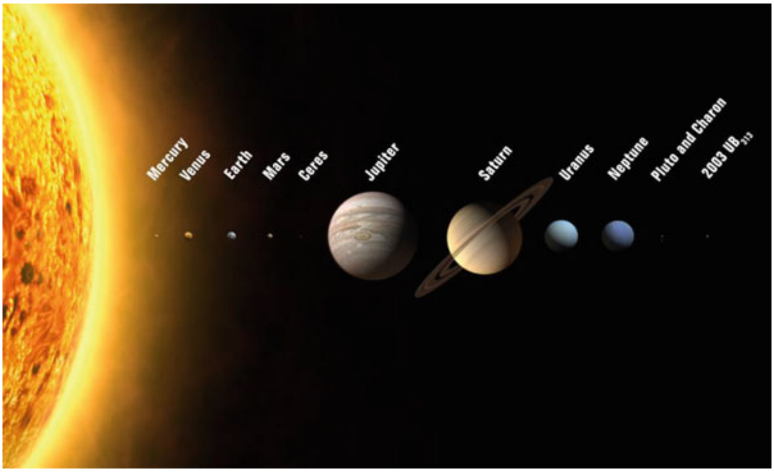


Fig. 7.6 Planets, other planet-like objects, and the Sun of the Solar System drawn to scale (size but not distance) (From au.org/publicpress/images/detail/iau0601a/)

A parsec is defined as the distance at which an object will appear to move one arcsecond of parallax when the observer moves one astronomical unit perpendicular to the line of sight to the observer, and is equal to approximately 3.26 light-years (1 parsec (pc) = 3.26 light years). A kiloparsec (kpc) is equal to one thousand parsecs or $3.26 \times 1{,}000 = 3{,}260$ parsecs. A megaparsec (Mpc) is equal to one million parsecs. A gigaparsec (Gpc) is equal to a billion parsecs.

Additional Readings

Barnsley, M. F., & Rising, H. (1993). *Fractals everywhere*. Boston: Academic Press Professional. ISBN 0-12-079061-0.

Lean, J. L., & Rind, D. H. (2009). American Geophysical Union. *Geophysical Research Letters, 36*, L15708. doi:10.1029/2009GL038932. 5 pp.

Lovelock, J. (1995). *The ages of Gaia: A biography of our living Earth*. New York: Norton. ISBN 0-393-31239-9.

Lovelock, J. (2009). *The vanishing face of Gaia: A final warning*. New York: Basic Books. ISBN 0-465-01549-8.

Sagan, C. (1995). *The Demon-Haunted World: Science as a candle in the dark* (p. 261). A Ballantine Book, New York: Random House. ISBN 0-394-53512-X.

Samson, J., et al. (2011). Geographic disparities and moral hazards in the predicted impacts of climate change on human populations. *Global Ecology and Biogeography, 20*(4), 532–544.

Part III
Earth's Atmosphere

Chapter 8
Introduction to Earth's Atmosphere

Abstract The Earth's atmosphere is a thin envelope of gases surrounding the solid planet, the hydrosphere, and biosphere. The composition of the atmosphere consists largely of two elements, oxygen and nitrogen. The atmosphere also contains chemicals which absorb heat from the Earth's surface and radiate it in all directions including back to the surface. This results in the greenhouse effect that keeps the planet warm enough to sustain life. The greenhouse gases include water vapor, carbon dioxide, and methane. Carbon dioxide is the main greenhouse gas of concern today as it is increasing rapidly in the atmosphere largely as the result of the burning of fossil fuels. The Keeling curve shows the steady increase in carbon dioxide since 1958. Different zones of the atmosphere are defined. The effects of Arctic warming are causing changes in the Jet Stream. These changes are affecting weather patterns and weather uncertainty is increasing. The isotopes of carbon are listed and the significance of carbon-14 (^{14}C) is explained with reference to carbon dioxide from fossil fuels.

Keywords Thermosphere • Mesopause • Thermopause • Stratosphere • Ozone • Lapse rate • NOAA • Aerosols • CFCs • Methane • Keeling • Thunderstorm • Smog • Ferrel • Hadley • Polar • Exosphere • Isostatic • Rebound • PBL • Gigatonne • Westerlies • Contraction • Intertropical • Convergence

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_8,

Things to Know	
Thickness of the Atmosphere	Earth's Temperature
Lapse Rate	Inert Gases
Thermosphere	Chemical Composition of Earth's Atmosphere
Mesopause	Ozone Hole
Smog	Emitters of Carbon Dioxide
Stratopause	36,000 Million Metric Tons
O_3	NOAA
Tambora	Stratosphere
D, E, and F Layers	Aerosols
"Year Without a Summer"	Tropopause
CFCs	Exosphere
CH_4	Minus 15 Degrees Celsius
Ozone Layer	Jet Stream

8.1 Introduction

The atmosphere is the gaseous envelope which surrounds us. It is what we breathe and what provides oxygen to most animal life at the Earth's surface. The atmosphere is a relatively thin envelope compared to the mass of Planet Earth (Fig. 8.1).

Atmospheric contamination is a serious concern and may be invisible to humans as it begins to build and the concentrations of contaminants may be so gradual that it goes unnoticed. Some atmospheric contaminants may continue to build up and become visible, such as smog or the "brown haze" over cities, but the atmosphere is vitally important to the maintenance of life on Earth. There may be warning signs

Fig. 8.1 Earth's atmosphere from the International Space Station (ISS) (From NASA, Public Domain)

of atmospheric contamination, such as smog and haze that should be heeded so that things can be corrected before it becomes imminently dangerous to humans. Let's first take a look at the nature and characteristics of the atmosphere.

8.2 The Atmosphere

The atmosphere has provided for life on Earth for at least the last 3.5 billion years or so. Trilobites, ammonites, sea-scorpions, dinosaurs, mastodons, saber-toothed cats, and many other life forms that depended upon the atmosphere and hydrosphere have come and gone throughout Earth's history. These organisms are discussed in detail in Volume II of this textbook series.

8.3 Composition of the Atmosphere

The atmosphere is composed mainly of two elements; nitrogen and oxygen. These two elements comprise roughly 99.06% of the atmosphere. The other constituents of the lower atmosphere (within 25 km of Earth's surface) are listed below in Table 8.1.

All of the substances in Table 8.1 are important for one reason or another, but three stand out as influencing what is and has been occurring in the Earth's atmosphere. These three are the cause of great concern for the future of the planet. They are the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and ozone (O_3). All three are greenhouse gases (GHGs) and, along with water vapor, provide the Earth with the greenhouse effect. Carbon dioxide and methane trap heat near Earth's surface and ozone filters out UV rays that cause cancer and respiratory harm to animals living at the surface of the Earth.

Table 8.1 Average composition of the atmosphere below 25 km

Chemical Components of the Atmosphere		
Component	Chemical abbreviation	Volume % (dry air)
Nitrogen	N_2	78.08
Oxygen	O_2	20.98
Argon[a]	Ar	0.93
Carbon dioxide	CO_2	0.039
Neon[a]	Ne	0.0018
Helium[a]	He	0.0005
Hydrogen	H	0.00006
Krypton[a]	Kr	0.0011
Xenon[a]	Xe	0.00009
Methane	CH_4	0.0017
Ozone[b]	O_3	0.00006

[a]Inert gases

[b]Strictly speaking, the concentration of ozone in the atmosphere is variable so the total % may exceed 100%

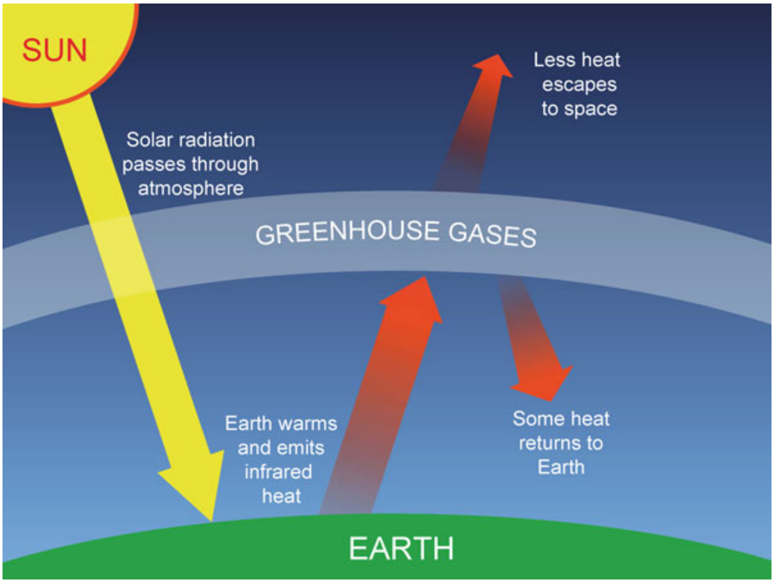


Fig. 8.2 The greenhouse effect. Greenhouse gases trap and re-emit heat energy back to Earth's surface. With the buildup of greenhouse gases in the past several decades, Earth now has the 'enhanced greenhouse effect'

The greenhouse effect is what keeps the Earth warm enough, but not too warm, to support life. This warmth is estimated to be about 33°C above what it would be without the greenhouse effect. As a result, the Earth's average global temperature is a balmy +15°C, instead of a −18°C. If the Earth's surface was −18°C, no life could exist on its surface. The greenhouse effect is what has caused life as we know it to originate and evolve on Earth. It is this greenhouse effect that has been in existence since humans evolved on this planet.

Humans have evolved on Earth under conditions that were not affected by humankind's current activities. Humans are at a unique time in Earth's history now when we can change the course of that history. We are the only species that has evolved the ability to project into the future and decide the fate of the planet and its life-sustaining features.

The illustration above (Fig. 8.2) shows how the greenhouse effect works. Solar radiation passes through the atmosphere, some is directly reflected back to space but most gets through and warms the Earth. As we've seen before, the incoming radiation is mainly ultraviolet (UV) radiation. This UV radiation heats the Earth which causes it to re-radiate heat in the form of infrared (IR) radiation. Much of this IR radiation is trapped near Earth's surface by the greenhouse gases that in turn re-radiate some of this back to the surface.

Greenhouse gases allow the Sun's radiation to pass through the atmosphere, heating the Earth's surface. Heat is re-radiated by the Earth's surface and much of it is trapped by greenhouse gases. These gases keep the Earth a pleasant average temperature of about +15°C. Of course, the temperature varies from place to place over the Earth's surface and from season to season and the +15°C is an average figure.

We will next take a look at the important greenhouse gases and the properties that make them so useful to mankind and the other species inhabiting the Earth.

8.3.1 Carbon Dioxide

Carbon dioxide is the gas that is most important in warming the Earth's atmosphere and its surface along with water vapor. It is so important that its role in warming the planet will be discussed separately in the following chapter.

All greenhouse gases trap heat in the lower part of the atmosphere and re-radiate it back to Earth, but carbon dioxide is special, which will become obvious in the paragraphs that follow. Water vapor does not last long in the atmosphere and falls as precipitation and condensation.

Carbon dioxide is a colorless gas and constitutes a very small percentage of the atmosphere. As will be discussed in succeeding Chap. 9, carbon dioxide is only 0.040% (400 ppmv, parts per million by volume) of the atmosphere, an infinitesimal amount. However, it is an extremely important gas because it is a major part of the carbon cycle, being used by plants in photosynthesis and by animals that consume plants, and by being a greenhouse gas that helps to warm the planet. Carbon dioxide is emitted naturally by volcanoes, hot springs, fumaroles, geysers, animals, and by the dissolution of carbonates in rocks of the Earth's crust. The recent (nineteenth, twentieth, and into the twenty-first century) increases of carbon dioxide in the atmosphere are unequivocally due to anthropogenic (i.e., man-made) causes, principally the burning of fossil fuels; and there are human fingerprints to prove that this is true.

Carbon dioxide levels fall in the spring and summer as plants consume the gas, and rise during the autumn and winter as plants go dormant, die, and decay. When plants and animals are buried and form coal, natural gas, and oil over tens and hundreds of millions of years, and are then burned at the Earth's surface to release energy, they release carbon dioxide back to the atmosphere. The illustration below, Fig. 8.3, is the well-known Keeling curve maintained by the U.S. National Oceanic and Atmospheric Administration (NOAA) at the Mauna Loa Observatory in Hawaii.

Carbon dioxide has a high affinity for heat capture and retention in the infrared and near-infrared wavelengths while being transparent to ultraviolet and visible light from the Sun. In other words, a majority of ultraviolet light from the Sun is transmitted through the atmosphere to the Earth's surface but carbon dioxide and other greenhouse gases trap heat radiation in the lower part of the atmosphere near the Earth's surface and keep it from escaping back into space. After a greenhouse gas traps a packet of infrared radiation, the gas re-radiates it partially out to space, partially to other greenhouse gas molecules in the atmosphere, or back to the Earth's surface. As carbon dioxide increases in the atmosphere, Earth's temperature also

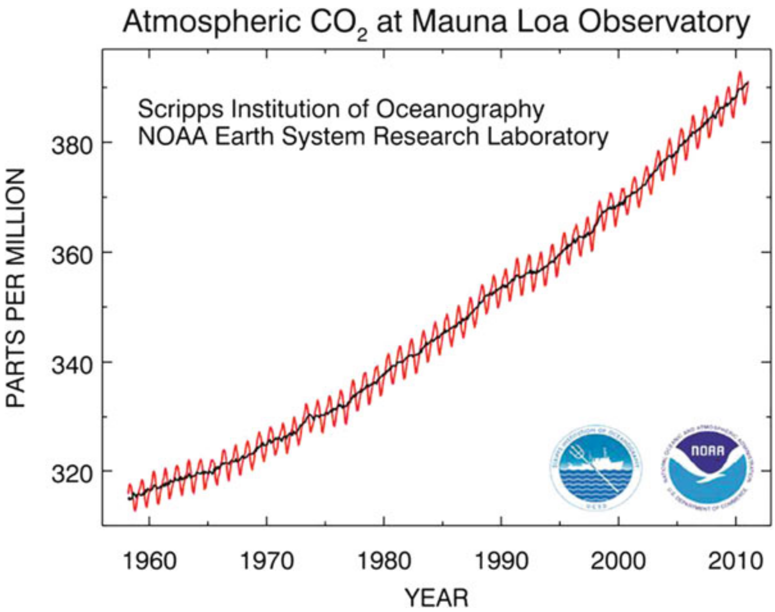


Fig. 8.3 The record of CO_2 increases in the atmosphere at Mauna Loa Observatory since 1958. This is the famous Keeling curve. The *red line* shows the seasonal variation in CO_2, lowest in the summer and highest in the winter; vegetation in middle latitudes in the Northern Hemisphere takes in CO_2 in the spring and summer and releases it in the fall and winter. The *black line* is the average annual concentration (NOAA, Public Domain)

increases. Earth's average global temperature at its surface increases because of the rise in greenhouse gas concentration in the atmosphere.

Earth has an energy imbalance, as we saw in a previous chapter. There is more energy coming in from the Sun than is being radiated back out into space by the Earth and this has been measured accurately by orbiting satellites and other instruments. The amount of radiation being lost to space from the Earth is becoming less and less with time as CO_2 concentration in the atmosphere is increasing. That carbon dioxide causes global warming is a scientific fact, as it is a fundamental fact of physics that carbon dioxide absorbs infrared radiation and re-radiates it back to the Earth's surface. This fact has been demonstrated in laboratories, in the field, and by satellites many times since the nineteenth century.

Carbon dioxide has been much higher in atmospheric concentrations in the geologic past than it is today. But this does not mean that it is a good thing today; that is, that the increase in CO_2 today does no harm. Some skeptics and deniers would have us believe CO_2 is not important to today's climate and they cite the miniscule amount as a percentage of atmospheric composition, but as we've already seen, it is extremely important to recognize its influence on the warming Earth.

CO_2 has fluctuated wildly throughout geologic time, being extremely high for the first few hundred million years of the Phanerozoic Eon and most likely was much higher during the Precambrian (older than 540 million years ago). The higher atmospheric concentrations of CO_2 in the past have been attributed to the vast intervals of time the carbon cycle needs to remove carbon from the atmosphere, thus allowing carbon dioxide to remain high for a large portion of geologic time. Plots of carbon dioxide over hundreds of millions of years show a gradual decline in concentration with time.

The high CO_2 values during early Earth history and the steadily declining values are due primarily to the speeding up of the passage of carbon atoms from their original volcanic sources into sediments as these are eroded from the continents and buried in lakes, along the course of rivers, and in the ocean basins. The continents stand higher today than perhaps at any previous time during Earth history, due largely to isostatic rebound from the most recent glaciation and retreat and the high-standing Alps, Andes, Rockies, and Himalaya Mountains and the Tibetan Plateau. These continental areas are still being uplifted by Earth processes today. To lower atmospheric CO_2 over a long period of time, one has to expose fresh rocks to provide calcium and/or to bury organic materials and these processes have taken enormous intervals of geologic time. These processes are discussed further in Volume II of this textbook series.

The greenhouse effect of CO_2 has been known since Fourier's research in 1824 and it was quantified by Arrhenius in 1896, as we saw in a preceding chapter. CO_2 absorbs and re-emits infrared (heat) radiation in the atmosphere warming the lower troposphere of the Earth and the Earth's surface. This is an undeniable fact of physics, but climate change deniers insist that this is not so; they have offered no proof of their claims.

In the more recent geologic past (revealed by several lines of evidence), as carbon dioxide has increased in the atmosphere, temperature of the lower troposphere has increased. As carbon dioxide has decreased in the atmosphere, temperature has decreased.

There is a direct correlation between carbon dioxide and temperature of the lower troposphere throughout Earth's history where such information is available and can be interpreted. There is evidence from the most recent episodes of glaciation on Earth that temperature rises before carbon dioxide, then carbon dioxide builds up in the atmosphere until it decreases again as temperature falls before the next glaciation. Climate scientists show evidence that the initial glaciation was most likely triggered by Earth's orbital cycle but the later glaciations and interglacial episodes were controlled by carbon dioxide. This relationship between glaciation and carbon dioxide is discussed further in a later chapter. It appears that carbon dioxide concentration in the atmosphere is acting as the Earth's thermostat as the carbon dioxide levels track Earth's temperature throughout a large portion of geologic time.

As geologists, climate change scientists, and paleoclimatologists refine their methods, develop new ones, and increase the accuracy of their studies, much more information and technologies are becoming available to analyze the effects of carbon dioxide and Earth's temperatures millions and millions of years in the past. And the results of all of these studies show a direct empirical relationship between carbon dioxide and Earth's surface temperature. The coincidence of this over millions and millions of years of Earth history is striking and is surely not an accident, although it is well known that correlation does not prove cause and effect. However, when this correlation exists between carbon dioxide increases and temperature increases are combined with all the other evidence from physics and paleoclimatology, this correlation takes on additional significance.

Carbon dioxide is not the only greenhouse gas. Water vapor is the most abundant and obvious of the greenhouse gases, but water vapor is flushed out of the atmosphere regularly by condensation and precipitation. There are other more potent greenhouse gases than water and carbon dioxide and they are discussed further in later chapters and only briefly introduced here.

Methane is a more potent greenhouse gas than either water vapor or carbon dioxide. Nitrous oxide is even more potent than methane. But it is carbon dioxide that forms the matrix which holds some water vapor and other greenhouse gases in the atmosphere. Carbon dioxide also is long-lived in the atmosphere, perhaps as long as a thousand years, and mixes throughout the troposphere, whereas water vapor precipitates out as rain, mist, sleet, hail, or snow and methane is oxidized to carbon dioxide. Because carbon dioxide is long-lasting, it becomes mixed throughout the atmosphere and is a very effective greenhouse gas. As its concentration in Earth's atmosphere is increasing at present, the temperature is also increasing and scientists are beginning to see cause and effect.

Some climate change deniers claim that more carbon dioxide is added to the atmosphere by volcanoes than by humans. This is incorrect. The anthropogenic burning of fossil fuels causes over one hundred times (130+ times) more carbon dioxide emissions annually than volcanoes.

Published estimates based on research findings of the past 30 years for present-day global emission rates of carbon dioxide from subaerial and submarine volcanoes range from about 150 million to 270 million metric tons of carbon dioxide per year, with an average of about 200 million metric tons.

These global volcanic estimates are utterly dwarfed by carbon dioxide emissions from fossil fuel burning (coal, petroleum), cement production, gas flaring and land use changes; these emissions accounted for some 36,300 million metric tons (36 gigatonnes or billion tons) of carbon dioxide in 2008, according to an international study published in December 2009. Even if one takes the highest estimate of volcanic carbon dioxide emissions at 270 million metric tons per year, human-emitted carbon dioxide levels (at 36,000 million metric tons) are more than 133.333 times higher than volcanic emissions.

Carbon dioxide may remain in the atmosphere for hundreds of years and possibly thousands of years and this longevity allows carbon dioxide to become well mixed throughout the atmosphere.

There are several facts of physics that have never been disputed in the scientific literature that relate to carbon dioxide and its role in rising Earth temperatures, and they are as follows:

- The atmospheric carbon dioxide concentration has increased steadily since the beginning of the Industrial Revolution, after being nearly constant for a couple of thousand years. The pre-industrial carbon dioxide level is estimated at about 280 ppm. Carbon dioxide has been continuously monitored at the NOAA Mauna Loa Observatory since 1958 and has resulted in what is known as the Keeling Curve (see Fig. 8.3).

- The surplus atmospheric carbon dioxide has an isotope composition that can only come from fossil fuels. The increase in concentration is not natural; it comes from human activities. There are three isotopes of carbon in nature: carbon-12 (^{12}C), carbon-13 (^{13}C), and carbon-14 or radiocarbon (^{14}C). Studies of carbon isotope ratios prove that the bulk of the additional carbon dioxide in the atmosphere comes from the burning of fossil fuels. There is no ^{14}C being added to the atmosphere beyond that which occurs naturally. There would be additional ^{14}C added to the atmosphere from any source other than fossil fuels.
- The radiative properties of carbon dioxide have been measured in the laboratory since Fourier and Arrhenius in the nineteenth century. Carbon dioxide absorbs thermal infrared (i.e., heat) radiation and re-radiates heat back to the Earth's surface.
- Because carbon dioxide has an infrared and heat-absorbing physical property, the increase in its concentration has increased the infrared opacity of the Earth's atmosphere and blocks the outward radiation of heat. This blocking and re-radiating of heat has been measured and is being measured in laboratories since the nineteenth century and since 1978 by Earth-orbiting satellites. Less heat is escaping to outer space from the Earth's surface and more is being trapped and re-radiated to the surface.
- More net energy is now coming into the Earth's atmosphere from sunlight than is going back out to space as heat radiation. This is being accurately measured by instruments both at Earth's surface and by satellites in orbit around the Earth.
- Conservation of energy is a fundamental law of physics. When more energy comes in than goes out of a system, the system warms.
- The Earth's temperature is increasing by an amount that is consistent with predictions, based on the laws of physics and the well-known heat-absorbing properties of the excess carbon dioxide in the atmosphere.
- Measurements show that night-time temperatures are increasing faster than day-time temperatures, just as physicists and climate change scientists have predicted. The excess carbon dioxide and other greenhouse gases cause a warmer night-time atmosphere. The main source of heat at night is greenhouse gases but they do not affect the brightness of the Sun.
- Measurements show that the top of the atmosphere is getting colder, just as physicists and climate change scientists predicted, because the excess carbon dioxide in the lower atmosphere is blocking the heat from below. The troposphere is warming, the tropopause is rising, and the stratosphere is cooling.
- Heat-sensing instruments on satellites have measured a reduction in the amount of infrared radiation coming from the atmosphere, at the exact wavelengths predicted by physicists and climate change scientists. Less heat radiating from Earth to outer space means more heat is being captured by greenhouse gases.

Those that claim that carbon dioxide does not cause the Earth to warm must be prepared to refute one or more of the above facts, and so far no one has been able to do this (as of June 2012).

8.3.2 Methane (CH_4)

Methane is a greenhouse gas approximately 21 times more effective than carbon dioxide in trapping and re-radiating heat to the Earth's surface. It varies as to its effectiveness compared to carbon dioxide depending on how long it remains in the atmosphere.

Methane is a hydrocarbon gas produced both through natural sources and human activities, including the decomposition of wastes in landfills, agriculture, and especially rice cultivation, as well as ruminant digestion and manure management associated with domestic livestock. Methane is much less abundant than carbon dioxide in the atmosphere but is increasing in concentration due to its release by melting permafrost and by methane clathrates in shallow marine environments. Methane remains in the atmosphere for approximately 9–15 years and eventually is converted to carbon dioxide by oxidation.

The sudden release of methane into the atmosphere by rising temperatures is one of the main causes of concern for global warming. If permafrost continues to melt and the oceans continue to warm and the huge quantities of methane that are stored there are released to the atmosphere and converted to carbon dioxide, runaway global warming and the Venus syndrome could be fatal to most, if not all, life on the planet. The Venus syndrome is an atmosphere like that of the planet Venus whose atmosphere is largely comprised of carbon dioxide. This is a truly doomsday scenario as no life exists on Venus.

Methane is not as long-lasting in the atmosphere as is carbon dioxide, but this is little consolation as they are both greenhouse gases, methane is converted to carbon dioxide, and carbon dioxide becomes well-mixed and is long-lasting in the atmosphere.

8.3.3 Nitrous Oxide (N_2O)

Nitrous oxide (N_2O) is produced by both natural and human-related sources. Primary human-related sources of N_2O are agricultural soil management, animal manure management, sewage treatment, mobile and stationary combustion of fossil fuel, and nitric and other acid production. Nitrous oxide is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests.

Nitrous oxide is a clear, colorless gas, with a slightly sweet odor. Due to its long atmospheric lifetime (approximately 120 years) and heat trapping effects (about 310 times more powerful than carbon dioxide on a per molecule basis), N_2O is an important greenhouse gas. It is commonly known as "laughing gas."

8.3.4 Ozone (O_3)

Ozone is an important greenhouse gas but is even more important to life on Earth as an absorber of the Sun's ultraviolet radiation. In the troposphere, ground-level or "bad" ozone is a pollutant that is a significant health risk, especially for humans with asthma or other respiratory problems. It also damages crops, trees and other vegetation. It is a main ingredient of urban smog often seen in major metropolitan areas of the world.

The stratospheric or "good" ozone is a layer that extends upward from about 6 to 30 miles and protects life on Earth from the Sun's harmful ultraviolet (UV) radiation. This natural shield has been gradually depleted by man-made chemicals such as chlorofluorocarbons (CFCs). A depleted ozone shield allows more UV radiation to reach the ground, leading to more cases of skin cancer, cataracts, and other health and environmental problems. The "ozone hole" over Antarctica received a great deal of publicity after its discovery in 1985. The Antarctic ozone hole was discovered by British scientists of the British Antarctic Survey.

After a series of rigorous meetings and negotiations, the Montreal Protocol on Substances that Deplete the Ozone Layer was finally agreed to on 16 September 1987 at the Headquarters of the International Civil Aviation Organization in Montreal, Canada. This is now referred to simply as the Montreal Protocol.

The ozone "hole" is really a reduction in concentrations of ozone high above the Earth in the stratosphere (Fig. 8.5). The ozone hole has steadily grown in size (up to 27 million square kilometers) and length of existence (from August through early December) over the past two decades. The size is expected to begin to be reduced and return to its pre-1980 size by 2070, according to the U. S. National Oceanic and Atmospheric Administration (NOAA). The Antarctic ozone hole had reached the size of North America by the fall of 2011.

An Arctic ozone hole has also been discovered and is thought to be due to an increasingly cold stratosphere, which results from the greenhouse effect. If more heat is trapped in the troposphere, less is available to warm the stratosphere.

8.3.5 Chlorofluorocarbons (CFCs)

Chlorofluorocarbons are substances that are completely anthropogenic. They do not occur as a result of natural causes or processes.

The non-reactivity of CFCs, so desirable to industry, allows them to drift for years in the atmosphere until they eventually reach the stratosphere. High in the stratosphere, intense UV solar radiation severs chlorines away from the CFCs, and it is these unattached chlorines that are able to catalytically convert ozone molecules into oxygen molecules. It is these catalytic reactions that were leading to the destruction of the ozone layer in the stratosphere prior to the acceptance of the Montreal Protocol in 1987.

8.3.6 Other Trace Gases

Other trace gases in the atmosphere include the noble gases, inert or unreactive gases, of which the most abundant is argon. Other noble gases include neon, helium, krypton and xenon. Hydrogen is also present in trace quantities in the atmosphere, but because it is so light, over time much of it has escaped to space from Earth's gravitation. Water vapor is also a trace gas, is not well mixed in the atmosphere, and is flushed out of the atmosphere by precipitation.

8.3.7 Aerosols

Aerosols are liquids and solids which are dispersed in the atmosphere and consist of soot, dust, sea salt crystals, spores, bacteria, viruses, and many other types of materials which float around in the air.

Aerosol concentration in the atmosphere varies widely but is thought to average about one part per billion (ppb). Despite this small fraction, aerosols play an important role in climate change. Volcanic dust after violent explosive eruptions may produce aerosols (volcanic ash, sulfur, and dust) which block a percentage of the Sun's radiation from impacting Earth. This has caused cooling of the surface of the planet for as long as 1–2 years. Liquids as aerosols cause more dispersion of the Sun's radiation and solid aerosols block the Sun's rays.

The year 1816 is referred to as "the year without a summer" due to a series of volcanic eruptions, the last of which was the explosive eruption of Mount Tambora in Indonesia in 1815, the largest known eruption in over 1,600 years and possibly the largest eruption in the history of humankind. A solar minimum may also have contributed to the coldness during the summer months. It snowed in the northeastern part of the U.S. in New York, Connecticut, and most of New England in June. Nearly a foot of snow fell in Quebec City, Canada in early June. Crops were lost and there was an additional loss of most summer-growing plants. There was regional malnutrition, starvation, and an increased death rate.

Aerosols also scatter incoming solar radiation resulting in slight cooling as this scattering occurs in all directions, some of which impacts the Earth's surface.

8.4 Lapse Rate

Lapse rate is the rate of decline of temperature with altitude in the atmosphere, thus

$$\lambda = dT / dz$$

Where λ is the lapse rate of temperature divided by units of altitude, T = temperature and z = altitude. Although the actual atmospheric lapse rate varies, under normal atmospheric conditions the average atmospheric lapse rate results in a temperature decrease of 3.5°F (1.94°C) per 1,000 ft (304 m) of altitude, or height above the Earth's surface. The actual lapse rate varies from place to place and from time to time over the Earth and it may be reversed in the case of an air inversion, where the temperature increases with altitude. The lapse rate may be expressed as a wet and a dry lapse rate and using either the metric or English system.

8.5 Vertical Structure of the Atmosphere

The Earth is a layered planet. The atmosphere is layered, there are layers in the Earth's crust, and there are layers below the crust until one arrives at the center of the Earth.

The atmosphere may be thought of as a column of air (Fig. 8.5). It consists of (from bottom to top) the troposphere, stratosphere, mesosphere, thermosphere, exosphere, and magnetosphere (not shown in Figs. 8.5 or 8.6). Each layer has its own set of characteristics and is described below. Each layer grades into the adjacent layer.

The troposphere is the layer where most clouds and weather occur. There are some clouds that form in the stratosphere but their effect on weather is minimal.

The troposphere and stratosphere are separated by the tropopause. The stratosphere and mesosphere are separated by the stratopause. The mesosphere and thermosphere are separated by the mesopause.

The tropopause is the area of the atmosphere where the temperature stops cooling and starts warming. It is a temperature gradient, as are the other layers of the atmosphere, and one layer grades into the other. The tropopause varies in height depending on its latitude as can be seen in Fig. 8.4.

The mesopause is the coldest place on Earth with temperatures as low as −100°C (−146°F or 173 K). The altitude of the mesopause for many years was assumed to be at around 85 km, but observations to higher altitudes and modeling studies in the last few years (since the year 2000) have shown that in fact the mesopause consists of two temperature minima; one at about 85 km and a stronger minimum at about 100 km in elevation above Earth's surface (Fig. 8.5).

The ozone layer is in the lower part of the stratosphere (Fig. 8.6) and filters out enough ultraviolet radiation from Sunlight to protect animal and plant life living at Earth's surface.

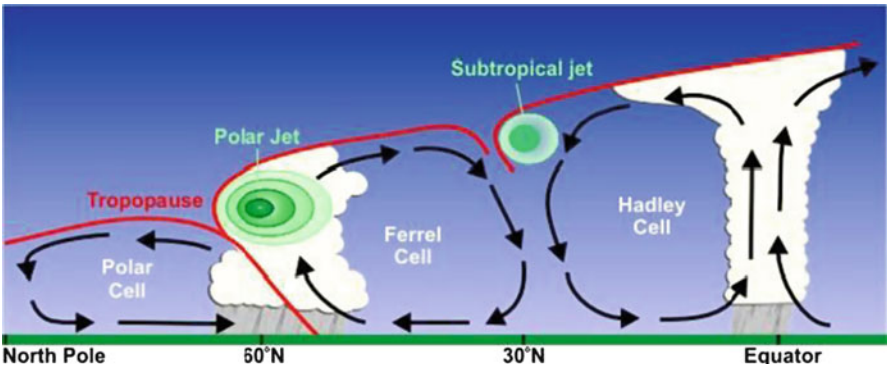


Fig. 8.4 The tropopause varies in elevation within the atmosphere being higher at the Equator and lower at the poles (NOAA, Public Domain)

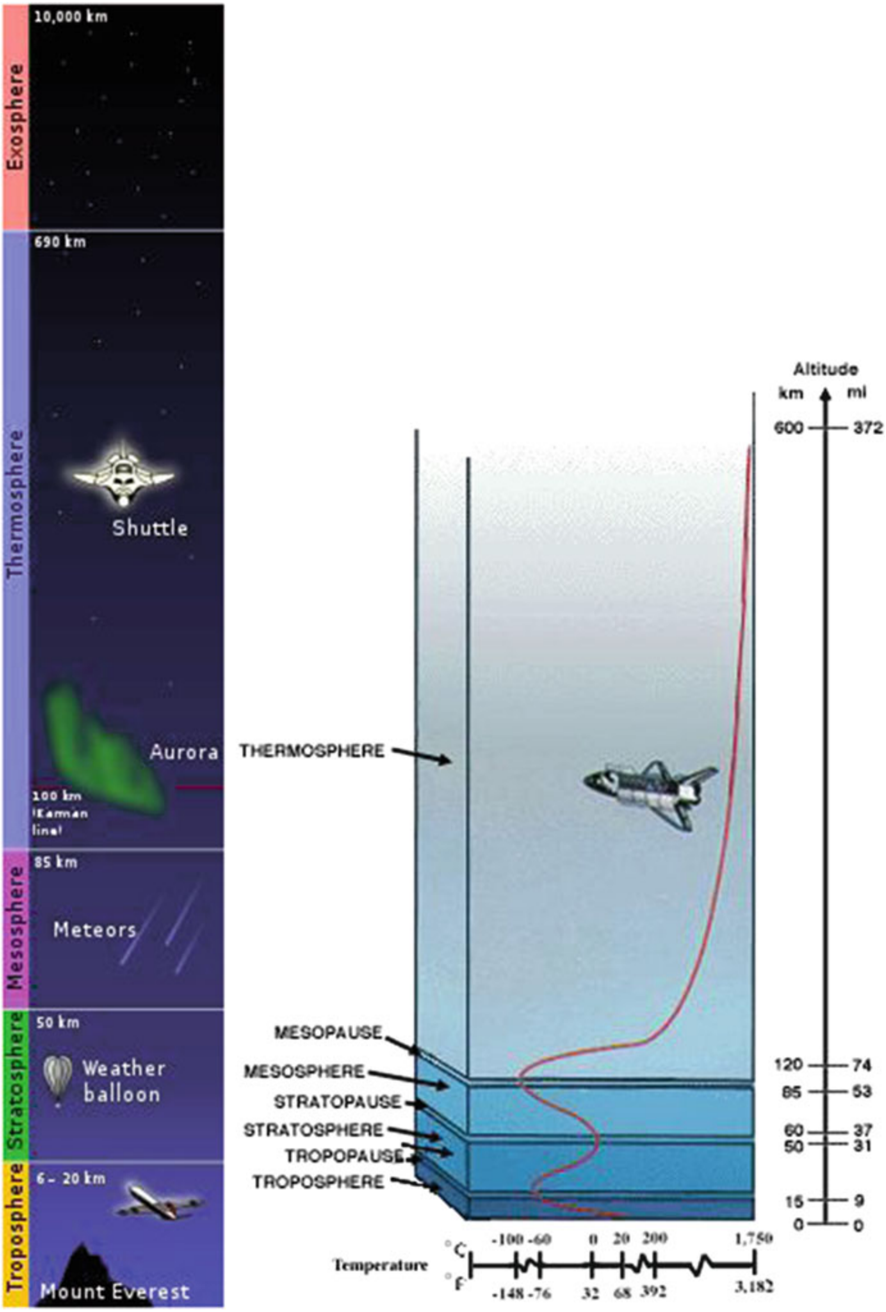


Fig. 8.5 Vertical slice through the Earth's atmosphere, not to scale, showing the five main layers and the tropopause, stratopause, and mesopause (From NASA, Public Domain)

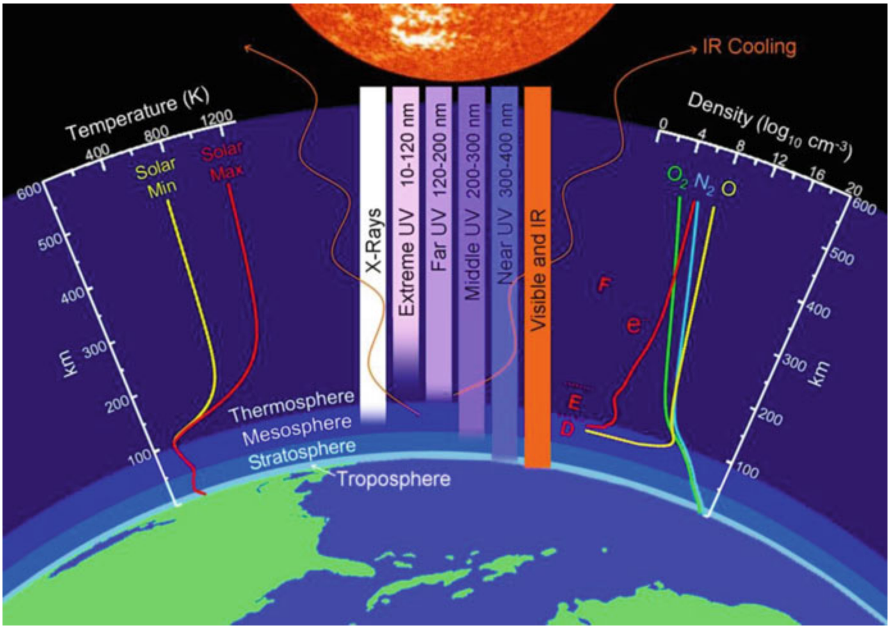


Fig. 8.6 Layers of Earth's upper atmosphere showing the penetrations of X-rays, UV rays, visible and IR radiation, temperature and density variations in the different layers (Credit: John Emmert/NRL, NASA, Public Domain)

The tropopause has been rising in altitude for the past several decades due to global warming. As the troposphere warms and the air expands, the tropopause rises.

The atmosphere's lowest or bottom layer, the layer in contact with the Earth, is the troposphere. The troposphere is the layer where weather occurs and it extends from the Earth's surface to about 20 km in height.

The troposphere has a temperature gradient, warmer at its base and cooler at its top. The base of the troposphere is getting warmer and this warmer air is increasing vertically. The temperature gradient from top to bottom in the troposphere is lessening. Greenhouse gases are keeping the troposphere warm at the base. The Sun's rays impact the Earth's surface and warm it. This in turn, along with heat radiation from greenhouse gases, further warms the lower atmosphere.

Above the troposphere is the stratosphere. The stratosphere extends above the troposphere for about 30 km, to a height of around 50 km. Jet planes fly in the stratosphere and temperature increases near the top because it's warmed by the Sun. The ozone layer is contained within the lower part of the stratosphere and absorbs harmful ultraviolet rays from the Sun. Ultraviolet (UV) rays are known to cause skin cancer and have other undesirable impacts on humans and other species.

Chemical composition in the stratosphere changes dramatically due to the ozone layer, but is otherwise rather consistent throughout. Ozone molecules are being destroyed at the South Pole causing the layer to become so thin that scientists call it a "hole."

The ozone layer is thinning due to destruction by atoms of chlorine and bromine. The main source of these chemicals is transportation through the atmosphere of freons and halons, totally anthropogenic and emitted from Earth's surface by humans. These substances are commonly referred to as ozone-depleting substances (ODSs). As emissions of these substances increase, the ozone depletion increases.

Above the stratosphere is the mesosphere, which extends from about 50 km to about 85 km within which temperatures decrease upward again. The coldest parts of the atmosphere occur in the mesosphere and may reach −100°C.

Above the mesosphere lies the thermosphere, which is a thick layer and extends to about 690 km. In the thermosphere the air is thin and is very sensitive to solar activity. As one goes up in the thermosphere, temperatures increase. Astronauts in the International Space Station orbit the Earth in this layer and the Space Shuttle flies into this layer. The thermosphere may heat to 1,500°C due to incoming solar radiation.

Recently (July 2011), the thermosphere has undergone a contraction which is causing some concern among atmospheric and climate change scientists. The thermosphere, which blocks harmful ultraviolet rays, expands and contracts regularly due to the Sun's activities. Since 2007, the Sun has been in a period of solar activity known as a solar minimum and sunspots have been a rarity. The contraction happened during the deep solar minimum of 2008–2009, a fact which comes as little surprise to researchers. The thermosphere always cools and contracts when solar activity is low. In this case, however, the magnitude of the collapse was two to three times greater than low solar activity could explain, and scientists have so far been unable to explain it completely.

Figure 8.6 shows the penetration of various types of radiation passing through various atmospheric layers and those absorbed by the Earth's atmosphere, as well as variations in density and temperature in the atmosphere.

8.6 Atmospheric Circulation

Wind is defined simply as moving air. Wind on the Earth is caused by different atmospheric pressure or by air being moved by convection. Convection moves air vertically and in a circular motion, up and down, as opposed to laterally from Equator to pole.

The lower part of the atmosphere is sometimes referred to as the planetary boundary layer (PBL) where it is influenced by its contact with the Earth's surface (Fig. 8.7). It is in this layer that most turbulence occurs and vertical mixing is greatest. Above the PBL, the wind is approximately parallel to the isobars of a weather or barometric map and the winds are said to be geostrophic. Within the PBL the wind is affected by surface drag and flows across the isobars.

In Fig. 8.8, typical development of a thunderstorm is shown. Cumulous clouds develop from convection as hot moist air rises from the Earth's surface to higher and higher elevations. As the cumulus clouds grow larger, there is air circulation within them and the moist air eventually chills and precipitates as rainfall in a thunderstorm. Three stages in the development of a thunderstorm are shown in Fig. 8.8; (1) a towering cumulus stage, (2) a mature stage, and (3) the dissipating stage.

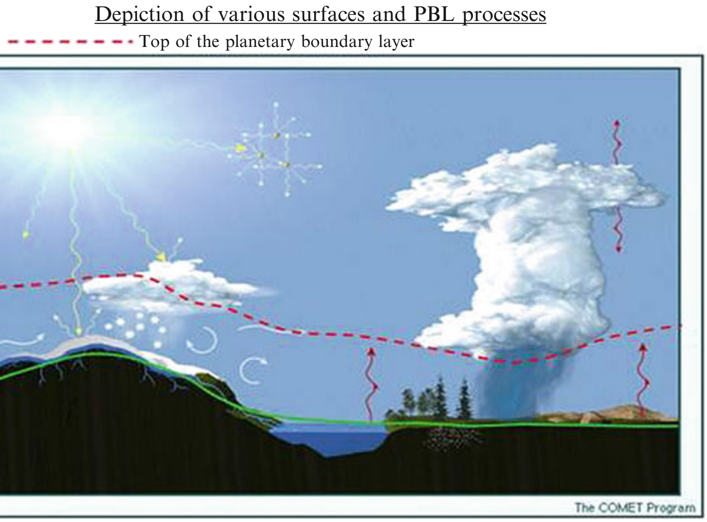


Fig. 8.7 The vertical movement of air within the lower part of the atmosphere. Depiction of where the planetary boundary layer (PBL) lies on a sunny day (*red dashed line* represents the top of the PBL; *arrows* represent direction of air movement) (NOAA, Public Domain)

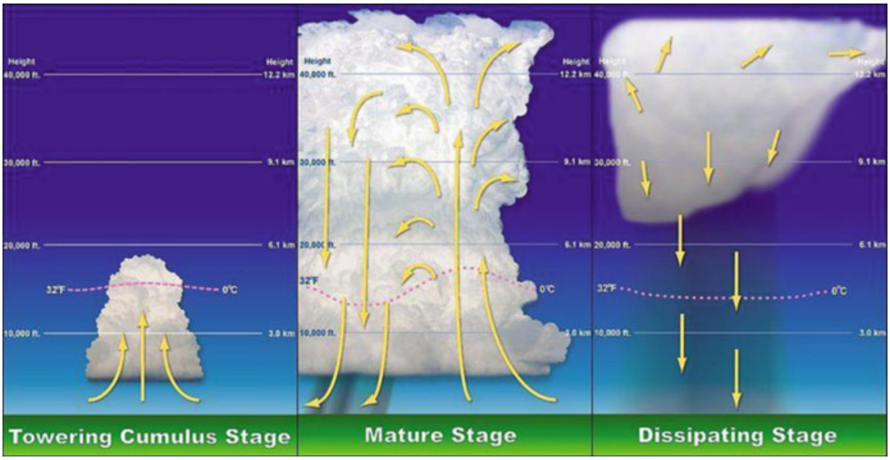


Fig. 8.8 The formation and dissipation of a thunderstorm (From NOAA, Public Domain)

Air moves from high pressure areas to areas of low pressure. Barometric pressure is the weight of a column of air, or atmospheric pressure. On weather maps, high and low pressure areas are marked "H" and "L" respectively and contour lines connecting points of equal barometric pressure (isobars) are drawn. If these isobars are close together, wind is stronger; further apart, the wind is not as strong.

Global warming has caused the troposphere to warm and a warming troposphere, where the majority of weather occurs, means more moisture and more energy for

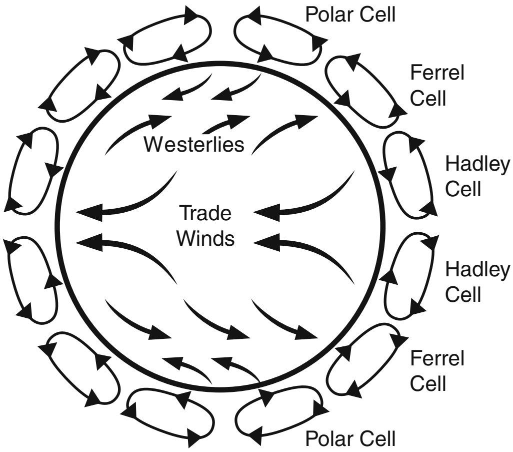


Fig. 8.9 Global circulation of Earth's atmosphere displaying Hadley cell, Ferrell cell and Polar cell (Redrawn by John Cook from NASA, Public Domain)

storms to develop. The atmosphere in 2012 holds about 4% more moisture than it did before the middle of the last century. Warmer air holds more moisture than colder air and this moisture has to fall somewhere. Therefore there is more uncertainty in the weather patterns that develop; more storms in some areas, more wind shear and more tornadoes, more droughts in some areas, more heat waves, etc.

Global warming is also affecting the Jet Stream, a river of air which flows aloft and meanders like a river on land. It circles the Earth in the northern latitudes. As the Arctic region warms and there is less sea ice formed, more heat energy is released to the atmosphere in the Arctic.

The Jet Stream separates the cold air of the Arctic north of the Jet Stream from warm air south of the Jet Stream. As the Arctic warms and there is less temperature difference on both sides of the Jet Stream, the air movement slows and its meanders become larger. There are larger loops in its course. A large southern loop causes cold air to move south; a larger northern loop causes warm air to move north.

The Sun heats the ground or ocean surface most intensely in tropical areas. The heated air rises, and as it rises, it cools; and as it cools it loses its moisture as rain or snow, depending on the temperature. This belt of converging air masses, called the doldrums due to low air and water circulation sometimes causing sailing ships to struggle to escape the region, includes some of the rainiest areas on Earth. The cooled, now drier air is forced by continuously rising air to move out of the way, and so it moves towards the temperate latitudes. Air moves by convection from tropical to temperate to Polar Regions. Air also moves laterally by differences in pressure.

Such air from the tropics meets air moving down from the poles at about 30°N and °S, called the horse latitudes, where it settles. Here the sinking air compresses, warms, and absorbs moisture from the surface. This is why the major desert belts of Earth lie in the horse latitudes. This warm, dry air is displaced by more sinking air and so some of it returns back to the Equatorial zone, and some returns to the poles. Such cycling air between low and mid-latitudes defines a Hadley Cell (see Fig. 8.9).

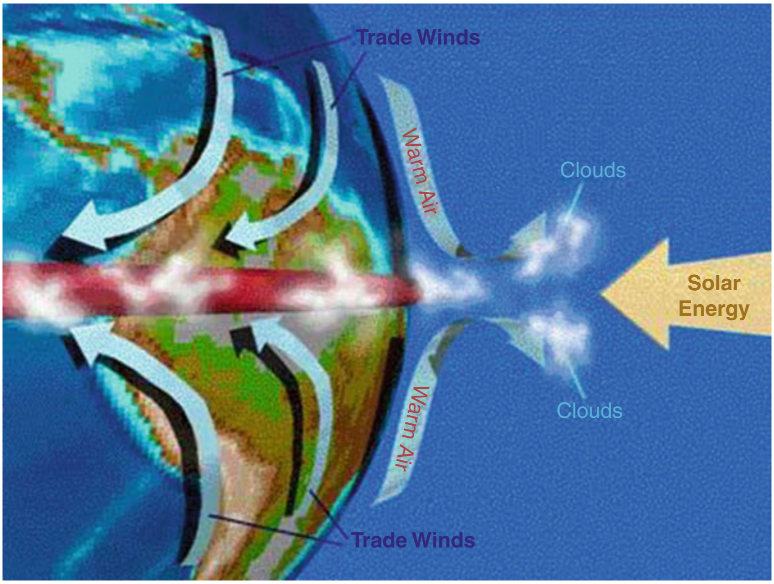


Fig. 8.10 Solar energy causing the circulation of the atmosphere (NASA, Public Domain)

A similar cell forms between the horse latitudes and the stormy polar fronts at 60°N and 60°S, where warm temperate air moving toward the poles meets very cold air rolling down from the poles. The lighter warm air is forced to rise over the denser cold air, which chills it and forces precipitation. From this polar front, air returns both toward the Equator and toward the poles. Air immediately over the pole sinks. While it is not warm, it is extremely dry (only centimeters of snow every year). From the poles, air within the polar cap streams back towards the polar front.

Thus, six belt-like Hadley Cells circulate air from pole to pole and establish patterns of climate over the planet. The cells are also characterized by specific patterns of wind flow, a function of the Coriolis force generated by the spin of the Earth. In the temperate zone between the horse latitudes and the polar front, the prevailing westerlies dominate air circulation. In the tropics, the easterly trade winds dominate. Winds around the poles are also easterly. Winds are named from the directions from which they come; therefore, easterlies come from the east, westerlies from the west.

The Ferrel Cell is a secondary circulation feature dependent for its existence upon the Hadley cell and the Polar cell. The Ferrel Cell behaves as an atmospheric "ball bearing" between the Hadley cell and the Polar cell, and comes about as a result of the eddy circulations (the high and low pressure areas) of the mid-latitudes. For this reason it is sometimes known as the "zone of mixing." At its southern extent (in the Northern Hemisphere), it overrides the Hadley cell, and at its northern extent, it overrides the Polar cell. Just as the Trade Winds (Figs. 8.9 and 8.10) are to be found below the Hadley cell, the Westerlies

Fig. 8.11 Dunes of Maspalomas in Gran Canaria, one of the Canary Islands (Public Domain)

can be found beneath the Ferrel cell. Thus, strong high pressure areas which divert the prevailing westerlies, such as a Siberian high (which could be considered an extension of the Arctic high), could be said to override the Ferrel cell, making it discontinuous.

One result of wind activity is that it carries small particles; especially in areas where the land surface consists of loose materials. Moving air is able to pick up loose particles, such as sand and dust, and transport them until there is a loss of wind velocity. It then deposits these particles, sometimes in various sand deposits known as sand dunes (Fig. 8.11). Deposits of finer materials like dust are left on the windward side of obstructions or simply scattered across the landscape.

Additional Readings

Ahrens, C. D. (2005). *Essentials of meteorology*. Belmont: Thomson/Brooks/Cole.

Danielson, L., & Abrams, E. (2003). *Meteorology*. New York: McGraw Hill. ISBN: 0073659630, 9780073659633

Sanchez-Lavega, A. (2010). *An introduction to planetary atmospheres*. Boca Raton: Taylor & Francis. ISBN 978-142-006-732-3.

Seinfeld, J. H., & Pandis, S. N. (2006). *Atmospheric chemistry and physics: From air pollution to climate change* (2nd ed.). Hoboken: Wiley.

Volk, T. (2008). *CO2 rising: The world's greatest environmental challenge* (223 pp). Cambridge: The MIT Press. ISBN 978-0-262-22083-5.

Chapter 9
Carbon Dioxide, Other Greenhouse Gases, and the Carbon Cycle

Abstract The physical and chemical properties of carbon dioxide are essential for the existence of humankind on Earth because of its role in the greenhouse effect. Water vapor, methane, and nitrous oxide are also important greenhouse gases as they help keep the planet warm. The carbon cycle is important for life on Earth because life is carbon based. An illustration in this chapter shows how carbon moves through the environment. Sources and sinks of several of the greenhouse gases are discussed. The ozone hole is discussed with its ramifications for causing harm to life forms. Global Warming Potentials (GWPs) are defined relative to CO_2. Other greenhouse gases are discussed.

Keywords Halocarbons • Methane • IPCC • Dry ice • Keeling • GtC • Dry ice • ENSO • GWP • TOA • Carbon • Cycle • GPP • SAR • ESRL • Gigatonne • Source • Sink • Clathrate • Disequilibrium • Ice core • Montreal Protocol • Nitrous • Oxide • Oxidation • Reduction

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_9,

Things to Know	
0.040%	IPCC
Halocarbons	Hydroxyl Radical
Laughing Gas	2.36 ppm
1991 Eruption	SAR
Clathrate Gun Hypothesis	CO_2
Nitrous Oxide GWP	Sinks of Methane
Nitric Oxide	Mt. Pinatubo
GtC	IR
GWP	Carbon Dioxide
CFCs	Carbon Cycle
Dry Ice	ENSO
Keeling Curve	Global Warming Potential
Sinks of Carbon Dioxide	UV
Sources of Carbon Dioxide	CH_4
Reservoir Sizes of Carbon Dioxide in GtC per Year	Sources of Methane
−109.3°F	Greenhouse Gases
Ozone Hole	350 ppm or Less
Carbon Dioxide Trends in the Atmosphere	TAR
Carbon Cycle Equilibrium	1.9 ppm per Year

9.1 Introduction

Greenhouse gases remained in fairly constant concentrations until the Industrial Revolution beginning around the middle of the eighteenth century. Beginning in the mid-1700s these gases, carbon dioxide, methane, and nitrous oxide show a constantly increasing concentration in the atmosphere accelerating in the later twentieth and early twenty-first centuries. There is little doubt that these increases are mainly derived from humankind's burning of fossil fuels. The illustration below (Fig. 9.1) shows that the atmospheric concentrations of three greenhouse gases were relatively stable in the atmosphere until the eighteenth century when they began to increase rapidly in concentration.

9.2 Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) is an extremely important greenhouse gas as we've seen in earlier sections of this text, especially in Chap. 8. Carbon dioxide is a greenhouse gas that transmits visible light but absorbs strongly in the infrared and near-infrared, before slowly re-emitting the infrared at the same wavelength as that which was absorbed. It is a very small percentage of the total atmosphere (0.040%) and because of this it is difficult for some to recognize its importance as a major heat-trapping substance.

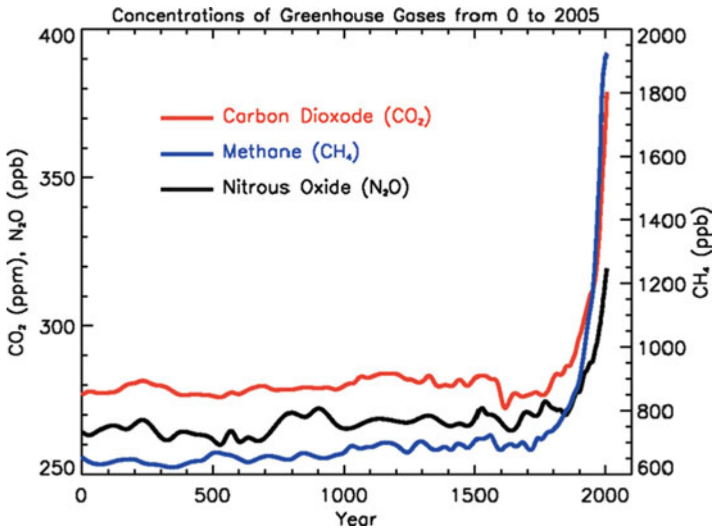


Fig. 9.1 Atmospheric concentrations of important long-lived greenhouse gases over the last 2,000 years. Increases since about 1750 are attributed to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion air molecules, respectively, in an atmospheric sample (From IPCC AR4 2007)

Carbon dioxide and water vapor are the two most important greenhouse gases as they readily block infrared (IR) radiation from escaping to the stratosphere and outer space. This heat energy is what keeps the Earth warm enough for life to exist and thrive. How do these compounds accomplish this? Let's look at carbon dioxide first.

One way to look at how greenhouse gases work in the atmosphere is to consider an analogy to the way an automobile's interior heats rapidly in sunlight. Glass acts as an absorber of both UV and IR waves. One can sit in an enclosed car in the sunlight and not get sunburned because of the absorption of UV rays by the windshield and windows in the car. One sitting in the car can also realize the rapid heating of the car's interior due to the blocking of the IR rays from escaping the enclosed interior of the car and keeping the heat inside. The windshield and windows act in a manner similar to greenhouse gases, allowing the UV rays to pass through them. Greenhouse gases trap heat inside the atmosphere as the glass traps heat inside the car. Visible light is let in but heat energy remains in the car. Greenhouse gases allow visible light in but block the flow of heat from escaping into space.

Carbon dioxide consists of three atoms, two of oxygen and one of carbon (CO_2). The atoms are held together by covalent bonds, that is, by a sharing of electrons. This allows the CO_2 molecule to vibrate in all three dimensions when agitated. Infrared radiation agitates the CO_2 molecule causing it to vibrate and absorb heat, then to re-radiate it in all directions as well as back to Earth's surface. This ability to absorb and then re-radiate heat is what makes the molecules of CO_2 and H_2O be effective greenhouse gases.

Carbon dioxide forms “dry ice” at −109.3°F. “Dry ice” is used to cool substances such as food and drinks in coolers but should not be used by humans in enclosed spaces. Carbon dioxide, like carbon monoxide, is denser than air and will displace the air in one’s lungs in a matter of a few hours in an enclosed air-tight space and cause suffocation and death.

During the last 250 years or so the absolute growth rate of CO_2 in the atmosphere has increased substantially; the first 50 ppm increase above the pre-industrial value was reached in the 1970s after more than 200 years, whereas the second 50 ppm was achieved in about 30 years. In the 10 years from 1995 to 2005 atmospheric CO_2 increased by about 19 ppm; the highest average growth rate recorded for any decade since direct atmospheric CO_2 measurements began in the 1950s. The average rate of increase in CO_2 determined by these direct instrumental measurements over the period 1960–2005 is 1.4 ppm per year. The rate of increase of carbon dioxide in the atmosphere in June 2012 stands at about 2 ppm per year.

The 2005 rate of increase of carbon dioxide in the atmosphere was 2.14 ppm year. The rate of increase is not steady from one year to the next but it is averaging around 2 ppm per year over the past several decades. For example, the Pinatubo volcanic eruption of 1991 slowed the increase for a few years. The massive release of sulfur dioxide during the eruption caused an increase in cloud cover which in turn resulted in cooling which then increased the dissolving of carbon dioxide in sea water. The resulting slight pause beginning in 1992 is visible in the Keeling Curve. The pause in the Keeling curve was canceled by an acceleration of CO_2 emissions in the next decade.

The Southern Oscillation also known as the El Niño-La Niña (ENSO) cycle also seems to have an effect on CO_2 levels in the atmosphere. The general trend, however, is unmistakable. The CO_2 concentration is increasing in the atmosphere and has been increasing for some time. And the rate of addition of carbon dioxide in the atmosphere is increasing.

The illustration shown in Chap. 4 in Fig. 4.4 is the solar radiation spectrum measured at the top of the atmosphere (TOA) and at sea level. Note the strong absorption bands for H_2O, CO_2, and O_3. Water vapor and ozone are compounds that absorb energy from the Sun as it passes through the atmosphere and also as it radiates back from the Earth’s surface. Carbon dioxide absorbs energy as it radiates back from the Earth’s surface.

9.2.1 The Keeling Curve

The Keeling Curve was introduced in the Introduction and is shown in Fig. 8.3. It illustrates the increase in atmospheric carbon dioxide from 1958 to the present (June 2012 at 396 ppm). Close examination of the curve will detect a dip in the curve beginning in 1992 as a result of the volcanic ash from the eruption of Mt. Pinatubo found its way to the stratosphere and resulted in a cooling of the planet for a couple

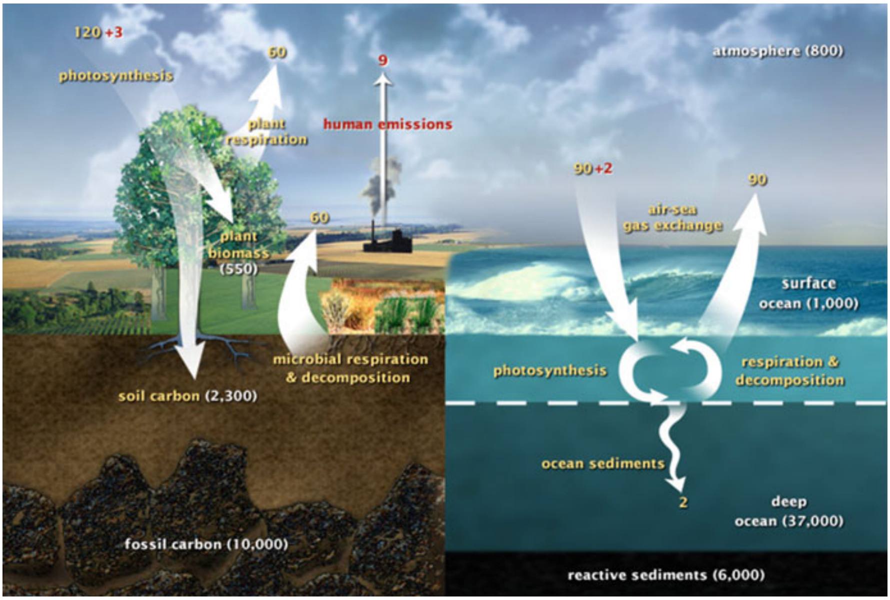


Fig. 9.2 The global carbon cycle showing the main annual fluxes in GtC year–1: pre-industrial 'natural' fluxes in *yellow* and 'anthropogenic' fluxes in *red* (Modified from Sarmiento and Gruber 2006, with changes in pool sizes from Sabine et al. 2004). The diagram of the carbon cycle shows the movement of carbon between land, atmosphere, and oceans in billions of tons of carbon per year. *Yellow* numbers are natural fluxes, *red* are human contributions in gigatonnes of carbon per year. *White* numbers indicate stored carbon (Based on IPCC AR4, WG1 Figure 8.3 by DOE and http://www.gfdl.noaa.gov/anthropogenic-carbon-cycle)

of years; again illustrating the correlation between Earth's temperature and carbon dioxide concentration in the atmosphere.

The curve shown in Fig. 8.3, as we saw in Chap. 8, was begun by C. David Keeling in 1958 at the Mauna Loa Observatory in Hawaii and is the longest continuous measurement of CO_2 in existence. Prior to Keeling's work, the correlation between rising carbon dioxide in the atmosphere and rising global temperature was not obvious. In fact, the rising carbon dioxide concentration in the atmosphere had been suspected due to the burning of fossil fuels, but it had not been scientifically documented, prior to the measurements by Keeling.

9.3 The Carbon Cycle

Carbon dioxide is an important link in the carbon cycle. The cycle is illustrated in Fig. 9.2.

The carbon cycle involves the movement of carbon through the Earth system pathways as follows:

- The atmosphere;
- The terrestrial biosphere, which is defined to include fresh water systems and non-living organic material, such as carbon in soil;
- The World Ocean, including dissolved inorganic carbon and living and non-living marine biota;
- The sediments including fossil fuels; and
- The Earth's interior, carbon from the Earth's mantle and rocks of the crust released to the atmosphere and hydrosphere by volcanoes and geothermal systems.

9.4 Carbon Dioxide and the Carbon Cycle

Carbon dioxide is part of the carbon cycle and as such should be in dynamic equilibrium with other things in the cycle, but it is not. There is an excess of carbon dioxide in the atmosphere as has been seen before in this text.

Figure 9.2 shows the carbon cycle with units of carbon in gigatonnes (1 gigatonne = 1 billion tonnes; GtC = gigatonnes of carbon). By far, the intermediate and deep ocean is the largest bank or reservoir of carbon on Earth, estimated at exceeding 37,000 gigatonnes of carbon in storage.

9.5 Sources and Sinks of Carbon Dioxide

Sources of carbon dioxide are such things as volcanoes, fumaroles, geysers, the burning of fossil fuels, conversion of methane, etc. Sinks of carbon dioxide are storage or areas that take up carbon dioxide such as the ocean, sediments, etc.

The movement of carbon, in its many forms, between the biosphere, atmosphere, oceans, and geosphere is described by the carbon cycle, illustrated in the diagram (Fig. 9.2). The carbon cycle is just one of the biogeochemical cycles but a very important one for life on the planet. Life on Earth of course is carbon based.

In Fig. 9.2, the natural or unperturbed exchanges (estimated to be those prior to 1750) among oceans, atmosphere and land are shown by the black numbers. The gross natural fluxes between the terrestrial biosphere and the atmosphere and between the oceans and the atmosphere are about 120 and 90 gigatonnes per year, respectively. Less than 1 gigatonne per year of carbon is transported from the land to the oceans via rivers either dissolved or as suspended particles. While these fluxes vary from year to year, they are approximately in balance when averaged over longer time periods. Additional small natural fluxes that are important on longer geologic time scales include conversion of organic matter from terrestrial plants into inert organic carbon in soils, rock weathering and sediment accumulation, and release from volcanic activity. The net fluxes in the 10,000 years prior to 1750, when averaged over decades or longer, are assumed to have been less than about 0.1 GtC per year.

Carbon dioxide has been increasing in the atmosphere at an ever increasing rate. The annual growth rate of atmospheric CO_2 was 2.36 ppm in 2010, one of the largest growth rates in the past decade. The average for the decade 2000–2009 was 1.9 ppm per year, 1.5 ppm for the decade 1990–1999, and 1.6 ppm for the decade 1980–1989. The 2010 increase brought the atmospheric CO_2 concentration to 396 ppm, 41% above the concentration at the start of the Industrial Revolution (about 280 ppm in 1750). The present concentration (400 ppm in June 2012) is the highest during at least the last 800,000 years and possibly in millions of years.

There is a difference in emitting carbon to the environment (in gigatonnes) and carbon dioxide (in gigatonnes) to the atmosphere and it is necessary to keep the two separate. In 2008, 8.67 gigatonnes of carbon were released from fossil fuels worldwide, compared to 6.14 gigatonnes in 1990. In addition, land use change contributed 1.20 gigatonnes in 2008, compared to 1.64 gigatonnes in 1990.

In the period 1751–1900 about 12 gigatonnes of carbon were released as carbon dioxide to the atmosphere from burning of fossil fuels, whereas from 1901 to 2008 the figure was about 334 gigatonnes. Humankind causes the emission of at least 30 gigatonnes of CO_2 per year to the atmosphere with 31.6 gigatonnes added to the atmosphere in 2011, according to the International Energy Agency (IEA).

Accumulation of atmospheric CO_2 is the most accurately measured quantity in the global carbon budget with an uncertainty of only about 4%. The estimated uncertainty in the global annual mean growth rate is about 0.1 ppm per year. The data are provided by the U.S. National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA/ESRL) and include early data from the Scripps Institution of Oceanography (SIO).

Carbon is stored in Earth materials such as carbonates (limestone, dolostone, and chalk) and silicate rocks, as sediments, in the oceans, soils, vegetation, and in fossil fuels such as coal, natural gas, and petroleum products. When these materials break down as the result of chemical weathering, carbon is released to the environment, to the atmosphere, and the ocean.

The carbon cycle is one of the biogeochemical cycles. Carbon moves through the carbon cycle as follows:

- From the atmosphere to vegetation which uses CO_2 in photosynthesis to produce oxygen and water;
- From plants to soils and sediments;
- From fossil fuels to the atmosphere;
- From the atmosphere to the ocean;
- From the ocean to the atmosphere;
- From the surface of the ocean to deeper parts of the ocean;
- From animals to the atmosphere;
- From vegetation to animals;
- From chemical weathering (dissolution) to the ocean;
- From the burning of fossil fuels to the atmosphere and ocean.

Most of the carbon at present is moving from fossil fuels to the atmosphere and ocean and this has upset the natural equilibrium of the carbon cycle. Humans have

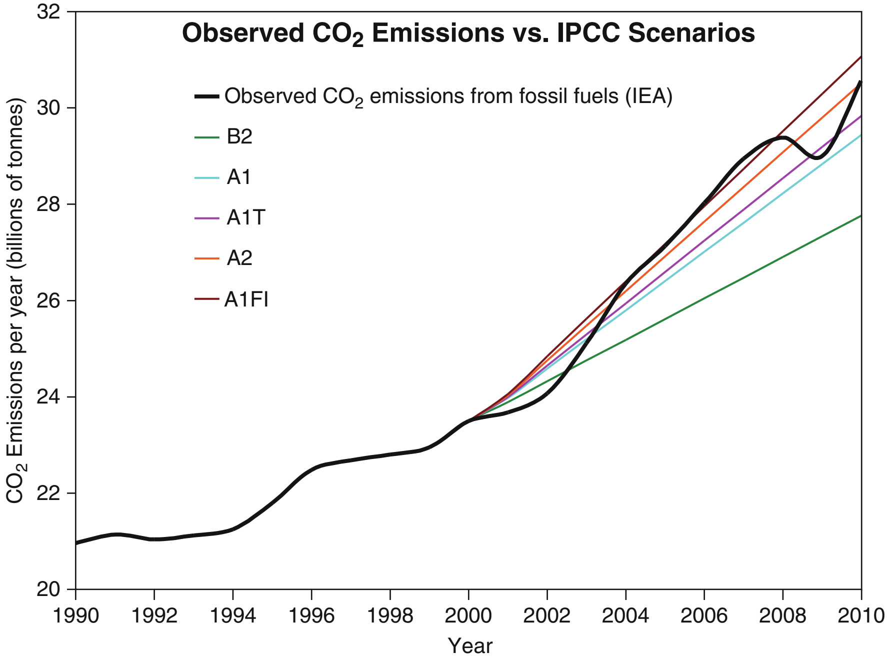


Fig. 9.3 U.S. Energy Information Administration (EIA) global human CO_2 annual emissions from fossil fuels estimates vs. IPCC SRES scenario projections. The IPCC Scenarios are based on observed CO_2 emissions until 2000, at which point the projections take effect

been altering the atmospheric parts of the carbon cycle by cutting down trees, raising crops, and burning fossil fuels. After thousands of years of equilibrium, the addition of carbon to the atmosphere and oceans by humans has upset this natural state so that we now have a major excess of carbon throughout the ecosystems of the planet.

Over the long term, the carbon cycle has seemed to maintain a balance that has prevented all of Earth's carbon from entering the atmosphere, as it does in the case of Venus, or from being stored entirely in rocks. This balance helps keep Earth's temperature relatively stable, like a thermostat until the thermostat is changed (Fig. 9.3).

This thermostat works over a few hundred thousand years, as part of a slow carbon cycle. This means that for shorter time periods, tens to a hundred thousand years, the temperature of Earth can vary. And, in fact, Earth swings between ice ages and warmer interglacial periods on these time scales. Parts of the carbon cycle may even amplify the long-term temperature changes.

On very long time scales (millions to tens of millions of years), the movement of tectonic plates and changes in the rate at which carbon seeps from the Earth's interior may change the temperature on the Earth thermostat. Earth has undergone such a change over the last 65 million years, from the extremely warm climates of the Cretaceous (roughly 145–65.5 million years ago) to the glacial climates of the Pleistocene (roughly 1.8 million to 11,500 years ago; see the Geologic Time Scale in Appendix I).

At the ocean surface, where air meets water, carbon dioxide gas goes in and out of the ocean in a steady exchange with the atmosphere. Once in the ocean, carbon dioxide gas reacts with water molecules to release hydrogen, making the ocean more acidic. The hydrogen reacts with carbonate from rock weathering to produce bicarbonate ions. Many organisms living in ocean waters use calcium carbonate to build their shells and skeletons while others use silica and vertebrates use tricalcium phosphate to build bones and teeth.

9.5.1 Sources of Atmospheric Carbon Dioxide

The vast majority of atmospheric carbon dioxide is from the burning of fossil fuels by humans for heat and electricity, the internal combustion engine which uses a derivative of fossil fuel (gasoline), the making of cement, and the conversion of methane coming from shallow seas and the melting of permafrost, in addition to some of the sources listed above. Volcanoes also emit carbon dioxide to the atmosphere but in much fewer quantities than does humankind. The latter (humankind) emits over 100 times the amount of the former (volcanoes).

Sources of atmospheric CO_2 can be divided into natural and anthropogenic. Natural CO_2 includes that from animals, the ocean surface, and volcanoes.

Anthropogenic sources include the burning of fossil fuels (power stations and transportation), cement production, and land-use changes (principally deforestation).

Methane is converted to carbon dioxide in the atmosphere by a simple chemical reaction:

$$\mathrm{CH_4 + O_2 = CO_2 + H_4}\hat{}$$

$\mathrm{H_4}$ is a gas and is driven off.

9.5.2 Oxidation – Reduction of Carbon

Carbon dioxide (CO_2) is a product of the oxidation of carbon. Methane (CH_4) is an example of reduction in the state of carbon. Pure carbon (C) exists by itself in nature in only two minerals, diamond and graphite. Graphite is what is used as “lead” in pencils which is not lead (Pb) at all.

Carbon occurs in nature in many different natural substances such as coal, oil, natural gas, and the minerals calcite, aragonite, and dolomite. Calcite and dolomite are major rock-forming minerals (limestone and dolostone, respectively) and aragonite occurs as “mother of pearl” on the inside of certain sea shells.

The majority of carbon is stored in the Earth in the form of carbonates. Carbonates cannot be used as fuel because the carbon is bound up in the rocks and is inaccessible. Other sources of carbon that can be used as fuel are coal, oil (petroleum), and natural gas.

9.5.3 Sinks of Atmospheric Carbon Dioxide

Carbon dioxide readily dissolves in water, and the oceans provide a huge reservoir of carbon. Across the World Ocean there is a continual cycle of equilibration of dissolved carbon dioxide in water with carbon dioxide in the atmosphere. According to the Second Law of Thermodynamics, if ocean water is cooler than the air above it, CO_2 will dissolve into the ocean along with the heat exchange and become a sink for the greenhouse gas. Where the air over the ocean is cooler than the water, ocean water will give up heat as well as CO_2 to the atmosphere and become a source of the greenhouse gas. The physics of the ocean-atmosphere exchange of CO_2 is not quite that simple because of the partial pressure of the gases in the two media.

The partial pressure of a gas is a measure of thermodynamic activity of the gas’s molecules. Gases will always flow from a region of higher partial pressure to one of lower pressure; the larger this difference, the faster the flow. Gases dissolve, diffuse, and react according to their partial pressures, and not according to their concentrations in gas mixtures or liquids.

Around 88,000 million tonnes of carbon is released from the surface of the world’s oceans each year, with an annual uptake by the oceans of 90,000 million tonnes. Consequently, the net uptake of carbon dioxide by oceans is estimated to be approximately 2,000 million tonnes annually.

Chemists and chemical oceanographers tell us that the carbon dioxide which dissolves in our oceans occurs in three main forms. Aside from the normal carbon dioxide form, it is also found as bicarbonate and carbonate ions. Most, about 90% exists as bicarbonate with carbonate ions acting as the link between carbon dioxide and bicarbonate. As concentrations of carbon dioxide increase, the supply of carbonate ions becomes limited and so the oceans become less and less able to take up carbon dioxide from the atmosphere.

The ocean currently acts as a sink for carbon dioxide. There is constant interchange between the ocean surface and the atmosphere. Photosynthesis by surface algae and diatoms provide a sink in addition to the interchange between ocean surface water and the atmosphere. Constant agitation by waves and ocean currents also cause CO_2 to escape the oceans.

The other major sinks of atmospheric CO_2 are sediments, soils, land vegetation and photosynthesis by land plants and ocean algae and diatoms.

9.5.4 Carbon Cycle Disequilibrium

If the amount of carbon emitted to the atmosphere equaled the amount of carbon being removed by sinks, the carbon cycle would be in equilibrium. But this is not the case and the carbon cycle is in disequilibrium primarily because more carbon is being released to the atmosphere than is being taken up by the carbon sinks. This excess carbon production in the atmosphere has been the case since the Industrial Revolution began and has been increasing since the beginning of fossil fuel burning. As a result of this loss of equilibrium, the Earth's temperature is rising.

It is assumed that prior to the Industrial Revolution the carbon fluxes into and out of the carbon cycle were equal. But after the Industrial Revolution began, more carbon has been emitted to the atmosphere and the CO_2 concentration in the atmosphere has dramatically increased. This disequilibrium has caused a perturbation in the climate system and the system is in the process of readjustment; this readjustment is resulting in the climate system warming.

As of June 30 of 2012, the carbon dioxide level in the atmosphere stood at 400 ppm as measured by the U.S. National Oceanic and Atmospheric Administration (NOAA). One year ago (in May of 2011), the CO_2 level stood at 393.06 ppm. The value 10 years ago on the above date was 373.93 ppm (see IPCC Emission Scenarios in Fig. 9.3).

If the current trend continues with the business-as-usual high emissions path, the consequences for the planet could be dire.

Some of the impacts listed in the IPCC 2007 AR4 report for global warming of 2–4.5°C above pre-industrial levels include:

- Hundreds of millions and possibly over a billion humans exposed to increased stress on water resources;
- 30–40% of species at risk of extinction around the globe;
- About 30% of global coastal wetlands lost. This may be much greater if the ice caps of Greenland and Antarctica collapse;
- Increased damage from floods and storms;
- Widespread coral reef mortality;
- Terrestrial and oceanic biospheres tend toward a net carbon source;
- Reduction in agricultural productions;
- Increased human morbidity and mortality from heat waves, floods, and droughts.

9.5.5 Restoring Carbon Cycle Equilibrium

Carbon dioxide stays in the atmosphere for hundreds or possibly as long as a thousand years. The atmosphere contains a reservoir of carbon dioxide which is being added to constantly as it has been since before the Industrial Revolution. If carbon dioxide could be reduced to the level that it was before humankind began adding it to the atmosphere and before the Industrial Revolution (~280 ppm), the system would return to a state of equilibrium if there was no future perturbation to the climate system. But the prospect of this happening during this century (the twenty-first) is not good. Even if all additions of CO_2 to the atmosphere stopped suddenly today there would still be warming for at least the next 30 years or so due to the residual CO_2 in the atmosphere.

It can be seen in Fig. 9.2 that by far the ocean is the largest reservoir of CO_2 on the planet. The solubility of carbon dioxide in ocean water is greater when the water is cold and less when it is warm. The solubility decreases as the ocean water warms and as the ocean warms it becomes a source of CO_2 rather than a sink. One of the dangers of global warming is that the oceans will begin to give up the tremendous amounts of stored CO_2 and this could happen rather suddenly. Climate change scientists know from geologic and ice core data that major climate changes have occurred rather suddenly in the past and this may have happened as a result of the ocean becoming a source of CO_2.

The release of CO_2 from ocean water is analogous to opening a warm carbonated soft drink. The ocean chemistry is more complex than that but the analogy is appropriate. Warm water gives up its CO_2 with release of pressure (opening the can or bottle, especially if shaken vigorously). This occurs in oceanic water when there is upwelling from the deep ocean, especially when one considers that the upwelling is from the cold deep water to the warmer oceanic surface water. Warmer water gives up CO_2 (a source) while colder water absorbs it (a sink).

The additional carbon dioxide in the atmosphere is causing additional warming. This is an example of a positive feedback loop. Carbon dioxide in the atmosphere causes the ocean to warm and the ocean gives up more carbon dioxide to the atmosphere which causes more warming, etc.

Restoring carbon dioxide equilibrium is not possible under the current circumstances of humankind's continuing to add an increasing amount of carbon dioxide and other greenhouse gases to the atmosphere as time passes. The disequilibrium in the carbon cycle will continue to grow and the planet will continue to warm as long as nothing changes in the disequilibrium equation. In order to stop or at least reduce the effects of global warming, atmospheric concentration of carbon dioxide must be reduced to 350 ppm or less, according to some of the world's leading scientists active in climate change science.

9.6 Methane (CH_4)

Methane (CH_4) is a greenhouse gas that remains in the atmosphere for approximately 9–15 years. It is approximately 25 times more effective in trapping heat in the atmosphere than carbon dioxide (CO_2) over a 100-year period and is emitted from a variety of natural and human-influenced sources. Human-influenced sources include landfills, natural gas extraction, animal flatulence, petroleum systems, agricultural activities especially the cultivation of rice, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial processes.

Methane is the primary constituent of natural gas and is an important energy source. As a result, efforts to utilize methane emissions can provide significant energy, economic and environmental benefits if precautions are made to prevent its escaping into the atmosphere and from exploding due to a spark.

9.6.1 Sources and Sinks of Atmospheric Methane

Methane is emitted to the atmosphere from both anthropogenic and natural sources. Human activities include the burning of fossil fuels, animal enteric fermentation, rice cultivation, biomass burning, and waste management. Natural sources of methane are wetlands, gas hydrates (methane clathrates) in ocean water, melting permafrost, termites releasing methane from woody tissue, the ocean, freshwater bodies, soils, coal, and wildfires. Accidental explosions related to the underground mining of coal are usually the result of explosions of methane gas.

Methane is a more powerful greenhouse gas than carbon dioxide, being about 25 times more effective in capturing and re-radiating infrared heat back to the Earth's surface.

Each greenhouse gas has a global warming potential (GWP) which is defined as follows: the GWP of a greenhouse gas is the ratio of heat trapped by one unit mass of the greenhouse gas to that of one unit mass of CO_2 over a specified time period. The global warming potential represents how much a given mass of a chemical contributes to global warming over a given time period compared to the same mass of carbon dioxide. Carbon dioxide's GWP is defined as 1.0.

As part of its scientific assessments of climate change, the Intergovernmental Panel on Climate Change (IPCC) has published reference values for GWPs of several greenhouse gases. While the most current estimates for GWPs are listed in the IPCC's Fourth Assessment Report, the U.S. EPA analyses use the 100-year GWPs listed in the IPCC's Second Assessment Report (SAR) to be consistent with the international standards under the United Nations Framework Convention on Climate Change (UNFCCC; IPCC 1996). According to the SAR, methane is 21 times more effective at trapping heat in the atmosphere when compared to CO_2 over a 100-year time period, so its GWP is 21.

Methane is more abundant in the Earth's atmosphere today than it has been in at least the last 400,000 years based on analyses of ice cores.

Methane in the atmosphere has increased as humans have continued to burn fossil fuels. Currently the amount of methane emitted to the atmosphere is greater than is being removed, so its concentration is increasing. The rate of growth of methane concentration in the atmosphere is comparable to that of carbon dioxide.

The greatest potential for massive releases of methane to the atmosphere is from methane clathrates in permafrost and shallow marine continental shelves, particularly in the Arctic. The shallow seas north of Canada and Siberia have already been seen to be releasing methane bubbles to the atmosphere. As these seas continue to warm, the release from these areas will become greater.

Scientists think that at least some of the major episodes of species extinctions in the geologic past have been as a result of relatively sudden methane releases, and this is a reason for concern. Is the Earth heading for another mass extinction? All we can conclude at present is that trends of temperature and bubbling methane releases are leading us in that direction.

Sudden releases of methane causing rapid global warming and feedbacks have been referred to as the "Clathrate Gun Hypothesis" and have been proposed as a cause of the relatively sudden onset of interglacial intervals during the Pleistocene.

The major sink for methane is the chemical reaction with hydroxyl radicals (OH-) in the atmosphere and the conversion to carbon dioxide. Other sinks of methane are stratospheric removal by hydroxyl radicals and consumption by microbial communities in the upper reaches of soils.

9.7 Nitrous Oxide

Nitrous oxide (N_2O) is a long-lived important greenhouse gas that is commonly known as "laughing gas" because of its use as an anesthetic in medical procedures. It has an atmospheric lifetime of 120 years and has a GWP of 310 over 100 years. It gives rise to nitric oxide (NO) when in contact with oxygen. At room temperature, nitrous oxide is colorless, non-flammable with a sweet smell and taste. It is used in rocketry and as a propellant in auto racing.

Nitric oxide reacts with ozone and is an ozone depleting substance (ODS).

9.7.1 Sources and Sinks of Atmospheric Nitrous Oxide

The primary sources of human-influenced emissions of nitrous oxide to the atmosphere are agricultural soil management, animal manure management, sewage treatment, mobile and stationary fuel combustion, adipic acid, and nitric acid production. Nitrous oxide is also emitted naturally from a wide variety of biological sources.

Tropical soils are probably the most important source of N_2O to the atmosphere and as the tropics expand toward higher latitudes with global warming, this is likely to increase. The ocean is also an important source of nitrous oxide, as are cultivated soils, biomass burning, and such industrial sources as nylon production.

The major sinks of N_2O are stratospheric photo-oxidation and photo-dissociation. Consumption by soils may be a small sink but this has not been quantified.

9.7.2 Increases in Atmospheric Nitrous Oxide Concentration

In 1998, the atmospheric concentration of nitrous oxide was 314 ppb, an increase of 44 ppb from its concentration in the pre-industrial level of 270 ppb.

9.8 Halocarbons

The halocarbons include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methylhalides, carbon tetrachloride (CCl_4), and the halons (bromides). All of the halocarbons are strong greenhouse gases and remain in the atmosphere for several decades. Also, halocarbons that contain chlorine and bromine contribute to stratospheric ozone depletion. The chlorine and bromine halocarbons have largely been reduced in production due to the Montreal Protocol and its amendments.

9.8.1 Sources and Sinks of Halocarbons

The CFCs and HCFCs are totally anthropogenic and do not occur in nature. Their presence in the atmosphere is entirely artificial. They have been used extensively in foam production, as aerosol propellants, in air conditioning units, and refrigerants.

The Montreal Protocol has been effective in reducing atmospheric concentrations of CFCs and HCFCs and provides an example of the benefits of an international agreement, the terms of which have been adhered to and have resulted in avoiding a potential environmental crisis. Ozone depletion, if allowed to continue unabated, would result in increased risk of cancer, respiratory distress, and other health-related illnesses. The expanding ozone thinning in the Northern Hemisphere is currently a reason for concern.

Halocarbons are destroyed primarily by photo-dissociation and photo-oxidation in the stratosphere. They are relatively inert and remain in the atmosphere for long periods. Methylhalides and HCFCs are removed from the troposphere mainly by reactions with OH and NO_3. Some of these gases are removed from the atmosphere by the ocean.

9.8.2 Increases in Atmospheric Halocarbons Concentration

Concentrations of halocarbons in the atmosphere are measured in parts per trillion by volume (pptv). Concentrations greatly increased when production increased in the 1930s until the Montreal Protocol. There is indication that their concentration has decreased substantially since the protocol was implemented.

9.9 Ozone

Ozone (O_3) is found throughout the atmosphere but is a pollutant in the troposphere and beneficial in the stratosphere. There is concern at present about an Arctic ozone hole, but an ozone hole over the Antarctic has been measured since the 1950s as seen in Fig. 9.4.

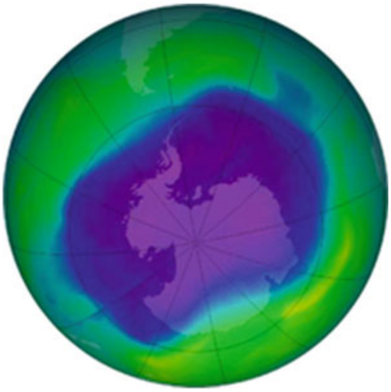


Fig. 9.4 View from the Earth's South Pole. Image of the largest Antarctic ozone hole ever recorded (September 2006, NASA, Public Domain)

Because the Earth is warming, temperatures in the troposphere warm while the stratosphere cools. The North Pole has experienced recent cold stratosphere temperatures and a reduction of ozone. Stratospheric ozone forms a blanket around the Earth about 12 miles up in the atmosphere and serves to protect life on Earth from harmful UV radiation from the Sun.

A continuing stratospheric cooling is reducing the ozone layer to about one half of its normal thickness. An ozone hole is not an actual hole, but a severe thinning of the polar ozone layer. Some scientists are predicting that the thinning could reach as far south as New York City during the twenty-first century.

The Arctic ozone hole could expose over 700 million people plus wildlife and plants to dangerous ultraviolet rays from the Sun. This seems to be the trend due to continued global warming and destruction of ozone in the stratosphere.

Global warming is depleting the ozone layer throughout its extent as the stratosphere cools. Stratospheric clouds form in the ozone layer and chemical reactions take place within them. These reactions activate chlorine ions present and make it easier for destruction of the ozone layer. The prediction is that within the next 20 years, the Arctic ozone hole will be as big if not bigger than the one currently over the South Pole. This Arctic ozone reduction could be blown south by high-altitude winds and could appear over much of the most heavily populated areas of North America and Europe. Scientists estimate that a 10% reduction in ozone will result in a 25% increase in non-melanoma skin cancer rates for temperate latitudes by the year 2050. A larger decrease in the ozone concentration could bring an epidemic of skin cancer and other maladies.

Scientists predict that if the Arctic ozone hole continues to expand, it will not recover as easily as had been thought. More polar clouds are forming in the stratosphere which activate stratospheric chlorine and they remove nitrogen compounds that act to moderate the destruction of ozone. The degree of Arctic ozone destruction in 2011 is unprecedented but it is not surprising and it will continue for some time into the future.

9.10 Other Trace Gases

The other trace gases like nitrogen oxides (e.g., NOx), carbon monoxide and the volatile organic compounds (VOCs) have little direct effect on greenhouse gas radiative forcing in the atmosphere. But they have indirect effects on other atmospheric chemicals such as ozone.

Nitric oxide (NO) is an air pollutant produced by coal-fired power plants and automobile exhausts. Nitric oxide in the atmosphere combines with water to form nitric acid, which is the main acid causing acid rain. It is also one of the chemicals that contribute to ozone depletion.

9.11 Atmospheric Residence Time of Greenhouse Gases

Each greenhouse gas has an atmospheric resident time, i.e., how quickly the gas is removed from the atmosphere. This resident time varies depending on several factors, such as its concentration, its inertness or reactivity, how soon it will be taken up by the ocean, microbes, or other aspects of the Earth systems. Carbon dioxide, the major greenhouse gas responsible for global warming, has an adjustment time of from 50 to 200 years. Methane has an adjustment time of from 12 to 17 years while for nitrous oxide it is 120 years. Lifetimes in the atmosphere for other greenhouse gases are quite variable.

All of the greenhouse gases with the exception of ozone and the CFCs have increased in atmospheric concentration in the last 260 plus years since the beginning of the Industrial Revolution.

Additional Readings

Archer, D. (2005). The fate of fossil fuel CO_2 in geologic time. *Journal of Geophysical Research, 110*(C9), C09S05. doi:10.1029/2004JC002625.

Denman, K. L., et al. (2007). Couplings between changes in the climate system and biogeochemistry. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge/New York: Cambridge University Press.

Friedlingstein, P., et al. (2006). Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. *Journal of Climate, 19*, 3337–3353.

Houghton, R. A. (2003). Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. *Tellus, 55B*(2), 378–390.

Sabine, C. L., et al. (2004). The oceanic sink for anthropogenic CO_2. *Science, 305*(5682), 367–371.

Sarmiento, J. L., & Gruber, N. (2006). *Ocean biogeochemical dynamics* (503 pp). Princeton: Princeton University Press.

Chapter 10
Earth's Albedo, Radiative Forcing and Climate Change

Abstract Albedo is defined as the degree of reflectivity of a substance. Albedo values are given for common Earth substances. Radiative forcing of the climate system is introduced and the relative forcings by principal substances are given. Earth's energy is received mainly from the Sun and is received at the top of the atmosphere. This solar radiation cascades through the atmosphere which acts as a transparent window through which most of the radiation is allowed to pass. The Sun radiates energy as a blackbody that appears very bright due to its very high temperature. Most matter acts as a blackbody and radiates energy dependent on its temperature. The Earth's moon is a relatively low temperature blackbody and we see its radiation as moonlight. The changing climate (global warming) is due mainly to the cascading energy scenario but the climate is also responsive to energy within the Earth.

Keywords Clouds • Albedo • Reflectivity • Radiative • Forcing • Fourier • GTP • Temperature • Terawatts • Contrails • Blackbody • Deforestation • Orographic rainfall

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
GTP	Deforestation's Effect on Albedo
750	Albedo of Fresh Snow
TAR	Terawatts
Radiative forcing of CO_2	Earth's Average Albedo
Albedo	3.4 W/m^2

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_10,

Things to Know	
LLGHGs	GWPs
Contrails	Sand Albedo
IPCC	Radiative
Radiative Forcing	W/m^2
Forcing	Reflectivity
Cumulus Clouds	Albedo of Water with the Sun Near the Horizon
Fourier	Two Ways of Expressing Albedo
Clouds' Effects on Climate	Uncertainty of Cloud Albedo Effect
Blackbody Radiation	

10.1 Introduction

Albedo is the reflectivity of a substance. Everything at Earth's surface has the ability to reflect and absorb light and therefore has an albedo. It is possible for a substance to have an albedo of 0, as carbon black, which absorbs 100% of the light that impacts it. The average albedo of the Earth is approximately 0.31 which means that ~31% of the radiant energy that is received at the Earth's surface is reflected back toward space.

As defined by the Intergovernmental Panel on Climate Change (IPCC), radiative forcing is a measure of how the energy balance of the climate system is altered. Radiative forcing can be measured from the change in the energy balance of the climate system when factors that affect climate are altered. "Radiative" signifies that the factors affect the balance between incoming solar radiation and outgoing infrared radiation within the Earth's atmosphere. Positive forcing warms the surface while negative forcing cools it. Forcing values are expressed in Watts per square meter (W/m^2).

10.1.1 Earth's Albedo

Earth's albedo is its degree of reflectivity. It is defined as the fraction of sunlight reflected from a surface.

Earth's albedo or reflectivity is also a factor in warming the planet and affecting the thermostat. The albedo plays an important role in climate feedbacks.

Earth reflects about 31% of the energy it receives from the Sun back into space. This is an average for the entire Earth. But certain parts of Earth's surface have different albedos as listed below in Table 10.1 and shown in Fig. 10.1.

10.1.1.1 Solid Earth Albedo

Man's effect on the solid Earth has been mainly from deforestation and the construction of cities and other structures that affect the albedo. Forests have a relatively low albedo compared to concrete and soils. Concrete has a higher albedo than asphalt.

Table 10.1 Average albedos (reflectivities) for different Earth materials

Albedo's of common earth surfaces	
Type of surface	**Albedo**
Sand	0.3–0.3
Grass	0.2–0.25
Forest	0.05–0.10
Water	0.03–0.05
Water with sun near horizon	0.5–0.8
Fresh snow	0.8–0.85
Thick cloud	0.7–0.8

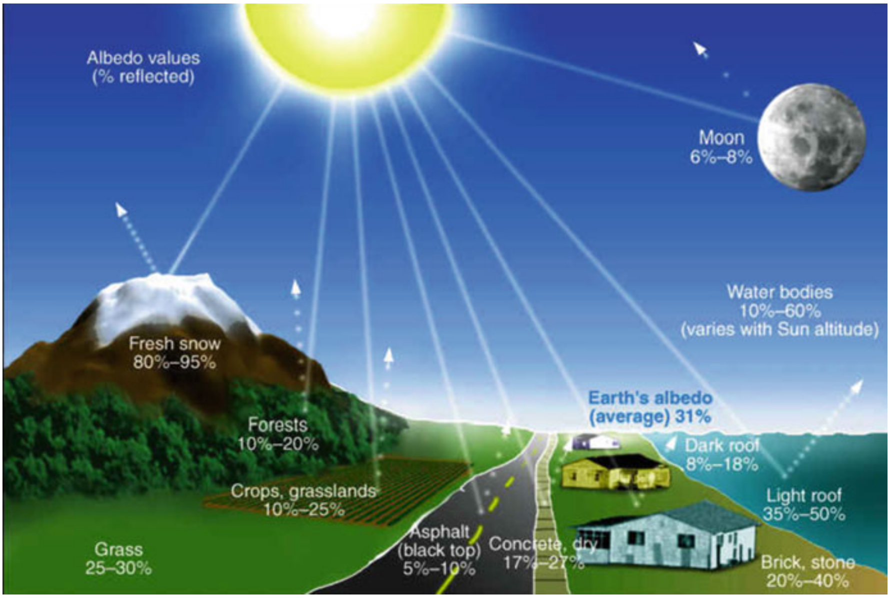


Fig. 10.1 Reflectivity or albedo of various surfaces expressed as percentages of light reflected (From http://marineecology.wcp.muohio.edu/climate_projects_04/snowball_earth/web/WebpageStuff/albedo.html)

Earth's albedo also depends on the angle of the Sun's rays striking the surface. More of the rays are reflected the steeper the angle of incidence, i.e., more sunlight is reflected near the Equator than at the poles, if everything else is equal. The range of reflectivity is on the order of from 0.01 to 0.4, or expressed as a percentage, 1–40%.

10.1.1.2 Ocean Albedo

Ocean reflectivity varies with the incidence of the Sun's rays striking it. The World Ocean is a great source of heat but the mixing of ocean waters is not rapid. The ocean surface layer warms during the day and cools at night, just as the solid Earth.

In general the ocean absorbs more radiation than does the solid Earth and its overall albedo is less.

10.1.1.3 Glacial Ice Albedo

Clean glacial ice has the highest albedo of any natural substance but it diminishes with material the glacier carries at its surface. Dirty ice absorbs more heat than clean ice. Clean glacial ice may reflect between 80 and 90% of the Sun's rays. Recent reports (June 2012) indicate a darkening of the Greenland ice and a rapidly decreasing albedo. This will greatly increase the rate of loss of the ice sheet as more sunlight is absorbed by the darker glacial ice.

10.1.1.4 Water Vapor

Water vapor is a greenhouse gas but it also has an albedo. When it causes clouds to darken, it adds heat to the atmosphere and its albedo is lowered.

10.1.1.5 Cloud Albedo

Clouds are important in warming the planet but their albedo varies by the type of cloud, with the variation ranging from a minimum of near 0 (very dark clouds) to a maximum of about 0.8 (very white clouds). Clouds reflect more sunlight than do land and water. The function of clouds in warming and cooling the Earth is variable and difficult to model. Sometimes clouds cover half the Earth, while other times much less.

10.1.1.6 Deforestation and Albedo

Deforestation for any purpose has increased the Earth's albedo. Trees are absorbers of heat and have a low albedo. Deciduous trees have an albedo of around 0.15–0.18 and coniferous trees have an albedo of about 0.09–0.15.

Albedo is the degree of reflectivity of a substance or a planetary body. A change of just 1% to the Earth's albedo has a radiative effect of 3.4 W/m^2.

10.1.2 Radiative Forcing

The following definition of radiative forcing is used in this text: an externally imposed perturbation in the radiative energy budget of Earth's climate system, which may lead to changes in climate parameters and is expressed in W/m^2.

The definition that the IPCC AR4 WG1 uses is as follows: "the change in net (down minus up) irradiance (solar plus longwave; in W/m^2) at the tropopause after allowing

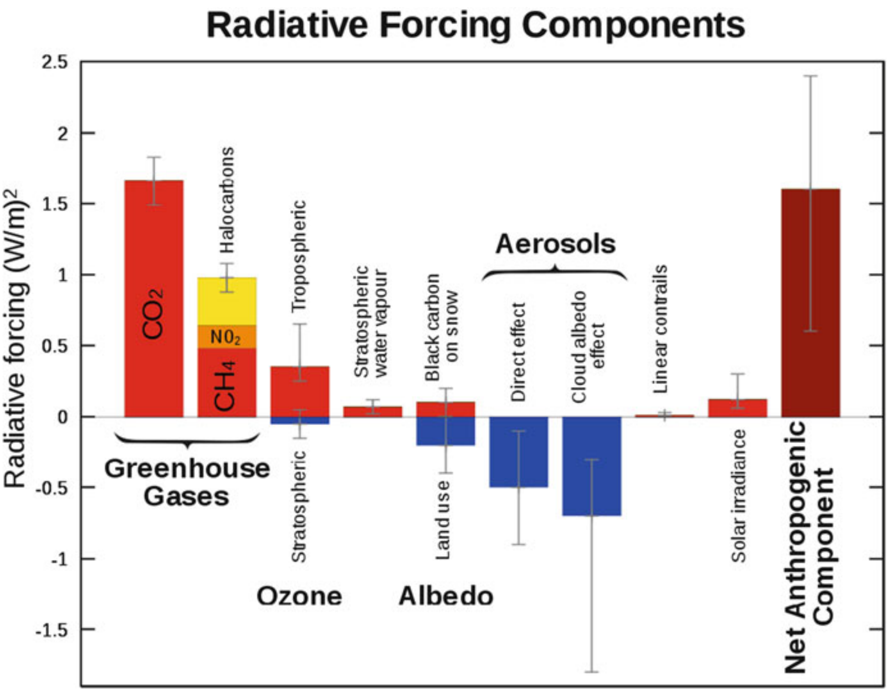


Fig. 10.2 This figure summarizes the IPCC's conclusions (2007) on radiative forcing by anthropogenic drivers with a warming (in *red*) and cooling (in *blue*) effect on the Earth's climate from 1750 to 2005. Note the error bars for each column. These indicate the assessed level of uncertainty assigned to each factor by the IPCC in 2007. The column at the far *right* shows the net global warming induced by humans (Adapted from IPCC Fourth Assessment Report, AR4 2007)

for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values."

The above quotation is from the IPCC AR4 2007 report, Working Group I, The Physical Science Basis, in Sect. 3.2 and it is because of such statements that the IPCC AR4 reports are read with some difficulty.

The increasing concentration of greenhouse gases has increased the amount of radiative forcing by these gases due to the enhanced absorption of terrestrial infrared radiation. It is possible to quantify the radiative forcing from the increases in greenhouse gas since the beginning of the Industrial Revolution around 1750. Figure 10.2 above shows the radiative forcing of the Earth's climate system in watts per square meter from 1750 to 2005. Watts per square meter are from minus two to plus two for the agents listed in the illustration below (Long Lived Greenhouse gases [LLGHGs], ozone, albedo, stratospheric water vapor, total aerosols, solar irradiance, and contrails from jet aircraft). The illustration above (Fig. 10.2) shows the effects of radiative forcing with the total net of anthropogenic forcings being by far the greatest factor.

The current level of radiative forcing, according to the IPCC AR4, is 1.6 W per square meter. That doesn't sound like much until you consider the total land area of the Earth and multiply it out, which gives a total warming effect of about 800 terawatts; more than 50 times the world's average rate of energy consumption, which is currently about 15 terawatts.

10.1.2.1 Factors Affecting Greenhouse Radiative Forcing

Greenhouse gases act as radiative forcing agents within the climate system. These gases have absorption bands in the thermal infrared part of the spectrum which allows them to trap the terrestrial radiation and re-radiate heat back to Earth. This is a fact that has been known since Fourier's experiments in the early 1800s.

The strength and wavelength of these absorption bands is of fundamental importance for a molecule in being able to act as a forcing agent. For example, CO_2 is so abundant in the atmosphere relative to the other effective greenhouse gases that the atmosphere is opaque over the short distance at the center of its 15 μm absorption band (see Fig. 4.4). The addition of only a small amount of gas absorbing at this wavelength has an effect on the net radiative flux at the tropopause (the top of the troposphere).

Gases that remain in the atmosphere for long periods of time before they are removed or converted to another gas influence the forcing potential of the gas.

Several greenhouse gases have indirect effects on radiative forcing on the climate through their interactions with atmospheric chemical processes. A good example is the oxidation of methane in the atmosphere which leads to the production of carbon dioxide and increases the latter's concentration in the atmosphere.

A major concern at present (June 2012) is the loss of methane during the extraction of shale gas by hydraulic fracturing (commonly referred to as fracking). Several recent studies indicate that the loss of methane by this process may negate the use of natural gas from this source as a substitute for burning coal.

10.1.3 Global Warming Potentials (GWPs)

Global warming potential is a relative measure of how much heat a given greenhouse gas traps in the atmosphere. A GWP compares the amount of heat trapped by a certain mass of the gas to the amount of heat trapped by a similar mass of carbon dioxide. A GWP is calculated over a specific time interval, commonly 20, 100 or 500 years. GWP is expressed as a factor of carbon dioxide (whose GWP is standardized to 1). For example, the 20 year GWP of methane is 56, which means that if the same weights of methane and carbon dioxide were introduced into the atmosphere, that methane will trap 56 times more heat than the carbon dioxide over the next 20 years.

Another metric that has been used by the IPCC and others is the Global Temperature Potential (GTP). The GTP provides an alternative approach by comparing global mean temperature change at the end of a given time horizon. Compared to the GWP, the GTP gives equivalent climate response at a chosen time, while putting much less emphasis on near-term climate fluctuations caused by emissions of short-lived species (e.g., CH_4). Although it has several known shortcomings, a multi-gas strategy using GWPs is very likely to have advantages over a CO_2-only strategy.

Although many climate change scientists have pointed out the flaws, GWPs remain the recommended metric for the IPCC and others to compare future climate impacts of emissions of long-lived climate gases.

10.1.4 Calculation of Greenhouse Gas Radiative Forcing

A wide range of direct and indirect measurements confirm that the atmospheric concentration of CO_2 has increased globally by about 120 ppm over the last 260 plus years, from a concentration of 280 ppm in the pre-industrial era (AD 1750) to 400 ppm in 2012. During this period, the growth rate of CO_2 in the atmosphere increased substantially: the first 50 ppm increase above the pre-industrial value was reached in the 1970s after more than 200 years, whereas the second 50 ppm was achieved in about 30 years. In the 10 years from 1995 to 2005 atmospheric CO_2 increased by about 19 ppm; the highest average growth rate recorded for any decade since direct atmospheric CO_2 measurements began in the 1950s. The average rate of increase in CO_2 determined by these direct instrumental measurements over the period 1960–2005 is 1.4 ppm per year. This has recently increased to a projected 2+ ppm per year.

High-precision measurements of atmospheric CO_2 are essential to the understanding of the carbon cycle budgets. The first *in situ* continuous measurements of atmospheric CO_2 made by a high-precision gas analyzer were implemented by C. D. Keeling from the Scripps Institution of Oceanography (SIO). These began in 1958 at Mauna Loa, Hawaii. The data documented for the first time that not only was CO_2 increasing in the atmosphere, but also that it was affected by cycles caused by seasonal changes in photosynthesis in the terrestrial biosphere. This is the reason for the up and down seasonal concentrations in the Keeling Curve (Figs. 2.2 and 8.3). These measurements were followed by continuous *in situ* analysis programs at other sites in both hemispheres.

10.1.5 Radiative Forcing of Ozone

The radiative forcing for ozone is more complex than that of CO_2 because of vertical variations in concentration. Tropospheric ozone is a pollutant but is regionalized over highly populated urban areas. Decreases in stratospheric ozone actually increase solar radiation and reduce greenhouse radiation. The decreased greenhouse radiation results in surface cooling.

10.1.5.1 Stratospheric Ozone

Global stratospheric ozone for the period 2000–2003 was approximately 4% below the 1964–1980 average values, although the Northern Hemisphere thinning appears to be increasing more rapidly. The stratospheric ozone radiative forcing has been estimated to be −0.05 between pre-industrial times and 2005 by the IPCC.

10.5.2 Tropospheric Ozone

The IPCC AR4 (2007) estimates the radiative forcing from tropospheric ozone to be +0.35 which is unchanged from the Third Assessment report (IPCC AR3 2001). The more recent estimate is based on model simulations due to the limited spatial and temporal coverage of observations.

There is interchange between tropospheric ozone and stratospheric ozone that makes quantification of ozone more uncertain than it would otherwise be.

10.1.6 Aerosols

Radiative forcing by aerosols is accomplished in two ways:

1. Directly from reflecting and absorption of solar radiation; and
2. Indirectly through modifying the optical properties and lifetimes of clouds (mainly in the troposphere).

10.1.6.1 Sources and Sinks of Aerosols

An important aspect of aerosols is their role in cloud formation. Aerosols in the atmosphere originate from several sources, such as volcanic eruptions, dust, sulphates, biomass burning, fossil fuel, organic carbon, fossil fuel black carbon, are all identified as having a significant anthropogenic effect on radiative forcing. Aerosols may be emitted as particulate matter or formed in the atmosphere from chemical reactions with certain gases.

Aerosols are removed from the atmosphere by transfer to the Earth's surface or by volatilization. Whenever it rains, aerosols are brought down to the Earth's surface from the atmosphere.

Stratospheric aerosols formed as a result of volcanic eruptions can remain in the atmosphere for months and as long as 2 years or more based on actual historical measurements after violent explosive volcanic eruptions.

10.1.6.2 Radiative Forcing by Aerosols

Aerosols in the atmosphere affect climate directly through reflection and absorption of solar radiation and indirectly by modifying the optical properties and lifetimes of clouds (mainly in the troposphere).

Radiative forcing by aerosols is more complex than that of well-mixed greenhouse gases because aerosols are not thoroughly mixed. The effect of aerosols on radiative forcing is largely due to their size, chemical composition, and position in the atmosphere.

Scientists estimate that anthropogenic aerosols contribute between 10 and 20% of the atmospheric mass burden and 50% of the global mean aerosol optical depth (a measure of transparency). Also, most aerosols have a short lifetime in the atmosphere (days to weeks) and their sources are strongly correlated with their location in the atmosphere.

The now defunct satellite SeaWifs provided three decades and longer satellite data on aerosols which is the longest single-satellite record of aerosols to date (July 2011). The record covers the period between 1997 and 2010 and complements records from the MISR and MODIS satellite instruments. In October 2011 a new satellite, NPOESS Preparatory Project (NPP) delivered a scanning radiometer called VIIRS into orbit that measures aerosol content in the atmosphere. Another satellite, Glory, launched in March 2011, would have also monitored aerosols but it failed to reach orbit due to catastrophic failure of its rocket.

10.1.7 Direct Radiative Forcing

Aerosol particles in the 0.1–1.0 μm (one millionth of a meter) diameter range have the highest efficiency per unit mass for optical interactions with incoming solar radiation due to the similarity of particle size and radiation wavelength. Sulphate aerosols and organic matter are therefore most effective at scattering and absorbing the short-wave radiation.

Large injections of sulphate aerosol precursors into the stratosphere from volcanic eruptions are well known from records of historical eruptions.

The major contributions to the anthropogenic component of the aerosol optical depth arise from sulphates produced from sulphur dioxide released during fossil fuel combustion and from organics released by biomass burning. To date, estimations of global negative forcing associated with anthropogenic aerosols are based on a number of modeling studies, due primarily to a lack of observational data.

Using an aerosol radiative-convective model, climate scientists obtained a figure of -0.6 W/m^2 for direct global radiative forcing due to anthropogenic sulphate alone, while others obtained a value of -0.3 W/m^2 for the Earth, and -0.43 W/m^2 for the Northern Hemisphere. The localization of the forcing, due to local emission sources and the short lifetimes of tropospheric sulphate aerosols, is almost always clearly noticeable.

10.1.8 Indirect Radiative Forcing

The global energy balance is sensitive to cloud albedo, and most particularly towards marine stratus (low-level) clouds which cover an average of about 25% of the Earth. Cloud albedo is itself sensitive to changes in the cloud droplet number concentration. The droplet number depends, in a complex manner, on the concentration of cloud condensation nuclei (CCN), which, in turn, depends on aerosol concentration. Through this indirect effect, the negative radiative forcing caused by anthropogenic aerosol emissions might be further increased.

Particles of sizes around 0.1 μm diameter composed of water soluble substances are highly effective as CCN. This includes both sulphate aerosols and organic aerosols from biomass burning. Estimates from modeling studies of the indirect radiative effects of aerosols vary widely. Despite the level of uncertainty, indirect negative radiative forcing is believed to be comparable to the direct forcing.

10.1.9 Total Anthropogenic Radiative Forcing: Greenhouse Gases and Aerosols

Direct greenhouse forcing has been estimated with a fairly high level of confidence, while levels of aerosol forcing and indirect ozone forcing are relatively poorly constrained. An estimate of the net global-mean radiative forcing due to all anthropogenic activity since pre-industrial times is given in Fig. 10.2. The net positive anthropogenic forcing from 1750 to 2005 is approximately 1.6 W/m^2.

10.1.10 Observed Climate Variations

There is considerable model- and observation-based evidence that indicates a causal relationship between the net positive global mean radiative forcing and the observed global temperature increase during the twentieth century. There is definitely a strong correlation.

The warmer atmospheric temperatures (global warming) observed over the past several decades are expected to lead to a more vigorous hydrological cycle, including more extreme rainfall events which are already occurring. In 1998 a study reported that from 1910 to 1996 total precipitation over the contiguous U.S. had increased, and that 53% of the increase came from the upper 10% of precipitation events (the most intense precipitation). The percent of precipitation coming from days of precipitation in excess of 50 mm has also increased significantly. These trends are not inconsequential. More frequent and intense precipitation events are causing more erosion of soils, stream banks, and shorelines. This can be seen in many parts of the world today. Recent (2012) studies have shown that the atmosphere contains about 4% more moisture than before the Industrial Revolution and that moisture falls as precipitation, mainly rain and snow.

Rain falls as showers or as steady rains with rapidly changing intensity. Convective precipitation falls over a certain area for a relatively short time (scattered showers), as convective clouds have limited horizontal extent. Most precipitation in the tropics appears to be convective; however, it has been suggested that stratiform precipitation also occurs in mature thunderstorms. Hail is an indication of convection. In mid-latitudes, convective precipitation is associated with cold fronts (often behind the front), squall lines, and warm fronts in very moist air. Of course, most precipitation falls in the ocean as ocean water covers 71% of Earth's surface.

10.1.11 Clouds and Their Impacts on Climate Change

Clouds are visible masses of water droplets or ice crystals suspended in the atmosphere above the surface of the Earth or any other planetary body. There are four basic types of clouds: cumulus, stratus, cirrus, and nimbus. Illustrations of the various cloud types may be found in any meteorology textbook, online, or in an encyclopedia and will not be given in this text.

Cloud effects on temperature and long-range climate change are difficult to calculate and model. Light, fluffy clouds reflect a great deal of sunlight during the day but have little effect at night. Dark, ominous clouds absorb sunlight. Do clouds have a major or minor effect on Earth's global temperature?

Recent (2010, 2011, and 2012) studies of cloud effects on global temperature have found that they have a slight warming effect. Dessler (2010) used cloud measurements over the entire planet by the Clouds and the Earth's Radiant Energy System (CERES) satellite instruments from March 2000 to February 2010 to attempt to determine the cloud feedback. Dessler concluded that although a very small negative feedback (cooling) could not be ruled out, the overall short-term global cloud feedback is probably positive (warming), and may be strongly positive. His measurements showed that it is very unlikely that the cloud feedback will cause enough cooling to offset a significant amount of human-caused global warming.

Clouds may develop vertically like the cumulus cloud. Cumulus clouds are formed most commonly through either thermal convection or frontal lifting and can rise to heights in excess of 39,000 ft (see Fig. 8.8). They release considerable amounts of energy through condensation of water vapor within the cloud itself. Cloud types include fair-weather cumulus and cumulonimbus.

Clouds are further classified according to the height of their cloud base. For example, cloud names containing the prefix "cirri-", as in cirrus clouds, are found at high levels; clouds with the prefix "alto-", as in altostratus, are found at middle levels.

10.1.11.1 High-Level Clouds

High-level clouds form above 20,000 ft (6,000 m) and are mainly composed of ice crystals. They are typically thin and white but can appear in an array of colors when the Sun is setting or low on the horizon. Cloud types include cirrus and cirrostratus.

10.1.11.2 Mid-Level Clouds

Mid-level clouds typically occur between 6,500 and 20,000 ft (2,000–6,000 m). They are most often composed primarily of water droplets but can be composed of ice crystals if the temperatures are cold enough. Cloud types include altocumulus and altostratus.

10.1.11.3 Low-Level Clouds

Low-level clouds are composed mostly of water droplets as their bases lie below 6,500 ft (2,000 m). However, when temperatures are cold enough they may also contain ice particles and snow. Cloud types include nimbostratus and stratocumulus.

10.1.12 Orographic Rainfall

Orographic or relief (i.e., topographic) rainfall is caused when masses of air pushed by wind are forced up the side of elevated land formations, such as large mountains like the Sierra Nevada Mountains in the western U.S. They form regional climatic conditions (Fig. 10.3 below).

The lift of air up the side of the mountain results in adiabatic cooling, and ultimately condensation and precipitation. In mountainous parts of the world subjected to relatively consistent winds (e.g., the trade winds), a more moist climate usually prevails on the windward side of a mountain than on the leeward (downwind) side. Moisture is removed by orographic lift, leaving drier air (katabatic wind), (e.g., Santa Ana winds in the U.S. in Southern California) on the descending (generally warming), leeward side where a rain shadow is observed.

In Hawaii, Mount Wai‘ale‘ale, on the island of Kauai, is notable for its extreme rainfall, as it has the highest average annual rainfall on Earth, with 460 in. (12,000 mm). Storm systems affect the area with heavy rains between October and March. Local climates vary considerably on each island due to their topography, divisible into windward and leeward regions based upon location relative to the higher mountains and prevailing wind directions.

In South America, the Andes mountain range blocks Pacific moisture that arrives in that continent, resulting in a desert-like climate just downwind across western Argentina. The Sierra Nevada range creates the same effect in North America forming

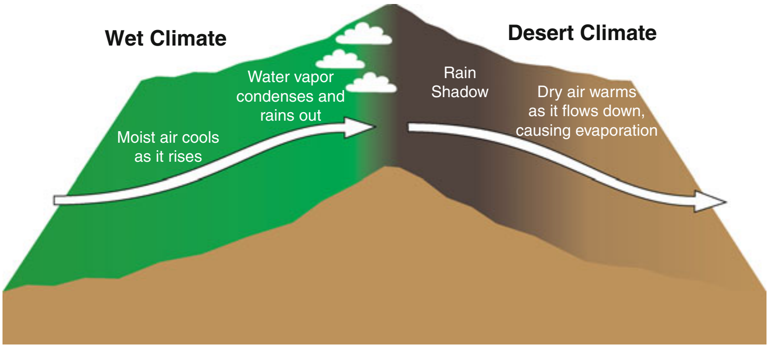


Fig. 10.3 Orographic effect. A rain shadow created by a mountain range at nearly right angles to prevailing winds that creates rain on the windward side of the mountain and desert climate on the leeward wide of the mountain (Credit: John Cook)

the Great Basin desert; the Mojave Desert and the Sonoran Desert are also rain-shadow deserts.

Additional Readings

Ahrens, C. D. (2006). *Meteorology today. An introduction to weather, climate, and the environment* (8th ed.). Belmont: Thompson, Brooks/Cole.

Gurneym, R. J., et al. (1993). Atlas of satellite observations related to global change. Great Britain: Cambridge University Press. 470 pp

Intergovernmental Panel on Climate Change's Fourth Assessment Report. (2007). Changes in atmospheric constituents and radiative forcing, pp. 133–134. Cambridge/New York: Cambridge University Press.

Landsberg, P. T. (1990). Bosons: black-body radiation. *Thermodynamics and statistical mechanics* (p 208 *ff*) (Reprint of Oxford University Press 1978 ed.). Courier Dover Publications. ISBN 0-486-66493-7. Mineola, NY, USA

Roman, M. O., et al. (2010). Assessing the coupling between surface albedo derived from MODIS and the fraction of diffuse skylight over spatially-characterized landscapes. *Remote Sensing of Environment, 114*, 738–760. doi:10.1016/j.rse.2009.11.014.

Shine, K. P., et al. (2003). An alternative to radiative forcing for estimating the relative importance of climate change mechanisms. *Geophysical Research Letters, 30*(20), 2047. doi:10.1029/2003GL018141.

Chapter 11
Atmospheric Circulation and Climate

Abstract Earth's atmosphere, made up essentially of the gases that surround our planet, consists of circulation patterns that move air from one place to another and from the surface to higher elevations. There are lateral and vertical ways to force air to move and these are explained in this chapter. The Coriolis Effect, as well as its effect on atmospheric circulation, is explained. Trade winds, polar highs, westerlies, easterlies, doldrums, and horse latitudes are explained and illustrated. Air movement over the Western Hemisphere is illustrated. The Intertropical Convergence Zone (ITCZ) and Horse Latitudes as well as Hadley, Polar, and Ferrel cells are explained and illustrated. The dangers of increased energy and uncertainty concerning future weather events are discussed. Some extreme weather events occurring during 2011–2012 are enumerated and explained in the context of changing climatic conditions (i.e., the "new normal").

Keywords Coriolis • Trade • ITCZ • Convergence • Hadley • Ferrel • Cell • Horse • Latitudes • Siberian • Polar • Subtropical • Rotation • Axis • Winter • Insolation • Trade • Winds • PBL • Jet stream • GCMs • Barometric • Extreme • Weather • Flooding • Cyclones

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_11,

Things to Know	
Hadley Cell	ITCZ
Horse Latitudes	High Pressure Systems
Insolation	Earth's Revolution
Barometric Pressure	Siberian High
Rising Air	Troposphere
Subtropical High	Earth's Rotation
Icelandic Low	Ferrel Cell
Winter Insolation	PBL
Trade Winds	Jet Stream
Subpolar Low	Westerlies
Polar Lows	ITCZ Northern Shift
Bermuda High	SE Trade Winds
Subtropical Jet	Doldrums
Convection Cell	Coriolis Effect
Future Projections for Atmospheric Circulation	Azores High
Extreme Weather Events	The New Normal

11.1 Introduction

Circulation in the atmosphere is controlled by Earth's rotation, barometric pressure, topography, ocean currents, and differences in temperature, salinity, and moisture.

Differences in barometric pressure occur when air flow is slowed causing a mass of air to build up over a particular location thus increasing air pressure. Heating and cooling the air also create variations in air pressure. When air is heated it expands and rises; and if pushed away aloft, surface air pressure decreases. Conversely if air is cooled, it subsides toward the surface causing air pressure to increase. In other words, hot air rises and cold air descends and this movement affects air moving both laterally and vertically.

11.2 Atmospheric Circulation

If Earth had a simplified atmosphere in a non-rotating state, the majority of the Sun's energy would be incident on the Earth at the equator and the Earth would uniformly heat at the equator and be cold at the poles. Convection cells would develop, one in each hemisphere, to transport heat from the equator to the poles in relatively straight paths. But the Earth does rotate from west to east and completes a rotation on its axis approximately every 24 hours (Fig. 11.1) and forces build up in the atmosphere as a result. The main and most recognizable force is the Coriolis force resulting in the Coriolis Effect, the result of which is air masses turning to the right

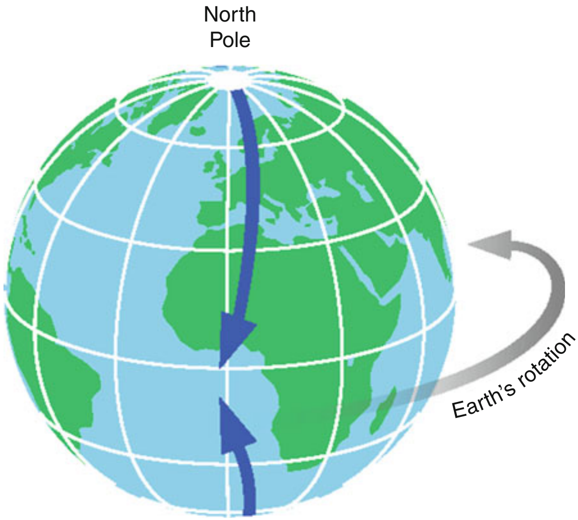


Fig. 11.1 The Coriolis Effect as seen from an oblique view of the Earth. Earth's rotation indicated by the *grey arrow*; the Coriolis Effect represented by the *blue arrows* which shows deflection of moving air masses or objects in both hemispheres, to the *right* in the north and to the *left* in the south (Credit: John Cook)

in the Northern Hemisphere and to the left in the Southern Hemisphere as illustrated by the blue arrows in Fig. 11.1.

As a result of Earth's rotation atmospheric circulation is more complex than it would be with no rotation.

The illustration below (Fig. 11.2) shows the rotating Earth with three cells developing in each hemisphere. Those nearest the equator are Hadley cells. Going towards the poles, the next cells are the Ferrel cells and the ones at or near the poles are Polar cells.

The Earth doesn't just rotate on a vertical axis; its axis is tilted and as the Earth revolves around the Sun, each hemisphere is alternately bathed in the more direct sunlight. Because of this axial tilt, half the Earth receives more sunlight during the summer and the other half, at the same time, during the winter. In other words, when the Northern Hemisphere is experiencing summer, the Southern Hemisphere is having winter (see Fig. 11.3).

11.3 Insolation

As the Earth rotates on its axis and revolves around the Sun, the amount of sunlight received by different parts of the Earth varies. For example, more sunlight is received by the Northern Hemisphere during the summer months and less during the winter months (Fig. 11.3).

Figure 11.4 below shows movement of air due strictly to Earth's rotation and without the influence of land masses. Land masses divide high and low pressure systems into separate air masses on either side of the continents.

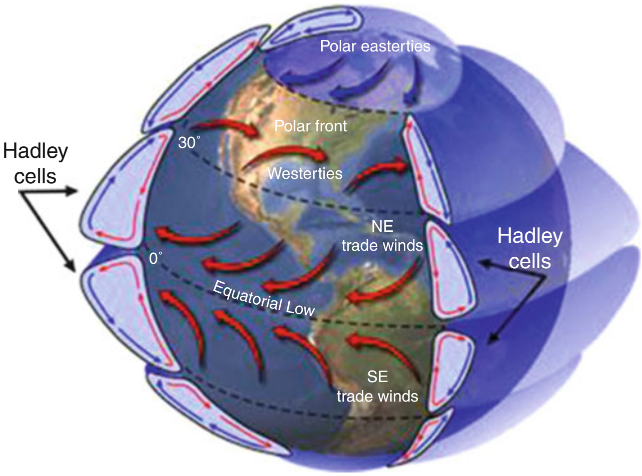


Fig. 11.2 Idealized, three cell atmospheric convection in a rotating Earth. The three cells being either three cells north or south of the equator. The deflections of the winds within each cell is caused by the Coriolis Force (Credit: John Cook)

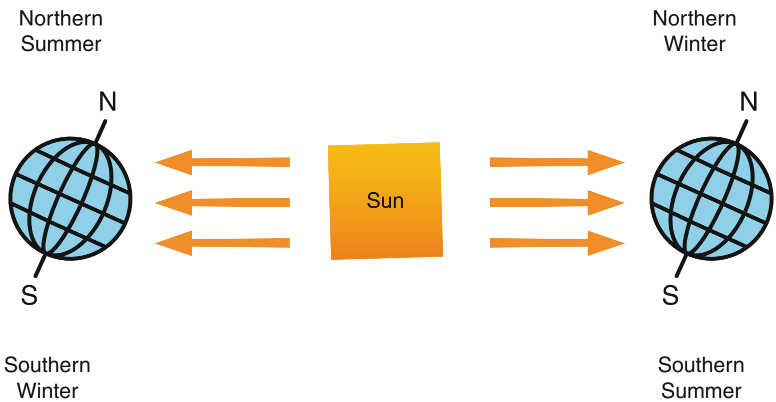


Fig. 11.3 The effect of Earth's obliquity on insolation, the amount of energy received by the Earth at different seasons of the year (summer and winter) (Source: John Cook)

11.4 Air Flow Patterns

Air flows from areas of high pressure to areas of low pressure and moving air is called wind. Wind on the Earth is caused by different atmospheric pressure or by air being moved by convection. Convection moves air vertically and in a circular motion, up and down, as opposed to laterally from equator to pole. The air from

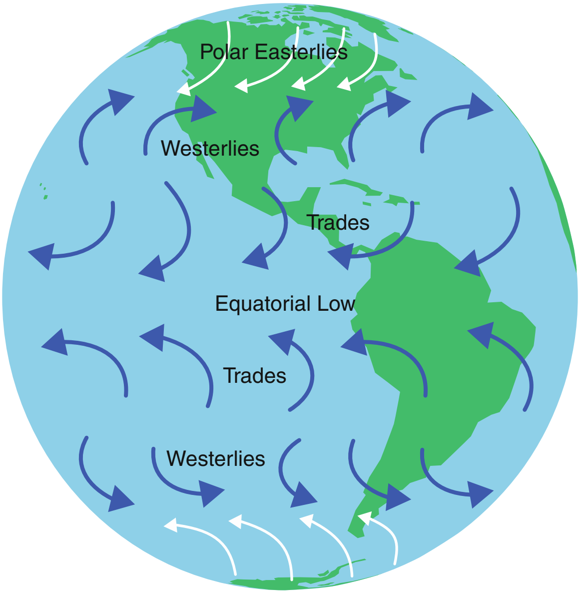


Fig. 11.4 Idealized winds generated by Coriolis force (Credit: John Cook)

equator to poles moves mainly by the Hadley, Ferrel, and Polar cells and from high pressure areas to those of low atmospheric pressure.

The lower part of the atmosphere is sometimes referred to as the planetary boundary layer (PBL) where it is influenced by its contact with the Earth's surface. It is in this layer that most turbulence occurs and vertical mixing is great. Above the PBL, the wind is approximately parallel to the isobars of a weather or barometric map and the winds are said to be geostrophic. Within the PBL the wind is affected by surface drag and flows across the isobars, which are lines of equal barometric pressure.

Air moves from high pressure areas to low pressure areas. Barometric pressure is the weight of a column of air, or atmospheric pressure. On weather maps, high and low pressure areas are marked H and L respectively and contour lines connecting points of equal barometric pressure (isobars) are drawn. If these isobars are close together, wind is stronger; further apart, the wind is not as strong. The analogy with topographic contour lines is that when contour lines are closer together the slope is steeper; when they are further apart the slope is more gradual.

The Sun heats the ground or ocean surface most intensely in tropical areas. The heated air rises and as it rises it cools and loses its moisture as rain or snow, depending on the temperature. This belt of converging air masses, called the doldrums due to low air and water circulation sometimes causing sailing ships to struggle to escape the region, includes some of the rainiest areas on Earth. The cooled, now drier air is forced by continuously rising air to move out of the way, and so it moves towards the temperate latitudes. Air moves by convection from tropical to temperate to Polar Regions. Air also moves laterally by differences in pressure.

Such air from the tropics meets air moving down from the poles at about 30° N and S, called the horse latitudes, where it settles. Here the sinking air compresses, warms, and absorbs moisture from the surface. This is why desert belts lie in the horse latitudes. This warm, dry air is displaced by more sinking air and so some of it returns back to the equatorial zone, and some returns to the poles. Such cycling air between low and mid-latitudes defines a Hadley Cell (see Fig. 11.2).

A similar cell forms between the horse latitudes and the stormy polar fronts at 60° N and 60° S, where warm temperate air moving toward the poles meets very cold air rolling down from the poles. The lighter warm air is forced to rise over the denser cold air, which chills it and forces precipitation. From this polar front, air returns both toward the Equator and toward the poles. Air immediately over the pole sinks. While it is not warm, it is extremely dry (only centimeters of snow every year). From the poles, air within the polar cap streams back towards the polar front.

Thus, six belt-like cells circulate air from pole to pole and establish patterns of climate over the planet. The cells are also characterized by specific patterns of wind flow, a function of the Coriolis force generated by the spin of the Earth (Fig. 11.1). In the temperate zone between the horse latitudes and the polar front, the prevailing westerlies dominate air circulation. In the tropics, the easterly trade winds dominate. Winds around the poles are also easterly. Winds are named from the directions from which they come; therefore, easterlies come from the east, westerlies from the west.

The Ferrel Cell is a secondary circulation feature, dependent for its existence upon the Hadley cell and the Polar cell. The Ferrel Cell behaves much as an atmospheric conduit between the Hadley cell and the Polar cell, and comes about as a result of the eddy circulations (the high and low pressure areas) of the mid-latitudes. For this reason it is sometimes known as the "zone of mixing". At its southern extent (in the Northern Hemisphere), it overrides the Hadley cell, and at its northern extent, it overrides the Polar cell. Just as the Trade Winds are to be found below the Hadley cell, the Westerlies can be found beneath the Ferrel cell. Thus, strong high pressure areas which divert the prevailing westerlies, such as a Siberian high (which could be considered an extension of the Arctic high), could be said to override the Ferrel cell, making it discontinuous.

The illustration below (Fig. 11.5) shows the high and low pressure systems in January. The ITCZ is the Intertropical Convergence Zone where the Trade Winds converge. The ITCZ shifts to the north in summer. The red arrows in Fig. 11.5 indicate wind directions.

A major atmospheric current that affects weather and climate in the Northern Hemisphere continents of North America and Europe, including the British Isles, is the Jet Stream, sometimes a single current, sometimes multiple currents as shown below (Figs. 11.6, 11.7, and 11.8). The Jet Stream is a strong current or currents of air somewhere between 10 and 15 km (6–9 miles) above the earth's surface near the boundary of the troposphere and the stratosphere. The position of this upper-level Jet Stream denotes the location of the strongest surface temperature contrast between cold air to the north and warm air to the south and shows a stronger demarcation during the winter months.

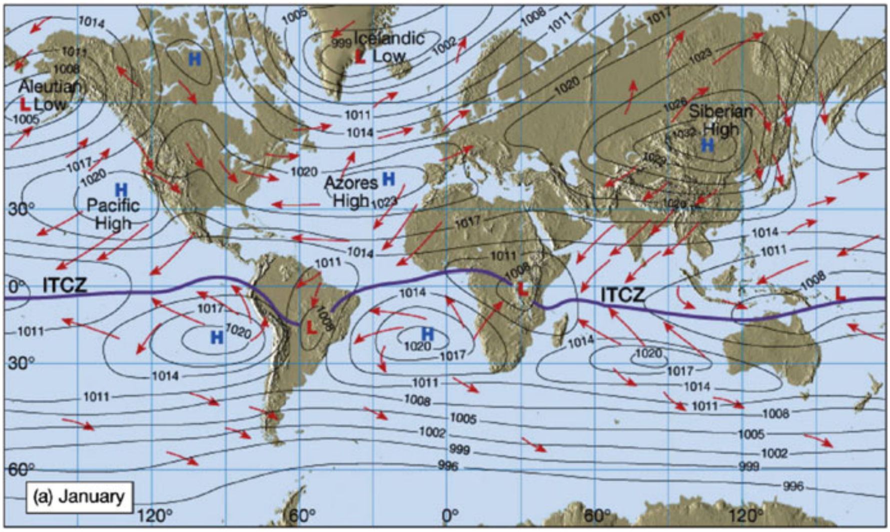


Fig. 11.5 Atmospheric circulation in January showing the southern shift of ITCZ in January

11.5 Climate Change Effects on Atmospheric Circulations

As Earth and its atmosphere continue to warm, atmospheric circulation will drastically change with major changes being increased moisture in some areas, drought in others, and increased weather uncertainty across the Earth's surface. This changing weather uncertainty has already begun. If atmospheric circulation changes, oceanic circulation will eventually also change.

Global warming will alter atmospheric currents in unpredictable ways in many areas. The warming is expected to be greatest over land and in high latitudes. The effects are projected to be greater over the Northern Hemisphere than the Southern Hemisphere as the former is warming more rapidly than the latter at present.

It is very likely that hot extremes, heat waves and heavy precipitation events will become more frequent. The heavy precipitation events will be due to the increased moisture in the atmosphere. Based on a range of models, it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea-surface temperatures. There is less confidence in projections of a global decrease in numbers of tropical cyclones. The apparent increase in the proportion of very intense storms since 1970 in some regions is much larger than simulated by current models for that period and may increase in number and intensity with even greater warming in the future. If more energy continues to be added to the atmosphere as heat, more unusual weather events can be expected.

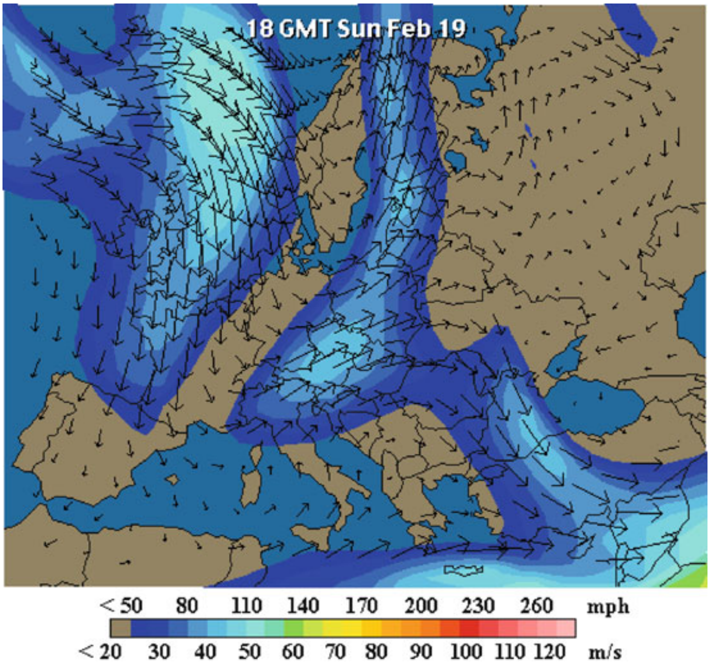


Fig. 11.6 Atmospheric circulation over the European continent showing Jet Streams in February 2012 (From http://www.wunderground.com/global/EU_2xJT_Index.html)

Fig. 11.7 An unusual region of atmospheric pressure over the Arctic has kept the polar jet stream (*green*) locked up at far northern latitudes, causing a warm, dry U.S. winter (Image: Courtesy of NOAA, Public Domain)

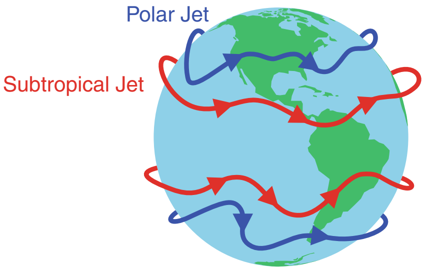


Fig. 11.8 Polar and subtropical jet streams in both hemispheres (Credit: John Cook)

Extra-tropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation, and temperature patterns continuing the broad pattern of observed trends over the last half-century.

There is an improving understanding of projected patterns of precipitation as the result of more sophisticated computer models. Increases in the amount of precipitation are very likely in high-latitudes, while decreases are likely in most subtropical land regions (by as much as about 20%), continuing observed patterns in recent trends.

Glaciers will continue to melt and sea level will continue to rise. Regions of the Earth where populations depend on glacial melt water will have to find new water sources or migrate to areas where there are more water resources. The increased sea level rise will also displace billions of people that will have to move inland.

A changed climate and atmospheric circulation will have a profound impact on agriculture and thus on food supplies. Growing seasons will be affected and agriculture will have to migrate to higher elevations and latitudes. Some of this migration can be seen today with plants and animals. Certain plants are also germinating earlier each year and the life cycles of some insects are being effected by earlier springs and later fall seasons.

As sea level rises, inland seas will develop over current land areas and will result in moderating the climate extremes but this will happen over hundreds of thousands of years as it has in the geologic past. However, it may happen more suddenly if the Greenland and Antarctic ice sheets collapse, as is an eventual certainty with increased warming, and the accompanying sea-level rise will displace millions of people living in low-lying areas today.

11.6 Extreme Weather Events

Climate change scientists and meteorologists are calling 2011 one of the worst years on record for climate extremes and 2012 may be worse. Already in June of 2012, over 3,000 heat records have been broken in the U.S. alone. From torrential, flooding downpours to record heat and cold, the events have been spread out from coast-to-coast and border-to-border in the United States. In September 2011 the following events took place in the United States:

11.6.1 Washington, D.C. Metro Rainfall

An incredible 7.03″ of rain fell in 3 h on September 8, 2011 to the south of D.C. in Ft. Belvoir, VA. According to the National Weather Service in Baltimore/Washington, this has a less than 0.1% chance of happening in a given year, making it a 1,000-year rainfall event.

To the west of D.C. in Reston, VA, 6.57″ of rain fell in 6 h on September 8, 2011. According to the National Weather Service in Baltimore/Washington, this has a 0.2% chance of happening in a given year, making it a 500-year rain event. The same is true for Franconia in Fairfax County, VA where 5.47″ fell in 3 h.

11.6.2 Binghamton, N.Y. – Rainfall

7.49″ of rain on September 7 was the wettest day in history. The old record of 4.24″ on September 30, 2010 was crushed. September 2011 will also go down as the wettest month in history.

11.6.3 Allentown, PA. – Rainfall

With almost 13″ of rain, September 2011 is the wettest September on record. Amazingly, August was the wettest month on record (13.47″). Records date back to 1922.

11.6.4 Harrisburg, PA – Rainfall

With more than 18″ of rain, September 2011 is the wettest September on record. The rains this month also pushed the Pennsylvania State Capitol to its wettest year on record, beating out 1972.

11.6.5 Cincinnati, Ohio – Rainfall

3.76″ of rain on September 26, 2011 was the wettest September day in history. Records date back to 1871.

11.6.6 Dayton, Ohio – Rainfall

September 2011 is the wettest September on record with more than 10″ of rain.

11.6.7 Colorado Springs, Colorado – Rainfall

4.50″ of rain on September 14, 2011 was the wettest day in history. Records date back to 1894. The 2-day total (September 14–15 of 2011) of 5.36″ is the wettest 2-day period on record.

11.6.8 Tucson, Arizona – Rainfall

As of September 28, 2011 the southeast Arizona city has seen 5.60″ of rain. This makes September 2011 the wettest on record.

Propelling them to this record was 2.84″ on September 15. This was the 5th wettest day on record.

11.7 Record Heat

11.7.1 Houston, Texas

Hit 102° on September 13, 2011. This was the hottest day ever recorded so late in the year.

11.7.2 Dallas, Texas

Temperatures soared to 107 degrees on September 13, 2011. This was the hottest day ever recorded so late in the year.

11.7.3 Phoenix, Arizona

Low temperature of 91° on September 5, 2011 was the hottest low temperature ever recorded in September.

11.7.4 Seattle, Washington

Recorded 8 straight days with 80+ degree days temperatures from September 3 through September 11, 2011. This is the most consecutive 80-degree days ever recorded in September.

11.7.5 Corpus Christi, Texas

One hundred and three degrees on September 25, 2011 was the hottest temperature ever recorded so late in the season. Records date back to 1887.

11.8 Record Cold

11.8.1 International Falls, Minnesota

The nation's icebox lived up to its reputation in September 2011. The low temperature of 19° on September 15, 2011 was the coldest temperature so early in the season and also the first time temperatures have fallen into the teens during September. Later in the month, a daily record high of 82° was set on September 28, 2011.

11.9 Record River Flooding

Heavy rains from the remnants of Tropical Storm Lee caused record river flooding in many locations in New York and Pennsylvania on September 8 and 9, 2011.

This included the Susquehanna River at Binghamton, N.Y., Wilkes-Barre, PA and Meshoppen, PA. The Swatara Creek in Hershey, PA beat the previous record level by 10 ft!

11.10 Tropical Storm Lee's Tornadoes

According to at least one severe weather expert, the preliminary tornado count from Tropical Storm Lee and its remnants is 38. This is the second most tornadoes on record from a tropical storm that did not reach hurricane strength.

The events described above are based on a report by Chris Dolce, a meteorologist with the Weather Channel. And these weather events are only for 1 month in 1 year in one country, the United States in 2011.

11.11 Other Meteorological Events

The World Meteorological Organization reported on Friday, March 23, 2012 that last year (2011) was the eleventh hottest year on record for Earth.

Extreme weather events were devastating in their impacts and affected nearly all regions of the globe over the past decade. They included severe floods and record hot summers in Europe; a record number of tropical storms and hurricanes in the Atlantic in 2005; the hottest Russian summer since 1,500 in 2010 and the worst flooding in Pakistan's history.

Last year alone (2011), the United States suffered 14 weather events which caused losses of over $1 billion each.

On March 13 and 19 of 2012, historical heat records were exceeded in over 1,000 places in North America.

Scientists believe these extreme weather events are being caused by man-made global warming. In this year alone (2012) massive blizzards have struck the U.S. Northeast, tornadoes have ripped through the nation, mighty rivers like the Mississippi and Missouri have flowed over their banks, and floodwaters have covered huge swaths of Australia as well as displaced more than five million people in China and devastated Colombia. And this year's natural disasters follow on the heels of a staggering litany of extreme weather in 2010, from record floods in Nashville, Tenn., and Pakistan, to Russia's brutal heat wave.

The WMO Commission for climatology provides more information about Global Weather and Climate Extremes at: http://wmo.asu.edu/

Additional Readings

Emanuel, K. A. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. *Nature, 436*(4), 686–688. August 2005, doi:10.1038/nature03906.

Intergovernmental Panel on Climate Change (IPCC). (2007). AR4, 2007, Section 2.7. *Has climate variability, or have climate extremes, changed?*. Cambridge/New York: Cambridge University Press.

Mogil, M. H. (2007). *Extreme weather* (pp. 210–211). New York: Black Dog & Leventhal, Publisher. ISBN 978-1-57912-743-5.

Persson, A. (2006). Hadley's principle: Understanding and misunderstanding the trade winds. *History of Meteorology, 3*, 17–42.

Part IV
The World Ocean and Climate

Chapter 12
The World Ocean

Abstract Oceans cover about 71% of Earth's surface. There are five ocean basins that are interconnected by circulation and are separated by continental land masses except for the Southern Ocean. Ocean water is surprisingly uniform; at least as far as near-surface waters are concerned. Ocean circulation is caused by atmospheric circulation, temperature differences, bottom configuration, and salinity differences. Ocean acidification, one very important aspect of rising carbon dioxide levels, is explained. Dying coral reefs and shell-baring organisms and the effects of rising carbon dioxide levels on oceans are discussed. Ocean acidification is one of the main results of carbon dioxide buildup in the atmosphere.

Keywords Acidification • Ocean • World • Oceanographers • Concentration • Chlorine • Sodium • Composition • Current • Greenland • Upwelling • Basin • Mixing • AMOC • Denmark • DSOW • Ridge • Mixed • Icelandic • Jet • Bicarbonate • Elements • Equatorial • Salinity • Thermohaline • Lake Agassiz • Atlantic • Pacific • Density • Phytoplankton • Conveyor

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_12,

Things to Know	
71% of the Earth's Surface	One World Ocean
700 m	The Great Conveyor Belt
Bicarbonate	Ocean Basins
Upwelling	North Icelandic Jet
Oceanographers	Chlorine Concentration in Sea Water
Sea Water Composition	North Equatorial Current
Two Most Abundant Elements in Sea Water	Southern Ocean
Red Sea	Ocean Mixing of Carbon Dioxide
Thermohaline Circulation	South Equatorial Current
Sodium Concentration in Sea Water	Alaska Current
AMOC	Ocean Acidification
HCO_3^-	Mixed Layer
Major Ocean Currents	Atlantic Meridional Overturning Circulation
Benguela Current	Denmark Strait Overflow Water (DSOW)
Greenland-Scotland Ridge	Phytoplankton
East Greenland Current	How is Sea Life Affected by Ocean Acidification
Lake Agassiz	IPCC AR4

12.1 Introduction

The World Ocean refers to the fact that all ocean waters on Earth are interconnected and there is or can be interchange of water between the separate ocean basins. The World Ocean is surprisingly uniform in composition as a result of this interchange and oceanic currents. When sea level rises, it rises all over the world, which is called a eustatic sea level rise to distinguish it from a local or tectonic sea level rise. Sea level may also be affected locally by means other than tectonic, such as anthropogenic construction.

The IPCC AR4 2007 reported that between 1961 and 2003, ocean temperature had risen 0.10°C from the ocean surface to a depth of 700 m and the ocean heat content from the surface to 3,000 m had increased at the rate of 0.21 W/m^2 averaged globally over the ocean surface. Two-thirds of this warming occurred to a depth of 700 m. There has been some cooling of the ocean surface since 2003 which means that heat is most likely being transferred to greater depths as would be expected from the Second Law of Thermodynamics.

12.2 The World Ocean

The World Ocean covers almost ¾ (71%) of the surface of Earth. This is the reason our planet looks like a blue marble from outer space (see frontpiece). Ocean water consists of salts which have been derived mainly from the Earth's surface by

Table 12.1 Average chemical composition of sea water (From Wikipedia)

Average composition of sea water			
Element	Percent	Element	Percent
Oxygen	85.84	Sulfur	0.091
Hydrogen	10.82	Calcium	0.04
Chloride	1.94	Potassium	0.04
Sodium	1.08	Bromine	0.0067
Magnesium	0.1292	Carbon	0.0028

weathering and erosion; and a very minor amount of salt which has been derived from igneous activity in the oceans themselves. Maps exhibiting the world's oceanic waters show that they are a continuous body of water encircling the Earth separated geographically by land masses, except for the Southern Ocean. For convenience, the World Ocean is divided into a number of principal areas and each is considered a separate ocean basin. Five oceanic divisions are usually recognized and are listed below.

These separate ocean basins have come into existence at different times and have been subjected to different forces and events throughout their geologic history. Professionals who study oceans are oceanographers and they usually recognize the five different ocean basins as follows:

- Atlantic;
- Pacific;
- Indian;
- Arctic; and
- Antarctic (or Southern).

Ocean waters are surprisingly uniform in composition in the open ocean basins and the average composition of sea water is given in Table 12.1.

As one might expect, oxygen and hydrogen are the most abundant elements, followed by chlorine and sodium.

12.3 Ocean Salinity

The most saline part of the oceans on Earth is in the Red Sea, shown in Fig. 12.1, because of its high rate of evaporation and the fact that it is nearly surrounded or enclosed by dry land or desert. The Red Sea is only open at the south to the Gulf of Aden and to the north by the Suez Canal to the Mediterranean Sea. The Mediterranean Sea is also a portion of the World Ocean with a high salinity for the same reasons.

Salinity is usually expressed as parts per thousand, which is approximately equal to grams per kilogram of solution.

Ocean water has an average salinity of around 3.5 parts per thousand which becomes less near shorelines that have large freshwater streams flowing into the ocean.

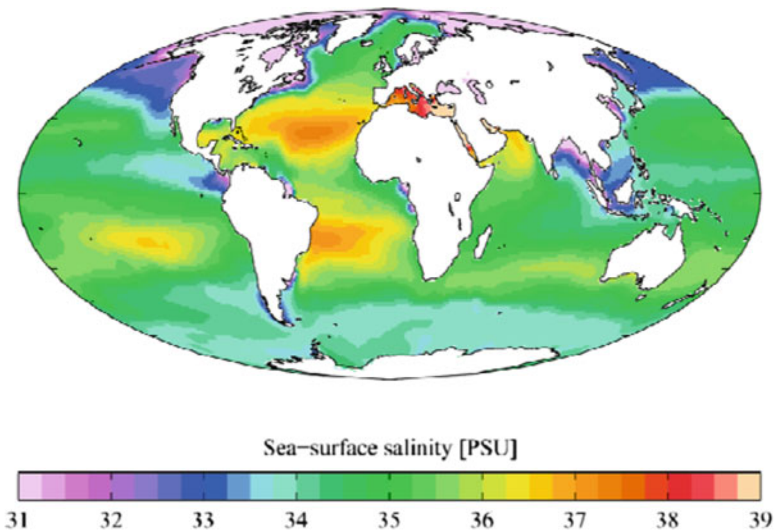


Fig. 12.1 Annual mean sea surface salinity in practical salinity units (PSU) (From Plumbago, Wikipedia, GNU Free Documentation license)

The variation in global ocean salinity is shown in Fig. 12.1. The Red Sea and the Mediterranean Sea show the highest rate of salinity represented by red in the figure.

12.4 Ocean Topography

To a large portion of the human population, the ocean is represented by their familiarity with a sandy beach. In communities near the ocean it is common to hear something like "Let's go down to the beach today." But the ocean is much more than just the beach, although the beach is important. Beaches are not present everywhere that oceans are found. There are some places where solid rock walls form the intersection of land and sea, and there is no beach.

Shorelines form the intersection of land and sea and these may be straight or irregular as seen from above or from map view. Seaward of the shoreline is the continental shelf, continental slope, and abyssal plain of the deep ocean (Fig. 12.2).

The Fig. 12.2 is a cross-section of a typical shoreline consisting of the coast, continental shelf, continental slope, an area called the continental rise, and the open ocean.

The continental shelf, continental slope, and continental rise are geologically part of the continent and are underlain by continental rocks such as granite and limestone. The Earth's crust is substantially thicker beneath the continent than beneath the ocean basin.

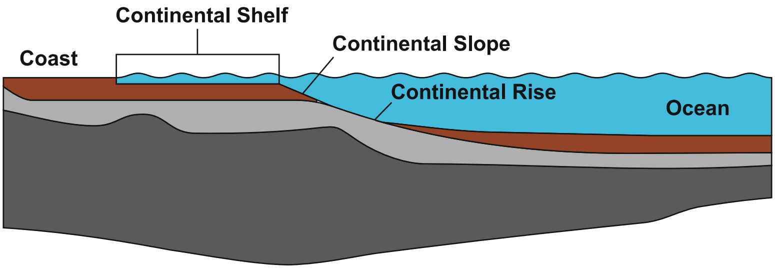


Fig. 12.2 Diagrammatic cross-section of the shoreline with the ocean and continent shown. Coast, continental shelf, continental slope, continental rise, and open ocean (http://www.onr.navy.mil/focus/ocean/regions/oceanfloor2.htm, Public Domain; redrawn by John Cook)

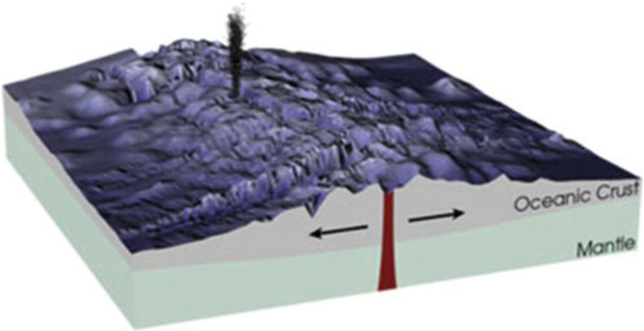


Fig. 12.3 Mid-ocean ridge with a black smoker showing movement of plates away from the ridge. The *red area* in the *middle* of the ridge is new crust being add at the ridge forcing the crust apart as indicated by the *arrows* (NASA, Public Domain)

The ocean basins are characterized by having a mid-ocean ridge system that separates two active oceanic plates. These plates are being forced apart by new material that is being added at the ridge by magma being emplaced along the center of the ridge (red area in Fig. 12.3). As new crust is being added along the mid-ocean ridges, older crust is being subducted to depths within the Earth in ocean trenches.

A recently (August 2011) discovered current, the North Icelandic Jet (NIJ) in the North Atlantic deep ocean, shown below (Fig. 12.4), has been recognized as contributing to the Earth's climate system.

Scientists have confirmed the presence of the NIJ, a deep-ocean circulation system off Iceland. It could significantly influence the ocean's response to climate change.

The NIJ contributes to a key component of the Atlantic Meridional Overturning Circulation (AMOC), critically important for regulating Earth's climate.

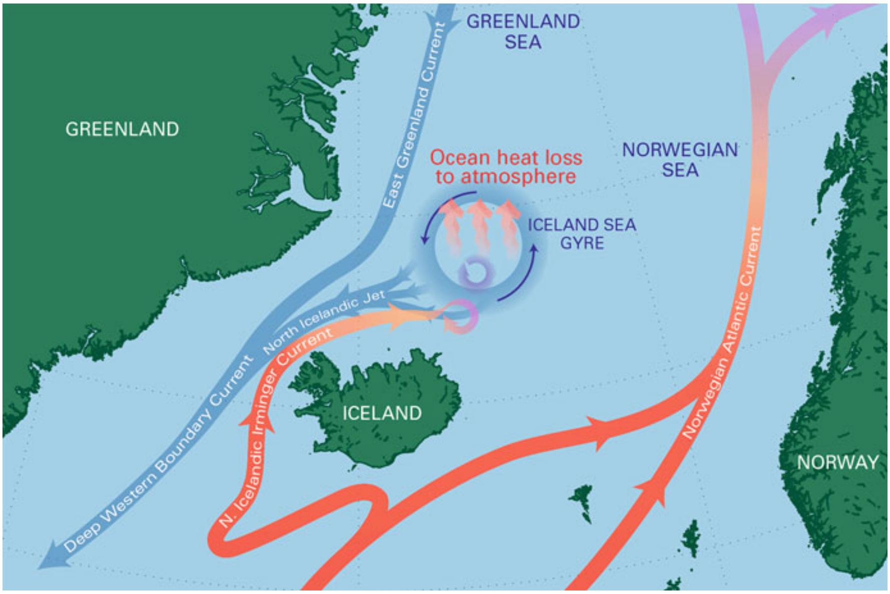


Fig. 12.4 North Icelandic Jet contributes to key component of ocean circulation. Northern Denmark Strait showing newly discovered deep current, in relation to known pathway (From WHOI)

As part of the planet's reciprocal relationship between ocean circulation and climate, the AMOC transports warm surface water to high latitudes where the water warms the air, then cools, sinks and returns toward the Equator as a deep flow.

Crucial to this warm-to-cold oceanographic mixing is the Denmark Strait Overflow Water (DSOW), the largest of the deep, overflow plumes that feed the lower limb of the AMOC and return the dense water south through gaps in the Greenland-Scotland Ridge.

For years it has been thought that the primary source of the Denmark Overflow was a current adjacent to Greenland known as the East Greenland Current (see Fig. 12.4). However, this view was recently called into question by two oceanographers from Iceland who discovered a deep current flowing southward along the continental slope of Iceland. They named the current the North Icelandic Jet and hypothesized that it formed a significant part of the overflow water.

Some scientists have been concerned that this overturning loop (some call it a conveyor belt; the AMOC) is slowing down due to a rise in global temperatures. They suggest that increasing amounts of fresh water from melting ice and other warming-related phenomena are making their way into the northern North Atlantic, where it could freeze and decrease the ability of the loop to deliver as much warm water as it does now.

Eventually, this could lead to a colder climate in the northern hemisphere.

While this scenario is far from certain, researchers need to better understand the overturning process in order to make accurate predictions about the future of climate change and circulation interaction.

12.5 The World Ocean and Carbon Dioxide

The majority of carbon dioxide emitted by burning fossil fuels is taken up by the ocean (about 51%). The excess heat due to the energy imbalance of Earth is also largely taken up by the oceans. So why should mankind worry about global warming and the burning of fossil fuels adding carbon dioxide to the Earth system if the oceans are absorbing the CO_2 and excess heat? Some skeptics have said that we don't need to worry because the oceans would simply take up the excess carbon dioxide and heat. But this has not happened; carbon dioxide keeps increasing in the atmosphere and the globe keeps warming.

Evidence suggests that the past and current ocean uptake of human-derived (anthropogenic) CO_2 is primarily a physical response to rising atmospheric CO_2 concentrations. Whenever the partial pressure of a gas is increased in the atmosphere over a body of water, the gas will diffuse into that water until the partial pressures across the air-water interface are equilibrated. However, because the global carbon cycle is intimately embedded in the physical climate system there exist several feedback loops between the two systems. For example, increasing CO_2 modifies the climate which in turn impacts ocean circulation and therefore ocean CO_2 uptake. Changes in marine ecosystems resulting from rising CO_2 and/or changing climate can also result in changes in air-sea CO_2 exchange. These feedbacks can change the role of the oceans in taking up atmospheric CO_2 making it very difficult to predict how the ocean's role in the carbon cycle will operate in the future.

The World Ocean has absorbed the majority of its CO_2 in the upper 700 m. There is very little interchange between the surface of the ocean and the ocean at depth except in special circumstances where deep ocean water is brought to the surface. Most of the heat and carbon dioxide are taken up by only the first few meters of the ocean, a small percentage of the total volume of sea water. Ocean waters are stratified with little interchange between layers.

Carbon dioxide is more soluble in cold water than in warm water. It takes about a year for CO_2 to be absorbed into ocean water if the surface water is cool enough to absorb it, and the ocean is warming at an ever increasing rate. As the ocean warms, it will release CO_2 and at a certain point ocean waters will become a source of CO_2 instead of a sink.

The ocean surface is warming faster than at ocean depth and there is minimal mixing between the ocean surface and the ocean depths. Some recent measurements have shown warming at depth and this warming is likely to increase.

Throughout geologic history, the world's oceans have been taking carbon dioxide out of the atmosphere and releasing it again in a steady exchange. The ocean also takes up carbon dioxide through photosynthesis by plant-like organisms known as phytoplankton, as well as by simple chemistry; carbon dioxide dissolves in cool water. It reacts with seawater, creating carbonic acid. Carbonic acid in turn releases hydrogen ions, which combine with carbonate in seawater to form bicarbonate, a form of carbon that doesn't escape from the ocean easily.

The concentration of carbon dioxide in ocean water depends on the amount of CO_2 in the atmosphere and the temperature of the water as well as the partial pressure differences in the two media.

Ocean and carbon dioxide exchange is a physico-chemical process, primarily controlled by the air-sea difference in gas concentrations and the exchange coefficient, which determines how quickly a molecule of gas can move across the ocean-atmosphere boundary. It takes about 1 year to equilibrate CO_2 in the surface ocean with atmospheric CO_2, so it is not unusual to observe large air-sea differences in CO_2 concentrations. Most of the differences are caused by variability in the oceans due to biology and ocean circulation.

12.6 Ocean Acidification

Ocean acidification is the lowering of the ocean pH and the increasing concentration of acid in the World Ocean. The ocean contains a very large reservoir of carbon that can be exchanged with the atmosphere because CO_2 reacts with water to form carbonic acid and its dissociation products. As atmospheric CO_2 increases, the interaction with the surface ocean will change the chemistry of seawater resulting in ocean acidification and this has already begun, as coral-reef environments are showing. The simplest chemical reaction that takes place when carbon dioxide comes in contact with water is the following:

$$CO_2 + H_2O \rightarrow H_2CO_3$$

Coral reefs, one of the most important and fragile ecosystems on the planet, are wasting away as ocean water becomes more acidic and the corals die. Corals form the framework of the coral reefs of the world, such as the Great Barrier Reef of Australia, the coral reefs of atolls of the Pacific, reef environments around the Caribbean islands, the Bahama Banks, the southern Florida Peninsula, and other parts of the tropics.

It is not just the coral reef environments of the planet that are in trouble, but benthic (bottom-dwelling) communities throughout the oceans, especially those near the continents in more shallow marine waters. All organisms that extract calcium from ocean waters to make hard parts from $CaCO_3$, such as clams, oysters, and other shell-bearing organisms as well as vertebrates that use tricalcium phosphate (Ca_3 $(PO_4)^2$) to build their skeletons are in danger of not being able to build their protective hard parts to survive as the World Ocean becomes more acidic.

The actual chemical reaction that takes place during ocean acidification is as follows:

$$CO_2 + H_2O + CO_3^{2-} \rightarrow 2HCO_3^{-}$$

Ocean waters have a major influence on world climates and they are a major sink and potential source of carbon dioxide. The oceans are expanding in volume due to warming and the melting of ice worldwide and sea level is rising. Warm ocean water has less capacity to hold carbon dioxide than cold ocean water. As ocean water continues to warm, it will eventually become a CO_2 source and begin to add CO_2 to the atmosphere.

As humans continue to burn fossil fuels and atmospheric carbon dioxide levels go up, the ocean absorbs more carbon dioxide to stay in balance. But as the carbon dioxide levels increase in the oceans, chemical reactions lower the water's pH, making it more acidic. As temperatures rise, carbon dioxide escapes from the ocean much like an open can of soda going flat on a warm day (the carbon dioxide escapes even faster if it is shaken). Carbonate gets used up and is replenished by upwelling of deeper waters, which are rich in carbonate dissolved from limestone and other rocks from the continents (and perhaps minor amounts from the ocean floor and submarine volcanoes).

In the period 1995–2010 alone, acidity increased 6% in the upper 100 m of the Pacific Ocean from Hawaii to Alaska, as reported by ocean scientists. A National Research Council study released in April 2010 concluded that "the level of acid in the oceans is increasing at an unprecedented rate." A 2012 paper in the journal *Science* examined the geological record in an attempt to find a historical analog for current global conditions as well as those of the future. The researchers determined that the current rate of ocean acidification is faster than at any time in the past 300 million years.

12.7 Oceanic Circulation

Oceanic circulation is often referred to as the "Great Conveyor Belt" as it conveys and distributes energy throughout the oceanic world. Without this "conveyor belt" distribution, places at the same latitude across the globe would be expected to have the same average temperatures. However, because of this circulation, Norway, located at similar latitude to Manitoba, Canada has an average annual temperature that is nearly 20°F warmer.

In the open ocean, far from shore, wind-driven currents bring cool waters and fresh carbonate to the surface. The new, colder water from below takes up more carbon to reach equilibrium with the atmosphere, while the older water carries carbon it has captured deeper into the ocean. There is constant circulation within the ocean but it takes hundreds of thousands of years if not millions for complete oceanic mixing.

Ocean circulation is essential for energy distribution throughout the planet. The major ocean currents are shown in Fig. 12.5 and it is these currents that are largely responsible for the redistribution of energy throughout the World Ocean system. The major oceanic currents are listed in the table below (Table 12.2) along with their directions of flow.

Each of these currents shown in Fig. 12.5 impacts climate throughout the globe. Note the Coriolis effect on the ocean currents in both the Northern and Southern Hemispheres.

The Antarctic Circumpolar current circles the Southern Hemisphere continent of Antarctica and keeps interchange of warmer waters from the Atlantic and Pacific at

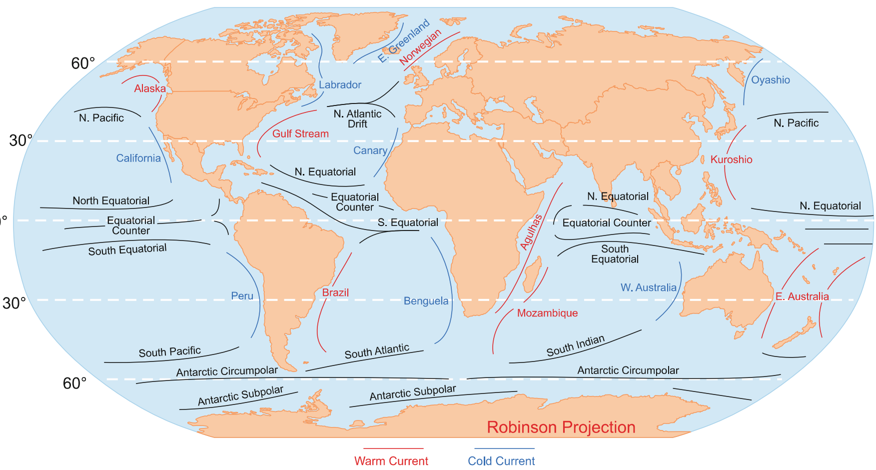


Fig. 12.5 Major ocean currents in the World Ocean

a minimum. However, western Antarctica is beginning to warm and sea ice to melt and this could interfere with the lack of interchange with warmer waters. Warmer waters flowing toward the Antarctic continent will hasten the wasting away of the continental ice cap. Major portions of the western Antarctic ice cap are reported to be collapsing into the Southern Ocean.

Ocean composition, distribution, circulation, and evolution are important in aspects of climate change science as they have been throughout Earth's history.

12.7.1 Thermohaline Circulation

Thermohaline circulation has been referred to as a "conveyor belt" of the ocean. It is oceanic circulation caused by differences in density which are caused by differences in water temperature and water salinity. These properties are measurable and are known with a high degree of certainty.

Cold water is heavier than warm water and water with a high degree of salinity is heavier than water with a low salinity and these differences cause major circulation to take place throughout the World Ocean. This circulation takes place because of density gradients created by heat and salinity differences. Wind driven surface currents, such as the Gulf Stream, flow toward the poles from the equator, cool, and eventually sink at high latitudes. In the Southern Hemisphere, the warm waters from the equator sink beneath the Southern Ocean before upwelling. The oldest waters found in the ocean basins have upwelled in the northern Pacific with a transit time of around 1,600 years.

The thermohaline circulation plays an important role in supplying heat to the Polar Regions and in regulating the amount of sea ice in these regions (Fig. 12.6), although poleward heat transport outside the tropics is considerably larger in the

Table 12.2 Major ocean currents with their flow directions

Major ocean currents
East Greenland Current – flows southwest along the east coast of Greenland
Labrador Current – flows south around the east coast of Labrador
North Pacific Current – flows to the east in the northern Pacific
North Equatorial Current – flows westward north of the equator
North Atlantic Drift – gives rise to the Norwegian Current
Gulf Stream – flows from the Gulf of Mexico toward western Europe
Equatorial Counter Current – flows against the North and South Equatorial Currents
Norwegian Current – a warm current that flows out of the North Atlantic Drift
Oyashio Current – flows south along the east coast of Japan
Kuroshio Current – flows northeast away from Japan
South Equatorial Current – flows south of the equator to the west
Alaska Current – flows north west, then west, then southwest around the southern area of Alaska
Brazil Current – flows southwest along the east coast of South America
California Current – a cold water current flowing southeast along the California coast
Peru Current – flows north and northwest along the Peruvian coast
Benguela Current – flows north along the west African coast
South Atlantic Current – flows northeast from the Antarctic Circumpolar Current
South Pacific Current – flows east-northeast in the south Pacific
East Australia Current – flows southwest along the east coast of Australia
Antarctic Circumpolar Current – flows around the continent of Antarctica
Antarctic Subpolar Current – flows to the west north of Antarctica
Western Australian Current – flows north along the west coast of Australia
Mozambique Current – flows southwest along the east coast of Africa
Aguilnas Current – flows southwest along the east coast of Africa landward of the Mozambique Current
Canary Current – flows southwest along the northwest coast of Africa
South Indian Current – flows east and northeast toward the southern Indian Ocean

atmosphere than in the ocean. Changes in the thermohaline circulation are thought to have significant impacts on the Earth's radiation budget. It may also play an important role in determining the concentration of carbon dioxide in the atmosphere.

Large influxes of low density melt-water from the historical glacial Lake Agassiz and deglaciation in North America, beginning about 20,000–18,000 years ago, are thought to have led to a disruption of deep water formation and subsidence in the extreme North Atlantic and may have caused the climate episode in Europe known as the Younger Dryas, from 12,800 to 11,500 years ago.

Additional Readings

Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC). (2008). *Position analysis: CO2 emissions and climate change: OCEAN impacts and adaptation issues*. Hobart: Antarctic Climate and Ecosystems Cooperative Research Centre. ISSN 1835–7911.

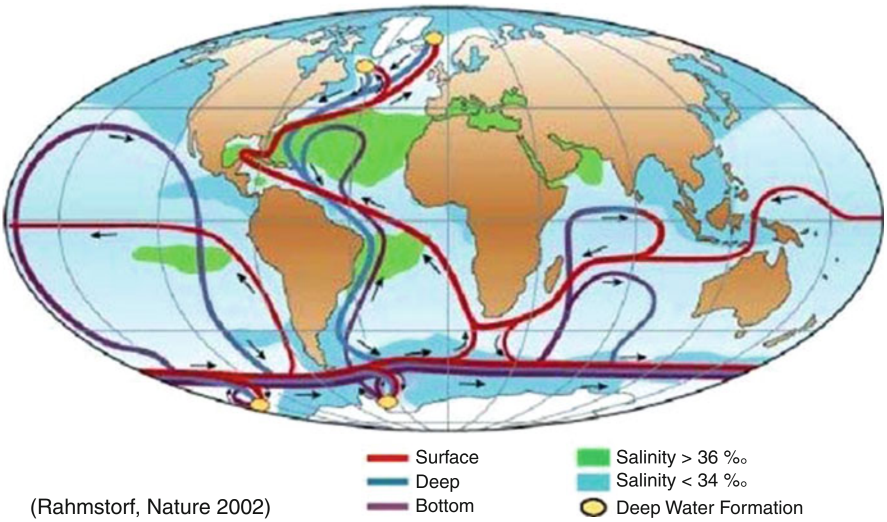


Fig. 12.6 Global Thermohaline Circulation. This collection of currents is responsible for the large-scale exchange of water masses in the ocean, including providing oxygen to the deep ocean. The entire circulation pattern takes ~2,000 years (From NASA, Public Domain)

Atkinson, M. J., & Cuet, P. (2008). Possible effects of ocean acidification on coral reef biogeochemistry: Topics for research. *Marine Ecology Progress Series, 373*, 249–256. doi:10.3354/meps07867.

Berger, W. H. (1990). The Younger Dryas cold spell – A quest for causes. *Global and Planetary Change, 3*(3), 219–237. doi:10.1016/0921-8181(90)90018-8. Bibcode 1990GPC.....3..219B.

Caldeira, K., & Wickett, M. E. (2003). Anthropogenic carbon and ocean pH. *Nature, 425*(6956), 365. doi:10.1038/425365a. Bibcode 2001AGUFMOS11C0385C. PMID 14508477.

Cicerone, R., Orr, J., Brewer, P., et al. (2004). The Ocean in a High CO_2 World. *EOS Transactions American Geophysical Union, 85*(37), 351–353. doi:10.1029/2004EO370007. Bibcode2004EOSTr..85R.351C.

Doney, S. C. (2006). The dangers of ocean acidification. *Scientific American, 294*(3), 58–65. doi:10.1038/scientificamerican0306-58. ISSN 0036-8733. PMID 16502612.

Feely, R. A. (2004). Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science, 305*(5682), 362–366. doi:10.1126/science.1097329. PMID 15256664.

Jacobson, M. Z. (2005). Studying ocean acidification with conservative, stable numerical schemes for nonequilibrium air-ocean exchange and ocean equilibrium chemistry. *Journal of Geophysical Research-Atmospheres, 110*, D07302. doi:10.1029/2004JD005220. Bibcode 2005JGRD..11007302J.

Kleypas, J. A. et al. (2006). *Impacts of ocean acidification on coral reefs and other marine calcifiers: A guide for further research*. Report of a workshop held 18–20 April 2005, St. Petersburg, FL, sponsored by National Science Foundation, NOAA and the U.S. Geological Survey, 88 pp.

Niiler, P. P., et al. (2003). Dynamically balanced absolute sea level of the global ocean derived from near-surface velocity observations. *Geophysical Research Letters, 30*(22), 2164. doi:10.1029/2003GL018628.

Orr, J. C., et al. (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature, 437*(7059), 681–686. doi:10.1038/nature04095. Bibcode2005Natur.437..681O. PMID 16193043.

Review of Past IPCC Emissions Scenarios. IPCC Special Report on Emissions Scenarios, ISBN 0521804930. http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=10

Richardson, P. L. (1980). The Benjamin Franklin and Timothy Folger charts of the gulf stream. In M. Sears & D. Merriman (Eds.), *Oceanography, the past*. New York: Springer.

United States National Research Council. (2010). *Ocean acidification: A national strategy to meet the challenges of a changing ocean*. US National Academy of Sciences. http://dels.nas.edu/Report/Ocean-Acidification-National-Strategy/12904

Chapter 13
Ocean Heat Content and Rising Sea Level

Abstract Ocean heat is increasing, especially in the upper 700 m and sea level is rising worldwide. A worldwide rise in sea level is known as a eustatic sea level rise. Factors affecting climate are complex but El Niño and La Niña are well established. Together they form the ENSO, or El Niño (and La Niña) Southern Oscillation in the equatorial Pacific that affects weather worldwide. Wetlands are an important ecosystem and many are being lost as a result primarily of sea level rise but because of other activities and influences by humankind as well.

Keywords Arctic • Oscillation • NAMO • AO • Ice • Polar • Caps • Eustatic • NAO • ENSO • El Niño • La Niña • Sea • Level • Coastal • GRACE • Negative • AMO • Icelandic • Azores • Jet • Stream • Expansion • Gulf • Multidecadal • Argo • Floats • Calving • Wetlands

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
Sea Level	NAMO
El Niño	Polar Ice Caps
Wetlands	NAO
Eustatic	North Atlantic
Calving	ENSO
Coastal Areas	Water Expansion

(continued)

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_13,

(continued)

Things to Know	
Darwin, Australia	70 Years
Tectonics	Argo Floats
SOI	AO
Baffin Bay	18,000 years ago
Eustatic Sea Level	Jet Stream
La Niña	SST
Arctic Oscillation	GRACE
Sea Ice	Industrial Revolution
Dust Bowl	Positive Oscillation Phase
Inverse Barometric Effect	Negative Oscillation Phase
Rising Sea Level Projections	Gulf Stream

13.1 Introduction

The Earth is warming, ice is melting, and sea level is rising. Water expands as it is heated and the World Ocean is expanding causing a worldwide increase in sea level. The World Ocean is also rising due to the melting of glaciers and polar ice caps. The ocean has been rising worldwide relative to land since the last continental glaciation began to recede about 20,000–18,000 years ago and has been rising faster during the last 200 plus years since the Industrial Revolution.

There are exceptions to rising sea level in certain areas where Earth movements, i.e., tectonics, have caused shorelines to rise faster than sea level is rising. Tectonic activity along shorelines may result in the appearance of a lowering of sea level, but it is local or regional, not worldwide. Episodes of heavy precipitation on land and higher evaporation rates over the ocean have caused from time to time a temporary lowering of sea level in some areas by taking water out of the oceans and delivering it to land as precipitation.

13.2 Global Warming and Sea Level Rise

Warming is causing glacial ice to collectively disappear. The title of a 2009 book by Henry Pollack entitled "A World without Ice" paints a picture of a planet that will be unrecognizable to any space traveler returning to Earth after an absence of 300 years or so. Earth is losing an amazing amount of ice annually, and this ice loss is being accurately measured by NASA's GRACE satellites, a pair of satellites that measure the Earth's gravity differences in great detail. The total global ice mass lost from the world's glaciers and ice caps is approximately 150 billion tons annually according to a recent study by scientists at the University of Colorado (http://www.colorado.edu/news/releases/2012/02/08/cu-boulder-study-shows-global-glaciers-ice-caps-shedding-billions-tons-mass). The world's glaciers and ice caps had lost about 148 billion tons, or about 39 cubic miles of ice annually from 2003 to 2010. The total does not count the mass from individual glacier and ice caps on the fringes of the Greenland and Antarctic ice sheets, roughly an additional 80 billion tons.

There is a direct relationship between glacial ice and worldwide (eustatic) sea level. As glacial ice is reduced, eustatic sea level rises. As glacial ice expands, eustatic sea level is lowered. Glaciers may be thought of as storage units for freshwater. As this freshwater is released when glacial ice is receding, eustatic sea level rises.

Sea ice does not have this relationship with sea level. Sea ice is frozen sea water except for "sea ice" that has resulted from the calving of glacial ice. Calving is the process that gives rise to icebergs and involves the breaking off of a part or parts from glaciers on land that flow into the sea.

13.3 Arctic Oscillation (AO) and Arctic Sea Ice

The Arctic Oscillation refers to opposing atmospheric pressure patterns in northern middle and high latitudes and has a major effect on climate in the Northern Hemisphere.

The AO exhibits a "negative phase" with relatively high pressure over the polar region and low pressure at mid-latitudes (about 45° North), and a "positive phase" in which the pattern is reversed. In the positive phase, higher pressure at mid-latitudes drives storms farther north and changes in the circulation pattern bring wetter weather to Alaska, Scotland and Scandinavia, as well as drier conditions to the western United States and the Mediterranean. In the positive phase, frigid winter air does not extend as far into the middle of North America as it would during the negative phase of the oscillation. This keeps much of the United States east of the Rocky Mountains warmer than normal, but leaves Greenland and Newfoundland colder than usual. Weather patterns in the negative phase are in general "opposite" to those of the positive phase, as illustrated below (Fig. 13.1).

Over most of the past century, the Arctic Oscillation alternated between its positive and negative phases. Starting in the 1970s, however, the oscillation has tended to stay in the positive phase, causing lower than normal arctic air pressure and higher than normal temperatures in much of the United States and northern Eurasia.

Arctic sea ice forms the northernmost ice field on Earth and each year it is being reduced in volume. Arctic sea ice extent for January 2011 was the lowest in the satellite record for that month but the extent of sea ice may be a poor means of comparison of ice loss from year to year. Sea ice may expand in extent yet decrease in volume as new and thinner sea ice expands at the expense of thicker older sea ice.

The Arctic Oscillation is an atmospheric circulation pattern in which the atmospheric pressure over the polar regions varies in opposition with that over middle latitudes (about 45° North) on time scales ranging from weeks to decades. The oscillation extends through the depth of the troposphere. During the months of January through March it extends upward into the stratosphere where it modulates in the strength of the westerly vortex that encircles the Arctic polar cap region (Fig. 13.1). The North Atlantic Multidecadal Oscillation (NAO or NAMO) and Arctic Oscillation (AO) are different ways of describing the same phenomenon, although some meteorologists distinguish the two. One way of distinguishing them is as follows: the pressure field from 70° north latitude up to the North Pole is called

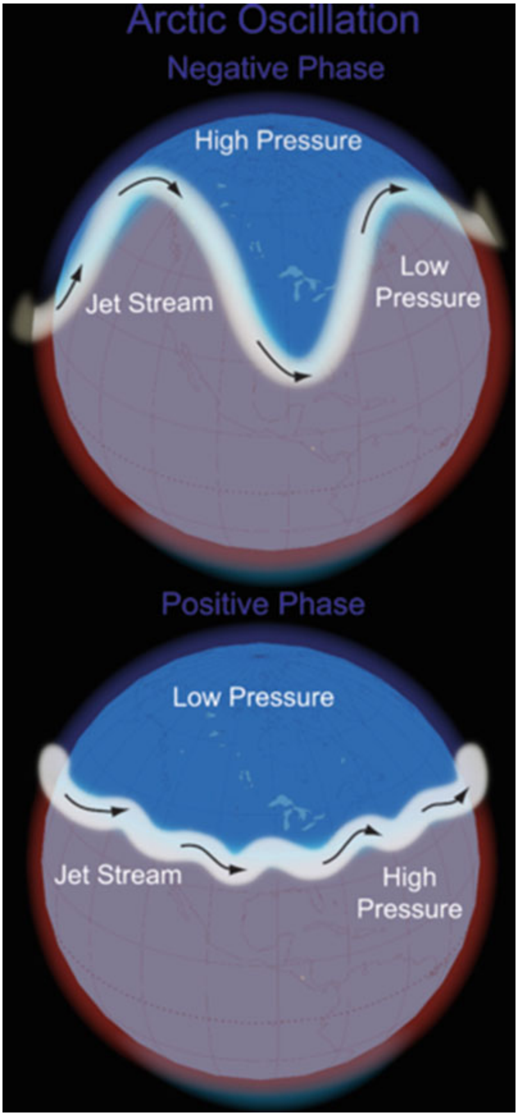


Fig. 13.1 Arctic Oscillation positive and negative phases (Public Domain)

the Arctic Oscillation. The pressure field from 70 degrees down to the subtropics is called the North Atlantic Oscillation. Sometimes it is convenient to discuss them separately; at other times it is convenient to discuss them as one oscillation.

The Arctic is warming faster than the rest of the Earth, as Earth scientists and climate change scientists have been predicting for some time and the north polar ice cap is rapidly disappearing (see Fig. 13.2).

The AO/NAO is a fluctuation in the barometric pressure between the Icelandic low and the Azores high. It varies over time with no predictable periodicity. The AO/NAO is a largely atmospheric condition. It is one of the most important manifestations of climate fluctuations in the North Atlantic and surrounding humid climates on land.

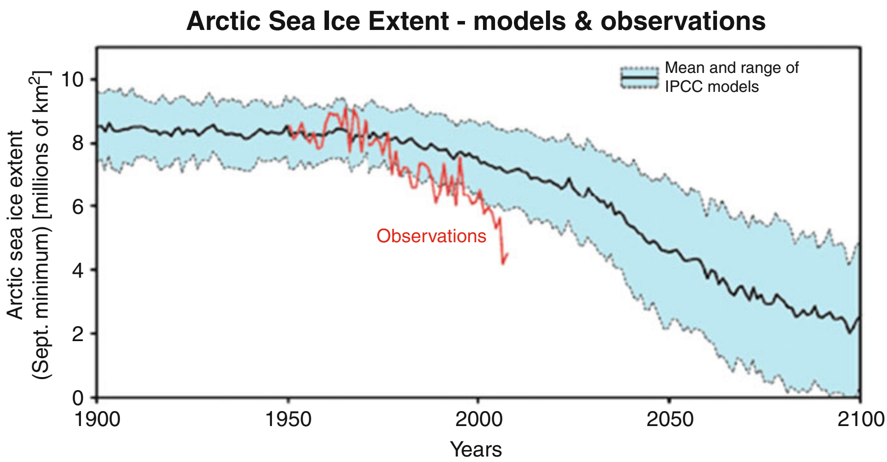


Fig. 13.2 Arctic sea ice is disappearing faster than the IPCC models predicted (From http://www.copenhagendiagnosis.com/)

The Arctic Oscillation affects sea level in the north Atlantic. When the AO/NAO is positive, there is a regional rise in sea level due to the "inverse barometric effect." The "inverse barometric effect" is when sea level is raised due to lowered barometric pressure. A barometric pressure fluctuation on the order of milibars can result in sea level fluctuations in centimeters.

Air temperatures over much of the Arctic were 2–6°C (4–11°F) above normal in January 2011. Over the eastern Canadian Arctic Archipelago, Baffin Bay, Davis Strait, and Labrador Sea, temperatures were at least 6°C (11°F) higher than average. Temperatures were near average over the western Canadian Arctic Archipelago and Scandinavia.

In winter (NH) 2010, warm temperatures in January came from two sources; unfrozen areas of the ocean continued to release heat to the atmosphere, and the wind patterns accompanying the negative phase of the Arctic oscillation brought warm air into the Arctic. Near the end of January 2011 the negative Arctic oscillation pattern broke down and turned positive, which usually favors ice growth.

Arctic sea ice has been retreating and getting thinner each year since satellite records have been kept beginning in1979.

13.4 Atlantic Multidecadal Oscillation (AMO)

The AMO is a series of long-duration changes in the sea surface temperature (SST) of the North Atlantic Ocean, with cool and warm phases that may last for 20–40 years at a time with a difference of about 1°F between extremes. These changes are natural and have been occurring for at least the last 1,000 years. The AMO has been in the warm phase since the 1990s.

The Atlantic Multidecadal Oscillation is based on the SST variability in the North Atlantic. The number of tropical storms in the northern Atlantic that can mature into severe hurricanes is much greater (at least twice as many) during warm phases of the AMO than during cool phases.

The AMO can be correlated with air temperatures and rainfall over much of the Northern Hemisphere. It is also correlated with changes in the frequency of North American droughts. It either obscures or exaggerates the global temperature increase due to global warming.

The AMO is related to the past occurrence of major droughts in the Midwest and the Southwest. When the AMO is in its warm phase, these droughts tend to be more frequent and severe. The opposite is true for negative AMO. Two of the most severe droughts of the twentieth century occurred during the positive AMO between 1925 and 1965; the Dustbowl of the 1930s and the 1950s drought. Florida and the Pacific Northwest tend to be the opposite. A warm AMO brings more rainfall to these areas.

There is an apparent periodicity for the AMO of about 70 years (between 50 and 90 years). Models of the ocean and atmosphere that interact with each other indicate that the AMO cycle involves changes in the south-to-north circulation and overturning of water and heat in the Atlantic Ocean. This is the same circulation that scientists think weakens during ice ages, but in the case of the AMO the changes in circulation are much more subtle than those of the ice ages. The warm Gulf Stream current off the east coast of the United States is part of the Atlantic overturning circulation. When the overturning circulation decreases, the North Atlantic temperatures become cooler.

13.5 Pacific Decadal Oscillation (PDO)

The Pacific Decadal Oscillation (PDO) is a shifting of Pacific Ocean temperatures north of 20 °N. It consists of a warm or positive phase and a cool or negative phase. During a warm or positive phase, the western Pacific becomes cool and part of the eastern Pacific warms. During a negative phase, the opposite is true. The leading hypothesis is that the PDO is caused by ENSO. The PDO has been traced back to 1661 through tree-ring analysis. The PDO shifts phases on a time scale of 20–30 years. A related shift with sea-surface temperatures and sea-level pressure patterns has been named the Interdecadal Pacific Oscillation (IPO) with a cycle of 15–30 years. There is also a quasi-decadal oscillation (QDO) with a period of 6–12 years that straddles the equator.

13.6 Future Potential Sea Level Rise

Global average sea level rose at an average rate of around 1.7 mm per year over 1950–2009 and at a satellite-measured average rate of about 3.3 mm per year from 1993 to 2009, an increase from earlier estimates. Sea level is rising faster than the earlier predictions.

If all the ice on Earth at present disappeared including continental, ice cap, and mountain glaciers plus permafrost, the United States Geological Survey estimates that sea level will rise about 260 ft (nearly 80 m). The effects of this sea level rise on human populations would be disastrous.

Today's densely populated low level mega-deltas, such as the Mississippi River, the Mekong, and Nile deltas are especially vulnerable to sea-level rise. More than one million people living in the Ganges- Brahmaputra, Mekong and Nile deltas will be directly affected by a 1 m rise in sea level simply if current rates of sea-level rise continue to 2050. Some 75% of the populations that will be affected live on the Asian mega-deltas and smaller deltas near sea level, with a large proportion of the remainder living on deltas in Africa. These impacts would increase dramatically with accelerated sea-level rise. Today, over 70% of the world's population (seven billion plus in 2012; the seven billion mark was reached in October 2011) lives on coastal plains and estuaries. Many island states such as the Maldives would cease to exist. The average elevation of the Maldives islands is 4′ 11″ with the highest point being 7′ above sea level.

The main factors causing sea level to rise are the heat expansion of the oceans by global warming and the melting of glacial ice on land.

Sea level rise is expected to continue for centuries. In 2007, the Intergovernmental Panel on Climate Change (IPCC) projected that during the twenty-first century, sea level will rise another 18–59 cm (7.1–23 in), but these numbers do not include "uncertainties in climate-carbon cycle feedbacks nor do they include the full effects of changes in ice sheet flow." Although IPCC explicitly refrained from projecting an upper limit of total sea level rise in the twenty-first century, 1 m of sea level rise is well within the range of more recent projections. From recent measurements of sea level worldwide, it is generally agreed that the IPCC projections were conservative.

On the timescale of centuries to millennia, the melting of ice sheets could result in even higher sea level rise. Partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic ice sheet, could contribute 4–6 m (13–20 ft) or more to sea level rise. These ice sheets are already showing signs of collapsing.

The 2007 Fourth Assessment Report (IPCC AR4 2007) projected century-end sea levels using the projections in the Special Report on Emissions Scenarios (SRES). SRES developed emissions scenarios to project climate change impacts. The projections based on these scenarios are not predictions, but reflect plausible estimates of future social and economic development (e.g., economic growth, population level). The six SRES scenarios projected sea level to rise by 18–59 cm (7.1–23 in). Their projections were for the time period 2090–2099, with the increase in level relative to average sea level over the 1980–1999 timeframe. This estimate did not include all of the possible contributions of ice sheets.

More recent research from 2008 observed rapid declines in ice mass balance from both Greenland and Antarctica, and concluded that sea-level rise by 2100 is likely to be at least twice as large as that presented by IPCC AR4, with an upper limit of about 2 m.

A literature assessment published in 2010 by the US National Research Council described the above IPCC projections as "conservative," and summarized the results of more recent studies. These projections ranged from 56 to 200 cm (22–79 in), based on the same period as IPCC AR4.

Loss of wetlands is an additional adverse effect of sea level rise. Wetlands are defined as land saturated with water and they represent some of the most important ecosystems on Earth. Wetlands are also considered the most biologically diverse of all ecosystems, serving as home to a wide range of plant and animal life. The United Nations has determined that environmental degradation is more prominent within wetland systems than any other ecosystem on Earth and a large part is due to sea level rise and the impact of the encroachment of salt water.

13.7 Ocean Heat Content

The vast majority of global warming is going into the World Ocean. The World Ocean is the largest collector of solar energy on Earth.

This ability to store and release heat over long periods of time gives the ocean a major role in stabilizing Earth's climate system. Waves, tides, and ocean currents constantly mix the ocean and move heat from warmer to cooler latitudes and to deeper levels. The majority of ocean temperature data is from the upper 700 m of the ocean. Deeper readings are more difficult and expensive to obtain.

Earlier readings of the ocean's temperature required ships to insert sensors or sample collectors into the water. This time-consuming method could provide temperatures for only a small part of the planet's vast ocean and for only the upper few meters and it was not terribly accurate. To get global coverage, scientists turned to satellites that measure the height of the ocean's surface. As water warms it expands, so estimates for ocean temperature can be deduced from sea surface heights. To obtain deeper temperature readings, a different method was needed.

To get a more complete picture of ocean heat content at different depths, scientists and engineers use a range of temperature-sensing instruments. Among these are a fleet of more than 3,000 robotic "floats" that measure ocean temperature around the world. Known as Argo floats, the sensors drift through the ocean at different depths. Every 10 days or so, according to their programmed instructions, they rise through the water, recording temperature (and salinity) as they ascend. When a float reaches the surface, it sends its location and other information to scientists via satellites, and then it descends again. The readings are then converted to joules (a standard unit of energy defined as "the work required to produce 1 W of power for 1 s") that allow scientists to compare heat in the ocean to heat in other parts of Earth's climate system.

It is evident from analyses of the ocean temperature readings that more than 90% of the warming that has happened over the past 50 years on Earth has occurred in the ocean. Though the atmosphere has been spared from the full extent of global warming for now, the heat already stored in the ocean will eventually be released, causing Earth to warm even more rapidly in the future.

At present, warming of ocean water is raising eustatic sea level because water expands when it warms. When combined with water from melting glaciers, the rising sea threatens natural ecosystems and human-made structures near coastlines around the world. Warming ocean waters are also causing thinning of ice shelves and sea ice, both of which have further consequences for Earth's climate system. Warming ocean waters also threaten marine ecosystems and human livelihoods. For example, warm waters and ocean acidification due to carbon dioxide jeopardize the health of corals, and in turn, the communities of marine life that depend on them for shelter and food. Ultimately, people who depend upon marine fisheries for food and jobs will eventually face negative impacts from a warming and acidifying ocean. Many of these impacts are beginning to be felt.

13.8 El Niño – La Niña (or ENSO)

The El Niño and La Niña events involve tropical Pacific water temperatures and their effects on climate throughout the world, especially in the tropics and low- to mid-latitudes.

El Niño is characterized by unusually warm ocean temperatures in the equatorial Pacific as opposed to La Niña which is characterized by unusually cold temperatures in the equatorial Pacific. Typically, El Niño happens at irregular intervals of 3–7 years and lasts 9 months to 2 years. It shows quasiperiodicity (irregular periodicity).

El Niño usually starts with mild trade winds bringing warmer waters east that pile up along the west coast of South America. Normally, waters off the west coast of South America are cool due to upwelling adjacent to the coast. This upwelling of deep oceanic water brings nutrients from depth to the surface and supports an abundant fish population. It also brings carbon dioxide to the surface where it is lost to the atmosphere as the water warms on its ascent.

At higher latitudes in each hemisphere, El Niño and La Niña are just two of the factors that influence climate; there are many others. However, the impacts of El Niño and La Niña at these latitudes are substantial and can be most clearly seen in winter. In the continental U. S., during El Niño years, temperatures in the winter are warmer than normal in the North Central States, and cooler than normal in the Southeast and the Southwest. During a La Niña year, winter temperatures are warmer than normal in the Southeast and cooler than normal in the Northwest.

ENSO is an acronym from **E**l **N**iño **S**outhern **O**scillation. ENSO is an oscillation of the ocean-atmosphere system in the tropical Pacific that affects the global weather. Weather effects of ENSO include increased rainfall across the southern part of the United States and in Peru, resulting in extensive flooding and drought in the western Pacific, including devastating fires in Australia.

In normal, non-El Niño conditions the trade winds blow towards the west across the tropical Pacific. These winds pile up warm surface water in the western Pacific so that the sea surface is about 1/2 m higher at Indonesia than at Ecuador. During El Niño conditions, the trade winds diminish in the central and western Pacific causing a depression of the thermocline (a layer that marks a change in temperature) in the eastern Pacific and an elevated thermocline in the west.

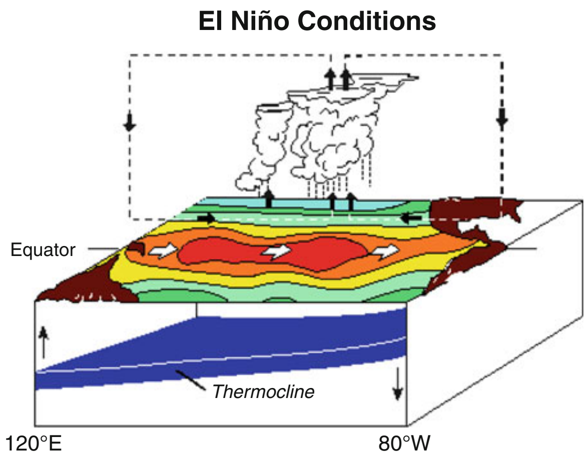


Fig. 13.3 Block Diagram showing El Niño conditions in the tropical Pacific (From http://www.pmel.noaa.gov/tao/; Public Domain)

The illustrations 13.3, 13.4, and 13.5 show typical El Niño, normal, and La Niña conditions in the equatorial Pacific with land areas shown in brown, South America and North America in the east and Indonesia in the west.

During El Niño, rainfall and thunderstorm activity diminishes over the western equatorial Pacific and increases over the eastern half of the tropical Pacific. El Niño episodes feature large-scale changes in the atmospheric winds across the tropical Pacific, including reduced easterly (east- to- west) winds across the eastern Pacific in the lower atmosphere, and reduced westerly (west-to-east) winds over the eastern tropical Pacific in the upper atmosphere near the tropopause. These conditions reflect a reduced strength of the equatorial Walker Circulation, which in strong El Niño episodes can be completely absent.

The Walker Circulation or Walker Cell is an atmospheric circulation, mainly vertical but with a Hadley Cell (meridional) component (Fig. 13.6).

Maps showing sea surface temperatures during El Niño and La Niña episodes are shown in Fig. 13.7. High temperatures are indicated by red and cool temperatures are shown in blue.

During the developing phase of El Niño, the ocean structure at depth is characterized by an abnormally deep layer of warm water and an increased depth of the thermocline across the eastern tropical Pacific. The slope of the thermocline is reduced across the basin. In very strong El Niño episodes, the thermocline can become flat across the entire tropical Pacific for periods of several months.

The Southern Oscillation Index (SOI) is one measure of the large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific (i.e., the state of the Southern Oscillation) during El Niño and La Niña episodes. Traditionally, this index has been calculated based on the differences in air pressure anomaly between Tahiti and Darwin, Australia. In general, smoothed time series of the SOI correspond well with changes in ocean temperatures across the eastern tropical Pacific. The negative

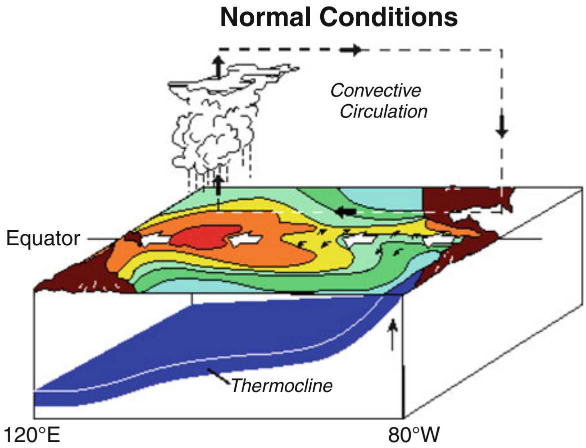


Fig. 13.4 Block Diagram showing normal conditions in the tropical Pacific (From http://www.pmel.noaa.gov/tao/; Public Domain)

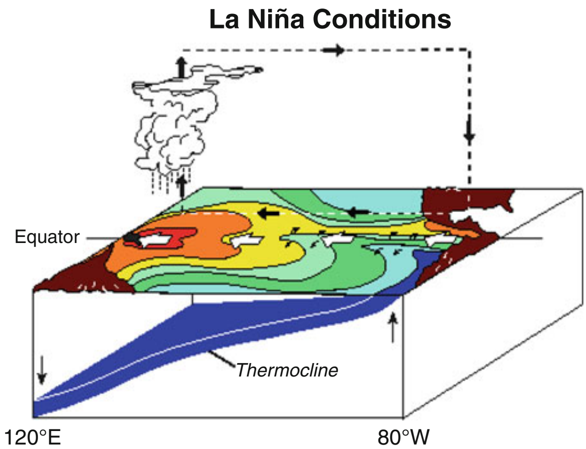


Fig. 13.5 Block diagram showing La Niña conditions in the tropical Pacific (From http://www.pmel.noaa.gov/tao/; Public Domain)

phase of the SOI represents below-normal air pressure at Tahiti and above-normal air pressure at Darwin. Prolonged periods of negative SOI values coincide with abnormally warm ocean waters across the eastern tropical Pacific typical of El Niño episodes. Prolonged periods of positive SOI values coincide with abnormally cold ocean waters across the eastern tropical Pacific typical of La Niña episodes.

During La Niña, rainfall and thunderstorm activity diminishes over the central equatorial Pacific, and becomes confined to Indonesia and the western Pacific. The area experiencing a reduction in rainfall generally coincides with the area of abnormally cold ocean surface temperatures. This pattern of rainfall departures spans nearly one-half the way around the globe, and is responsible for many of the global weather impacts caused by La Niña.

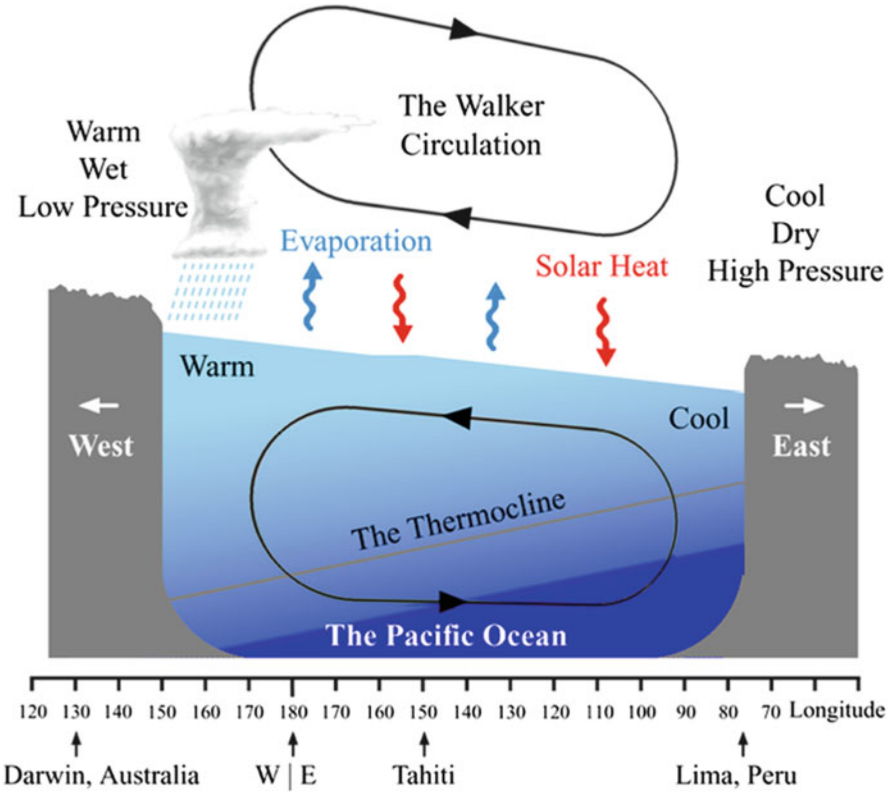


Fig. 13.6 Walker circulation in cross-sectional view. A schematic diagram of the quasi-equilibrium and La Niña phase of the southern oscillation (Public Domain)

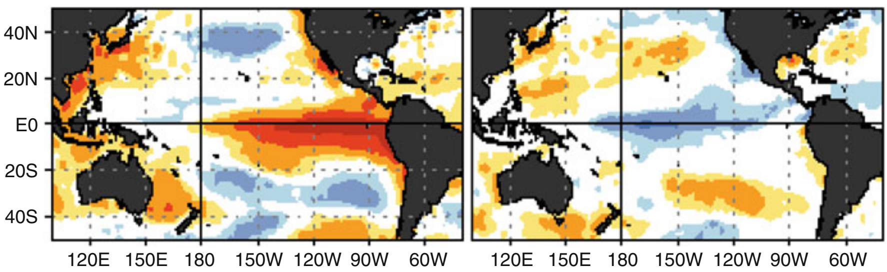


Fig. 13.7 El Niño (*left panel*) and La Niña (*right panel*) sea surface temperatures (From http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/enso_cycle.shtml, Public Domain)

Additional Readings

Church, J. A., et al. (2011). Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters, 38*, L18601, 8 pp. doi:10.1029/2011GL048794.

Levitus, S. (2000). Warming of the World Ocean. *Science, 287*, 2225–2229. doi:10.1126/science.287.5461.2225.

Lindsey, R. (2008). *Correcting ocean cooling*. *NASA Earth observatory*. Accessed 02 Feb 2011.

Meehl, G. A., et al. (2011). Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods. *Nature Climate Change, 1*(2011), 360–364. doi:10.1038/nclimate1229.

Palmer, M. D., et al. (2011). Importance of the deep ocean for estimating decadal changes in Earth's radiation balance. *Geophysical Research Letters, 38*. doi:10.1029/2011GL047835.

Philander, S. G. H. (1990). *El Niño, La Niña and the Southern Oscillation* (289 pp). San Diego: Academic.

Scott, M. (2006). *Earth's big heat bucket*. *NASA Earth observatory*. Accessed 02 Feb 2011.

von Schuckmann, K., Gaillard, F., & Le Traon, P. (2009). Global hydrographic variability patterns during 2003–2008. *Journal of Geophysical Research, 114*. doi:10.1029/2008JC005237.

Part V
Earth's Cryosphere and Recent Climate History

Chapter 14
Glaciers and the Latest Ice Age

Abstract The cryosphere consists of glacial ice, sea ice, ice shelves, ice caps, continental glaciers, valley glaciers, permafrost, and ice in rivers and lakes. Some of the cryosphere is temporary, such as sea ice near the North Pole and elsewhere, and it melts in warm months and re-freezes during colder months. Glacial ice on land represents a vast store of fresh water. It also is directly tied to sea level. For example, as glacial ice melts, sea level is raised worldwide. As glaciers expand, sea level is lowered worldwide. The two most important areas on Earth for freshwater storage are Greenland and Antarctica. Greenland's glaciers are receding faster than Antarctica's because global warming is affecting the Northern Hemisphere glaciers more so than those in the Southern Hemisphere. Sea ice is disappearing in the Northern Hemisphere and is sometimes expanding in the Southern Hemisphere. The rate of Greenland's ice loss is accelerating. Ice cores from the cryosphere tell scientists a great deal about the history of the atmosphere from gas bubbles trapped within them. Isotope studies tell us about past atmospheric compositions and temperatures. Glaciers were more extensive in the recent geologic past in what is generally known as the Pleistocene "ice age." Carbon dioxide and global temperatures have been correlated throughout the past 800,000 years from ice cores.

Keywords Ice • Greenland • Antarctica • NASA • Glacier • Continental • Valley • Calving • Iceberg • Petermann • Permafrost • Vostok • Methane • Sea • GLOFs • EPICA • Cryosphere • MODIS • GPS • Southern • Larsen • Isotopes • Oxygen-18 • Insolation • Tephrochronology • Seesaw • Milankovitch • Precession • Cores • Pleistocene • "Ice age" • Obliquity • Albedo

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_14,

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
Sea Ice	Precession
Permafrost	Deuterium
Mean Sea Level	Tephrochronology
Dansgaard-Oeschger Events	Glacial Lake Outbreak Floods (GLOFs)
Ice Shelves	Insolation
Ice Albedo	Methane
EPICA	Bipolar Seesaw
Calve, Calving	Iceberg
Carbon Dioxide	Greenland Ice Cap
MODIS	Mountain Glaciers
GPS	Sea Ice Extent
GRACE	Ross Ice Shelf
Milankovitch Cycles	Ice Volume
Isostatic Rebound	Southern Ocean
Petermann Glacier	Vostok Station
Larsen B Ice Shelf	Moraines
NASA	Rock Flour
Oxygen-18	Mid-Pleistocene Transition

14.1 Introduction

The cryosphere is that part of the Earth that is frozen throughout most of the year. Glaciers, ice caps, icebergs, sea ice, ice shelves, and permafrost make up the cryosphere and each is treated in the following chapters.

Glacial ice stores a large amount of fresh water and represents the largest reservoir of fresh water on the planet. Glacial ice is found today at or near both poles and in many of the highest mountain areas of the world. There is a direct relationship between glacial ice and sea level. When glaciers expand sea level is lowered. When glaciers retreat sea level is raised. Over the past several decades sea level has risen and glaciers have retreated, in some areas more so than in other areas.

Much of this frozen world, the cryosphere, is melting as a result of global warming and it is causing a world-wide rise in sea level and a release of methane

(CH_4) to the atmosphere as we have seen earlier in this text. The potential for sudden methane release will be treated in the following chapter, Chap. 15.

The cryosphere consists of those regions of the globe, both land and sea, covered by snow and ice. These include Antarctica, the Arctic Ocean, Greenland, parts of Northern Canada, parts of Northern Siberia, icebergs, sea ice, and most of the high mountain ranges throughout the world where sub-zero temperatures persist throughout the year.

The cryosphere plays an important role in the regulation of the global climate system. Snow and ice have a high albedo; they reflect much of the solar radiation they receive; as much as 90%. This results in cooling of the Earth and as glaciers expand they provide a negative feedback to global warming. But the overall extent of glacial ice throughout the world is diminishing, not expanding. Some glaciers may be expanding depending on local conditions, but worldwide glacial ice is becoming less and less and represents a classic example of a positive feedback to global warming. As the ice recedes, less sunlight is reflected and more absorbed by the bare, darker Earth causing another positive feedback loop.

Some parts of the Antarctic reflect as much as 90% of the incoming solar radiation, compared to a global average of 30%. Without the cryosphere, the global albedo would be considerably lower causing more energy to be absorbed at the Earth's surface rather than reflected, and consequently the temperature of the atmosphere would be much higher. Indeed, during the Cretaceous Period (120–65.5 million years ago) evidence suggests there was little or no snow and ice cover even at the poles and global temperatures were at least 8–10°C warmer than today and inland seas covered much of the continents. These inland seas greatly moderated the climate. The Cretaceous Period was a time of reining dinosaurs who roamed Earth largely from pole to pole on land, sea, and air.

The cryosphere also decouples the atmosphere and oceans which reduces the transfer of moisture and stabilizes the energy transfers within the atmosphere. The formation of sea ice in Polar Regions can initiate global thermohaline circulation patterns in the oceans (see Chap. 12, Fig. 12.6). The thermohaline circulation greatly influences the global climate system. The lack of sea ice may also shut down the thermohaline circulation, which may have a major negative effect on energy distribution on Earth. The presence of the cryosphere markedly affects the volume of the oceans and global sea levels, changes to which can affect the energy budget of the climate system. The climate system has a high degree of sensitivity to changing conditions within the system.

14.2 Greenland Ice Sheet

Greenland has the last remaining ice cap or ice sheet in the Northern Hemisphere and it is rapidly diminishing in volume (Figs. 14.1 and 14.2). Although the glacial ice in Greenland has often been considered as a single ice sheet, as more ice melts

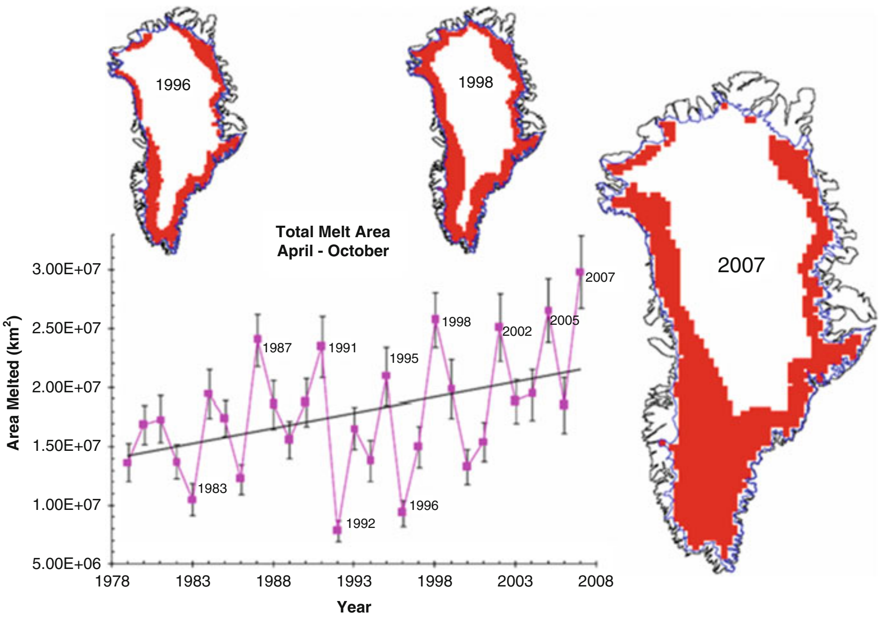


Fig. 14.1 A record melt extent was recorded in 2007. Meanwhile, the 28 year record of melt extent shows a statistically significant increasing trend (From http://cires.colorado.edu/science/groups/steffen/greenland/melt2005/index.html. *Source*: Steffen and Huff 2008, Steffen Research Group Web Page, NOAA/CIRES, Public Domain)

it becomes obvious that the ice sheet is made of individual glaciers that have had a history of being completely covered by glacial ice. Reference to the Greenland "ice sheet" is still valid.

The Greenland ice sheet is a vast body of ice covering 1,710,000 km^2 (660,235 square miles), roughly 80% of the surface of Greenland. It is the second largest ice body in the world, after the Antarctic Ice Sheet. The ice sheet in Greenland is almost 2,400 km (1,500 miles) long in a north-south direction, and its greatest width is 1,100 km (680 miles) at latitude 77°N, near its northern margin. The mean altitude (or elevation) of the ice is 2,135 m. The thickness is generally more than 2 km (1.24 miles) and over 3 km (1.86 miles) at its thickest point. It is not the only ice mass of Greenland. Isolated glaciers and small ice caps cover between 76,000 and 100,000 km^2 (29,344 and 38,610 square miles) around the periphery. Some scientists believe that global warming may be about to push the ice sheet over a threshold (or tipping point) where the entire ice sheet will melt in less than 100 years.

If the entire 2,850,000 cubic km (683,751 cubic miles) of ice were to melt, it would lead to a global sea level rise of 7.2 m (23.6 ft). This would inundate most coastal cities on Earth and remove several small island countries from the face of Earth, since island nations such as Tuvalu and Maldives have a maximum altitude

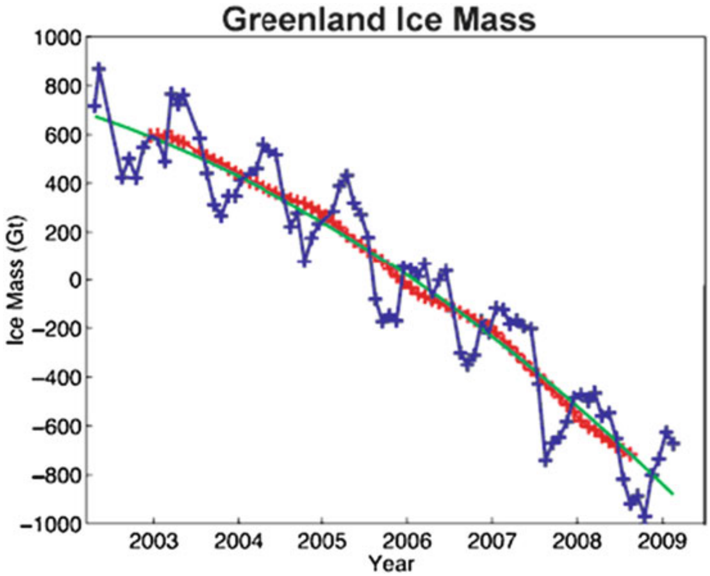


Fig. 14.2 Time series of ice mass changes for the Greenland ice sheet estimated from GRACE monthly mass solutions for the period from April 2002 to February 2009. Unfiltered data are *blue crosses*. Data filtered for the seasonal dependence using a 13-month window are shown as *red crosses*. The best-fitting quadratic trend is shown (*green line*) (From SkepticalScience.com, viewed 4/11/2012)

below or barely just above this number. For example, the highest point in the Maldives is just 7 ft above mean sea level (MSL) and the residents are already beginning to move to a mainland location.

Glaciers in west Greenland are melting 100 times faster at their end points beneath the ocean than they are at their surfaces, according to a NASA and a university study published online February 14, 2010 in *Nature Geoscience*. The results suggest this undersea melting caused by warmer ocean waters is playing an important, if not dominant, role in the current evolution of Greenland's glaciers, a factor that had previously been overlooked and not reported in the IPCC AR4 2007 report.

In fact, Greenland's glaciers are being melted by warmer ocean water at their terminus that is accelerating glacier movement from land to sea. In some of Greenland's glaciers the rate of movement toward the sea has been increased over 100% from 1 year to the next. The total ice loss from the Greenland subcontinent is shown in Fig. 14.2. The rate of this ice loss is accelerating.

In recent years, scientists have observed a widespread acceleration in the movement of Greenland's glaciers, associated with thinning of their lower reaches as they reach the sea. In the past decade, surface melting of glaciers around Greenland due to warm air temperatures has increased in both magnitude and area, while snowfall has increased just slightly. The result is a tripling in the amount of ice mass lost in Greenland between 1996 and 2007. Of this loss, between 50 and 60% is attributable to a speedup in the flow of outlet glaciers, with the remainder due to increased surface melting. As the glaciers flow into the sea, they melt or calve and float off into the open sea as icebergs, which cause a more rapid movement of land ice toward the sea.

The glaciers also melt along their submerged faces, where they come into contact with warm ocean waters. A warmer ocean erodes a glacier's submerged, grounded ice and causes its grounding line (the point at which a tidewater glacier floats free of its bed) to retreat. Little is known about these rates of undersea melting and how they may influence the glaciers. Indications are that the Greenland ice is disappearing more rapidly than predicted by the IPCC or any other recent study.

The melting of glaciers beneath the ocean surface causes deep, warm, salty water to be drawn up toward the glacier's face, where it mixes turbulently with the glacier's cold, fresh water. The water then rises along the glacier face, melting its ice along the way, then reaches the ocean surface and flows away from the glacier in a plume. An ocean temperature of 3°C (37.4°F) can melt glacial ice at a rate of several meters per day, or hundreds of meters over the course of a summer; and this glacial ice is not completely replenished during the following winters.

Figure 14.3 shows the recession of the Greenland glaciers as the rate of mass change. The recession (and thinning) is proceeding up the west coast as indicated by the loss of ice mass along the coast.

A recent international study finds that ice losses from Greenland's ice sheet, which have been increasing over the past decade in its southern region, are now spreading rapidly up its northwest coast (right side of Fig. 14.3).

The Greenland ice sheet is known to be a dynamic and unstable region with thousands of icebergs calving each year. In July 2008, a 27 km^2 iceberg broke free from the Petermann glacier with an approximate mass of 1–2 gigatonnes. Research by GISS and academic scientists indicates the ice-loss acceleration began moving up the northwest coast of Greenland staring in late 2005. The scientists drew their conclusions by comparing data from NASA's Gravity and Recovery Climate Experiment satellite system, or GRACE, with continuous GPS measurements made from long-term sites on bedrock at the edges of the ice sheet.

The data from the GPS and GRACE provided the researchers with monthly averages of crustal uplift caused by ice-mass loss (isostatic rebound). The team of scientists, which includes researchers from Denmark's Technical Institute's National Space Institute in Copenhagen and the University of Colorado at Boulder, combined the uplift measured by GRACE over United Kingdom-sized chunks of Greenland, while the GPS receivers monitored crustal uplift on scales of just tenths of a mile.

These changes on the Greenland ice sheet are happening fast, and Greenland is definitely losing more ice mass than scientists had anticipated. This trend is also seen in Antarctica, a sign that warming temperatures are having an unprecedented

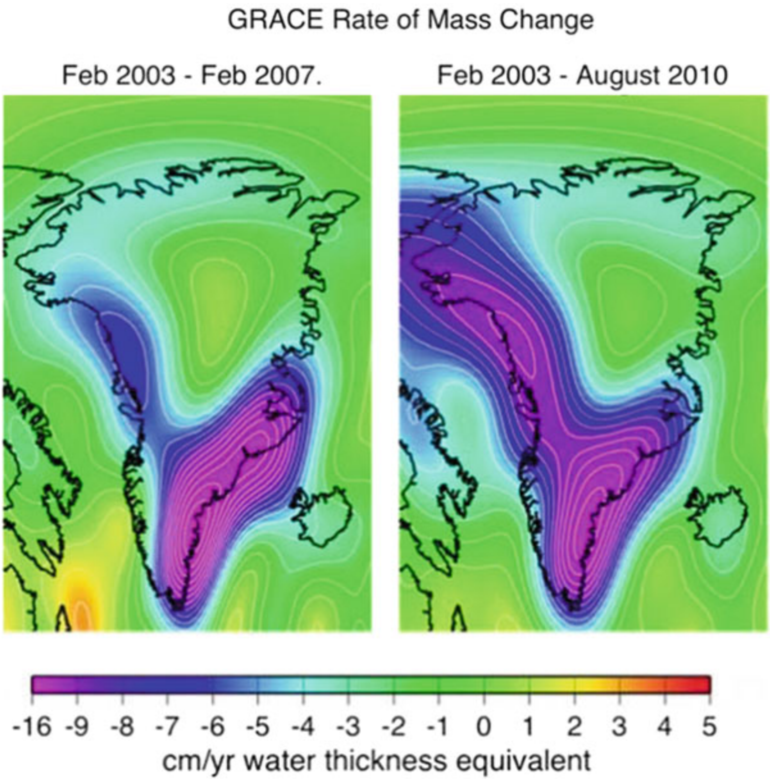


Fig. 14.3 Greenland ice cap with ice thickness contoured. The ice summit has a thickness of 3,207 m. The contour interval is 500 m. In 2010, Greenland temperatures were the hottest on record. It also experienced record setting ice loss by melting. This ice loss is reflected in the data from GRACE satellites which measure the change in gravity around the Greenland ice sheet (NASA, Public Domain)

effect on ice in Earth's colder regions. Recently acquired evidence indicates that the great ice sheets of the world are disappearing more rapidly than previously thought and the IPCC is in the process of revising its 2007 estimates in light of these new data for its AR5 report due in 2014.

The Greenland ice is often held in place by shallow ocean bottoms or continental shelves. Farther away from land, ocean currents play a greater role in moving and shaping ice. The East Greenland Current (see Fig. 12.5 and Table 12.2) flows southward from the Arctic along the island's eastern coast, carrying sea ice with it. Ice carried by this current occurs in large, thick pieces, and the ice in this swath along the Greenland coast almost certainly originated elsewhere.

Just as the relentless movement of water in rivers and streams can smooth the jagged edges of rocks over time, ocean currents can smooth ice fragments into round shapes.

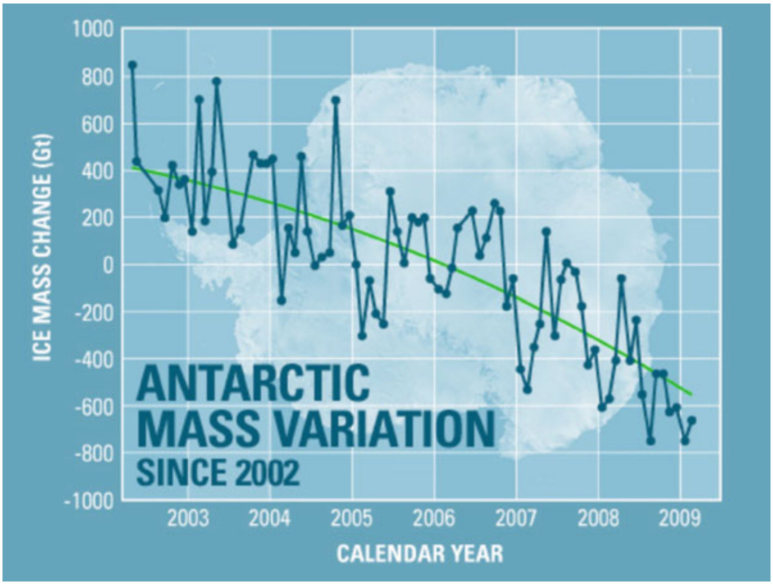


Fig. 14.4 Ice loss in Antarctica from 2002 through 2009 (From NASA, Public Domain)

Even farther out to sea than the large fragments of multiyear ice are much smaller pieces of ice, so small that they are at the mercy of even small surface currents. Collectively these tiny ice fragments form delicate swirls of ice.

If all the Greenland ice disappears, sea level will rise 26.3 ft according to an estimate by the United States Geological Survey. Tidal waters will also rise that much, tidal effects will move inland, and many of the world's cities will be inundated and millions of people will be displaced. This will cause untold turmoil among not only those displaced, but also among people where those displaced will go to find new places to settle and use resources. The rise in sea level is one of the most serious aspects of global warming.

14.3 Antarctica

The largest ice sheet (continental glacier) in the modern world is that of the southernmost continent, Antarctica and it is also loosing ice (Figs. 14.4, 14.5 and 14.6).

Antarctica is a desert and receives only 4–8 in. or less of precipitation annually. It is known to be windy but winds decrease toward the center of the continent. The coldest part of Antarctica is the eastern part, mainly because it is higher in elevation than in the west. Global warming is affecting the western part of the continent more than the eastern part and giant portions of ice shelves are now breaking off the western part.

While some areas of East Antarctica have been cooling in recent decades, the longer 50-year trend depicts that, on average, temperatures are rising across the

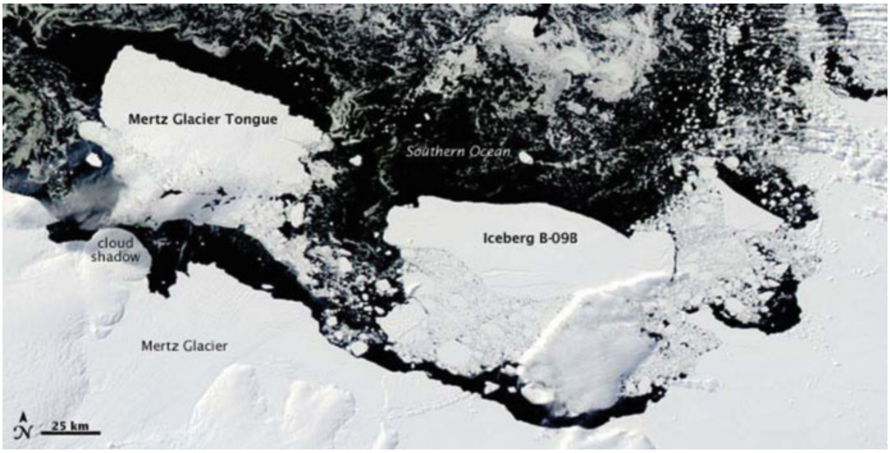


Fig. 14.5 East Antarctica ice breakup. Two massive icebergs drifted along the coast of East Antarctica in early March 2010. In mid-February 2010, the Rhode Island-sized Iceberg B-09B collided with the protruding Mertz Glacier Tongue along the George V Coast. The Mertz Glacier was already in the process of calving an iceberg when the arrival of the B-09B accelerated the process, leaving two icebergs the size of small states off this part of Antarctica's coast. The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite captured this true-color image of Iceberg B-09B and the newly created iceberg off the Mertz Glacier. Between each iceberg and the coast floats a mélange of smaller pieces of ice. Farther out to sea, delicate white swirls indicate a relatively thin layer of sea ice. Occasional clouds floating overhead cast shadows on the ice surfaces below (From http://carbon-based-ghg.blogspot.com/2011/02/east-antarctic-ice-sheet-may-not-be-as.html; NASA, Public Domain)

continent. If the West Antarctic ice sheet completely melted, global sea level would rise by 5–6 m (16–20 ft).

Both Greenland and Antarctic ice sheets have been extensively drilled and cored in the last few decades and the deepest cores are still being described (in December 2012). A Vostok station drilling team in 2011 drilled into the ice almost 4,000 m and came within a few meters of drilling into a large subglacial lake, Lake Vostok (Fig. 14.7). They had to stop drilling prior to February 6, 2011 due to the end of the summer season (in the Southern Hemisphere). The last plane left Antarctica on February 6 with the core hole only 20 m above the lake. The lake has not been exposed to Earth's atmosphere for about 15–20 million years. The current plan is to continue the drilling and sample the lake water during the next drilling season taking every precaution not to contaminate the lake. Just how this is to be done has not been made public as of December 2012. On February 5, 2012 a Russian team was reported to have completed the drilling and sampled Lake Vostok. The analysis of the sampling has not been made public as of December 2012. Later reports from the Russian team state that they did not obtain samples from Lake Vostok and the lake will be sampled when they return for the next field season, probably in 2013.

The illustration below (Fig. 14.9) contains the analysis from a core taken by the European Project for Ice Coring in Antarctica (EPICA) which covers the past 650,000 years of Earth history. The first 200,000 years or so of the record show peaks and val-

Fig. 14.6 Transantarctic Mountains, West Antarctica, East Antarctica. Antarctica is surrounded by the Southern Ocean and is the coldest place on Earth. The coldest temperature ever recorded was at the Russian Vostok station, −89.2°C (−128.6°F)

leys that are different from those from 430,000 years to the present. There has not been a good explanation as yet proposed for these differences. There is somewhat of a 100,000-year cyclicity pattern to the glaciations (as represented by the decreases in CO_2 and CH_4 concentrations) but this is the weakest of the Milankovitch cycles. Paleoclimatologists think that perhaps the initial episode of glaciation was the result of a Milankovitch cycle, but that CO_2 has controlled the other episodes in the cycle.

Temperature and carbon dioxide are shown to be related in some way, but such a relationship does not prove a cause and effect. Analysis of data from both EPICA and Vostok cores shows a lag of approximately 800 (or perhaps only 200) years of carbon dioxide behind temperature. This does not mean that this is *prima facie* evidence that temperature causes CO_2 to increase or that CO_2 is the cause of temperatures to rise. However, scientists know that the World Ocean absorbs the majority of Earth's carbon dioxide (a sink) and that a warming ocean will release carbon dioxide (a source) at a certain warming temperature. Therefore, it is not surprising

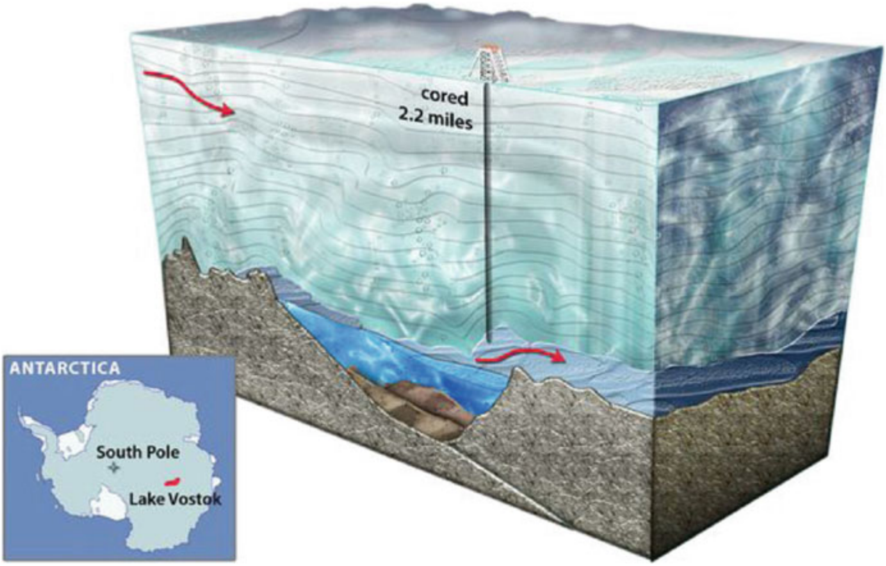


Fig. 14.7 Map of Antarctica and cross-section through the glacial ice to Lake Vostok (Illustration from the U.S. National Science Foundation, Public Domain)

that thousands of years ago a warming ocean gave up some of its carbon dioxide and "amplified" or led to a further increase in warming. This is another example of a positive feedback loop.

The illustration below (Fig. 14.8) shows carbon dioxide levels, temperature (°C), methane, solar variation at 65°N latitude, and oxygen-18 changes in a core from the Russian Vostok station in Antarctica. The age of this core goes back 420,000 years before the present.

In the illustration below (Fig. 14.9) two Antarctica ice cores are compared with ice volume over the past 420,000 years.

In both Figs. 14.8 and 14.9, note the relatively rapid rise in temperature compared to the slower decline in temperature, CO_2, and CH_4. Also note the good correlations with ice volume and the other parameters.

Locations for some of the sites and the geography of Antarctica are shown on Fig. 14.6.

14.4 Mountain Glaciers

Mountain glaciers are found in high mountain ranges throughout the world. They are tongues of ice which occupy former stream valleys. They modify these stream valleys by eroding and depositing material. Glaciers are a powerful erosive agent and convert V-shaped stream valleys in mountainous regions into U-shaped glacial valleys. Mountain glaciers are also referred to as alpine, valley, or piedmont glaciers depending on their location relative to the topography. Alpine glaciers are found in the Alps

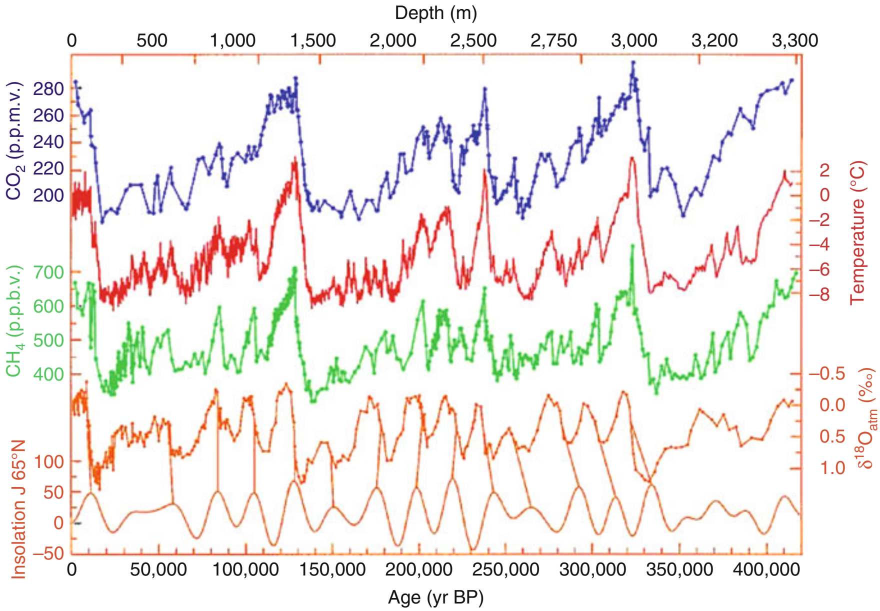


Fig. 14.8 CO_2, CH_4, insolation, $\delta^{18}O$, and temperature (°C) from Antarctica's Vostok ice core for the past 420,000 years. Current period is at *left*. From *bottom* to *top*: Solar variation at 65°N; (connected to ^{18}O); ^{18}O isotope of oxygen; Levels of methane (CH_4); Relative temperature; Levels of carbon dioxide (CO_2) (Government of the United States, Public Domain; Data obtained from the Vostok Ice Core)

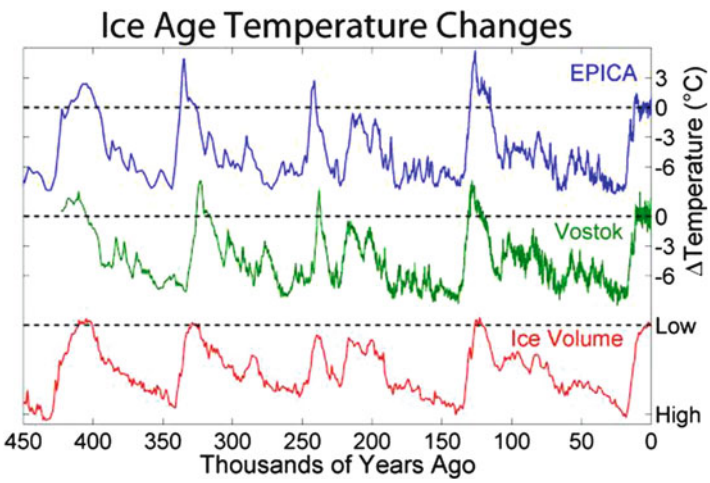


Fig. 14.9 Antarctic temperature changes and ice volume for the past 450,000 years as measured from ice cores from EPICA and Vostok

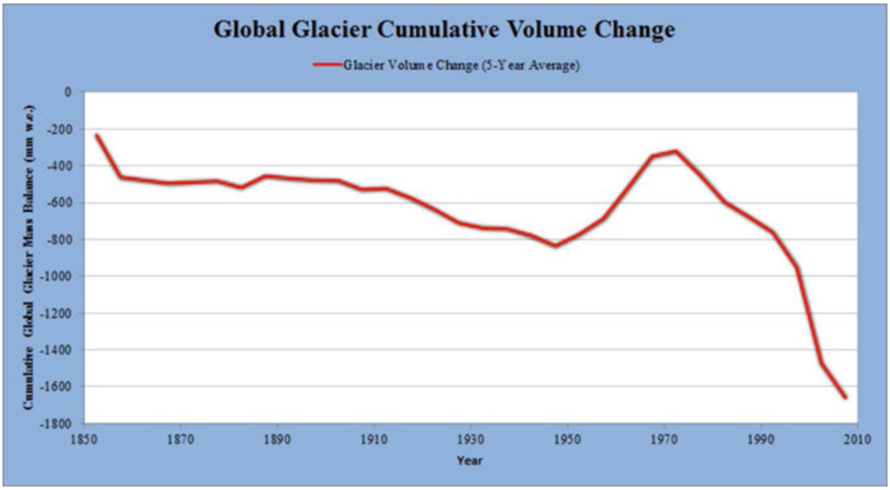


Fig. 14.10 Global glacier cumulative volume change (From Cogley 2009; NOAA, Public Domain)

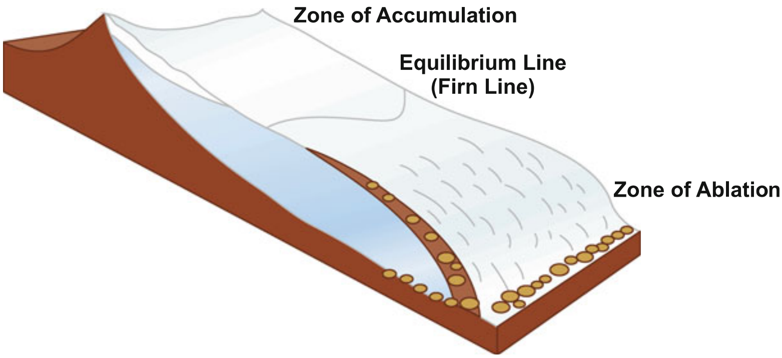


Fig. 14.11 Zones of accumulation and ablation, and the equilibrium line (Credit: John Cook)

or any high mountainous area. Valley glaciers occupy valleys and piedmont glaciers are usually formed by the coalescing of valley glaciers at the foot of a mountain.

Most mountain glaciers are receding at present. They are losing ice at a rate not previously known by mankind. Only a few glaciers are gaining ice. The great majority of glaciers throughout the world are retreating and losing ice. Some mountain glaciers are advancing but they are doing so under an unusual set of circumstances. Figure 14.10 shows the world-wide loss of glacial ice.

Glaciers are at equilibrium when the amount of feeder snowfall equals loss of ice at or near the glacier's terminus. As can be seen in the illustration (Fig. 14.11),

Fig. 14.12 The Bernard Glacier in Alaska's Saint Elias Mountains. The material it carries will be dropped as glacial till as the glacier recedes. Till is the general term that refers to all unsorted glacial deposits

a mountain glacier can be divided into a zone of accumulation and a zone of ablation separated by a zone of equilibrium (equilibrium line in Fig. 14.11). When annual accumulation exceeds annual ablation, the glacier advances. When annual ablation exceeds annual accumulation, the glacier retreats. When glacial ice retreats or is in equilibrium, the glacier itself continues to move downslope due to the influence of gravity and acts similar to a conveyor belt bringing rocks, soil, and ground-up rock (rock flour) to its terminus. The materials carried by the glacier and deposited as the ice recedes are called moraines and are further named according to their relationship to the glacier. Thus, there are terminal moraines which mark the glacier's terminus, medial moraines which are carried within the glacier, lateral moraines which were carried along the sides of the glacier, and end moraines which mark the various points of the terminus as the ice receded. The terminal moraine marks the end of the furthermost extent of the glacier.

Figure 14.12 shows the location of moraines carried by glaciers. Notice how the medial moraines are formed from former lateral moraines as tributary glaciers enter the main glacier.

A special case of the cryosphere is that of the Himalayan glaciers. These glaciers provide drinking, domestic, and agricultural water to over one billion people in Southeast Asia and they are rapidly losing ice. As these glaciers melt, there is an abundance of water and floods are common. Glacial lake outburst floods (GLOFs) are happening in the Andes and Asia as flood patterns and severity are changing (GLOFs for Asia are shown in Fig. 14.13).

The illustration below (Fig. 14.13) shows the cumulative frequency of glacial lake outburst events in the Himalayan region from the 1930s to the 1990s. These are

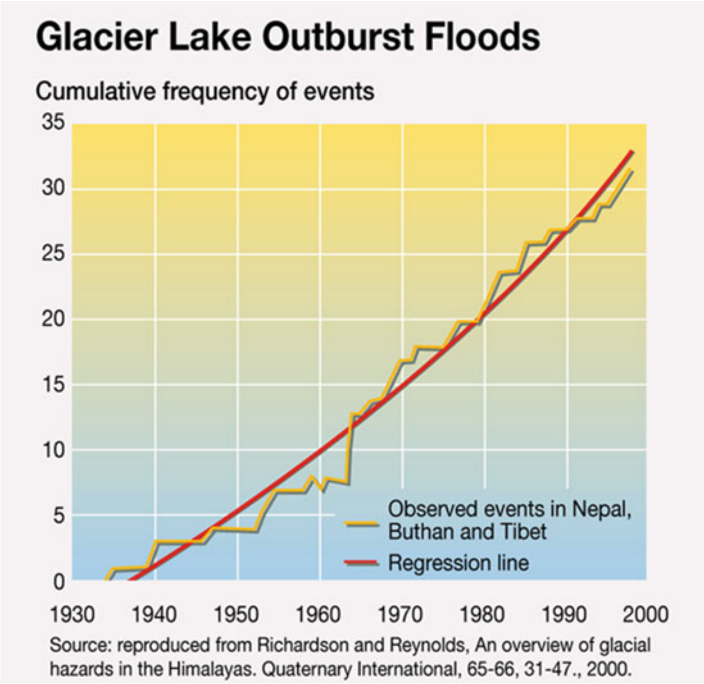


Fig. 14.13 Glacial Lake outbreak floods cumulative frequency in Asia (Reference from Richards and Reynolds 2000 is given above)

rapidly increasing and when the glaciers disappear, which is likely to happen before the middle of this (the twenty first century), a billion people will have to resettle or find other sources of water for drinking and agriculture.

Over half of the world's population lives in areas where the streams they depend upon originate in mountains with glaciers and snow. Global warming is an imminent threat to these people as the glaciers are rapidly receding and will almost certainly disappear before the end of this century; and many within the next 40 years. The results of climate change are being felt already in many areas as weather patterns change, rivers change their course, flooding increases in some areas, droughts increase in other areas, the number of major fires increase, agriculture is affected, drinking water is contaminated, and people must migrate to survive.

14.5 Ice Cores

Ice cores have been taken from drilling into glaciers and ice caps in many parts of the world and those from Greenland and Antarctica are especially well known.

Recent studies (2010–2012) have shown that ice also forms by meltwater from the glacial ice re-freezing at the bottom of glaciers. This does not affect data that are obtained from above the re-freezing zone but the re-frozen ice does provide a slick surface over which glacial ice can move more rapidly down slope, often toward the ocean.

As glacial ice forms from snow which accumulates year after year, it entraps part of the environment from which it forms such as dust from volcanic eruptions and air trapped in bubbles preserved in the ice. Thus, glacial ice cores tell scientists a great deal about Earth history at the time the ice was formed, especially the volcanic eruptions and the composition of the atmosphere. Glacial air bubbles also contain stable isotopes that are used to tell scientists past atmospheric temperatures.

14.6 Stable Isotope Analysis

Oxygen and carbon stable isotopes are the two most often used for environmental and climate change applications, although others are sometimes used.

Oxygen has three natural isotopes, ^{18}O, ^{16}O, and ^{17}O. Oxygen-16 (^{16}O) is the most abundant oxygen isotope found in nature with a small amount of oxygen-18 (^{18}O) and an even smaller amount of oxygen-17 (^{17}O). The oxygen isotope numbers refer to the atomic mass of each isotope. Therefore, ^{16}O is lighter than ^{18}O and it takes less energy to convert it to the vapor state when it is the isotope found in H_2O. Oxygen-16 is the first oxygen isotope to be converted to the vapor state when H_2O evaporates leaving the remaining H_2O enriched in ^{18}O. Oxygen-18 also liberates more energy when H_2O condenses.

Air masses moving from the tropics to higher latitudes have a lower ratio of ^{18}O to ^{16}O as condensation removes the ^{18}O first and the water vapor is enriched in ^{16}O.

The ratio of ^{18}O to ^{16}O is temperature dependent in the following way: as climate warms, the organisms in the oceans that use oxygen in the secretion of their skeletons (e.g., $CaCO_3$) secrete more of ^{18}O because the lighter ^{16}O is evaporated leaving behind more ^{18}O. Therefore, the ratio of the oxygen isotopes is higher during warm periods and lower during colder or cooler periods when evaporation is less. This ratio is very useful in distinguishing glacial from interglacial periods.

Carbon has three naturally occurring isotopes, ^{12}C, ^{13}C and ^{14}C. Carbon-12 and -13 are stable and occur in a consistent ratio of 99–1, respectively. Carbon-14 is formed in the atmosphere by cosmic radiation impacting nitrogen atoms and forms a negligible part of total carbon in the environment. It, however, is radioactive and has a half-life of 5,730 years. Radioactive carbon (or radiocarbon) is used to date materials that are 50,000 years and younger from plants and animals. When living, these organisms absorb carbon-12 and carbon-14 in a given ratio. When the organism dies, it stops absorbing carbon-14 and the carbon-14 begins to decay. By knowing the ratio of ^{12}C to ^{14}C when the organism died and determining how much ^{14}C is remaining, and knowing the half-life of ^{14}C as stated above, scientists can determine the age of the organism or its remains. After about 50,000 years there is not enough ^{14}C left to measure.

14.7 Ice Cores and Proxies

Ice cores are retrieved from glaciers and ice caps by a special coring or drilling method. If the snow and ice at the top of the glacier are soft, a hollow tube may be used to a depth where the ice becomes hard; hard ice necessitates the use of a core drill which involves a cutting tube and a drilling rig at the surface. The cutting material is at the end of a hollow tube and the drilling is done in 4- to 6-m increments. After the increment bottom or depth is reached, the tube is extracted from the borehole and the ice sample is retrieved from the tube. Collection of a long core record requires many cycles of lowering a drill/sample-tube assembly, cutting a core 4–6 m in length, raising the assembly to the surface, emptying the core barrel, and preparing a drill/sample-tube assembly for additional drilling. It is of course necessary to keep the samples well below freezing at all times after extracting the sample and adequate documentation of every step in this process is essential.

Ice cores form a continuous record of the atmospheric conditions only at the location from which the ice is retrieved. The bubbles in the glacial ice have samples of the atmosphere in them. These samples may give indications of the global climate throughout the world or they may not. If there is a correlation with events in Antarctica and Greenland cores, then confidence of a global record is increased.

Ice cores record volcanic eruptions as dark layers of volcanic ash. They also contain chemical signatures of fingerprint compounds from the beginning of the burning of coal.

14.7.1 Dating Ice Cores

Near the top of glacial ice, it is usually possible to identify annual layers of alternating light- and dark-colored bands. The light-colored bands represent summer and the dark-colored bands represent winter. The light- and dark-colored bands together represent 1 year.

Deeper below the ice surface, the original snow is recrystallized and the annual layers are indistinguishable. Dating the deeper ice becomes a much more difficult problem. Methods of dating ice cores can be summarized as follows:

- Layer counting;
- Glaciological modeling;
- Orbital tuning;
- Gas synchronization;
- Tephrochronology; and
- Correlation with other dated records.

Layer counting is used mainly in the upper few meters of glacial ice (Fig. 14.14). Other methods are necessary for ice below where annual layers are absent.

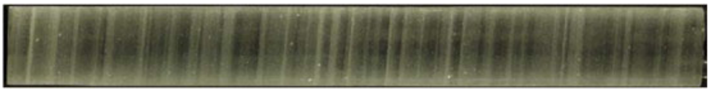


Fig. 14.14 Portion of an ice core showing annual layers (USGS, Public Domain)

Glaciological modeling takes advantage of physical constraints of accumulation and glacial flow to determining age.

Orbital tuning correlates cyclical variations with orbital variations such as the Milankovitch cycles, discussed later in this chapter. Earth's orbital parameters vary with a distinct periodicity: 100,000 and 400,000 for the eccentricity of the orbit, 41,000 for the Earth's axial tilt (obliquity) of the axis of rotation, and 23,000 and 19,000 for the precession of the vernal equinox.

Gas synchronization uses records of gases that are well mixed in the atmosphere to link ice core records. This has been used with $\delta^{18}O$ to compare the timing of deglacial changes recorded in Greenland and Antarctica. The rapid variations in atmospheric methane concentrations has allowed more accurate comparisons of the relationship between Dansgaard-Oeschger (rapid warming, gradual cooling) events in Greenland and warming events in Antarctica. This type of correlation has led to the "bipolar seesaw" hypothesis for latitudinal heat transfer in the Atlantic.

Tephrochronology uses the elemental composition and geochemical signature of volcanic ash (tephra) found in ice cores as stratigraphic markers. If the age of the volcanic eruption is known, tephra offer a means to date an ice core with radioisotopes and to correlate between ice cores in different parts of the world.

Correlation with other dated records allows researchers to establish relative chronologies between ice cores and with marine sediments.

14.7.2 Mountain Glacier Ice Cores

Mountain glaciers occur in the higher mountainous regions of Earth, such as the Himalayas, Andes, Rockies, Alps, Coast Ranges of the western U.S., and other high standing mountains. There are mountain glaciers on the equator in Ecuador.

Obtaining ice cores from mountain glaciers presents logistical problems as the drilling and sampling equipment have to be carried into the drilling site. In the case of coring of larger mountain glaciers it may be possible to fly it in by helicopter or small fixed-wing airplane. For these and other reasons, mountain glaciers have provided fewer cores than have the ice sheets of Greenland and Antarctica.

The illustration below (Fig. 14.15) shows the loss of mass in mountain glaciers from 1960 through 2006.

The illustration below (Fig. 14.16) is a summary of observed variation in the atmosphere from 1993 to 2003 during which ice melt contributed 0.6–0.8 mm/year rise in eustatic sea level.

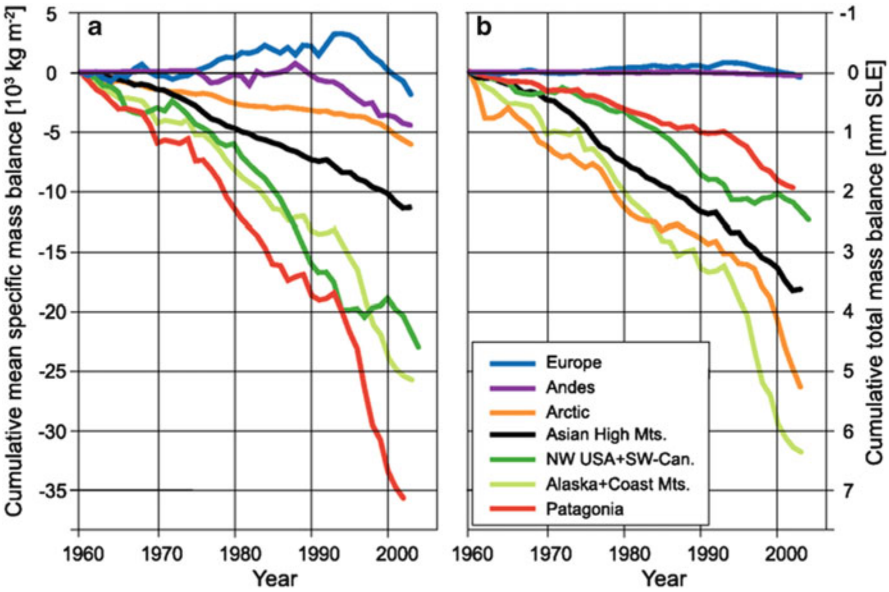


Fig. 14.15 Cumulative mean specific mass balances (**a**) and cumulative total mass balances (**b**) of glaciers and ice caps, calculated for large regions (Dyurgerov and Meier 2005). Mean specific mass balance shows the strength of climate change in the respective region. Total mass balance is the contribution from each region to sea level rise (From IPCC AR4 2007)

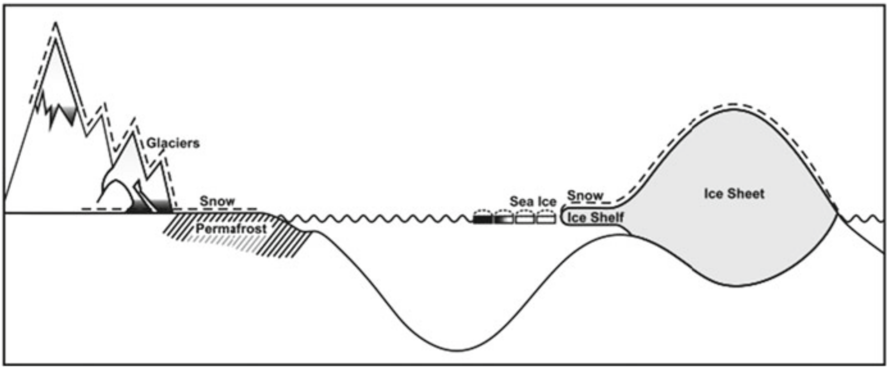


Fig. 14.16 Summary of observed variations in the cryosphere (Redrawn from IPCC AR4 2007 by John Cook)

There has been substantial retreat of arctic sea ice, especially in summer; the continued shrinking of mountain glaciers; the decrease in the extent of snow cover and seasonally frozen ground, particularly in spring; the earlier breakup of river and lake ice; and widespread thinning of Antarctic ice shelves along the Amundsen

Sea coast, indicating increased basal melting due to increased ocean heat fluxes in the cavities below the ice shelves. An additional new feature is the increasingly visible fast dynamic response of ice shelves, for example, the dramatic breakup of the Larsen B Ice Shelf in 2002, and the acceleration of tributary glaciers and ice streams, with possible consequences for the adjacent part of the ice sheets.

As ice shelves collapse, land glaciers that fed the ice shelves speed up in their way to the sea to replace the ice shelf that collapsed.

14.8 The "Ice Age"

The ice age most familiar is the most recent ice age or the extensive glaciation that occurred over most of the Northern Hemisphere and high mountain ranges during the past few hundreds of thousands of years. Earth has experienced several earlier "ice ages" dating back as far as 700 million years during Precambrian time and possibly even further back than that, if the "Snowball Earth" hypothesis proves to be correct. But we will concentrate on the most recent ice age because that is the one that presents us with the most evidence. It is sometimes referred to as the Pleistocene glaciation.

14.8.1 History

The Earth is still in an ice age as we have continental sized glaciers and ice at the poles and over Greenland and Antarctica. There are also numerous glaciers throughout the highest mountains of the planet. Glacial ice has been much more extensive in the past than it is today and most glacial ice on Earth is now receding. But what caused the ice sheets to grow in the first place? What causes ice ages?

In order for the climate to change it needs to have a forcing agent, as we have seen in earlier chapters, something that happened that caused the change. Let's look at a few things that might force the climate to change.

14.8.2 Climate Forcing by Orbital Variations

Earth's orbital variations include how it revolves around the Sun, how its rotational axis behaves, what its degree of inclination is to the Sun, and its axial precession.

Many climate change scientists think that orbital forcing started or triggered the latest, i.e., the Pleistocene, "ice age" and there is some supporting evidence for this hypothesis.

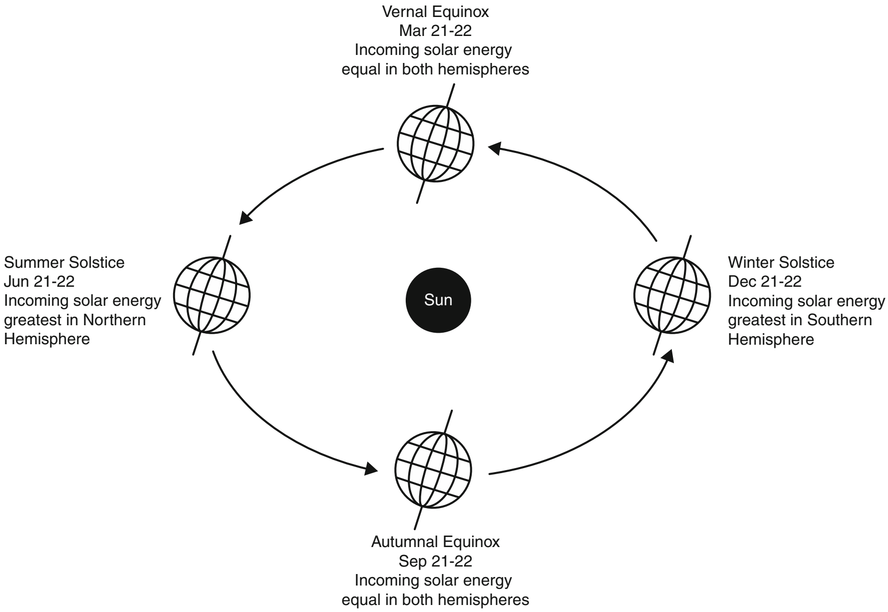


Fig. 14.17 Earth's rotation on its axis, its revolution around the Sun, the seasons of the year, the tilt of the Earth's axis, the solstices and equinoxes (Redrawn from NASA by John Cook)

Figure 14.17 shows the position of the Earth relative to the Sun at different times of the calendar year; the vernal and autumnal equinoxes and the winter and summer solstices. Notice the differences in sunlight striking the Earth at different times during the year. During the summer solstice the Northern Hemisphere is receiving more direct sunlight and during the winter solstice the Southern Hemisphere is receiving more direct sunlight.

The Earth's axis completes one full cycle of precession approximately every 26,000 years (see Fig. 14.19). At the same time, the elliptical orbit rotates, more slowly, leading to a 21,000-year cycle between the seasons and the orbit. In addition, the angle between Earth's rotational axis and the normal to the plane of its orbit moves from 22.1° to 24.5° and back again on a 41,000-year cycle; currently, this angle is 23.44° and is decreasing.

14.8.3 Eccentricity

The Earth's eccentricity is a measure of the departure of its ellipse from being circular. An exactly circular orbit has no eccentricity but the Earth has an eccentricity of between 0.005 and 0.058 (Fig. 14.18). The shape of the Earth's orbit varies in time between being nearly circular (low eccentricity of 0.005) and being mildly

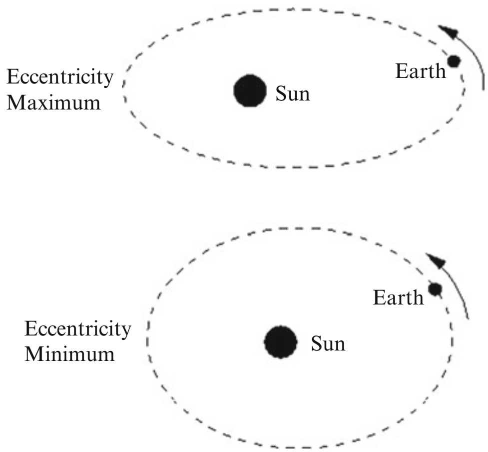


Fig. 14.18 Earth's orbital eccentricity (From NASA, Public Domain)

elliptical (high eccentricity of 0.058) and has a mean eccentricity of 0.028. The major component of these variations occurs on a period of 413,000 years. A number of other terms vary between components 95,000 and 125,000 years (with a "beat period" of about 400,000 years), and loosely combine into a 100,000-year cycle (variation of −0.03 to +0.02). The present eccentricity is 0.017.

If one looks at the beginning of each glacial advance during the Pleistocene, there is a periodicity of about 100,000 years, and the eccentricity may be an explanation for this periodicity. However, this is a relatively small forcing on the climate system and is thought to not be strong enough to trigger an ice age by itself.

14.8.4 Obliquity

The angle of the Earth's axial tilt (obliquity) varies with respect to the plane of the Earth's orbit (Fig. 14.19). These slow 2.4° obliquity variations are roughly periodic, taking approximately 41,000 years to shift between a tilt of 22.1° and 24.5° and back again. When the obliquity increases, the amplitude of the seasonal cycle in insolation (**IN**coming **SOL**ar radi**ATION**) increases, with summers in both hemispheres receiving more radiative flux (constant change) from the Sun, and the winters less radiative flux.

The changes in the summer and winter are not of the same magnitude. The annual mean insolation increases in high latitudes with increasing obliquity, while lower latitudes experience a reduction in insolation. Cooler summers are suspected of encouraging the start of an ice age by melting less of the previous winter's ice and snow. So it can be argued that lower obliquity favors ice ages both because of the mean insolation reduction in high latitudes as well as the additional reduction in summer insolation. However, no significant climate changes are associated with extreme axial tilts but they could be a contributing factor.

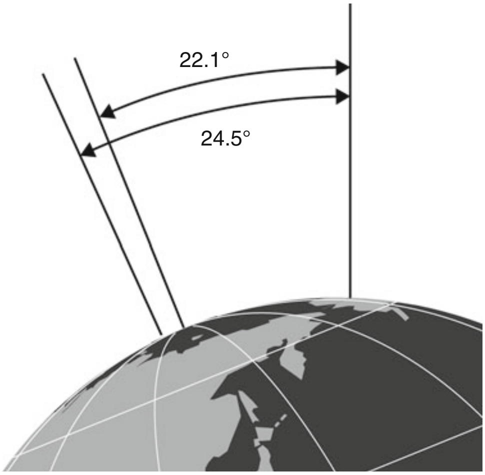


Fig. 14.19 22.1–24.5° range of Earth's obliquity (Credit: John Cook)

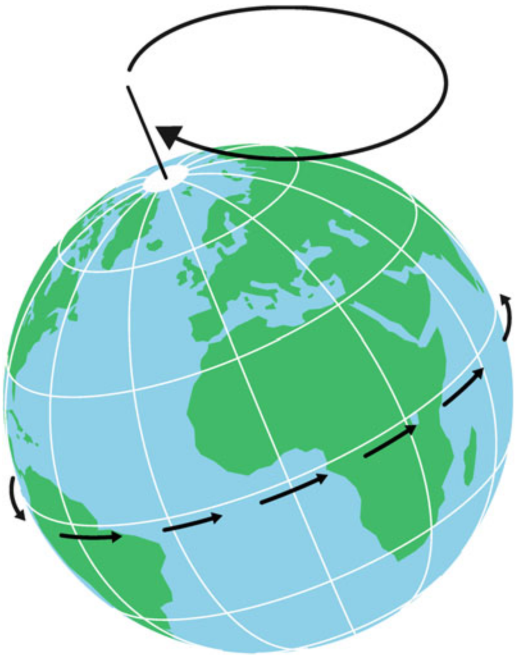


Fig. 14.20 Precessional movement of Earth's axis of rotation (Credit: John Cook)

14.8.5 Precession

Precession is the change in the direction of the Earth's axis of rotation relative to a fixed point, like a star, with a period of roughly 26,000 years. This gyroscopic motion (Fig. 14.20) is due to the tidal forces exerted by the Sun, moon, and other celestial

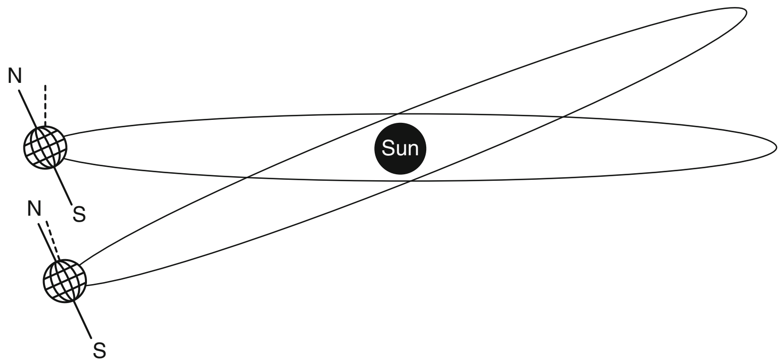


Fig. 14.21 Change in the Earth's orbital plane. Even if the spin axis always pointed in the same direction (for example, on a perfectly spherical planet) it would make a different angle with its orbital plane as the plane moved around (Credit: John Cook)

objects on the solid Earth, associated with the fact that the Earth is an oblate spheroidal shape and not a perfect sphere. The Earth bulges at the Equator and is slightly flattened at the poles making it an oblate spheroid. The Sun and Moon contribute to this shape.

When the axis is aligned so it points toward the Sun during perihelion (when it is closest to the Sun), one polar hemisphere will have a greater difference between the seasons while the other hemisphere will have milder seasons. The hemisphere which is in summer at perihelion will receive much of the corresponding increase in solar radiation, but that same hemisphere will be in winter at aphelion (when it is furthest from the Sun) and have a colder winter (Fig. 14.21). The other hemisphere will have a relatively warmer winter and cooler summer.

In addition, the orbital ellipse itself precesses in space, primarily as a result of interactions with Jupiter and Saturn. This orbital precession is in the same sense to the gyroscopic motion of the axis of rotation, shortening the period of the precession of the equinoxes with respect to the perihelion from 25,771.5 to ~21,636 years (Fig. 14.22).

14.9 Milankovitch Cycles and Ice Ages

Milutin Milankovitch (1879–1958) was a Serbian scientist and mathematician who was placed under house arrest during WWI when the Austro-Hungarian Empire declared war on Serbia, and had much time on his hands to do numerous calculations concerning the Earth's rotation on its axis and revolution around the Sun. He also did calculations of the amount of insolation the Earth received at various latitudes and used his calculations in his theory for the ice advances and retreats of the past 600,000 years of Earth history.

The Milankovitch or Astronomical Theory of Climate Change is an explanation for changes in climate which result from changes in the Earth's orbit around the Sun

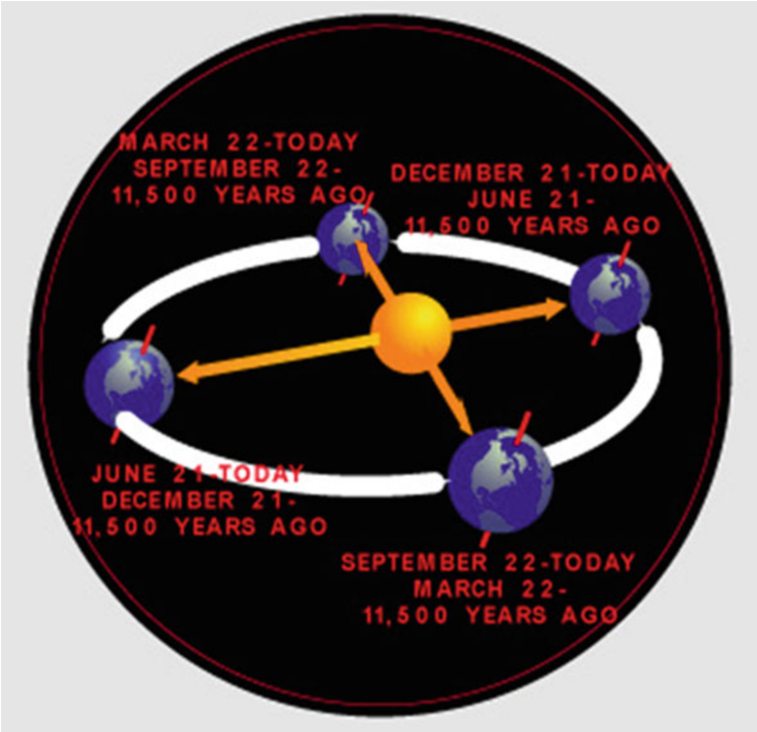


Fig. 14.22 The Earth's axis of rotation wobbles like a top on a ~23,000 year cycle. This causes the Earth's seasons to reach their maximum at different distances from the Sun due to the elliptical shape of the Earth's orbit (From the Science Museum of the U.S. National Academy of Sciences, http://www.koshland-science-museum.org/exhibitgcc/causes08.jsp, Public Domain)

and its rotation on its axis. Milankovitch calculated the slow changes in the Earth's orbit by careful measurements of the position of the stars, and through equations using the gravitational pull of other planets and stars. He determined that the Earth "wobbles" in its orbit. The Earth's "tilt" is what causes seasons, and changes in the tilt of the Earth change the strength of the seasons. The seasons can also be accentuated or modified by the eccentricity (degree of roundness) of the orbital path around the Sun, and the precession effect, the position of the solstices in the annual orbit (see Fig. 14.23).

The figure below (Fig. 14.24) shows insolation changes at various latitudes in mid-June for the last 1 million years. The Milankovitch cycles modulate the insolation received at the top of Earth's atmosphere.

Milankovitch's theory (the Milankovitch or Astronomical Theory of Climate Change) was largely ignored for about 50 years. Then, in 1976, a study published in the journal *Science* examined deep-sea sediment cores and found that Milankovitch's theory did in fact correspond to periods of climate change. Specifically, the authors were able to extract the record of temperature change going back 450,000 years and

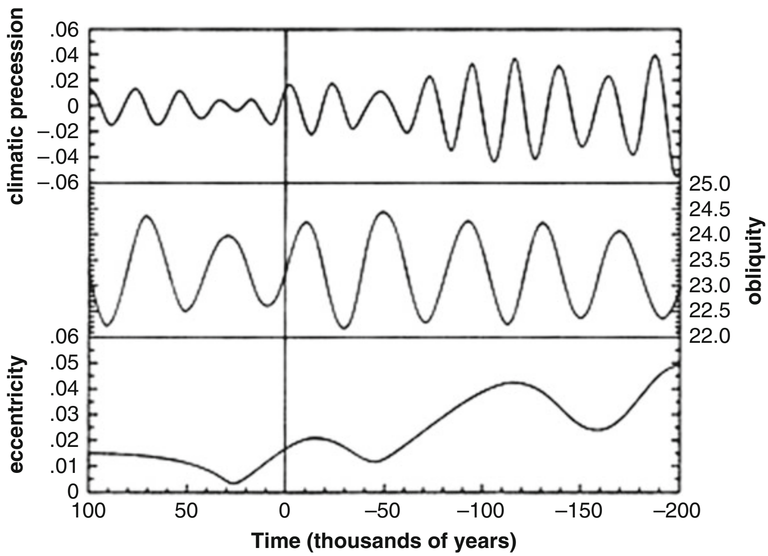


Fig. 14.23 Milankovitch calculated solar energy receipt during summer at 65°N for the past 600,000 years (also for 55° and 60°, but they are not shown in the above graph). The above graphs show calculated values for 300,000 years of orbital variation. The line labeled "0" represents today, while "–200" indicates 200,000 years in the past and "100" indicates 100,000 years from now. Milankovitch noticed that these cycles of orbital mechanics correspond to many indicators of past climate change, such as Ice Ages (From NASA, Public Domain; originally from Berger and Loutre 1991)

found that major variations in climate were closely associated with changes in the geometry (eccentricity, obliquity, and precession) of Earth's orbit. The Pleistocene ice ages had occurred when the Earth was going through different stages of orbital variation.

14.10 Solar Variations

Solar variations are climate forcings that cause climate changes on Earth. The Sun varies in the amount of energy that it provides to Earth. There are periods when there is more energy from the Sun and periods when there is less energy from the Sun. These are solar maxima and solar minima, respectively (Fig. 14.25). During a period of solar maximum, the Sun produces its maximum amount of energy and the Earth warms. During a solar minimum, the Sun produces its minimum amount of energy and the Earth should cool. The Sun has been in a period of solar minimum for the past several decades while the Earth continues to warm, so something other than the Sun must be causing global warming.

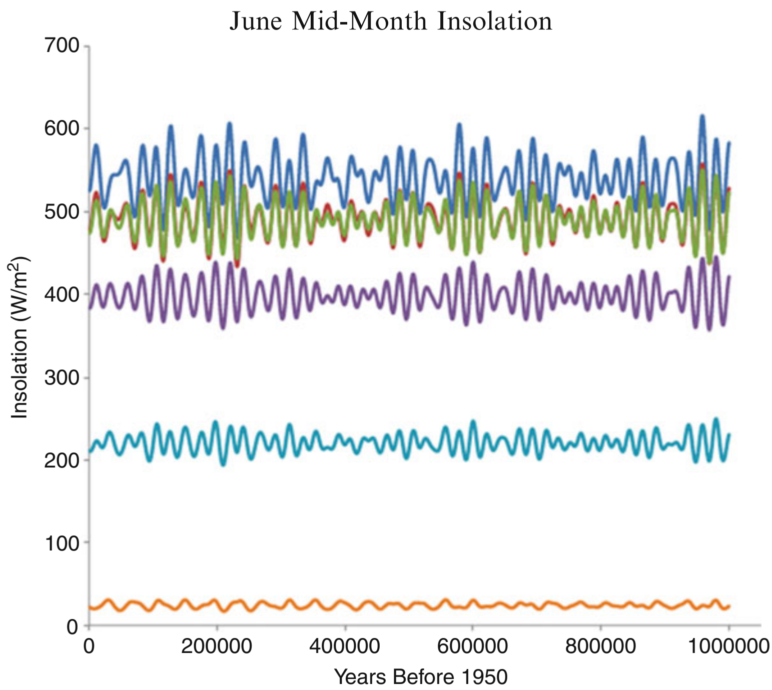


Fig. 14.24 June (daily averaged) insolation (W/m^2) over the last 1,000,000 years (0 = 1950) at (*blue* = 90 N), (*red* = 60 N), (*green* = 30 N), (*purple* = Equator), (*light blue* = 30 S), (*Orange* = 60 S). Data from Berger and Loutre (1991) (From Colose, C., SkepticalScience.com. Viewed 7-22-2011)

In 1978 NASA launched the first of several satellites that measure solar energy received by the Earth at the top of the atmosphere (TOA). The illustration below (Fig. 14.25) shows the results of some of these measurements from 1978 through 2010.

What is known about the internal structure of the Sun is shown in the illustration below (Fig. 14.27). The Sun's outer visible layer is the photosphere and its temperature is about 6,000°C. The photosphere has a mottled appearance due to the turbulent eruptions of energy.

Solar energy is created deep within the core of the Sun by nuclear reactions which produce helium from hydrogen. The difference in mass is converted to energy and makes its way to the surface by convection where it is released as light and heat.

Above the photosphere is the chromosphere. Solar energy passes through the chromosphere on its way out from the Sun. Faculae and solar flares arise in the chromosphere. Faculae are the lighter areas in the illustrations (Figs. 14.26 and 14.27). Faculae are bright luminous hydrogen clouds which form above regions where sunspots are about to form. Flares are bright filaments of hot gas emerging

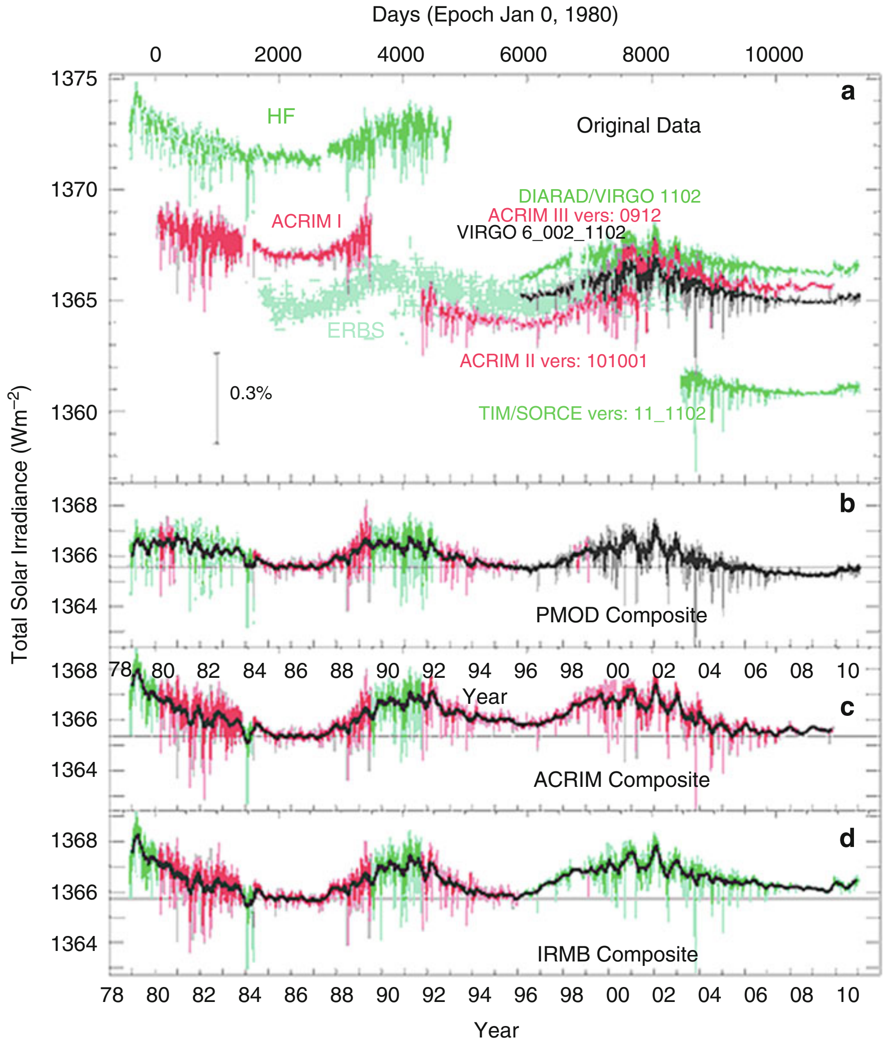


Fig. 14.25 Three solar maxima and three solar minima from 1978 to 2010. *Upper panel*: Compared are daily averaged values of the Sun's total irradiance (TSI) from radiometers on different space platforms since November 1978: HF on Nimbus7, ACRIM I on SMM, ERBE on ERBS, ACRIM II on UARS, VIRGO on SOHO, and ACRIM III on ACRIM-Sat. The data are plotted as published by the corresponding instrument teams. Note that only the results from the three ACRIMs and VIRGO radiometers have in-flight corrections for degradation. *Lower panels*: The PMOD, ACRIM and IRMB composite TSI as daily values plotted in *different colors* to indicate where the data are coming from (From http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant)

from sunspot regions. Sunspots are dark depressions on the photosphere with a typical temperature of around 4,000°C (7,000°F).

The outer part of the Sun's atmosphere is the corona. The corona can only be seen during total solar eclipses.

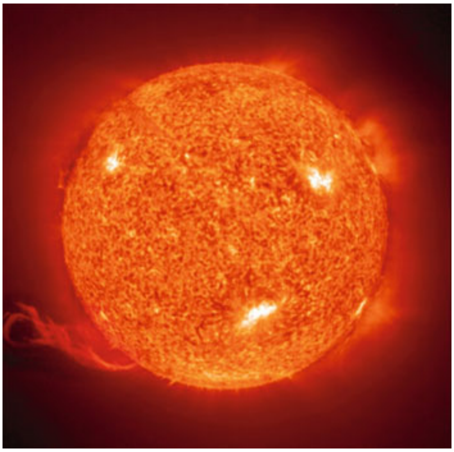


Fig. 14.26 An image of the Sun showing a number of solar flares and faculae (NASA, Public Domain)

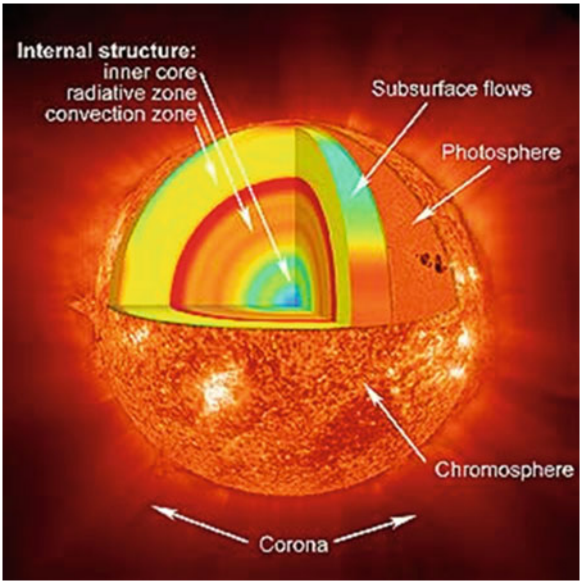


Fig. 14.27 Features of the Sun (From http://www.solarviews.com/eng/Sun.htm)

14.11 Questions Not Explained by Milankovitch Cycles

There are a number of unresolved questions that remain in the Milankovitch or Astronomical Theory of Climate Change, even during the more familiar Pleistocene timeframe. For instance, while changes in Earth's orbit match ice ages somewhat, the precise way the three Milankovitch variations regulate the timing of glacial-interglacial cycles is not well known.

For example, about 800,000 years ago a shift of the dominant periodicity from a 41,000-year to a 100,000-year signal in glacial oscillations occurred (called the

Mid-Pleistocene Transition), and while a lot of ideas exist for why this should be the case, there's no absolute answer for this shift. Explaining the 100,000-year recurrence period of ice ages is difficult because although the 100,000-year cycle dominates the ice-volume record, it is small in the insolation spectrum. Therefore, there is still a lot to be learned about the trigger(s) for an ice age.

Whatever it is that begins an ice age, it happens to the Northern Hemisphere first. If the North and South are alternatively near and far from the Sun during summer, why has glaciation been nearly globally synchronous? What connections are there between Northern insolation and Antarctic climate at the obliquity and precession timescales? What are the competitive roles between a further distance from the sun during summer and a longer summer? These questions are still not resolved. This problem also involves work at the interface of carbon cycle and ice sheet dynamics, processes that are in their infancy in terms of modeling.

It is also possible that some combination of forcing mechanisms combined at just the right instant in time that triggered the initiation of global glaciation. And it may be that other influences caused the subsequent periodicity of the glacial-interglacial episodes. We will consider some possibilities as we go along in this text.

Additional Readings

Benn, D. I., & Evans, D. J. A. (1999). *Glaciers and glaciation*. London/New York: Publisher Arnold, London 1998 (734pp) 50.00 (hardback) ISBN 0-340-65303-5 24.99 (paperback) ISBN 0-340-58431-0.

Bennett, M. R., & Glasser, N. F. (1996). *Glacial geology: Ice sheets and landforms*. New York/Chichester: Wiley. OCLC 37536152 33359888 37536152. ISBN 0-471-96344-5.

Berger, A., & Loutre, M. F. (1991). Insolation values for the climate of the last 10 million years. *Quaternary Sciences Review, 10*(4), 297–317.

Fröhlich, C. (2000). Observations of irradiance variability. *Space Science Reviews, 94*, 15–24.

Fröhlich, C. (2003). Long-term behaviour of space radiometers. *Metrologia, 40*, 60–65.

Fröhlich, C. (2004). Solar irradiance variability, Chapter 2: Solar energy flux variations. In *Solar variability and its effect on climate* (Geophysical Monograph Series No. 141, pp. 97–110). Washington, DC: American Geophysical Union.

Fröhlich, C., & Lean, J. (1998). The Sun's total irradiance: Cycles and trends in the past two decades and associated climate change uncertainties. *Geophysical Research Letters, 25*, 4377–4380.

Fröhlich, C., & Lean, J. (2004). Solar radiative output and its variability: Evidence and mechanisms. *Astronomy and Astrophysics Review, 12*, 273–320. doi:10.1007/s00159-004-0024-1.

Paterson, W. S. B. (1994). *Physics of glaciers* (3rd ed.). Oxford/Tarrytown: Pergamon Press. OCLC 26188. ISBN 0-08-013972-8.

Pollack, H. (2009). *A world without ice*. New York: Avery. ISBN 978-1-58333-357-0.

Post, A., & LaChapelle, E. R. (2000). *Glacier ice*. Seattle: University of Washington Press. ISBN 0-295-97910-0.

Roe, G. (2006). In defense of Milankovitch. *Geophysical Research Letters, 33*(24), L24703. doi:10.1029/2006GL027817. Bibcode 2006GeoRL..3324703R.

Wunsch, C. (2004). Quantitative estimate of the Milankovitch-forced contribution to observed Quaternary climate change. *Quaternary Science Reviews, 23*(9–10), 1001–1012. doi:10.1016/j.quascirev.2004.02.014. Bibcode 2004QSRv…23.1001W.

Chapter 15
Permafrost and Methane

Abstract Permafrost is defined as permanently frozen ground, except the upper part usually thaws during summer months. Most of the permafrost on Earth is in areas that were glaciated during the last ice age and are still cold enough to keep the ground frozen. There is a tremendous quantity of methane trapped in permafrost that is being released as the permafrost melts. Methane is 25 times more potent as a greenhouse gas than carbon dioxide, to which it eventually converts in the atmosphere. Methane clathrates are potentially the cause of relatively sudden climate changes in the geologic past (PETM) and today represent a potential clathrate gun hypothesis for future sudden climate change.

Keywords Methane • Permafrost • Line • Periglacial • Ice • Exothermic • NSIDC • PETM • Thermal • Maximum • Andes • Frozen • Gun • Peat • Clathrates • Paleocene • Eocene • EIA • Glaciation • Pleistocene • Drilling • Natural • Gas

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
Permafrost	Eocene
Horizontal Drilling	Periglacial
Dense Shale Deposits	Paleocene
Clathrates	Methane
18,000 Years Ago	Peat
24%	NSIDC

(continued)

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_15,

(continued)

Things to Know	
PETM	Methane Gun Hypothesis
North American Ice Line	Pleistocene
2.8 Miles	"Ice Age"
Eurasia	Exothermic
Methane Chemistry	Clathrate Gun Hypothesis

15.1 Introduction

Permafrost is a common product of the last continental glaciation in North America and Eurasia in the Northern Hemisphere and mountain glaciation in the higher mountain regions of the world. Its official definition, according to the NSIDC, is "permanently frozen ground, soil, sediment, or rock that remains at or below 0°C for at least 2 years. It occurs both on land and beneath offshore Arctic continental shelves, and its thickness ranges from less than 1 meter to greater than 1,000 meters." It can contain over 30% ice or practically no ice at all. It can be overlain by several meters of snow, or little or no snow. Permafrost is also a periglacial feature that is found around the edges of glacial ice today. Vast quantities of methane are bound up in permafrost and released to the atmosphere as it melts seasonally and due to global warming.

15.2 Distribution

The illustration below (Fig. 15.1) shows the extent of permafrost in the Northern Hemisphere. There are vast areas of permafrost in northern Canada, Alaska, Siberia, the Himalayas, Alps, and Rocky Mountains and Coastal ranges in the U.S. Not shown on the map are the locations of permafrost in the Southern Hemisphere in the high mountains of South America, the Andes Mountains. Permafrost areas also occur in Antarctica in regions not covered by glacial ice.

Permafrost regions occupy approximately 22.79 million km^2 (about 24% of the exposed land surface) of the Northern Hemisphere. In terms of area, permafrost can be characterized as continuous, discontinuous, sporadic, or isolated, but because these are descriptive terms, the boundaries separating different permafrost zones are gradational and not sharp.

Information about permafrost is critical to understanding climate change, other environmental concerns, construction, engineering, and architecture in areas underlain by permafrost. Construction in areas of permafrost is especially difficult as concrete cannot be used in foundations, roads, sidewalks, etc., because when concrete is settling it gives off heat (is exothermic) and melts the permafrost around it. Consequently, wood and plastic are often used in place of concrete and utilities and pipelines either are lined with insulation or constructed above ground.

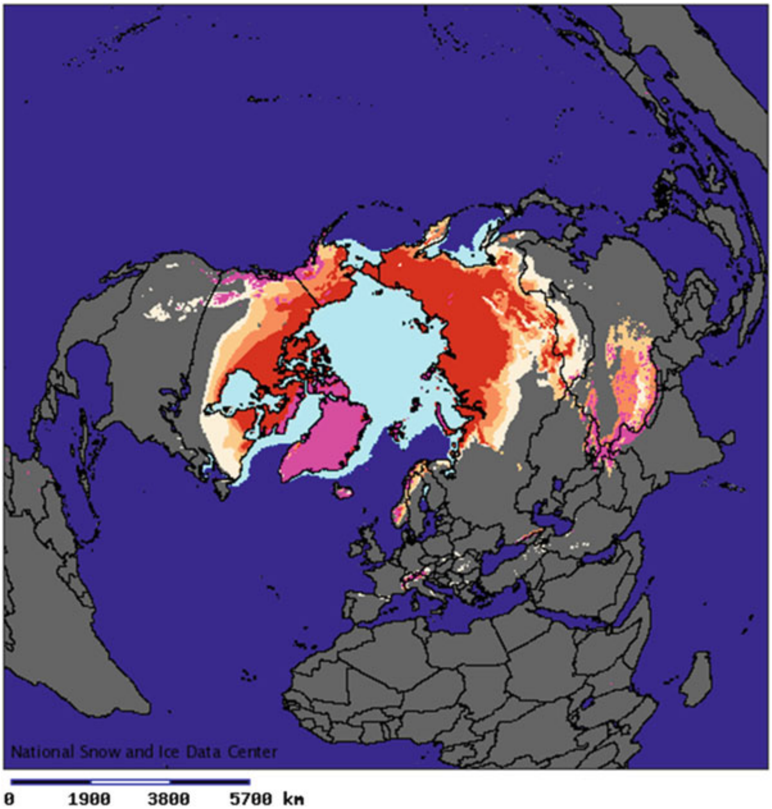


Fig. 15.1 Distribution of permafrost and ice in the Northern Hemisphere. Glaciers and the Greenland Ice Sheet are violet, and Arctic Sea Ice is *light blue* (From NSIDC/NOAA, Public Domain)

Land beneath glaciers would seem to always be frozen, but this is not the case. The historical approach to defining permafrost has been to assume that ground temperature equals air temperature, thus ground beneath glacial ice would be permafrost. Often the two temperatures are not the same and in some cases the ground is warmer than 0°C, especially near the terminus of the ice.

Permafrost underlies about 20% of the land in the Northern Hemisphere and is widespread within the Arctic Ocean's vast continental shelves and in parts of Antarctica. Most of the world's permafrost has been frozen for millennia and can be up to nearly 5,000 ft thick.

A 2009 study investigating the permafrost carbon-pool size estimates that 1,400–1,700 gigatonnes (Gt) of carbon are stored in permafrost soils worldwide. This carbon is both in methane (CH_4) and frozen peat and is rapidly being released to the atmosphere as the Earth warms. There are eyewitness reports of methane bubbling up from lakes and shallow marine environments in regions of permafrost surrounding the Arctic Ocean. There are videos on the internet of burning methane bubbling from holes in lake ice in northern high latitudes.

A possible analog to modern global warming is the Paleocene – Eocene Thermal Maximum (PETM), an episode in Earth history about 55 million years ago when the Earth warmed by several degrees in a relatively short few thousand years. Earth's atmospheric temperature is a result of energy input from the Sun minus what escapes back to space, as has been discussed earlier in this text, amplified by certain feedbacks in the climate system. Carbon dioxide, methane and other greenhouse gases in the atmosphere absorb and trap heat that would otherwise return to space.

The PETM was accompanied by a massive carbon input to the atmosphere, with ocean acidification, and was characterized by a global temperature rise of about 5 or 6°C in a few thousand years, a recent April 2012 study in the scientific journal *Nature*, concludes. Until now, it has been difficult to account for the massive amounts of carbon required to cause such dramatic global warming events.

Historically, the warming during the PETM has been related to the release of methane from shallow sea deposits of methane clathrates. The April 2012 report in *Nature* ascribes the carbon source to the continents, in polar latitudes where permafrost can store massive amounts of carbon that can be released as CO_2 and methane when the permafrost thaws. This new view is supported by calculations estimating interactions of variables such as greenhouse gas levels, changes in Earth's tilt and orbit, ancient distributions of vegetation, and carbon stored in rocks and in frozen soil.

During the PETM, the positive feedback effect of melting ice reducing albedo, temperature increases would have been greatest at the poles, which reached an average annual temperature of 10–20°C (50–68°F); the surface waters of the northernmost Arctic ocean warmed, seasonally at least, enough to support tropical life forms requiring surface temperatures of over 22°C (72°F).

15.3 Origin of Permafrost

Much of the current permafrost is due to the Pleistocene glaciation that began to recede for the last time 20,000–18,000 years ago. Prior to the recession of the ice and during the early parts of the recession, large areas of continental shelves were exposed to the atmosphere. During this exposure, a great deal of peat was deposited on these exposed continental shelves and methane accumulated in areas where oxygen was absent, such as swamp environments, which were common. Environments without oxygen are called anoxic or anaerobic. So today, the shallow continental shelf areas in the Arctic have large stores of methane, peat, and carbon dioxide. A release of this material to the atmosphere would have disastrous consequences for present life on Earth.

As mentioned previously, the Earth is still in an ice age as we have glaciers present and ice at the poles. We are presently in an interglacial stage of the "ice age," as glaciers are receding. But during an "ice age" glaciers contract and expand. During the maximum extent of the ice during the Pleistocene, permafrost was most likely more extensive than it is today as it was present around the edges of continental and mountain glaciers, in the exposed continental shelf areas, and beneath the glaciers themselves.

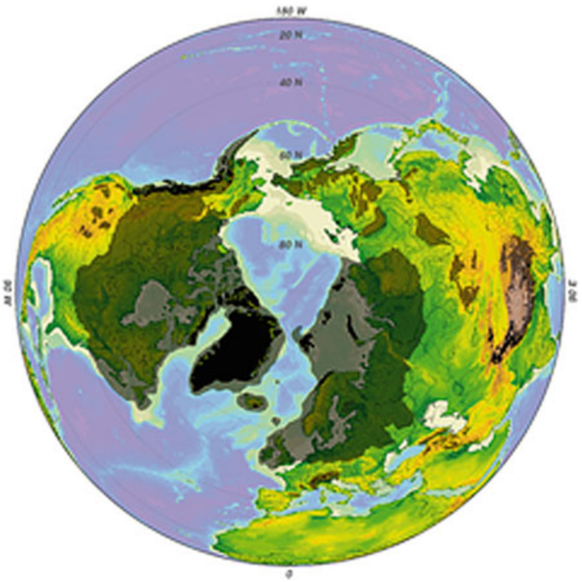


Fig. 15.2 Minimum (interglacial, *black*) and maximum (glacial, *grey*) glaciation of the northern hemisphere (From Wikipedia, Hannes Grobe, Creative Commons Attribution/Share-Alike License)

In North America, the last continental glacier covered all of Canada and what is now the United States north of a line that can be drawn on a map from Long Island, NY through Pennsylvania, along the Ohio River to the Missouri River (Fig. 15.2). This line is called the North American Ice Line and north of it the land (Fig. 15.3) was covered by a continental glacier about 2.8 miles thick (thinning toward its edges) only about 20,000 years ago. Northern Eurasia was also covered by a continental glacier.

The Southern Hemisphere was also glaciated with the extensive continental glacier over Antarctica and smaller glaciers in the southern Andes Mountains (Fig. 15.4).

Figure 15.4 shows the maximum extent of glacial ice during the Pleistocene glaciation.

15.4 Methane Chemistry

Methane is a simple molecule of one carbon atom surrounded by four atoms of hydrogen represented by its chemical formula of CH_4.

Methane is the principal component of natural gas and its use as a fuel is important. However, since it is a gas at normal physical and chemical conditions, it is difficult to transport from its source. At room temperature, methane is a colorless, odorless gas. The odor commonly associated with natural gas is due to an additive used as a safety factor.

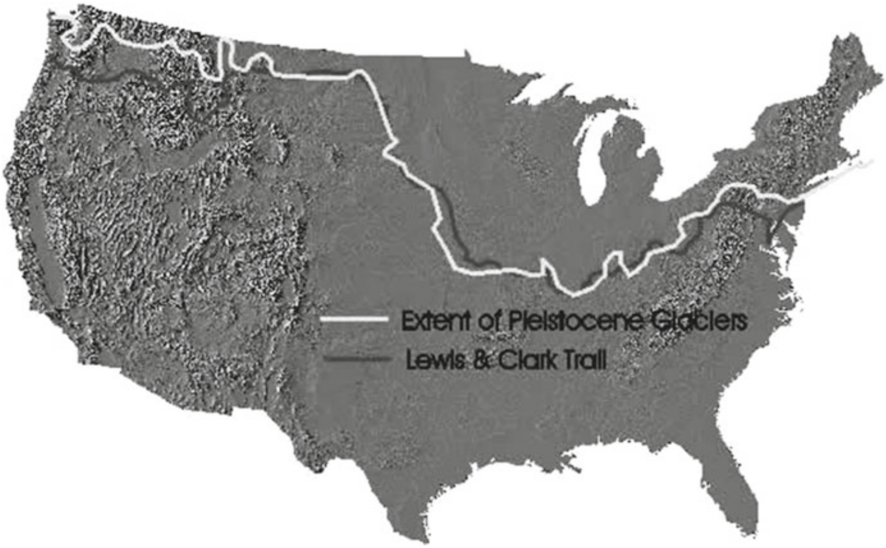
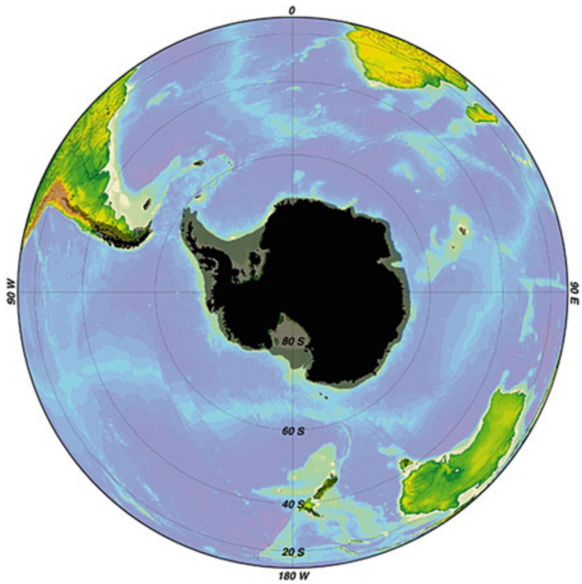


Fig. 15.3 The North American Ice Line (white line) and the trail followed by Lewis and Clark (From http://www.carnegiemnh.org/ip/tours/trail/red/4.jpg)

Fig. 15.4 Minimum (interglacial, *black*) and maximum (glacial, *grey*) glaciation of the southern hemisphere (From Wikipedia, Hannes Grobe, Creative Commons Attribution/ Share-Alike License)



Methane has a boiling point of −161°C (−257.8°F) at a pressure of one atmosphere. As a gas it is flammable only over a narrow range of concentrations (5–15%) in air. Liquid methane does not burn unless subjected to high pressure (normally 4–5 atm). Methane easily converts to carbon dioxide and water upon oxidation.

$$CH_4 + O_2 \rightarrow CO + H_2 + H_2O$$

The resulting H_2 oxidizes to H_2O, releasing heat. This reaction occurs very quickly, usually in significantly less than a millisecond.

$$2H_2 + O_2 \rightarrow 2H_2O$$

Finally, the CO oxidizes, forming CO_2 and releasing more heat. This process is generally slower than the other chemical steps, and typically requires a few to several milliseconds to occur.

$$2CO + O_2 \rightarrow 2CO_2$$

The result of the above is the following total equation:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Natural gas, of which methane is the principle component, is a relatively clean-burning fuel and is transported by tankers and truck as liquid natural gas (LNG) and by pipelines. It produces less carbon dioxide than other hydrocarbons such as gasoline, diesel, and coal.

Sources of methane are coal deposits, gas fields related to petroleum deposits, landfills, and livestock. The majority of coal mine explosions are the result of methane. Methane is also the main constituent of swamp gas, is produced in the cultivation of rice and other agriculture, is a product of manure and rumination. Perhaps the largest reservoir of methane is methane clathrates found in shallow continental shelf areas that were previously exposed to anaerobic conditions in swamps during the low stand of sea level during the Pleistocene glacial advances.

Methane is a potent greenhouse gas and remains in the atmosphere for approximately 10–15 years before it is completely converted to carbon dioxide and water. It has a Global Warming Potential (GWP) of 21 over 100 years. In 2010, methane levels in the Arctic were measured at over twice as high as at any time in the previous 400,000 years. Historically, methane concentrations in the world's atmosphere have ranged between 300 and 400 ppb (parts per billion) during glacial periods commonly known as ice ages, and between 600 and 700 ppb during the warm interglacial periods. It has a high global warming potential; 72 times that of carbon dioxide over 20 years, and 21 times over 100 years, and the levels are rising except for a recent leveling off and mysterious decline.

Relatively recent discoveries of natural gas from dense, organic shale deposits have added to the world's inventory of fuels. Natural gas is an efficient energy source and the cleanest-burning fossil fuel. Natural gas extracted from dense carbonaceous shale rock formations has become the fastest-growing source of gas in the United States and other parts of the world and could become a significant new global energy source. Although the energy industry has long known about huge gas resources trapped in dense shale rock formations in the United States, it is over the past decade (2002–2012) that energy companies have combined two established technologies, (1) hydraulic fracturing (“fracking”) and (2) horizontal drilling, to successfully unlock this resource.

Natural gas from these shale deposits has grown to 25% of U.S. gas production in just a decade and will be 50% by 2035, according to the U.S. Energy Information Administration (EIA). Developing this resource can help enhance energy security and strengthen economies. Shale gas is the largest contributor to the projected growth in natural gas production, and by 2035 shale gas production will account for 46% of the total U.S. natural gas production according to oil and gas companies.

The use of horizontal drilling in conjunction with hydraulic fracturing has greatly expanded the ability of producers to profitably produce natural gas from low permeability geologic formations, particularly dense shale formations. Application of fracturing techniques to stimulate oil and gas production grew rapidly in the 1950s, although experimentation dates back to the nineteenth century. Starting in the mid-1970s, a partnership of private operators, the U.S. Department of Energy (DOE) and the Gas Research Institute (GRI) began to develop technologies for the commercial production of natural gas from relatively shallow shale deposits in the Eastern United States. This partnership helped foster technologies that eventually became crucial to producing natural gas from shale rock, including horizontal wells, multi-stage fracturing, and slick-water fracturing. Practical application of horizontal drilling to oil production began in the early 1980s, by which time the advent of improved downhole drilling motors and the invention of other necessary supporting equipment, materials, and technologies, particularly downhole telemetry equipment, had brought some applications within the realm of commercial viability.

15.5 Future Projections for Permafrost and Methane

In the context of the future climate change, there are two key concerns associated with the thawing of permafrost; the detrimental impact on the infrastructure built upon it, and the feedback to the global climate system through potential emissions of greenhouse gases.

The upper part of permafrost, a few inches to a few feet in thickness, is called the “active layer.” It is this layer that melts in the warmer months of the year. The projection for the future is for the active layer to become deeper and thicker as the Earth warms.

A critical factor influencing the response of areas of permafrost to warming is the presence of ground ice. Ground ice generally is concentrated in the upper 10 m of permafrost; the very layers that will thaw first as permafrost degrades. This loss is effectively irreversible because once the ground ice melts it cannot be replaced for millennia, even if the climate subsequently cools. The response of the permafrost landscape to warming will be profound, but it also will vary greatly at the local scale, depending on ground-ice content. As substantial ice in permafrost is melted, there will be land subsidence, as ice occupies more space than its liquid equivalent.

A forerunner of future landscapes can be seen today in areas of massive ground ice areas such as in Siberia, where past climatic warming has altered the landscape by producing extensive flat-bottomed valleys. Ponds within such an area will eventually grow into thaw lakes. These thaw lakes continue to enlarge for decades to centuries because of wave action and continued thermal erosion of the banks. Liquefaction of the thawed layer will result in mudflows on slopes in terrain that is poorly drained or contains ice-rich permafrost. On steeper slopes there also will be landslides and mudslides.

The most sensitive permafrost areas are sea coasts bordered by ice-bearing permafrost that are exposed to the Arctic Ocean. Mean annual erosion rates vary from 2.5 to 3.0 m per year for the ice-rich coasts to 1.0 m per year for the ice-poor permafrost coasts along the Russian Arctic Coast. Over the Alaskan Beaufort Sea Coast, mean annual erosion rates range from 0.7 to 3.2 m per year with maximum rates up to 16.7 m per year. As global warming continues, these rates are certain to increase.

Observations show a consistent picture of surface warming and reduction in all components of the cryosphere, except Antarctic sea ice, which exhibits a small positive but insignificant trend since 1978.

15.6 Methane Gun Hypothesis

The methane gun hypothesis (also named the clathrate gun hypothesis) is an explanation for the rapid and continuing rise in temperature due to a sudden irreversible release of methane, with no chance of retrieval much like the firing of a gun.

During a geologically short amount of time at the transition between the Paleocene and Eocene epochs about 55 million years ago, carbon isotope ratios everywhere (the deep sea, on land, at the poles, and in the tropics) suddenly changed to favor the lighter ^{12}C isotope of carbon at the expense of heavier ^{13}C. The rapidity and size of this change was unprecedented in the interval that followed the demise of the dinosaurs, and this excursion was simultaneous with a short period of extreme global warming (around 3–4° globally, more in the higher latitudes). This interval was the Paleocene – Eocene Thermal Maximum (PETM) mentioned previously.

The only conceivable perturbation to the global carbon cycle that fits these data from the PETM is a massive input of light carbon that had been stored as methane clathrates, which are observed to be particularly high in ^{12}C. Nothing else could have been as fast-acting or have enough of the lighter isotope to have had the observed effects. Given that both CH_4 and its oxidization product CO_2 are greenhouse gases, this might explain the global warming leading up to the PETM as well.

In ocean sediments offshore of California, scientists from Woods Hole Oceanographic Institution recently (2011) found geochemical traces of clathrate releases at the same time as warming detected in the Greenland ice core records. In some records, there are spikes in the carbon isotope record, similar to the Paleocene-Eocene spike but of lower amplitude. This has led some scientists to propose the so-called clathrate gun hypothesis; that methane builds up in clathrates during cold periods and as a warming starts, it is explosively released leading to enhanced further rapid climate warming.

Some scientists think that the clathrate gun hypothesis may not be widely accepted because the records of methane in the ice cores seem to lag the temperature changes, and the magnitudes involved do not appear large enough to significantly perturb the radiative balance of the planet. There are others that disagree and argue that the data do not provide enough detail to resolve the time difference and that there has been plenty of methane in the past to provide the necessary climate change perturbation. There is also the possibility that estimates of methane bound up in clathrates have been low.

An alternative explanation for the PETM is that as the climate warms there is increased rain in the tropics and thus increased emissions of methane from tropical wetlands which need to have been large enough to counteract a probable increase in the methane sink. There is, however, much that we don't understand about the methane cycle during the ice ages, and maybe methane clathrates will eventually be considered a large part of the rapid climate change story.

Additional Readings

Alley, R. B. (2000). *The two-mile time machine: Ice cores, abrupt climate change, and our future*. Princeton: Princeton University Press.

Christensen, T. R., et al. (2004). Thawing sub-arctic permafrost: Effects on vegetation and methane emissions. *Geophysical Research Letters, 31*, L04501. doi:10.1029/2003GL018680.

EPICA Community Members. (2004). Eight glacial cycles from an Antarctic ice core. *Nature, 429*, 623–628. doi:10.1038/nature02599.

Hinrichs, K. U., et al. (2003). Molecular fossil record of elevated methane levels in late Pleistocene coastal waters. *Science, 299*, 1214–1217. doi:10.1126/science.1079601.

Intergovernmental Panel on Climate Change. (2001). *Climate change 2001: The scientific basis*. Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change. (2007). *Climate change 2007: The scientific basis*. Cambridge: Cambridge University Press.

Kennett, J. P., et al. (2003). *Methane hydrates in Quaternary climate change: The clathrate gun hypothesis*. Washington, DC: American Geophysical Union.

Lamb, H. H. (1972). *Climate past, present and future* (Vol. 1). London: Methuen & Co Ltd.

Ruddiman, W. (2003). The anthropogenic greenhouse era began thousands of years ago. *Climatic Change, 61*, 261–293. doi:10.1023/B:CLIM.0000004577.17928.fa.

Schmidt, G. A., & Shindell, D. T. (2003). Atmospheric composition, radiative forcing and climate change as a consequence of a massive methane release from gas hydrates. *Paleoceanography, 18*. doi:10.1029/2002PA000757.

Severinghaus, J. P., & Brook, E. J. (1999). Abrupt climate change at the end of the last glacial period inferred from trapped air in polar ice. *Science, 286*, 930–934. doi:10.1126/science.286.5441.930.

Wang, W. C., et al. (1976). Greenhouse effects due to man-made perturbation of trace gases. *Science, 194*, 685–690.

Part VI
Land and Its Climates

Chapter 16
Continents and Mountain Ranges

Abstract Continents and ocean basins make up the planet's crust, Earth's outermost layer. Continental areas consist of sialic materials and ocean basins consist of simatic materials, the two main rock types, based on their mineral composition, that make up the Earth's crust. There are several models for naming continents including a seven-continent model and a three-continent model. Both continents and ocean basins have mountain ranges and the continental ones, such as the Alps, Himalayas, Appalachians, and Rockies are better known. The Mid-Atlantic Ridge is most likely the best-known oceanic one. Continental climates are moderated by nearby bodies of water and often form rain-shadows. The continents have drifted to their present locations from a supercontinent called Pangaea that straddled the equator at times past. The mechanism for drifting continents is the concept of Harry Hess' sea-floor spreading that gave rise to the theory of plate tectonics.

Keywords Sial • Sima • Continent • Ocean • Basin • Landmass • Isthmus • Suez • Asia • Europe • Australia • Africa • Granite • Basalt • Gondwana • Laurasia • Pannotia • Eurasia • Supercontinent • Pangaea • Rodinia • Drift • Hess • Spreading • Islands • Arcs • Appalachians • Rockies • Alps • Guyots • Seamounts • Transantarctic • Asthenosphere • Convection • Caucasus

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_16,

Things to Know	
Continents	1.1 Billion
Sima	Eurasia
Rodinia	Seven Continent Model
Isthmus of Suez	Sial
Sea-Floor Spreading	Pangaea
Ocean Basins	Harry Hess
Transantarctic Mountains	Gondwana
Southern Alps	Beartooth
Plate Tectonics	Appalachians
Three Continent Model	Ural Mountains
Alfred Wegener	Six Continent Model

16.1 Introduction

A continent is a large landmass on Earth usually separated by ocean or other body such as a mountain range. In the seven-continent model (Fig. 16.1), the major continents are North America, South America, Asia, Africa, Antarctica, Europe, and Australia. North America and South America are separated by the Isthmus of Panama, Europe and Asia are separated by the Ural Mountains, Africa is separated from Europe by the Mediterranean Sea, Asia from Africa by the Isthmus of Suez. In geology and geography, Europe and Asia are combined into one continent, Eurasia which makes a six-continent model. The distribution of continents across

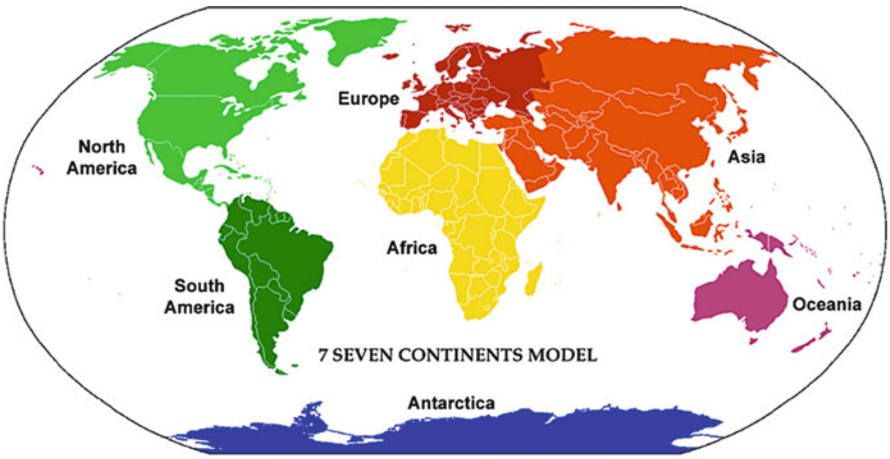


Fig. 16.1 *Color-coded map* showing the various continents. Similar *shades* exhibit areas that may be consolidated or subdivided (From Wikipedia, Public Domain)

the surface of Earth is very important for their effects on world-wide climate. If all continents are together straddling the equator the global climate is much different than it is when the continents are mainly in the Northern Hemisphere or migrating towards the poles and we know that in the geologic past continents have drifted across the face of the planet.

From a geological or physical geography perspective, a continent may be extended beyond the confines of continuous dry land to include the shallow, submerged adjacent area, the continental shelf and continental slope and the islands on the shelf as they are geologically part of the continent. From this perspective the edge of the continental shelf and continental slope represent the true edge of the continent, as shorelines vary with changes in sea level. In this sense the islands of Great Britain and Ireland are part of Europe, while Australia and the island of New Guinea together form a continent.

There are other definitions of continents such as the three-continent model: Eurafrasia (consisting of Africa, Asia and Europe), America (consisting of North America and South America), and Oceania (consisting of Australia, New Zealand, Melanesia, Micronesia, and Polynesia). The six-continent model combines Europe and Asia into one continent (Eurasia).

The positions of continents relative to each other, the equator, the poles, and the sea are all important as they relate to the climate of each at any point in time. The configuration of each continental land mass is also important as high-standing mountains have a climate that is different from adjacent lowlands. The proximity to large bodies of water is important climatically as coastal areas have climates directly affected by adjacent or near-by seas or other large bodies of water.

Continents that we see on maps today are not in the same places as they have been in the past. A map produced 300 million years ago would look much different than the map produced today.

16.2 Continental Drift

A German meteorologist and amateur geologist, Alfred Wegener, in the early part of the twentieth century (1912), first proposed that all of Earth's continents had once been joined in a single supercontinent. He published his ideas for this supercontinent in a book called *Die Entstehung der Kontinente und Ozeane* ("The Emergence of the Continents and Oceans"). The idea that South America and Africa had once been joined had first been proposed in the 1500s, shortly after the first maps of the world were published, but the idea was formalized and evidence for it first cited by Wegener.

Wegener mentioned structures shared by South America and Africa and other evidence for his supercontinent but his ideas were largely ignored by the scientific community at the time. Wegener proposed that the supercontinent had broken apart by the centrifugal force exerted by the Earth spinning on its axis of rotation. This idea was ridiculed by his fellow scientists because the centrifugal force is not great enough to separate continents. Also, geologists and especially geophysicists were

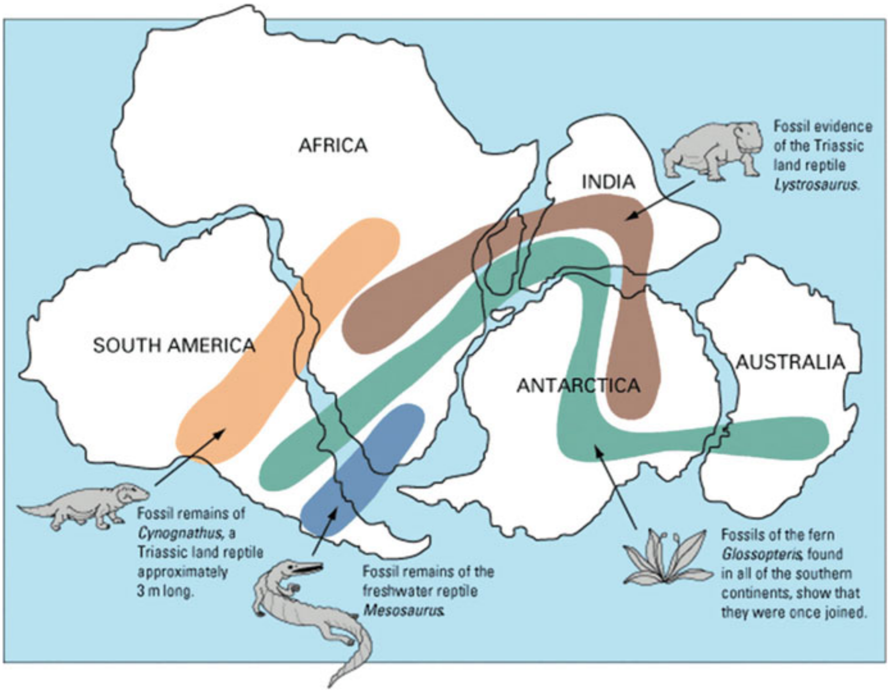


Fig. 16.2 Evidence of continental drift from the fossil record (USGS, Public Domain)

adamantly opposed to the idea of continental masses plowing through the rigid crust to move from place to place.

It wasn't until a mechanism was proposed and tested and voluminous evidence acquired, such as that illustrated in Fig. 16.2, that the concept of continental drift was accorded legitimacy by the scientific community. The fossil organisms shown in Fig. 16.2 were not able to swim or be carried over vast expansive areas of open ocean that exist today.

The mechanism for continental drift that was lacking during Wegener's time was finally conceived by a professor at Princeton University, Harry Hess, as we've seen earlier in this text.

16.3 Harry Hess and Sea-Floor Spreading

Harry Hess (1906–1969) has been previously mentioned in this text as the source of the concept of sea-floor spreading. His work set the stage for the later idea of Plate Tectonics. He served in the U.S Navy in WWII and with the blessing of his crew was able to survey the ocean floor of the Pacific Ocean basin with echo sounding equipment between his ship's battles.

Hess formulated a hypothesis about a spreading sea floor in 1959 in an informal manuscript that was widely circulated among his colleagues. It was later formally published (1962) in a paper entitled "History of Ocean Basins" which was one of the most important and groundbreaking contributions in the development of the theory of Plate Tectonics and of Earth science in general. Hess built upon the work of an English geologist, Arthur Holmes (1890–1965), who worked in the early to middle parts of the twentieth century. Holmes championed the concept of continental drift and the sea-floor spreading concept of Hess.

In Hess' 1962 paper, he described how seafloor spreading worked; molten rock (magma) oozes from the Earth's interior along the mid-oceanic ridges, creating new seafloor that spreads away from the active ridge and eventually sinks into the deep ocean trenches. The mechanism that causes this is convection cells in the Earth's mantle. Convection cells bring molten rock to the surface at mid-ocean ridges and the seafloor is forced apart and moved away from the ridges.

At the time of Hess' paper, there were certain questions about the seafloor that were still unanswered. It had been discovered that the ocean basins were not as old as they had been thought to be. Geologists had long thought that the ocean basins would yield sediments that would provide evidence for the beginning of time on Earth, the Earth's origin (about 4.54 billion years ago). This was not the case and Hess reasoned that sediment had been accumulating on the ocean floor for only about 300 million years. Hess estimated that it took that long for the ocean floor to move from the mid-ocean ridges to the oceanic trenches near the continents. Later sampling and age dating of oceanic rocks would prove Hess's estimates correct.

Hess' idea received the expected resistance from the numerous conservatives in the scientific community because geologists were still skeptical about a mechanism, although Hess knew that the oldest fossils found at that time on the seafloor were only about 180 million years old. He proposed that the mechanism for sea-floor spreading was new crust formed at the mid-ocean ridges that forced the seafloor to move to the trenches. Many still clung to the belief that continents and ocean basins had been too brittle for them to move great distances, as was called for by the sea-floor spreading concept, and the earlier concept of drifting continents by Wegener. After all, when struck by a hammer or other tool, most rocks shatter. Earlier ideas on continental drift had the continents plowing through the oceanic crust to their present locations and most geologists and geophysicists knew that this was simply not possible.

Hess was aware that there were limited ways to test his hypothesis, but later geophysical studies confirmed that oceanic crust was disappearing (subducting) into the Earth's oceanic trenches. Hess, unlike Wegener, lived to see the confirmation of his hypothesis and it resulted in the concept of Plate Tectonics that revolutionized the Earth sciences at the time. It has been described as a paradigm shift in Earth Science. It has caused geologists around the world to look at rocks and Earth history in an entirely different way than they had before.

Hess also discovered hills on the seafloor that had flat tops. These he called guyots, which are flat-topped volcanic hills that were built from the seafloor to the surface of the ocean when they were formed and had their tops cut off (eroded) by wave action and later sank to the bottom. Other hills on the sea floor were called seamounts. The guyots with their flat tops slowly sank below the surface under their own weigh (the geology building at Princeton University at the time was named Guyot Hall in honor of Harry Hess and his ground-breaking research).

16.4 Plate Tectonics

Plate tectonics is the theory of Earth history which has as its underlying concept the idea of continental drift. The concept evolved from evidence gathered from the continents and from the ocean basins of Earth. Plate tectonic theory says that the Earth's crust consists of relatively thin plate-like continental crust "floating" on a plastic-like substrate called the asthenosphere (see Fig. 16.5 below). Figure 16.5 shows the subduction of oceanic crust beneath a continental crust and the volcanoes at the surface. Movement of oceanic crust is due to the asthenosphere which is the upper part of Earth's mantle. The asthenosphere behaves as a plastic layer and moves because of convection cells in the mantle.

Oceanic plates (basaltic or simatic) are generally denser than continental plates (granitic or sialic). When an oceanic plate and a continental plate collide, the denser oceanic plate sinks beneath the continental plate. The oceanic plate is subducted beneath the continental plate. Geologists think that the oceanic plate is pulled down beneath the continental plate by an "arm" of a convection cell.

Figure 16.3 shows all of Earth's plates as they were in the supercontinent of Pangaea before its breakup. The red arrows indicate directions of movement of the plates as they broke apart.

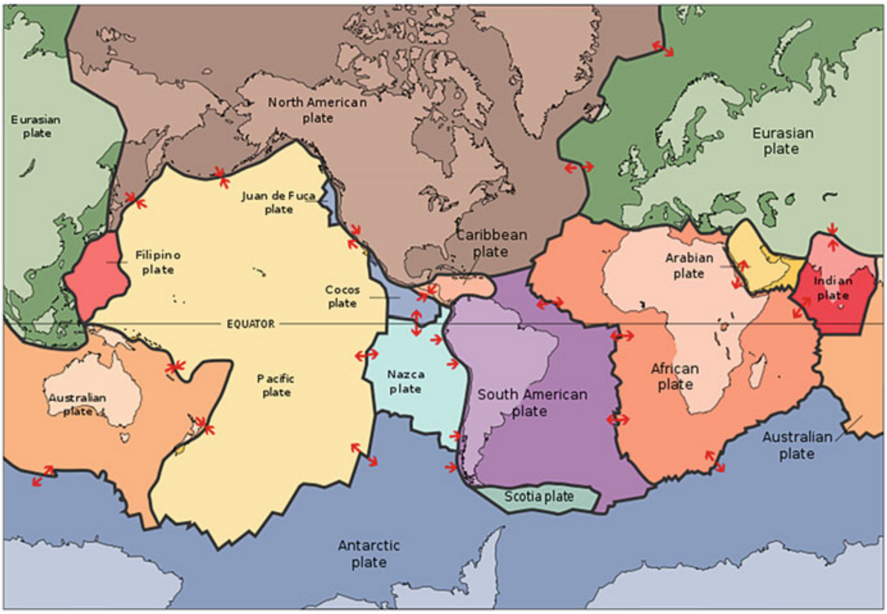


Fig. 16.3 The key principle of plate tectonics is that the lithosphere exists as separate and distinct tectonic plates, which float on the fluid-like (visco-elastic solid) asthenosphere. The relative fluidity of the asthenosphere allows the tectonic plates to undergo motion in different directions. This map shows 15 of the largest plates. Note that the Indo-Australian Plate may be breaking apart into the Indian and Australian plates, which are shown separately. *Red arrows* indicate relative plate movements (USGS, Public Domain)

Essential concepts of plate tectonic theory are the following:

1. Plate boundaries;
2. Subduction zones;
3. Rates of plate movement;
4. Mid-ocean ridges;
5. Hot spots;
6. Sea-floor spreading;
7. Magnetic reversals;
8. Oceanic trenches;
9. Island arcs;
10. Asthenosphere;
11. Convection in the Earth's mantle;
12. Differences between oceanic and continental crust).

16.4.1 Types of Plate Boundaries

Four types of plate boundaries exist, characterized by the way the plates move relative to each other. They are associated with different types of surface expression. The different types of plate boundaries are:

1. **Transform boundaries** – occur where plates slide or grind past each other along transform faults.
2. **Divergent boundaries** occur where two plates slide away from each other. Mid-ocean ridges (e.g., Mid-Atlantic Ridge) and active zones of rifting (such as Africa's Great Rift Valley) are both examples of divergent plate boundaries (Fig. 16.3).
3. **Convergent boundaries** (or active margins) occur where two plates slide towards each other commonly forming either a subduction zone (if one plate moves underneath the other) or a continental collision (if the two plates contain continental crust). Deep marine trenches are typically associated with subduction zones. Examples of this are the Andes mountain range in South America and the Japanese island arc.
4. **Plate boundary zones** occur where the effects of the interactions are unclear and the broad belt boundaries are not well defined.

Types of plate boundaries are illustrated in Fig. 16.5 below.

Plates move relative to each other on the order of millimeters a year, or at the most a centimeter a year. Their rate of movement varies but averages from about 10 to 160 mm per year. Some plates move slowly, then bound wildly at about a centimeter of movement all at once. This is thought to be due to the elastic nature of the plate substrate and perhaps is related to the elastic rebound theory of earthquakes.

Plate boundaries are where most crustal activity takes place. Around the Pacific Ocean is the "Circum-Pacific Ring of Fire" so called because of the earthquake and

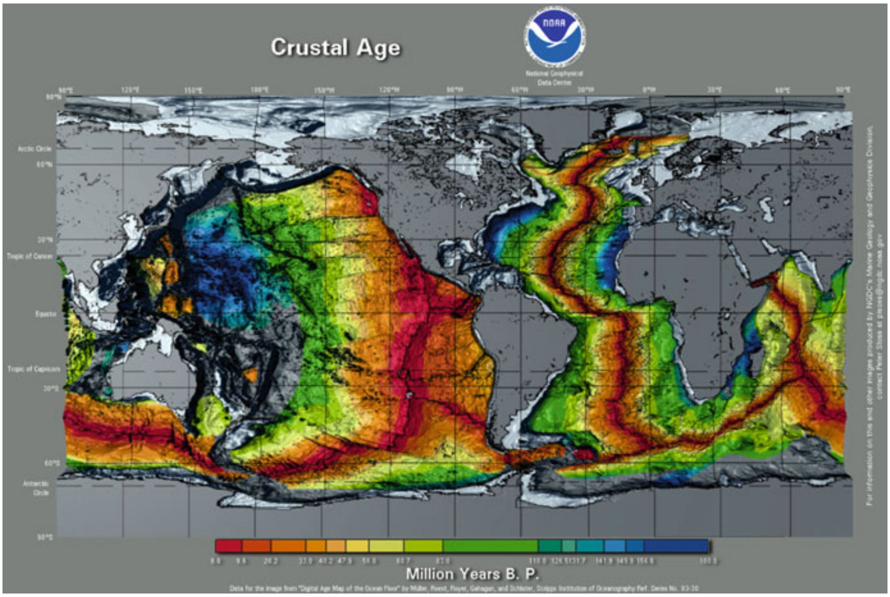


Fig. 16.4 Features of the ocean basins showing relative ages of the ridges and floors of the ocean basins (NOAA, Public Domain)

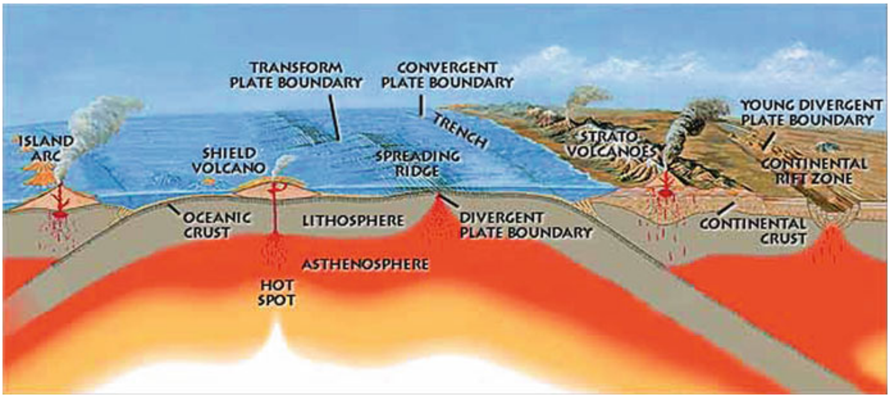


Fig. 16.5 Different types of plate boundaries (USGS, Public Domain)

volcanic activity on its margins. The figure below (Fig. 16.6) shows the distributions of earthquakes and volcanoes on plate boundaries of the world.

Earthquakes and volcanoes are not randomly scattered across the surface of Earth but occur in distinct areas; the circum-Pacific, the Mediterranean, Indonesia, Japan,

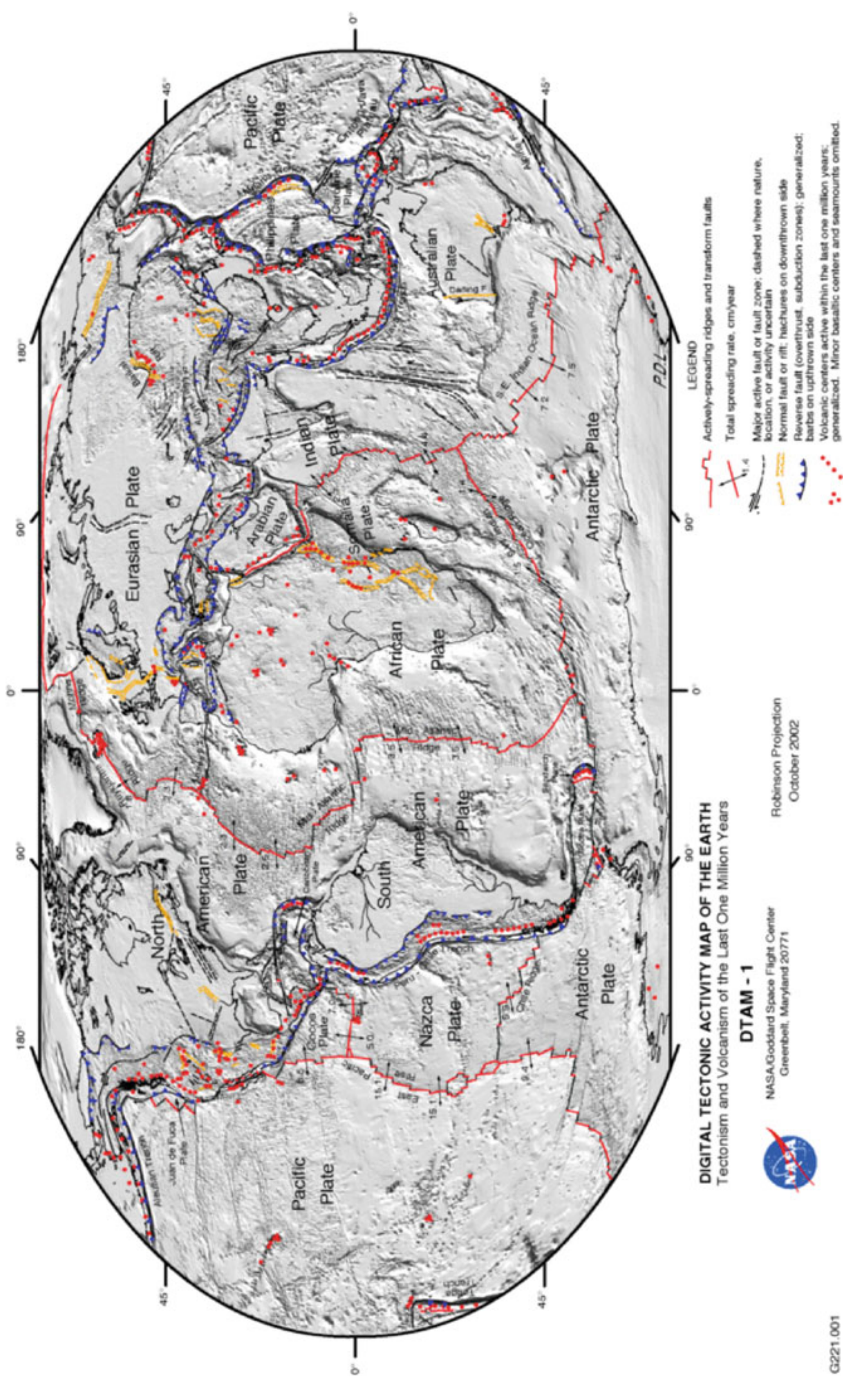


Fig. 16.6 Crustal plate boundaries showing the locations of earthquakes and the "ring of fire" around the Pacific Ocean Basin (From http://csep10.phys.utk.edu/astr161/lect/earth/evidence.html)

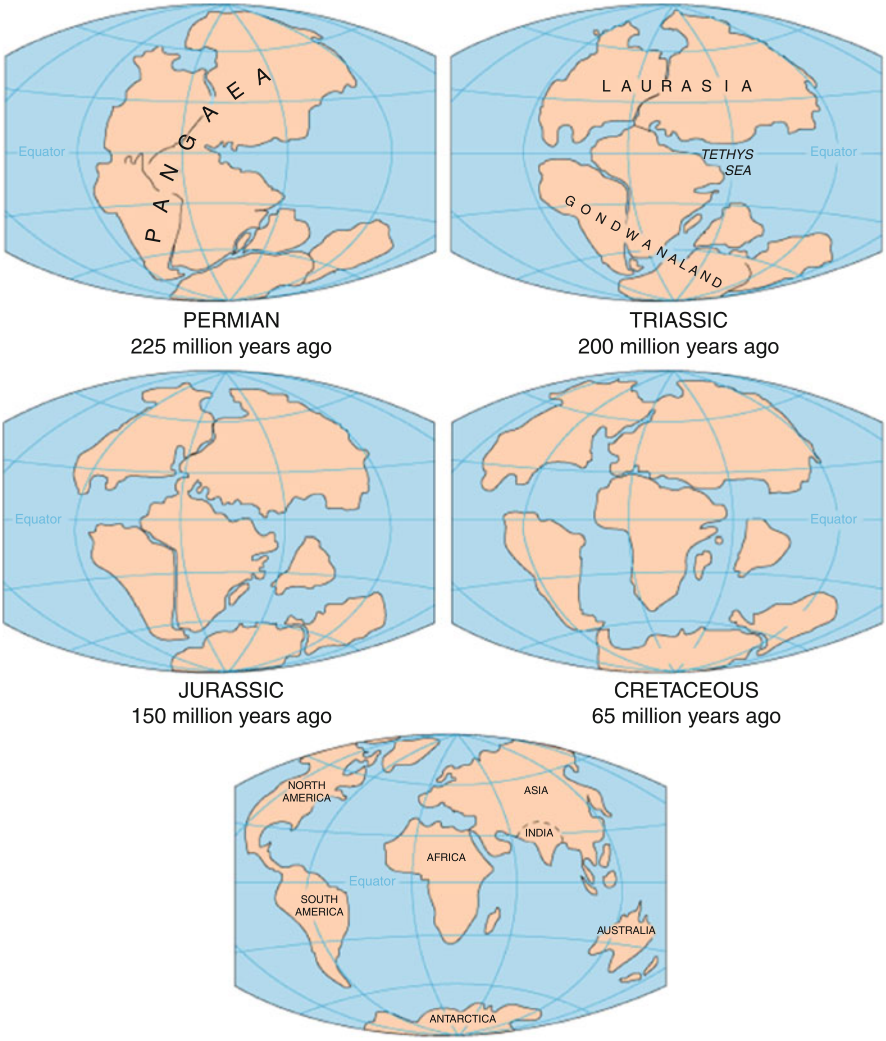


Fig. 16.7 Pangaea as it was in the Permian, how it broke apart, and how the continents are today (USGS, Public Domain)

Hawaii, and the Mid-Ocean ridges. In other words, earthquakes and volcanoes occur at the boundaries of plates and above hot spots (as in Hawaii).

The illustrations below in Fig. 16.7 show Pangaea as it was during the Permian and then as it has broken up through geologic Periods (Triassic, Jurassic, Cretaceous) and the continents have drifted to their current locations.

In geologic history, there have been a number of other supercontinents in addition to Pangaea; among them are the following with their years of existence:

- Gondwana (300–30 million years ago)
- Rodinia (1.1 billion–750 million years ago)

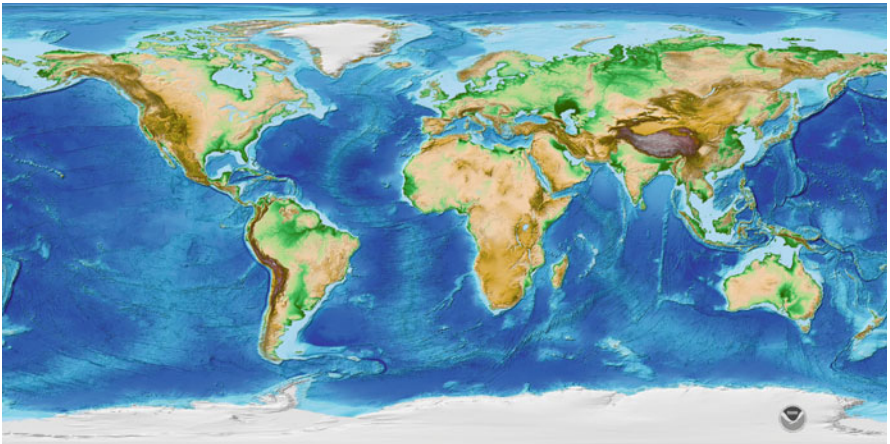


Fig. 16.8 Continental shelf areas of the world depicted in *light blue* (From NOAA, Public Domain)

- Laurasia (300–60 million years ago)
- Pannotia (600–540 million years ago)

These supercontinents represent areas of land that lasted for millions of years and eventually broke apart into various continents. The configuration of these land masses greatly affected Earth's climates of the past and most were centered along the equator at times (Fig. 16.7).

Geologically, continental areas consist of rocks that are high in silica and aluminum called sialic rocks (sial) and are represented by granite and rhyolite, whereas ocean basins are made up of rocks consisting of silica and magnesium or simatic rocks (sima) represented by basalt and gabbro. Other terms for continents and ocean basin rocks are acid and basic, respectively, although the terms do not refer to liquids called by the same names.

The largest continental shelf on Earth is the Siberian Shelf in the Arctic Ocean which stretches to 1,500 km (930 miles) in width. This continental shelf contains abundant reserves of carbon (methane) in the form of methane clathrates, as we've seen in a previous chapter (Chap. 15).

Continents with a great deal of relief (high standing mountain ranges, low valleys) usually have severe climatic conditions characterized by strong winds and diverse rainfall patterns. These types of climates are called continental climates. Some near coasts are modified by ocean currents.

16.5 Continental Mountain Ranges

Major mountain ranges of the continents are areas that tell scientists a great deal about how the Earth is made and are studied in order to unravel Earth's history. Maps showing major mountains can be found in a variety of sources including

Wikipedia and the many atlases and other resources available in online websites (e.g., wikipedia.org).

In the list below, no attempt was made to include all mountain ranges of the world. Major mountain ranges that can be found on most maps of the world are the following:

- The Appalachian Mountains are mainly in the continental United States but extend into southeastern Canada. They range from Newfoundland, Canada in the northeast to central Alabama, U.S. in the southwestern part of the range. They include the Piedmont, Blue Ridge, Ridge and Valley, and the Appalachian Plateau. The birth of the Appalachians, some 480 million years ago, marks the first of several mountain building plate collisions that culminated in the construction of the supercontinent Pangaea with the Appalachians near the center of that supercontinent. Because North America and Africa were connected at this time, the Appalachians formed part of the same mountain chain as the Little Atlas in Morocco. This mountain range, known as the Central Pangean Mountains, extended into Scotland, from the North America/Europe collision. Pangaea was a supercontinent consisting of Gondwana in the south and Laurentia in the north. Climates in the Appalachian Mountains are varied from season to season and from north to south. The Appalachian climate is affected by two ocean currents. The Labrador currents bring cold water south from the Arctic and cause freezing during the winter months in northern parts of the region. The Gulf Stream brings warm water north from the Caribbean and along the coast of North America before it turns east, crossing the Atlantic Ocean toward Europe. The meeting of the Gulf Stream and the Labrador Current also provides a great breeding ground for fish by enhancing the growth of plankton. The northern part of the region has an Arctic Climate, with extremely long, cold, winters and short, cool summers in Labrador, Newfoundland, and Nova Scotia.
- The Rocky Mountains are in the western part of North America in the United States and Canada. They are usually divided into the Northern, Middle, and Southern Rocky Mountains. Their geographic range is from northernmost British Columbia to New Mexico and south to Texas.
- The Andes Mountains are in western South America and constitute the longest continental mountain range in the world. The Andes Mountains are about 7,000 km (4,300 miles) long, about 200 km (120 miles) to 700 km (430 miles) wide (widest between 18° south and 20° south latitude), and of an average height of about 4,000 m (13,000 ft). The Andes extend from north to south through seven South American countries: Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile and Argentina. The mountain range started to be built as the supercontinent of Pangaea began to break up around 250–200 million years ago during the Triassic Period of Earth history. The South American plate began to move westward as the crust was being subducted beneath it and what are now the Andes Mountains were subjected to compressive forces that folded, faulted, and uplifted the rocks that make up the mountain range.

- Ural Mountains run approximately north-south in western Russia from the coast of the Arctic Ocean to the Ural River and northwestern Kazakhstan. The eastern side of the Urals marks the division between Europe and Asia. The Uralian orogeny (mountain-building episode) began about 250–300 million years ago. The areas west to the Ural Mountains are 1–2°C (2–4°F) warmer in winter than the eastern regions because the former are warmed by the Atlantic winds whereas the eastern slopes are chilled by the Siberian air masses. The average January temperatures increase in the western areas from −20°C (−4°F) in the Polar to −15°C (5°F) in the Southern Urals and the corresponding temperatures in July are 10°C (50°F) and 20°C (68°F). A normal winter usually has a high pressure system over Siberia causing a dry period east of the Urals.
- Himalayan Mountains are the world's highest and contain the world's highest peaks, including Mount Everest at 8,848 m (29,029 ft). Some of the world's major river systems arise in the Himalayas, such as the Indus River, and their combined drainage basin is home to some three billion people (almost half of Earth's population) in 18 countries, many of them depending on glacial meltwater from Himalayan glaciers for drinking water and agriculture. The Himalayas have profoundly shaped the cultures of South Asia; many Himalayan peaks are sacred in Hinduism, Buddhism and Sikhism. Geologically, the Himalayas originated by the impact of the Indian tectonic plate traveling northward at about 15 cm per year to impact the Eurasian continent, with first contact about 70 million years ago, and with movement continuing today in the Himalayans and the Tibetan Plateau.
- The Beartooth Range is located in Wyoming and Montana northwest of Yellowstone National Park. The Beartooth Mountains extend above the larger Beartooth Plateau, the largest true high elevation plateau in the United States. The range is made of largely Precambrian granite and metamorphic rocks.
- The Alpine Mountain Range (the Alps) is one of the great mountain range systems of Europe, stretching from Austria and Slovenia in the east through Italy, Switzerland, Liechtenstein, Germany, France and Monaco in the west. It is the result of the African Plate travelling northward and impacting the Eurasian Plate.
- Pacific Coastal Ranges lie near the Pacific Ocean along the west coast of North America from Alaska to Baja California. The Coast Ranges are separated from the higher mountains of the Cascade Range and the Sierra Nevada to the east by broad depressions such as the Puget Sound Lowland in Washington, the Willamette Valley in Oregon, and the Central Valley in California. The Klamath Mountains of northern California and the Transverse Ranges of southern California serve as links to the eastern ranges. On the west the coastal plain is narrow, and deep water occurs within 25 miles (40 km) of the coast. The average elevation of the Coast Ranges is about 1,000 m (3,300 ft).
- The Ouachita Mountains stretch from west central Arkansas to southeastern Oklahoma in the U.S. and were originally part of the Appalachian chain of mountains. The rocks comprising them are the same as the folded and faulted Appalachians. The Ouachita Mountains were formed by the South American

Plate moving northward impinging on the North American Plate about 300 million years ago. The climate is mild and humid throughout.

- The Apennine Mountains consist of a series of mountains, 200 km (750 miles) northwest to southeast along the length of the Italian peninsula. The western slope contains most of the cities of Italy. The southern end of the peninsula has a semi-arid climate. The Apennines began about 20 million years ago and are the result of both compressive forces in the east and extensional forces in the west.
- The Atlas Mountains lie in a northwestern stretch of Africa extending about 2,500 km (1,600 miles) through Morocco, Algeria, and Tunisia. They separate the Atlantic and Mediterranean from the Sahara Desert. The mountains belong to the Saharan climate zone. They began to form, about 300 million years ago, when North America, Eurasia, and Africa were joined throughout much of the Paleozoic.
- The Caucasus is a mountain system in Eurasia between the Black Sea and the Caspian Sea that many consider to be the dividing line between Europe and Asia. The climate varies with altitude and latitude. The higher portions of the Caucasus are much colder than the lower portions with a difference of 21°F between the two. The Caucasus Mountains formed largely as the result of a tectonic plate collision between the Arabian plate moving northward with respect to the Eurasian plate.
- The Hindu Kush Mountains are an 800 km (500 mile) mountain range that stretches between central Afghanistan and northern Pakistan and are part of the Himalayan chain. The Hindu Kush, running northeast to southwest across the country of Afghanistan, divides it into three major regions: (1) the Central Highlands, which form part of the Himalayas and account for roughly two thirds of the country's area; (2) the Southwestern Plateau, which accounts for one-fourth of the land; and (3) the smaller Northern Plains area, which contains the country's most fertile soil.
- Owen Stanley Range is the southeastern part of the central mountain chain in Papua New Guinea, which is part of Melanesia. Papua New Guinea lies north of Australia and is part of the Pacific Ring of Fire. Papua New Guinea is located at the junction of several tectonic plates.
- Haraz Mountains are in Yemen and are part of the Arabian Peninsula. They are also a part of the Sarawat Mountains that run parallel to the western coast of the Arabian Peninsula. The Sarawat start from the border of Jordan in the north to the Gulf of Aden in the south, running through Saudi Arabia and Yemen. They are geologically part of the Arabian shield and consist mainly of volcanic rocks.
- The Japanese Alps are the high standing mountains that split the Japanese island of Honshū. They consist of three mountain ranges in Japan.
- The Pamir Mountains consist of a mountain range in Central Asia formed by the junction of the Himalayas, Tian Shan, Karakoram, Kunlun, and Hindu Kush ranges. They are among the world's highest mountains and have been known as the "Roof of the World."
- The Zagros Mountains constitute the largest mountains in Iran and Iraq. They run along Iran's western border from northernmost Iran to the Strait of Hormuz and the Persian Gulf in the south. They have been formed by a collision of the Arabian Plate with the Eurasian Plate. Iran's main oilfields lie in the western central foothills of the Zagros mountain range.

- The Balkan Mountains run for 560 km from the Vrashka Chuka/Vrška Čuka Peak on the border between Bulgaria and eastern Serbia eastward through central Bulgaria to the Black Sea. The mountains are mainly in Bulgaria and are part of the great mountain chain with the Alps in the west and the Himalayas in the east.
- The Basque Mountains are located in the northern part of the Iberian Peninsula which includes Spain, Portugal, and Andorra as well as the British territory of Gibraltar. Geographically it is considered to be the eastern section of the larger Cantabrian Range. The range runs through the Basque area of Northern Spain.
- The Carpathian Mountains are a range of mountains forming an arc roughly 1,500 km (932 miles) long across Central and Eastern Europe, making them the second-longest mountain range in Europe (after the Scandinavian Mountains, 1,700 km (1,056 miles)). The Carpathians consist of a chain of mountain ranges that stretch in an arc from the Czech Republic (3%) in the northwest through Slovakia (17%), Poland (10%), Hungary (4%), and Ukraine (11%) to Romania (53%) in the east and to the Danube River between Romania and Serbia (2%) in the south. The highest range within the Carpathians is the Tatras, on the border of Poland and Slovakia, where the highest peaks exceed 2,600 m (8,530 ft).
- The Jura Mountains are located north of the Alps in France, Switzerland, and Germany. They are a folded and faulted mountain range sharing an evolutionary geologic history with the Alps.
- The *Massif Central* is an elevated region in central France and contains the largest concentrations of extinct volcanoes in the world. The Auvergne Volcanoes National Park is in the *Massif Central*. These volcanoes were visited by some of the early European geologists who were prominent in the basalt controversy that raged over the origin of this rock, one side arguing that its origin was as a precipitate from a universal ocean (from the biblical Noachian Flood) and the other side arguing for a volcanic origin. The volcanoes of the Auvergne settled the argument on the side of the volcanoes, as it is possible to trace basalt lava flows up to the volcanic vents from which they issued.
- The Pyrenees Mountains form the divide between France and Spain and the boundary runs along the crest of the mountains. The Pyrenees are older than the Alps and were formed when the plate on which the present-day Spain sits was pushed northward into present-day France causing the crust to squeeze the sediments and metamorphics making up today's Pyrenees Mountains. There is also granite in parts of the range. The mountains were beginning to form about 150 million years ago.
- The Scandinavian Mountains run through the Scandinavian Peninsula and are the longest mountain range in Europe stretching 1,700 km (1,056 miles) along the peninsula. The famous fjords of Norway are glacially carved from the former streams that entered the North Sea and the Norwegian Sea. The mountain system was originally connected to the mountains of Scotland and Ireland and the Appalachian Mountains of North America. These formed a continuous mountain range before the breakup of the supercontinent Pangaea.
- The Adirondack Mountains are located in the northeastern part of New York State in the U.S. They are sometimes included in the Appalachians but have greater similarity to the Laurentian Mountains of Canada. They consist of

metamorphic and igneous rocks and are part of the Grenville lobe of the Canadian Shield that covers most of eastern and northeastern Canada and all of Greenland. The rocks range in age from 1.0 billion to 880 million years in age.

- The Arctic Cordillera is a low-standing mountain range in the Canadian Arctic Archipelago that extends into part of northern Labrador and northern Quebec, Canada. It includes Ellesmere Island and Baffin Island, two of the better known islands of the archipelago.
- The Blue Ridge Mountains are a high-standing range of the Appalachians in the eastern part of the United States. The Blue Ridge Mountains contain the highest mountains in eastern North America south of Baffin Island and consists of metamorphosed lava flows (e.g., greenstone), gneisses, and limestones. The Blue Ridge extends into Pennsylvania as South Mountain. While South Mountain dwindles to mere hills between Gettysburg and Harrisburg, the band of ancient rocks that forms the core of the Blue Ridge continues northeast through the New Jersey and Hudson River highlands, eventually reaching The Berkshires of Massachusetts and the Green Mountains of Vermont. The Great Smokey Mountains are a part of the Blue Ridge in North Carolina and Tennessee.
- The Brooks Range runs from northern Alaska into the Yukon Territory of Canada and is considered part of the Rocky Mountains. The Brooks Range forms the northernmost drainage divide in North America, separating streams flowing into the Arctic Ocean from those flowing into the North Pacific.
- The Cascade Range is a major mountain range of western North America extending from British Columbia into northern California. The Cascades are part of the Pacific Ocean Ring of Fire and contain active volcanoes. Lassen Peak in California and Mt. St. Helens are two of the active volcanoes, the former erupting in 1914 and the latter in 1980. There have been minor eruptions later, the last in 2008.
- The Sierra Nevada is a mountain range in California and Nevada, USA. One of its main features is Yosemite National Park formed from glacial activity during the last ice age. The Sierra Nevada range made a formidable obstacle for the settlers migrating westward into California. The Sierra Nevada snowpack is the major water source for California.
- The Sierra Madre Oriental, Mexico is a mountain range in northeastern Mexico. Its uplift has caused changes in weather patterns through its length. It is drier than the surrounding areas. West of the range lies the Mexican Plateau.
- The Sierra Madre Occidental, Mexico is in western Mexico. A great deal of rainfall occurs in the mountain range and the land on either side is drier. The climate varies from north to south. There are two wet seasons including a summer monsoon and two dry seasons.
- The Transantarctic Mountains, Antarctica extend across the continent of Antarctica and most likely consist of several different mountain ranges. They divide the continent into east Antarctica and west Antarctica.
- The Southern Alps, New Zealand extend for much of the length of the island. They occur along a geological plate boundary and are part of the Pacific Ring of Fire. The highest peaks in the range have snow and ice all year. There are

numerous glaciers and glacial lakes throughout the range. Christchurch, New Zealand has been hit with major earthquakes in 2011 and 2012.
- The Laurentian Mountains of Canada are located in southern Quebec. They are an extension of the Adirondack Mountains in New York State, USA. They are part of the Glenville mountain- building episode of Precambrian age, 1.1 billion years old.

16.6 Islands

There are two main types of natural islands: continental islands and oceanic islands. The continental islands are made of sialic material like granite and oceanic islands are made of simatic material like basalt. There are also man-made islands usually of sand and clay that have been constructed in areas where the economy has taken over from the niceties of nature.

Continental islands lie on the continental shelf and oceanic islands lie in the open ocean surrounded by oceanic crust. A special type forms an island arc which has a unique significance to plate tectonics. Island arcs are arcuate volcanic islands that mark subduction zones where one plate is being pulled down (subducted) and the adjacent plate is over-riding the one being pulled down.

An island is usually defined simply as land that is surrounded by water.

Additional Readings

du Toit, A. L. (1937). *Our wandering continents; An hypothesis of continental drifting*. London: Oliver and Boyd.

Holmes, A. (1944). *Principles of physical geology* (1st ed.). Edinburgh: Nelson. ISBN 0174480202.

Kious, W. J., & Tilling, R. I. (2001, February). Historical perspective. In *This dynamic earth: The story of plate tectonics* (Online ed.). Washington, DC: U.S. Geological Survey. ISBN 01hj n rgrjhguitghtigu60482208.

Le Grand, H. E. (1988). *Drifting continents and shifting theories*. Cambridge: Cambridge University. ISBN 0-521-31105-5.

Lewis, M. W., & Wigen, K. E. (1997). *The myth of continents: A critique of metageography* (p. 40). Berkeley: University of California Press. ISBN 0-520-20742-4, ISBN 0-520-20743-2.

Ollier, C. D. (1996). Planet earth. In I. Douglas (Ed.), *Companion encyclopedia of geography: The environment and humankind*. London: Routledge.

Romm, J. (1994, February 3). A new forerunner for continental drift. *Nature, 367*(6462), 407–408. doi:10.1038/367407a0.

Wegener, A. (1929/1966). *The origin of continents and oceans*. New York: Courier Dover Publications. ISBN 0486617084.

Wikipedia – maps, photographs, texts describing world mountain ranges. (http://www.wikipedia.org).

Chapter 17
Climate Classifications

Abstract There are different criteria used to classify climates. The most common classification is the Köppen-Geiger classification that recognizes five major climatic zones: Tropical, Dry, Moderate (or Temperate), Continental, and Polar with sub-zones under each. Classifications of climate systems include those based on their origin or those based on their effects. The Bergeron classification is based on areas of origin for air masses. Thornthwaite devised a climate classification built on the physical interactions between local moisture and temperature. Disruption of climate and of the Jet Stream in the Northern Hemisphere due to arctic warming and sea ice melting is a concern.

Keywords Climate • Classification • Köppen • Biome • Bergeron • Polar • Taiga • Continental • Geiger • Thornthwaite • Steppe • Humid • Desert • Cyclones • Synoptic • Subarctic • Rainforest • Tundra • Boreal • Savanna • Stream • Jet • Sea • Ice • Geosphere • Atmosphere • Moist • Tropical

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_17,

Things to Know	
Köppen-Geiger classification	Thornthwaite classification
World climate zones	Polar
Jet Stream	Bergeron classification
Spatial synoptic classification	Rainforest
Tropical savanna	Alexander von Humboldt
Biome	Humid subtropical
Cyclones	Mediterranean climate
Steppe	Subarctic
Oceanic climate	Tundra
Taiga climate	Geosphere
Boreal climate	Sea ice
Precipitation effectiveness	Thermal classifications

17.1 An Introduction to Climate Classification

The definition of climate includes the weather of an area but it is not the same as weather, as has been discussed earlier. The climate is different in the Sahara than it is in Florida and the weather patterns are also different. The weather is what is happening now and may include a prediction such as "a 10% chance of rain tomorrow" or "it will be chilly tomorrow with a high of 50°," or "the chance of snow is 20%"; "the wind will be 15 mph out of the southwest" or it was like that yesterday or last week. Weather is short-term, climate is long-term. One can generalize about climate and state that it is milder near the tropics, harsher as one goes toward the poles. The mild climate near the equator may be interrupted by hurricanes or monsoons or other storms, but in the mid-latitudes there is little letup.

There is concern about the effect of climate change on weather in many parts of the world. Inhabitants of the Northern Hemisphere in particular are already seeing a disruption of "normal" weather patterns and as the climate continues to change, weather patterns will continue to be impacted.

A major concern among climate scientists is the future of the Jet Stream and its effect on weather in the Northern Hemisphere. The Jet Stream is a major air current of high-altitude air circling the globe in the Northern Hemisphere. This current has a major influence on climate as it meanders across the Northern Hemisphere continents and ocean basins. It separates warm air in the south from cold air in the north. The extent of the northern ice cap is decreasing rapidly due to global warming. As the ice recedes, more sunlight is absorbed by ocean waters and the Jet Stream is affected as the warming Arctic gives up more heat to the atmosphere. This causes the Jet Stream to slow and develop a widely meandering path when looked upon from above. The result is more warm air moving north and more cold air moving south.

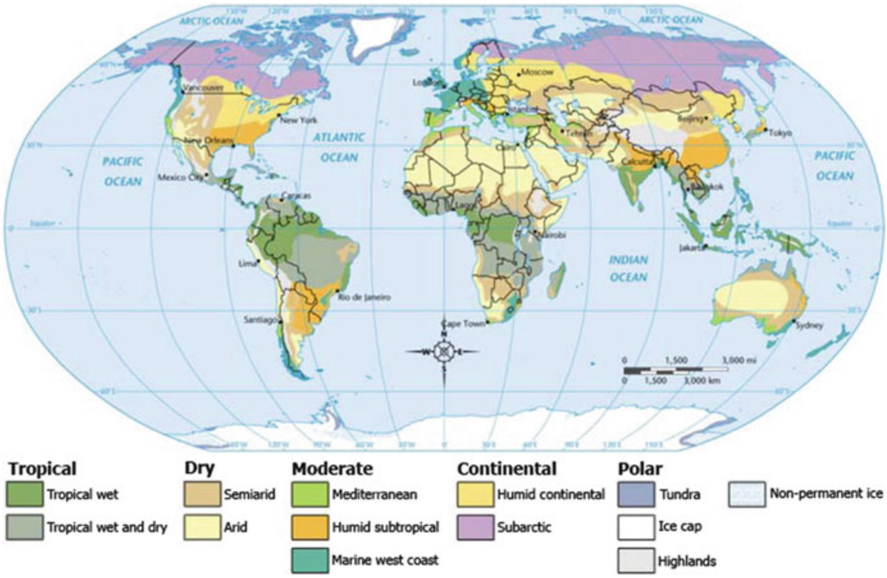


Fig. 17.1 The world's major climate zones

The result, in combination with more energy in the atmosphere, is greater instability in the Northern Hemisphere and a greater chance of severe storm activity.

The climate system is part of the Earth system and consists of the following spheres of influence: atmosphere, hydrosphere, cryosphere, geosphere, and biosphere. These spheres interact and the result is a complex climate system with a great many variables. However, it is possible to classify different aspects of the climate system and examine different types of climate throughout the globe.

The most common global climate classification used today is the Köppen-Geiger classification, usually referred to as the Köppen (often misspelled as "Koeppen") climate classification, which consists of five different climates designated Tropical, Dry, Moderate, Continental, and Polar (as seen in Fig. 17.1). Modern climate classifications fall into two groups: those that are based on origin (genetic) and those based on effects (empiric).

The original Greek word *klima*, from which the word climate is derived, was used to refer to the Sun's radiation angle of incidence with the Earth. The seasonal variation of this inclination depends on latitude and the Earth's position relative to the Sun. Early naturalists (Egyptian, Roman, and Greek) were aware of the profound effect of latitude on climate. In 1817 Alexander von Humboldt, a German naturalist, drew annual-mean temperatures on a world map. Wladimir Köppen (1846–1940) refined von Humboldt's map and plotted seasonal temperature ranges leading to his climate classification. Köppen's classification followed that of plants with major categories subdivided, and then subcategories divided again, etc. In fact Köppen had initially studied botany and completed a Ph.D. at Heidelberg, Germany on the effect of temperature on plant growth. At the highest level his system is based on five sets of temperature limits. These were developed from his categorization of thermal zones suited to various kinds of vegetation.

Köppen deduced geological climates in support of the continental drift theory formalized by his son-in-law, Alfred Wegener. He also became associated with Rudolf Geiger (1894–1981) and collaborated with him in producing a system of climate classification. Geiger was later responsible for further revisions. Geiger also established the discipline of microclimatology.

17.2 Air Masses

The atmosphere consists of air masses or bodies of air that have a set of characteristics such as temperature and moisture. These characteristics vary from one air mass to another. Air masses often show a fairly homogeneous temperature lapse rate (vertical temperature decrease with altitude) above the influence of the surface layer. At any given time, an estimated 50 distinct air masses are scattered across the face of the planet. Some are newly born and reflect their origin. Others are older and have only the smallest indication of their place of origin.

Different air masses are separated by narrow transition zones that analysts or meteorologists distinguish by drawing weather fronts, such as warm, cold, stationary and occluded fronts, between them. Sometimes these fronts indicate subtle transitions, perhaps only a shift in wind direction and they are hardly noticed as they pass. Others are vigorous where conflicts between warm and cold air masses produce strong weather systems such as severe thunderstorms, tornadoes, or heavy snowfalls. Often, the difference between air masses is so great that large cyclonic weather systems develop along the frontal boundary to cause the surface beneath to have high winds, rapidly changing temperatures, and heavy precipitation.

The differences among air masses was likely first recognized when humans realized that major changes in weather had recognizable, repeatable patterns such as cold, dry conditions coming from the north; hot and dry or hot and humid weather coming from the south.

Before the seventeenth century, early meteorologists used their senses to distinguish difference between air masses. In the seventeenth century, the invention of instruments such as the thermometer, barometer, and hygrometer allowed observers to objectively measure properties of the air. With the advent of regular weather observations across large regions of the continents and weather and climate records from locations around the globe, meteorologists began to see repeatable patterns that showed large bodies of air that could be distinguished by their degrees of temperature and humidity.

The first formal and widely disseminated theory of the impact of air mass differences came out of the famed Bergen School of Meteorology in Norway during the early decades of the 1900s. The Norwegian research group, which included Tor Bergeron, laid the foundation for modern weather analysis and forecasting. The group developed the concepts of frontal analysis, wave cyclone formation, and air mass analysis to name but a few of their achievements. Bergeron confirmed that certain characteristics of air masses did not substantially change for long periods of time as the air mass flowed over oceans and continents. Therefore, Bergeron concluded that knowledge of these characteristics was fundamentally important to improving weather forecasts.

Bergeron saw air masses as being of four types based on their area of origin: Equatorial, Tropical, Polar and Arctic (or Antarctic). From this, he developed a classification scheme that included distinguishing properties of temperature, humidity and aerosol content. With slight modifications, his classification system remains a viable concept today in weather analysis and forecasting.

Approximately 50 distinct air masses can be identified in the lower atmosphere near the surface of Earth at any one time. Most cover thousands of square kilometers and extend several kilometers vertically. Each one bears the mark of the region in which it was formed. Some of the 50 are young and fresh. Others are old and greatly transformed. Some are moving across the planet at speeds covering several hundred kilometers each day, others are nearly stationary.

Air masses acquire their characteristic temperature and moisture (or absolute humidity) signature from the source regions over which they are born. The ideal source region is one with light winds, particularly in the upper atmosphere so that the air mass remains in place long enough to acquire the temperature and moisture properties of the underlying surface throughout the air mass. Therefore, middle latitude regions where the weather systems move quickly across their surface, driven by fast-moving upper level air currents such as the Jet Stream are not good air mass breeding grounds.

Areas dominated by extensive areas of high pressure and light winds are the ideal breeding grounds for air masses. There are several such areas of extensive, semi-permanent high pressure around the globe in particular, two latitude belts in each hemisphere; one in the Polar Regions and the other in the subtropics.

Bergeron's classification system categorizes a place according to the frequencies with which it experiences various kinds of air mass. Each air mass is labeled in terms of the latitude at which its temperature had been determined previously, and the kind of surface there, either marine or continental (Figs. 17.2 and 17.3).

In the U.S., Warren Thornthwaite (1892–1963) developed a hierarchical classification based on the annual pattern of soil-moisture conditions. These were regarded as depending in a complicated manner on the monthly input as rain, and implicitly on the output as evaporation, indicated by temperature. Studies in New Zealand, for example, showed that Thornthwaite's classification made more sense than Köppen's, except at low latitudes. Later, the connection to soil moisture was made more explicit in Thornthwaite's landmark approach toward a more rational classification of climate. However, it involved an empirical formula for estimating evaporation, which was superseded the same year by the physics-based formula of Howard Penman (1909–1984) in England.

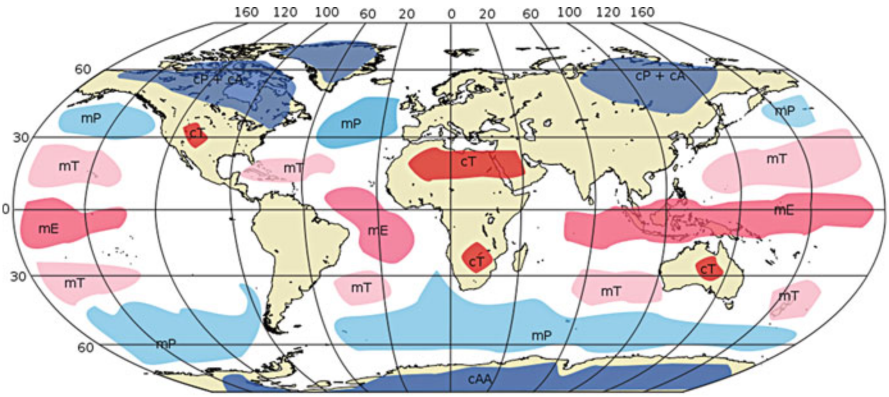
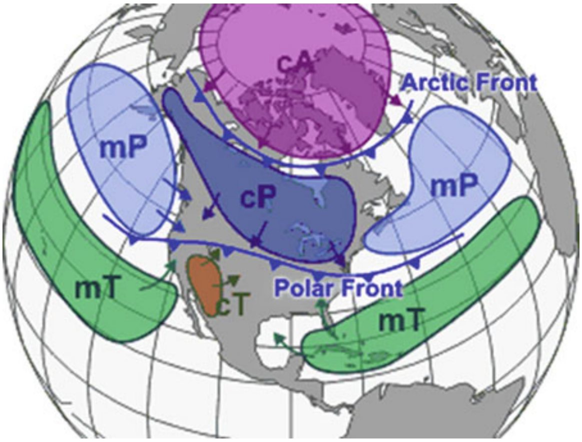


Fig. 17.2 Source regions of global air masses. (NASA, Public Domain)

Fig. 17.3 Source regions of common air masses (NOAA, Public Domain)



All these classification systems differ from what has been done since, in solving practical problems. Now climatologists use complex statistical procedures to group the climates of places and to define areas of similar climates.

Climate in a narrow sense is usually defined as the description in terms of the mean and variability of relevant quantities (e.g., temperature and precipitation) over a period of time ranging from months to thousands or millions of years. The usually accepted period for accepted climate data is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the variation, including a statistical description, of the climate system in an area or region.

Over geological time spans there are a number of nearly constant variables that determine climate including latitude, altitude, proportion of land to water, and proximity to oceans and mountains. These change only over spans of millions of years due to processes such as plate tectonics, continental drift, and mountain building. Other climate determinants are more dynamic; for example, the thermohaline circulation of the ocean leads to a 5°C (9°F) warming of the northern Atlantic Ocean compared to other ocean basins. Other ocean currents redistribute heat between land and water on a more regional scale. The density and type of vegetation coverage affects solar heat absorption, water retention, and rainfall on a regional level. Changes in the concentration of atmospheric greenhouse gases determine the amount of solar energy retained by the planet, leading to global warming or global cooling. The variables which determine climates are numerous and their interactions complex, but there is general agreement that the broad outlines are understood, at least as for the determinants of historical climate change are concerned.

17.3 Modern Climate Classification

Modern climate classification methods can be broadly divided, into (a) generic methods which focus on the causes of climate, and (b) empiric (or empirical) methods, which focus on the effects of climate. Examples of generic classification include methods based on the relative frequency of different air mass types or locations within synoptic (i.e., relating to or showing simultaneous weather conditions over a large area) weather disturbances. Examples of empiric classifications include climate zones defined by plant hardiness, evapotranspiration, or more generally the Köppen-Geiger climate classification which was originally designed to identify the climates associated with certain biomes (see Fig. 17.1). A common shortcoming of these classification schemes is that they produce distinct boundaries between the zones they define, rather than the gradual transition of climate properties as seen in nature.

17.3.1 The Bergeron Climate Classification

The most generic classification is that involving the concept of air masses. The Bergeron classification is the most widely accepted form of air mass classification. Air mass classification involves three letters (Figs. 17.2 and 17.3). The first letter describes its moisture properties, with c used for continental air masses (dry) and m for maritime air masses (moist). The second letter describes the thermal characteristic of its source region: T for tropical, P for polar, A for Arctic or Antarctic, M for monsoon, E for equatorial, and S for superior air (dry air formed by significant downward motion in the atmosphere). The third letter is used to designate the stability of the atmosphere. If the air mass is colder than the ground below it, it is labeled k. If the air mass is warmer than the ground below it, it is labeled w. While air mass identification was originally used in weather forecasting during the 1950s, climatologists began to establish synoptic (i.e., general) descriptions based on this idea in 1973.

The Spatial Synoptic Classification System (SSC) is based on the Bergeron classification scheme. There are six categories within the SSC scheme: (1) Dry Polar (similar to continental polar), (2) Dry Moderate (similar to maritime superior), (3) Dry Tropical (similar to continental tropical), (4) Moist Polar (similar to maritime polar), (5) Moist Moderate (a hybrid between maritime polar and maritime tropical), and (6) Moist Tropical (similar to maritime tropical, maritime monsoon, or maritime equatorial).

17.4 The Köppen-Geiger Classification

The Köppen-Geiger classification depends on average monthly values of temperature and precipitation (Fig. 17.4). The most commonly used form of the Köppen-Geiger classification has five primary types labelled A through E. These primary types are A, tropical; B, dry; C, mild mid-latitude; D, cold mid-latitude; and E, polar. The five primary classifications can be further divided into secondary classifications such as rain forest, monsoon, tropical savanna, humid subtropical, humid continental, oceanic climate, Mediterranean climate, steppe, subarctic climate, tundra, polar ice cap, and desert.

17.4.1 Group A Climates

Tropical climates (A) are characterized by high temperatures at sea level and lower elevations all year (12 months). Their temperatures average 18°C (64°F) or higher.

Tropical rain forests (Af) are characterized by high rainfall, with definitions setting minimum normal annual rainfall between 1,750 mm (69 in.) and 2,000 mm (79 in.). Mean monthly temperatures exceed 18°C (64°F) during all months of the year. Examples are Hilo, Hawaii and Singapore.

A tropical monsoon (Am) climate is a seasonal prevailing wind which lasts for several months, ushering in a region's rainy season. Regions within North America (Miami, Florida), South America, Sub-Saharan Africa, Queensland, Australia, and East Asia are monsoon regimes.

A tropical savanna (Aw) is a grassland biome located in semi-arid to semi-humid climate regions of subtropical and tropical latitudes, with average temperatures remain at or above 18°C (64°F) year round and rainfall between 750 mm (30 in.) and 1,270 mm (50 in.) a year. They are widespread on Africa, and are also found in India, the northern parts of South America (Rio de Janeiro, Brazil), Malaysia, and Australia (Darwin, Northern Territory).

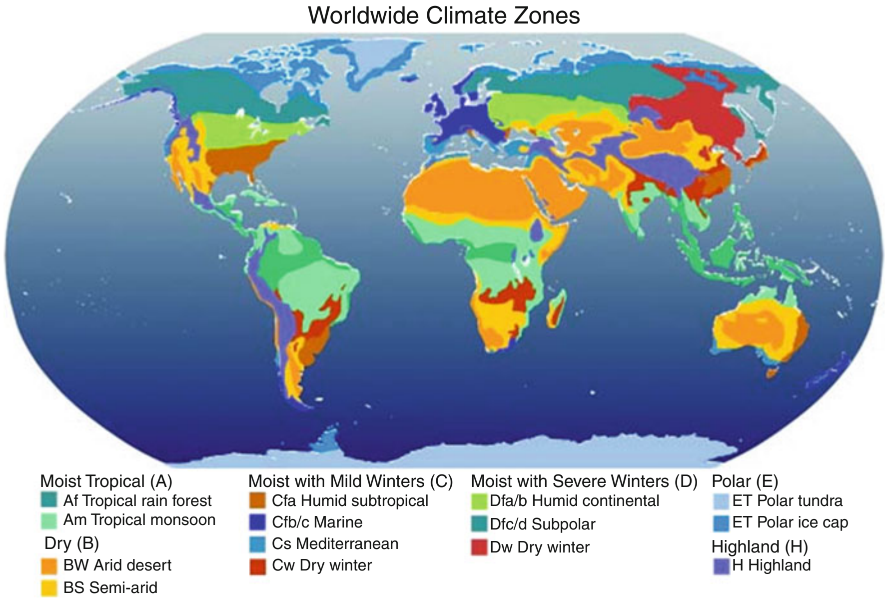


Fig. 17.4 World map of the Köppen-Geiger climate classification (From UCAR/NOAA, The COMET Program, Public Domain)

17.4.2 Group B Climates

Group B climates are dry, arid and semiarid climates. Precipitation is less than evaporation. BW is a desert climate and Bs is a steppe climate. A third letter can be used to indicate temperature, e.g., Yuma, Arizona (BWh).

A steppe is a dry grassland with an annual temperature range in the summer of up to 40°C (104°F) and during the winter down to −40°C (−40°F). Steppes are usually characterized by a semi-arid and continental climate. Extremes can be recorded in the summer of up to 40°C (104°F) and in winter, –40°C (–40°F). Besides this huge difference between summer and winter, the differences between day and night are also great. In the highlands of Mongolia, 30°C (86°F) can be reached during the day with sub-zero °C (sub 32°F) readings at night.

The mid-latitude steppes can be summarized by hot summers and cold winters, averaging 250–500 mm (10–20 in.) of precipitation per year. Precipitation level alone is not what defines a steppe climate. Potential evapotranspiration must also be taken into account. Prairies are steppe climates such as the central U.S. and western Canada.

17.4.3 Group C Climates

Group C climates are those temperate climates with an average temperature above 10°C (50°F) in their warmest months and a coldest month average between −3°C (27°F) and 18°C (64°F).

Mediterranean climates are dry-summer subtropical climates. They occur on the western side of continents between latitudes of 30° and 45°. Summers are hot and dry. Athens, Greece, Tel Aviv, Israel, Cape Town, South Africa, Los Angeles, California are examples.

The Mediterranean climate regime resembles the climate of the lands in the Mediterranean Basin, parts of western North America, parts of Western and South Australia, in south-western South Africa and in parts of central Chile. The climate is characterized by hot, dry summers and cool, wet winters.

An oceanic climate is typically found along the west coasts at the middle latitudes of all the world's continents, and in south-eastern Australia, and is accompanied by plentiful precipitation year round. London, England, Bilbao, Spain, Melbourne, Australia, Vancouver, British Columbia, Canada are examples.

The humid subtropical climate zone (Cfa, Cwa) is where winter rainfall (and sometimes snowfall) is associated with large storms that the westerlies steer from west to east. Most summer rainfall occurs during thunderstorms and from occasional tropical cyclones. Humid subtropical climates lie on the east side of continents, roughly between latitudes 20° and 40° away from the Equator.

17.4.4 Group D Climates

These are continental climates and they have an average temperature above 10°C (50°F) in their warmest months, and a coldest month average below −3°C (or 0°C). These climates usually occur in the interiors of continents, or on their east coasts, north of 40° North latitude. In the Southern Hemisphere, Group D climates are extremely rare due to the smaller land masses in the middle latitudes and the almost complete absence of land between 40° and 60° south latitude, existing only in some highland locations.

A subarctic climate has little precipitation, and monthly temperatures which are above 10°C (50°F) for 1–3 months of the year, with permafrost in large parts of the area due to the cold winters. Winters within subarctic climates usually include up to 6 months of temperatures averaging below 0°C (32°F). Chicago, Illinois, Cleveland, Ohio, Toronto, Ontario, Canada, Beijing, China, Bucharest, Romania are examples.

A humid continental climate (Dfa) is marked by variable weather patterns and a large seasonal temperature variance (Fig. 17.5). Places with more than 3 months of average daily temperatures above 10°C (50°F) and a coldest month temperature below −3°C (26.6°F) and which do not meet the criteria for an arid or semiarid climate, are classified as continental.

The taiga or boreal forest exists as a nearly continuous belt of coniferous trees across North America and Eurasia (Fig. 17.6). Overlying formerly glaciated areas and areas of patchy permafrost on both continents, the forest is a mosaic of successional and subclimax plant communities sensitive to varying environmental conditions. Taiga is the Russian name for this forest which covers so much of that country. However, the term is used in North America as well (Fig. 17.6).

Fig. 17.5 Humid continental climates throughout the world outlined in blue (Public Domain)

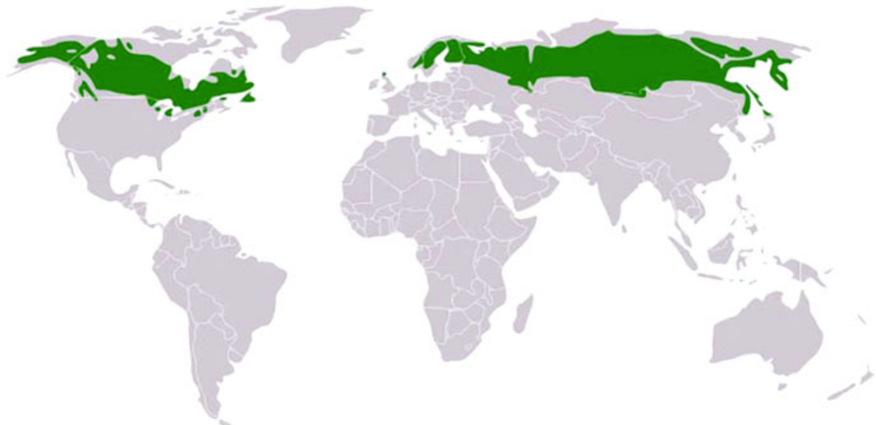


Fig. 17.6 Distribution of the taiga belt (Public Domain)

17.4.5 Group E Climates

Group E climates are characterized by average temperatures below 10°C (50°F) in all 12 months of the year.

Tundra occurs in the far Northern Hemisphere, north of the taiga belt, including vast areas of northern Russia and Canada (Fig. 17.7). Barrow, Alaska is an example.

A polar ice cap, or polar ice sheet, is a high-latitude region of a planet or moon that is covered in ice. Ice caps form because high-latitude regions receive less energy in the form of solar radiation from the Sun than equatorial regions, resulting in lower surface temperatures.

A desert is a landscape form or region that receives very little precipitation (Fig. 17.8). Deserts usually have a large diurnal and seasonal temperature range, with high daytime temperatures (in summer up to 45°C or 113°F), and low night-time

Fig. 17.7 Arctic tundra (Public Domain)

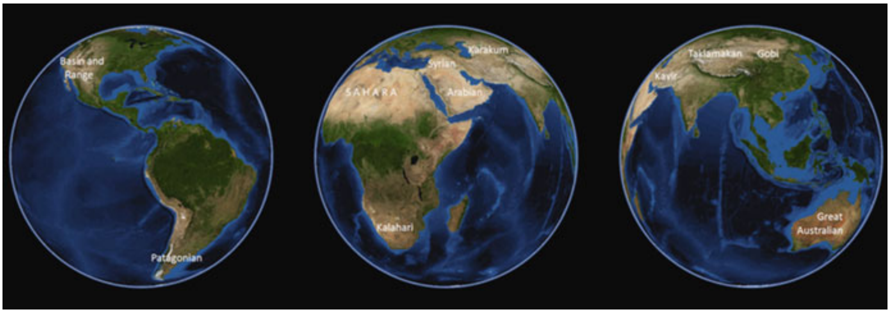


Fig. 17.8 Larger non-polar deserts of the world (NASA, Public Domain)

temperatures (in winter down to 0°C; 32°F) due to extremely low humidity. Many deserts are formed by rain shadows, as mountains cause moist air to rise and condense and block the path of moisture and precipitation to the desert. Rainfall will occur on the windward side of the mountain and dry air swoops down the leeward side.

17.5 The Thornthwaite Climate Classification

The Thornthwaite Climate Classification system is built on the physical interactions between local moisture and temperature rather than only the precipitation and temperature data. It represents a sophisticated and precise scheme of classification based on local surface water balances. Thornthwaite devised a number of specific indices to quantify necessary climatic components, including the moisture index (MI) and the potential evapotranspiration (PE) rate for a location.

Thornthwaite also derived a Thermal Efficiency Index (T/ET) of the ratio of temperature (T) to a calculated evapotranspiration (ET) value, and a Dryness Index (DI) and Humidity Index (HI) to identify the times of the year with water deficit or surplus.

The Thornthwaite climate classification requires monitoring the soil water budget using the concept of evapotranspiration. It requires monitoring the portion of total precipitation used to nourish vegetation over a certain area. It uses indices such as a humidity index and an aridity index to determine an area's moisture regime based upon its average temperature, average rainfall, and average vegetation type. The lower the value of the index in any given area, the drier the area is.

The moisture classification includes climatic classes with descriptors such as hyper-humid, humid, subhumid, subarid, semi-arid (values of −20 to −40), and arid (values below −40). Humid regions experience more precipitation than evaporation each year, while arid regions experience greater evaporation than precipitation on an annual basis. A total of 33% of the Earth's landmass is considered either arid of semi-arid, including southwestern North America, southwestern South America, most of northern and a small part of southern Africa, southwest and portions of eastern Asia, as well as much of Australia. Studies suggest that precipitation effectiveness (PE) within the Thornthwaite moisture index is overestimated in the summer and underestimated in the winter. This index can be effectively used to determine the number of herbivore and mammal species numbers within a given area. The index is also used in studies of climate change.

Thermal classifications within the Thornthwaite scheme include microthermal, mesothermal, and megathermal regimes. A microthermal climate is one of low annual mean temperatures, generally between 0°C (32°F) and 14°C (57°F) which experiences short summers and has a potential evaporation between 14 cm (5.5 in.) and 43 cm (17 in.). A mesothermal climate lacks persistent heat or persistent cold, with potential evaporation between 57 cm (22 in.) and 114 cm (45 in.). A megathermal climate is one with persistent high temperatures and abundant rainfall, with potential annual evaporation in excess of 114 cm (45 in.).

Additional Readings

Akin, W. E. (1991). *Global patterns: Climate, vegetation, and soils* (p. 52). Norman: University of Oklahoma Press. ISBN 0-8061-2309-5.

Kottek, M., et al. (2006). World map of the Köppen–Geiger climate classification updated. *Meteorologische Zeitschrift, 15*(3), 259–263. doi:10.1127/0941-2948/2006/0130. Bibcode 2006MetZe..15..259K.

McKnight, T. L., & Hess, D. (2000). Climate zones and types. In *Physical geography: A landscape appreciation*. Upper Saddle River: Prentice Hall. ISBN 0-13-020263-0.

Schwartz, M. D. (1995). Detecting structural climate change: An air mass-based approach in the North Central United States, 1958–1992. *Annals of the Association of American Geographers, 85*(3), 553–568. doi:10.1111/j.1467-8306.1995.tb01812.x.

Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. *Geographical Review, 38*(1), 55–94. doi:10.2307/210739.

Part VII
Climate Models

Chapter 18
Types of Models

Abstract Climate models range in complexity from very simple to very complex. General Circulation Models are the most complex and most require time on a supercomputer in order to utilize all the required data. Box models, Energy Balance models, Radiative-Convective models, and General Circulation models are all used to allow scientists to vary input and ask "what if" questions about the climate system. Validation of models is necessary in order to have confidence in modeling and for individual models. History matching (or hindcasting) is an integral part of the modeling process. The validation process allows scientists to have greater confidence in model results.

Keywords Hindcasting • Box • Model • Circulation • History • Matching • Grid • Projection • Prediction • Attribution • Validation • Parameterizing • GCMs • EBMs • RCMs • Confidence • Circulation • Trends • CCSM • GCSM • Boundaries

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_18,

Things to Know	
Box models	General circulation models
CCSM	History matching
GCSM	Physical climate models
Chemical climate models	Model grid
Model validation	Boundary conditions
Hindcasting	GEWEX
Energy balance models (EBMs)	UCAR
Radiative-Convective Models (RCMs)	EPRI
Parameterizing	Statistical-dynamical models (SDMs)
CERFACS	General circulation models (GCMs)
Model confidence and validation	

18.1 Introduction

There are various types of climate models. Some focus on certain things that affect climate such as the atmosphere or the oceans. Models that look at only a few variables of the climate system may be simple enough to run on a personal computer but more complex models are run on supercomputers.

All models are simplified versions of more complex systems. Climate models range in complexity from a simple box model to a complex general circulation model. Models must be designed to gain a better understanding of the climate system that is being modeled. Models provide climate change scientists with a quantitative means to obtain projections of what may happen to the climate system in the future.

18.2 Climate Models

Computer models of the coupled atmosphere-solar-land surface-ocean-sea ice system are essential scientific tools for understanding and projecting natural and human-caused changes in Earth's climate. Climate models can be used to map out trends in the climate system. They are not used to reveal specific events, such as a hurricane or a series of floods. Trends are important because they eliminate or smooth out single events that may be extreme.

Climate models allow climate change scientists to ask "what if" questions. They can vary the input and change the outcome to produce results which give an indication of what will happen to the climate if, for example, carbon dioxide is doubled or tripled or even reduced in the future. Climate models may also be used to vary the timeframes of climate change; changes that may take place over months, thousands, or millions of years.

Models are necessary for testing many technological advances before designing and building the real things. Climate modeling gives climate change scientists a means of projecting climate changes into the future. Projecting climate change is not the same as predicting climate change for one cannot predict the future. The most popular use of climate models in recent years has been to project temperature changes resulting from increases in atmospheric concentrations of greenhouse gases, especially carbon dioxide, but other greenhouse gases have been used as well.

A climate model must be compared to observational climate changes of the past (hindcasting or history matching) in order to use the model to project into the future.

18.2.1 Simplifying the Climate System

Before models can be constructed of the climate system, it is necessary to develop the equations that simulate the natural processes and to run tests of the models to determine whether they are correct or not. The development of climate models over the past 35 years is depicted by Fig. 18.1. The calibration of the model must be done using hindcasting or history matching. If the model matches the climate history of the past, it has a good chance of projecting climatic conditions into the future. This process involves several iterations of the model runs as well as numerous tweaks to the model.

The purpose of climate models is essentially to model the response of the climate to changes in the climate system by parameterizing the system and then changing certain parameters to measure the climate response. Parameterizing is simply breaking down the climate system into its individual parameters such as wind directions, ocean currents, etc.

Climate models are systems of differential equations derived from the basic laws of physics, fluid motion, and chemistry formulated to be solved on supercomputers. Some of the simpler climate models have been adapted to personal computers.

Models are constructed so that climate change scientists can vary the parameters to see the response the climate will have to changes in input, e.g., vary the incoming solar radiation at the surface of the Earth to be able to witness the climatic response. For example, climate change scientists need to know what effects the change in solar radiation will have on atmospheric and oceanic currents and where will these changes most likely occur. They often change the input of greenhouse gases to determine their effect on the Earth's temperature.

18.2.2 Boundary Conditions

Boundary conditions are set when the model is designed or redesigned or when the model is run. Boundary conditions may be the thickness of an atmospheric layer and its latitude and longitude. A boundary condition may be the input of carbon dioxide in parts per million or methane in parts per billion. Boundary conditions may be a period of time, decades, years, thousands and millions of years. In the

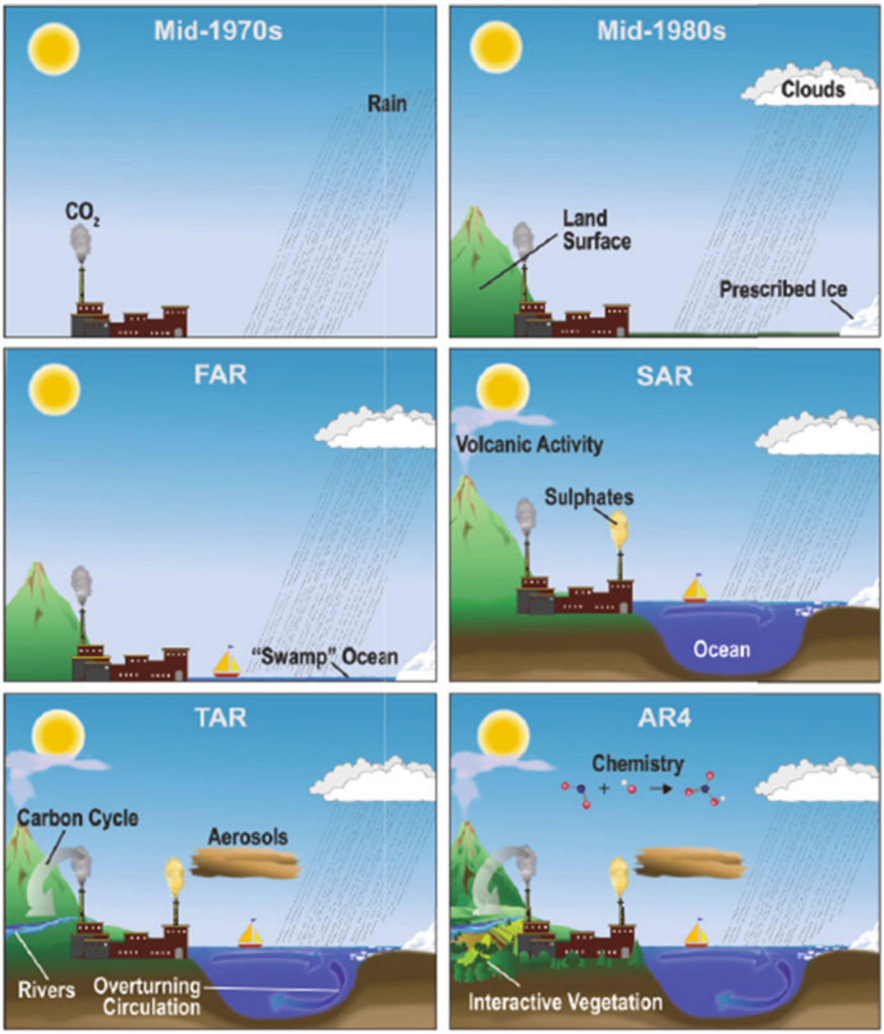


Fig. 18.1 Increasing complexity of climate models. (IPCC AR4 2007, Figure 1.2. The complexity of climate models has increased over the last few decades. The additional physics incorporated in the models are shown pictorially by the different features of the modeled world). (FAR = First Assessment Report; SAR = Second Assessment Report; TAR = Third Assessment Report; AR4 = Assessment Report 4)

modeling of ancient climates (paleoclimatology), the distribution of land and sea become boundary conditions. The elevation of the land surface where ancient mountains may have been could also serve as a boundary condition.

Boundary conditions must be accurately stated and input for each model run and their details precisely documented.

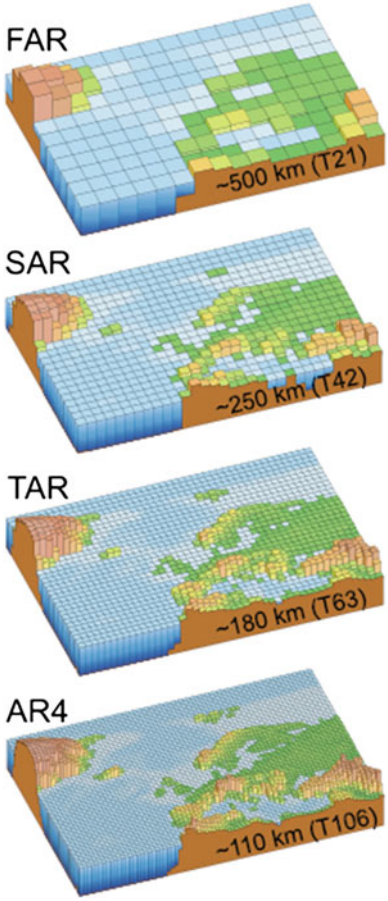


Fig. 18.2 Progression of degree of detail in climate models from the FAR to AR4. (IPCC AR4 2007, Figure 1.4. Geographic resolution characteristic of the generations of climate models used in the IPCC Assessment Reports: FAR (IPCC 1990), SAR (IPCC 1996), TAR (IPCC 2001), and AR4 (2007). The figures above show how successive generations of these global models increasingly resolved northern Europe. These illustrations are representative of the most detailed horizontal resolution used for short-term climate simulations. The century-long simulations cited in IPCC Assessment Reports after the FAR were typically run with the previous generation's resolution. Vertical resolution in both atmosphere and ocean models is not shown, but it has increased comparably with the horizontal resolution, beginning typically with a single-layer slab ocean and ten atmospheric layers in the FAR and progressing to about 30 levels in both atmosphere and ocean)

Climate models take into account many factors of the atmosphere, biosphere, geosphere, hydrosphere, and cryosphere to model the entire Earth system. They take into account the interactions and feedbacks between these different parts of the planet. The evolution or progress in climate modeling is illustrated by Figs. 18.1 and 18.2 that show the increasing level of detail over the time of the four IPCC reporting periods.

18.2.3 Climate Modeling Centers

Climate modeling is an international endeavor and a massive undertaking at present to build and tweak climate models so they can be as accurate as is humanly possible. There are several centers of climate modeling expertise throughout the world. A few of these centers and their web addresses are listed below:

- Cambridge Center for Atmospheric Science (U.K.) http://www.atm.damtp.cam.ac.uk/
- CERFACS Global Change and Climate Modeling (France) http://www.cerfacs.fr/globc/
- DOE Computer Hardware, Advanced Mathematics and Model Physics Program (CHAMMP) (USA) http://www.esd.ornl.gov/programs/chammp/chammp.html
- National Oceanic and Atmospheric Administration (NOAA) (USA) http://www.nasa.gov
- Climate Research Group University of Illinois (USA) http://crga.atmos.uiuc.edu/
- Climate Research Unit, University of East Anglia (U.K.) http://www.cru.uea.ac.uk/
- Climatic Impacts Centre, Macquarie University (Australia) http://cic.mq.edu.au/
- Colorado State University Department of Atmospheric Sciences (USA) http://www.atmos.colostate.edu/
- Coupled Model Intercomparison Project (CMIP) (USA) http://www-pcmdi.llnl.gov/covey/cmip/cmiphome.html
- Pennsylvania State University Earth System Science Center (USA) http://www.essc.psu.edu/
- German Climate Science Computing Center (DKRZ) (Germany) http://www.dkrz.de/index-eng.html
- Geophysical Fluid Dynamics Laboratory (GFDL) (USA) http://www.gfdl.gov/
- NASA Goddard Institute for Space Studies (GISS) (USA) http://www.giss.nasa.gov/
- Hadley Center for Climate Prediction and Research (U.K.) http://www.meto.govt.uk/sec5/sec5pg1.html
- Laboratoire de Meteorologie Dynamique du CNRS (France) http://www.lmd.ens.fr/english/
- Los Alamos Advanced Computing Laboratory Global Climate Modeling (USA) http://www.acl.lanl.gov/GrandChal/GCM/gcm.html
- Electric Power Research Institute (EPRI) Model Evaluation Consortium for Climate Assessment (MECCA) (USA) http://www.epri.com/Strategic/Environment/MECCA/MECCA.html
- MIT Climate Modeling Initiative (USA) http://geoid.mit.edu/climatemodel/climatemodel.htm
- NASA/GSFC Coupled Climate Dynamics Group (CCDG) (USA) http://pong.gsfc.nasa.gov

- NASA Langley Atmospheric Modeling Group (USA) http://rossby.larc.nasa.gov/
- NCAR Climate and Global Dynamics Division (CGD) (USA) http://www.cgd.ucar.edu/
- NCAR Climate Systems Model (CSM) (USA) http://www.cgd.ucar.edu/csm/index.html
- UCAR GENESIS Earth Systems Modeling Project (USA) http://www.cgd.ucar.edu/ccr/genesis.html
- UCAR Community Climate Model (USA) http://www.cgd.ucar.edu/cms/ccm.html
- Lawrence Livermore National Laboratory Program for Climate Model Diagnosis and Intercomparison (PCMDI) (USA) http://www-pcmdi.llnl.gov/
- University of Wisconsin-Madison Space Science and Engineering Center (SSEC) (USA) http://www.ssec.wisc.edu/
- NCAR Community Climate System Model (CCSM) http://www.cesm.ucar.edu/models/ccsm3.0/

Climate models allow us to test particular hypotheses about climate change. For example, we can use the models to tell us how much warming of the Earth we might expect for a given change in greenhouse gas concentrations; or what effect the slowing of a major ocean current would have on the Earth's temperature. The efficacy of using models is that we can vary the input and look at the effects on various environmental and global warming parameters.

Earth is a complex planet and because of this many of the models are very complex. Many of these more complex models include enough mathematical calculations that they must be run on supercomputers, which can do the calculations quickly. All climate models must make some assumptions about how the Earth works, but in general, the more complex a model, the more factors it takes into account, and the fewer assumptions it makes.

At the National Center for Atmospheric Research (NCAR), researchers work with complex models of the Earth's climate system. Their Community Climate System Model (CCSM) is so complex that it requires about three trillion mathematical calculations to simulate a single day on planet Earth. It can take thousands of hours for the supercomputer to run the model. The model output, typically many gigabytes in size, is analyzed by researchers and compared with other model results and with observations and measurement data.

There are currently several other complex global climate models that are used to project the current climate into climatic changes and they require supercomputers to run. Figure 18.3 below shows the development of complex climate models over the period from the mid-1970s to the early 2000s.

State-of-the-art climate models now include interactive representations of the ocean, the atmosphere, the land, hydrologic and cryospheric processes, terrestrial and oceanic carbon cycles, and atmospheric chemistry. Figure 18.4 shows the features that serve as input to the Community Climate System Model (CCSM) Version 3 computer model designed by UCAR.

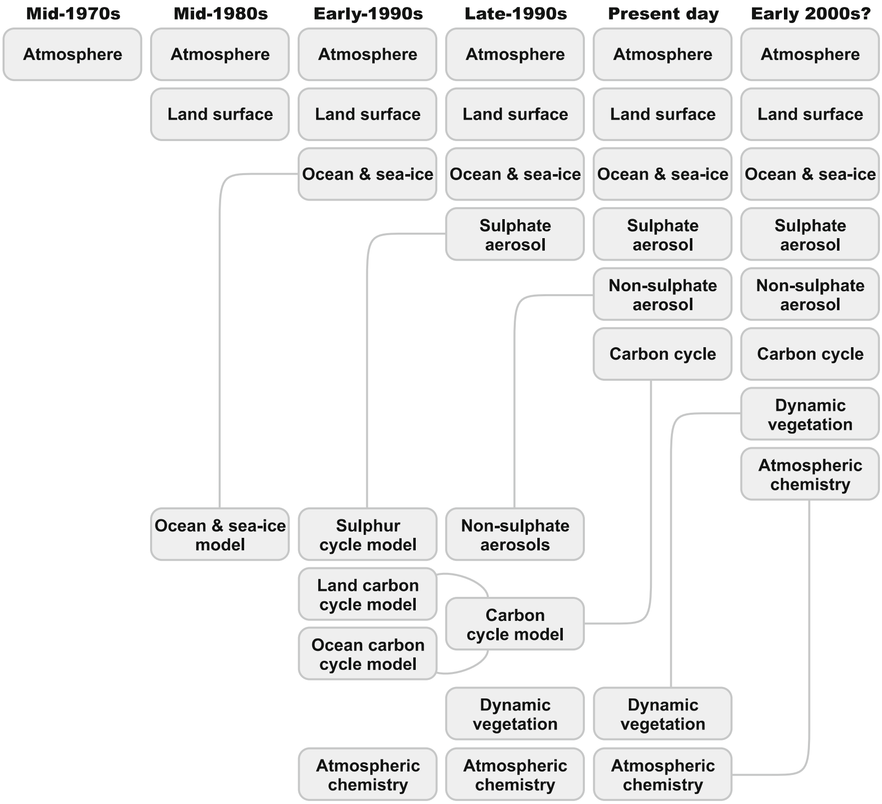


Fig. 18.3 Development of complex climate models. The figure illustrates the development of comprehensive climate models over the 25 years before the IPCC 2001 report showing how different components are first developed separately and later coupled together (Credit: Intergovernmental panel on Climate Change, Third Assessment Report, Technical Summary of Working Group I Report 2001)

For each grid point in a general circulation model, calculations are done for the atmosphere as follows:

- Motion of the air (winds);
- Heat transfer (thermodynamics);
- Radiation (solar and terrestrial);
- Moisture content (relative humidity); and
- Surface hydrology (precipitation, evaporation, snow melt and runoff).

These physical factors are calculated as are the interactions of processes among neighboring grid points. The computations are stepped forward in time from seasons to centuries depending on the timeframes of the studies.

Figure 18.5 illustrates the type of grid system utilized in the more complex GCMs.

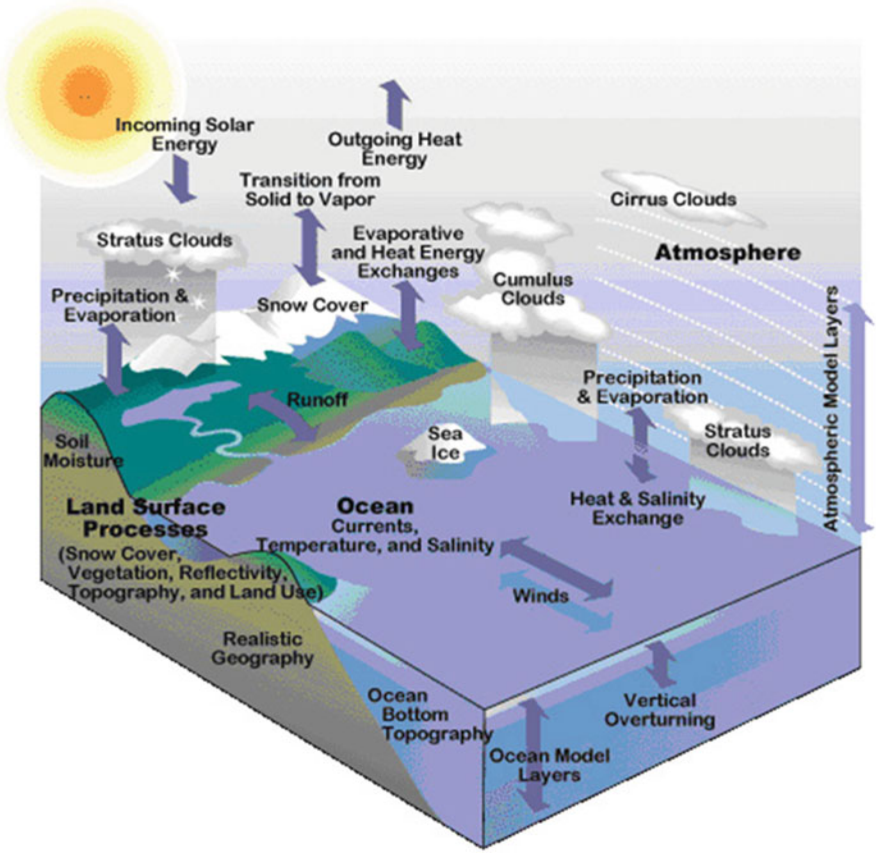


Fig. 18.4 Features represented by input to climate models. The Community Climate System Model (CCSM version 3) that is run with the supercomputer at the National Center for Atmospheric Research (NCAR) incorporates data about all of the natural processes shown in this diagram to simulate Earth's complex climate system (From UCAR)

State-of-the-art climate models now include interactive representations of the ocean, the atmosphere, the land, hydrologic and cryospheric processes, terrestrial and oceanic carbon cycles, and atmospheric chemistry and motion.

The accuracy of climate models is limited by grid resolution and our ability to describe the complicated atmospheric, oceanic, and chemical processes mathematically. Despite imperfections, models simulate current climate and its variability remarkably well. More capable supercomputers enable significant model improvements by allowing for more accurate representation of the physics and chemistry of the climate system.

Component-level evaluation of climate models is common. Numerical methods are tested in standardized tests, organized through activities such as the quasi-biennial Workshops on Partial Differential Equations on the Sphere. Physical

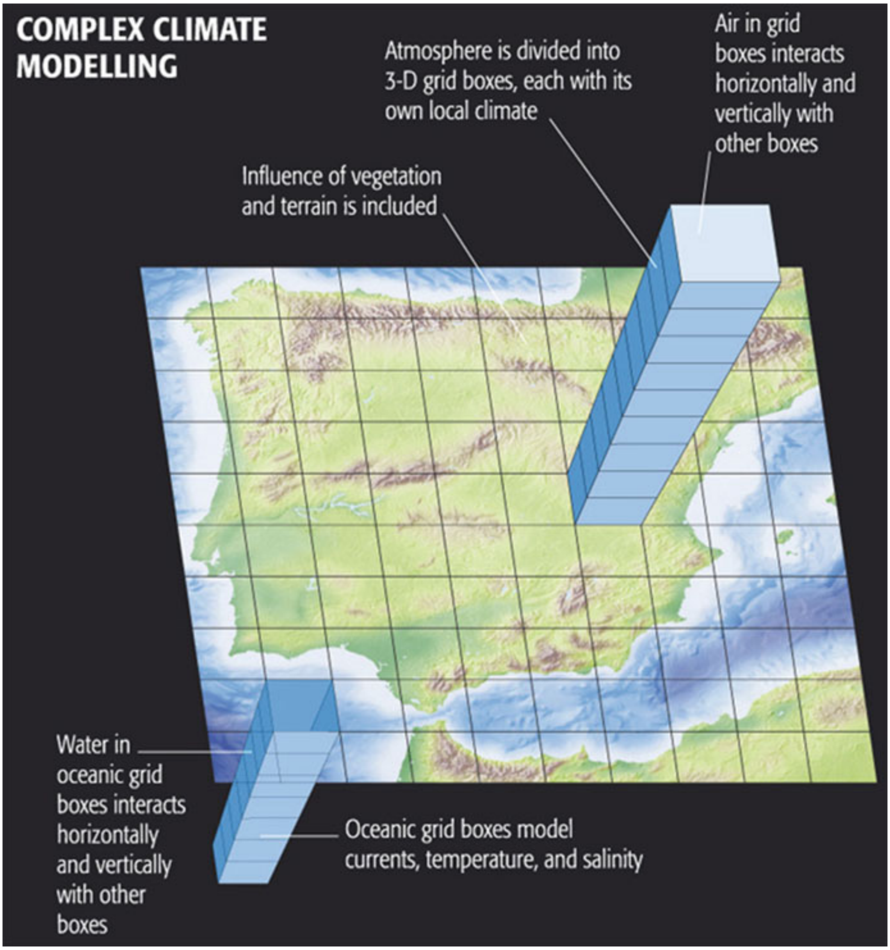


Fig. 18.5 A climate model showing the horizontal and vertical grids and the physical processes in a global circulation model (GCM) (From Mann and Kump, *Dire Predictions,* supported by the National Science Foundation, Public Domain)

parameterizations used in climate models are being tested through numerous case studies, some based on observations and some idealized, organized through programs such as the Atmospheric Radiation Measurement (ARM) program, EUROpean Cloud Systems (EUROCS), and the Global Energy and Water cycle Experiment (GEWEX) Cloud System Study (GCSS). These activities have resulted in a large body of published results.

System-level evaluation focuses on the outputs of the full model, i.e., model simulations of particular observed climate variables.

18.3 Types of Climate Models

There are two main types of models used by climate change scientists; physical climate models and chemical climate models, and there are several variations of each. Physical models simulate the parameters of atmospheric physics. Chemical models simulate changes in composition of atmospheric constituents. Both kinds of models can be combined to simulate how the climate will respond to changes in the physics or chemistry of the climate system.

Climate models are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. To run or use a model, scientists divide the planet into a 3-dimensional grid (as in Fig. 18.5), apply the basic mathematical equations, and evaluate the results. Supercomputers can do more than 80 million math calculations in less than an hour. Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid point and evaluate interactions with neighboring points on the grid. The grid may have thousands of points.

18.3.1 Box Models

Box models are simplified versions of complex systems. Within a box in a climate system model, concentrations of atmospheric constituents of the climate system are assumed to be homogeneous but can be changed with time. More complex box models use numerical techniques to solve concentration problems. Box models can be written to treat flows across and within ocean basins. Other types of modeling can be interlinked with box models, such as land use, allowing researchers to predict the interaction between climate and ecosystems. Box models may consist of more than one box and they may all be linked. Box models are used extensively to model environmental systems or ecosystems and in studies of ocean circulation and the carbon cycle. Simple box models are often used to derive analytical formulas. More complex box models are usually solved using numerical techniques.

18.3.2 Energy Balance Models

Energy balance models (EBMs) estimate the changes in the climate system from an analysis of the energy budget of the Earth. An Energy Balance Model does not attempt to resolve the dynamics of the climate system, i.e., large-scale wind and atmospheric circulation systems, ocean currents, convective motions in the atmosphere and ocean, or any number of other basic features of the climate system. Instead, it focuses on the energy and thermodynamics of the climate system. Energy

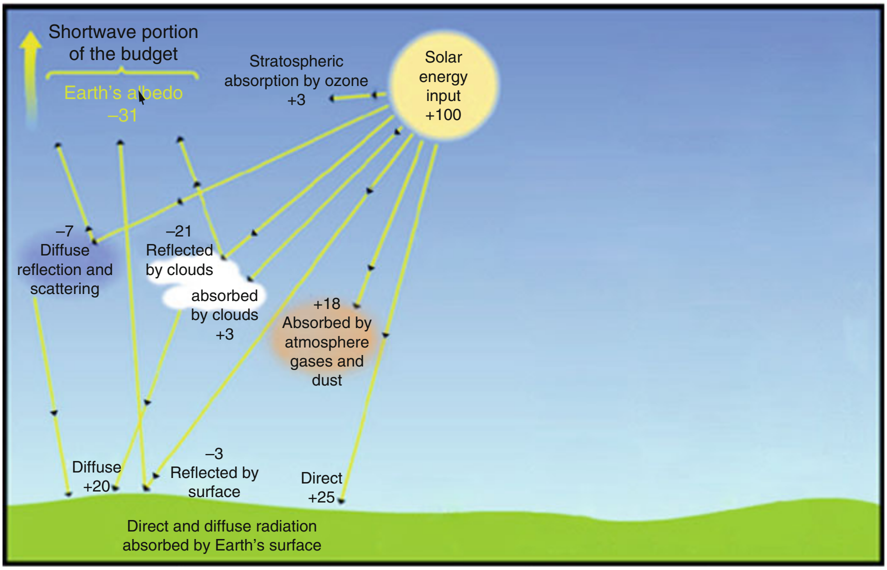


Fig. 18.6 Energy balance of Earth's climate system using a packet of 100 units of solar energy as input to the climate system. This input is shortwave or ultraviolet radiation (From https://www.e-education.psu.edu/meteo469/?q=node/202), (Used with permission)

balance models have proven useful in understanding mechanisms and feedbacks in the climate system. In their simplest form, they do not include any explicit spatial dimension, providing only globally averaged values for the computed variables.

In the illustrations (Figs. 18.6 and 18.7), 100 units of solar energy enter Earth's atmosphere as shortwave ultraviolet (UV) radiation. We will track these and see what happens to the 100 units throughout the climate system. Of these 100 units, 21 are reflected by clouds, 7 are diffused by scattering, and 3 are reflected by Earth's surface totaling 31 parts reflected or diffused. This number is the same as Earth's average albedo at ~31%. This leaves 69 of the packet of 100 still in the Earth system; 25% is directly absorbed by the Earth's surface, 3% is absorbed by clouds, 3% is absorbed by stratospheric ozone, 20% is diffused by the Earth's surface, and 18% is absorbed by greenhouse gases and aerosols in the atmosphere.

As the Earth's surface warms by shortwave ultraviolet radiation, it radiates heat in the form of longwave or infrared radiation (IR). The surface heat generates 45%, the atmosphere generates 21%, and 3% is generated by the ozone layer to space. This is the 69% that was left within the Earth system after 31% of the original 100% of solar input was reflected as albedo. Of the 69, 19% is given off by the surface as evapotranspiration, 4% is given up from the surface by convection, 14% is re-radiated by greenhouse gases, 8% is direct heat lost to space, 21% is atmospheric heat, 3% is heat from the ozone layer, equaling 69% that was in the climate system after the 31% of UV portion of the energy budget lost to space.

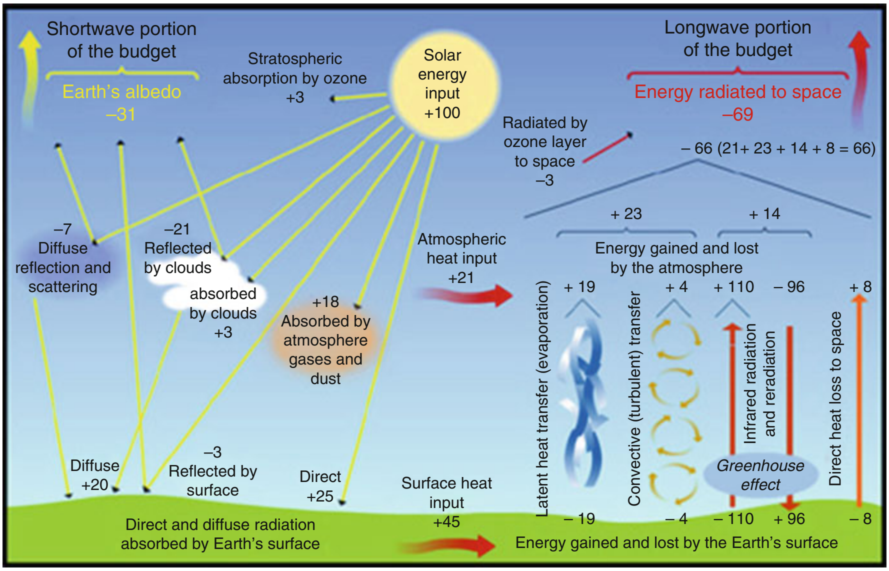


Fig. 18.7 Distribution of the 100 packet of ultraviolet solar radiation within the Earth's climate system and the longwave or infrared radiation of Earth's energy budget (From https://www.e-education.psu.edu/meteo469/?q=node/202) (Used with permission)

Energy balance models describe the climate system in terms of thermodynamics (e.g., heat, temperature). They have been used to show how energy enters and leaves the Earth's climate system and achieves equilibrium. By modeling the energy flow one can compute the effective temperature of Earth as well as the temperature at the surface.

Energy balance models simulate the global radiation balance between incoming solar radiation and outgoing terrestrial radiation. They also are used to simulate the latitudinal energy transfer within the Earth system. EBMs may be 0-dimensional or 1-dimensional. The zero dimensional EBM simply models the balance between incoming and outgoing radiation at Earth's surface. This balance is in reality quite complicated, and we have to make a number of simplifying assumptions if we are to obtain a simple conceptual model that encapsulates the key features. In zero dimensional models, Earth is considered a single point in space and only the global radiation balance is simulated. In 1-dimensional EBMs latitudinal differences, usually temperatures are modeled.

In 1-D models, temperature for each latitudinal band is calculated using a global average temperature compared to a latitudinal temperature. EBMs may also simulate energy transfers between the ocean and atmosphere.

Most energy balance models are not global models, but zonal or latitudinal models. As such, we must have an equation or part of an equation that accounts for the transfer of energy from one latitudinal zone to the next.

18.3.3 Radiative-Convective Models

Radiative-Convective models (RCMs) may be 1- or 2-dimensional. Height is the dimension added in both. RCMs simulate the transfer of energy through the atmosphere, the role of convection, energy transfer, and radiative differences that occur as energy moves vertically through the atmosphere (1-dimensional) and horizontally (2-dimensional). Radiative-convective models have advantages over the simple model; they can determine the effects of varying greenhouse gas concentrations on effective emissivity and therefore the surface temperature. But added parameters are needed to determine local emissivity and albedo and address the factors that move energy within Earth's climate system.

RCMs must contain information about radiation fluxes throughout the atmosphere including fluxes of land and solar radiation. They measure parameters such as surface albedo, clouds, and atmospheric turbidity and the effects in the different layers of the atmosphere. Heating rates of atmospheric layers are calculated based on the imbalance between the top and bottom of each layer. Vertical profiles, lapse rates, are calculated as is convection within the atmosphere.

RCMs are most important in measuring changes in forcing that have their origins in the Earth-atmosphere exchanges such as volcanic eruptions.

18.3.4 Statistical-Dynamical Models

Statistical-dynamical models (SDMs) are mainly 2-dimensional (2-D) models with one horizontal and one vertical dimension. Standard SDMs combine horizontal energy transfer with the radiative-convective transfer of RCMs. Wind speed and direction are modeled based on statistical relationships. Laws of motion are used to calculate the diffusion of energy through the climate system.

Statistical-Dynamical models are used mainly in investigations of horizontal energy transfer and the processes that affect that transfer. These are generally 2-D, with one horizontal and one vertical dimension, although there are some models with two horizontal dimensions.

They combine the horizontal energy transfer of EBMs with the radiative-convective functions of RCMs. However, the equator-pole transfer is more accurately simulated than in EBMs, based on theoretical and empirical relationships of the cellular flow between latitudes.

These models are useful for simulating and studying horizontal energy flows, and processes that disrupt them.

18.3.5 General Circulation Models

The first general circulation climate model that combined both oceanic and atmospheric processes was developed in the late 1960s at the NOAA Geophysical Fluid

Dynamics Laboratory. By the early 1980s, the United States' National Center for Atmospheric Research (NCAR) had developed the Community Atmosphere Model; this model has been continuously refined into the 2000s. Coupled ocean–atmosphere climate models such as the Hadley Centre for Climate Prediction and Research's HadCM4 model are currently being used as inputs for climate change studies.

General Circulation models (GCMs) are the most complex models used in climate change science. They are 3-dimensional and are based on the laws of physics. They include each of the following:

- Conservation of energy;
- Conservation of momentum;
- Conservation of mass; and
- The Ideal Gas Law.

GCMs are used to calculate global factors, not regional ones, and they use tremendous amounts of computer time. They must calculate each parameter for each node point over the entire globe and this requires use of a supercomputer.

GCMs must be tested at the systems level by running the entire model and comparing the results with observations. Models are also tested at the components level, i.e., by isolating components and testing them independently.

Models used by the IPCC are tested by climate scientists and programmers worldwide prior to being used by the IPCC. Bugs are worked out and errors are corrected and various groups throughout the world are conducting climate model intercomparisons. This work has been going on since the 1980s. There are now several dozen intercomparison groups covering all climate model components and coupled model configurations (Fig. 18.8).

18.4 Confidence and Validation

Confidence in a climate model can be gained through simulations of the historical record (history matching or hindcasting), but such opportunities are much more limited than are those available through weather prediction. These and other approaches are discussed below.

Validation of climate models involves a comparison of the model output with observations of changes in the atmosphere. There are some climate scientists that believe that models are validated by the climate scientists and programmers who build and run the models and that there is no need for independent validation. However, with the public perception of climate models being what it is, it is certainly suggested at this time in climate change science to go through an independent validation process and the modeling groups do just that. Lawrence Livermore National Laboratory's Program for Climate Model Diagnosis and Intercomparison (PCMDI) serves as a validation source for international groups and a clearinghouse for models used to model current and project future climate change.

Confidence in climate models increases with independent validation, history matching, and comparing model results with observations.

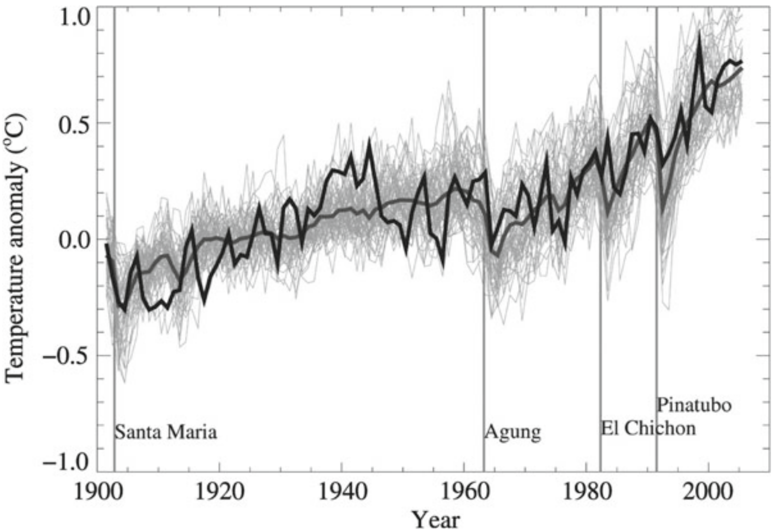


Fig. 18.8 Global mean near-surface temperatures over the twentieth century from observations (*black*) and as obtained from 58 simulations produced by 14 different climate models driven by both natural and human-caused factors that influence climate (*light grey thin lines*). The mean of all these runs is also shown (*thick grey line*). Temperature anomalies are shown relative to the 1901–1950 mean. *Vertical grey lines* indicate the timing of major volcanic eruptions. (IPCC AR4 2007; redrawn by John Cook)

Additional Readings

Archer, D. (2011). *Global warming: Understanding the forecast* (2nd ed.). Hoboken: Wiley. ISBN-10: 0470943416; ISBN-13: 978-0470943410.

Archer, D., & Pierrehumbert, R. T. (Eds.). (2011). *The warming papers: The scientific foundation for the climate change forecast*. Hoboken: Wiley-Blackwell.

Bolin, B. (2007). *A history of the science and politics of climate change. The role of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Houghton, J. (2009). *Global warming: The complete briefing* (4th ed.). Cambridge: Cambridge University Press.

IPCC, in IPCC TAR SYR. (2001). In Watson, R. T., The Core Writing Team (Eds.), Climate change 2001: Synthesis report. *Contribution of working groups I, II, and III to the third assessment report of the intergovernmental panel on climate change*. Cambridge University Press, ISBN 0-521-80770-0 (pb: 0-521-01507-3).

Jin, M., & Liang, S. (2006). An improved land surface emissivity parameter for land surface models using global remote sensing observations. *Journal of Climate, 19*(12), 2867–2881. doi:10.1175/JCLI3720.1.

Meehl, G. A., et al. Climate change 2007 Chapter 10: Global climate projections, in IPCC AR4 WG1 (2007). Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., et al. (Eds.). Climate change 2007: The physical science basis. *Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, ISBN 978-0-521-88009-1 (pb: 978-0-521-70596-7).

Pierrehumbert, R. T. (2011). *Principles of planetary climate*. Cambridge: Cambridge University Press.

Soden, B. J., & Held, I. M. (2006). An assessment of climate feedbacks in coupled ocean–atmosphere models. *Journal of Climate, 19*, 3354–3360. doi:10.1175/JCLI3799.1.

Sokolov, A. P., et al. (2009). Probabilistic forecast for 21st century climate based on uncertainties in emissions (without policy) and climate parameters. *Journal of Climate, 22*(19), 5175–5204. doi:10.1175/2009JCLI2863.1.

Wang, W. C., & Stone, P. H. (1980). Effect of ice-albedo feedback on global sensitivity in a one-dimensional radiative-convective climate model. *Journal of the Atmospheric Sciences, 37*(3), 545–552. doi:10.1175/1520-0469(1980)037<0545:EOIAFO>2.0.CO;2. Bibcode 1980JAtS…37..545W.

Part VIII
Climates of the Past (Paleoclimatology)

Chapter 19
Ancient Climates and Proxies

Abstract Paleoclimatology is the study of climates of the past. This study uses historical records, direct lines of evidence, and proxies to determine past climates. As we go back in time from the present, the less confidence we have in the data, so paleoclimatologists rely on converging data paths to increase confidence in the results and conclusions. Ice cores tell scientists a great deal about the ancient composition of the atmosphere by analyzing the air bubbles contain within them. These air bubbles within the ice contain samples of the atmosphere at the time they formed. Stable isotopes from ice and sediment samples reveal temperature data by proxy. Pollen, tree rings, coral growth, cave deposits, assemblages of organisms hold clues to past climates.

Keywords Pollen • Isotopes • ^{18}O • Radiocarbon • Trees • Rings • Corals • Dansgaard-Oeschger • Foraminifera • Cave • Organisms • Geochemistry • Fossil • Aeolian • Milankovitch • Tephrochronology • Dendrochronology • Dendroclimatology • Terrigenous • Sediment • Biogenic • Orbital • SMOW • Periglacial • Loess • Lacustrine • Glacial • Limnology • Palynology

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and each chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_19,

Things to Know	
Proxy	Orbital tuning
Paleoclimatology	Lëss
Stable isotopes	Biogenic sediment
Palynology	Periglacial material
Fossil pollen	Tephrochronology
Proxy types	Assemblages of organisms
Coral growth	Limnology
Terrigenous sediment	Dendroclimatology
Lacustrine	Biogenic sediment
Geochemistry	Uniformitarianism
Sr/Ca	Bipolar seesaw
Milankovitch	Foraminifera
Cave deposits	Mg/Ca
SMOW	Tree rings
Aeolian deposits	Dansgaard-Oeschger events

19.1 Introduction

Paleoclimatology is the study of ancient climates and involves using what is known about variables in present climate science to interpret past climates. In that sense, it uses the principle of uniformitarianism from geology, "the present is the key to the past." The opposite principle is also used, that the past is key to the present.

Proxies are substitutes for data directly obtained. Proxies are what paleoclimatologists gather from natural recorders of climate variability such as tree rings, ice cores, fossil pollen, ocean sediments, coral, isotope analysis, foraminifera and other fossil shells, and historical data. By analyzing records taken from these and other proxy sources, scientists can extend our understanding of climate changes far back beyond the 130+-year instrumental record that began in the 1880s. Paleoclimatologists try to obtain age information from multiple sources to reduce age uncertainty, and paleoclimatic interpretations must take into account uncertainties in time control or the interval of time the study encompasses.

Paleoclimatic reconstruction methods have advanced in the past several decades and range from direct measurements of past change, e.g., ground temperature variations, gas content of ice core air bubbles, ocean sediment pore-water change, and glacier size changes, to proxy measurements involving the change in chemical, physical and biological parameters that reflect past changes in the environment where the proxy entity grew or existed.

Many living creatures, such as insects, corals, and other organisms alter their growth and/or population dynamics in response to changing climatic conditions and these climate-induced changes are recorded in the past growth of living and fossil specimens or assemblages of organisms. Tree rings, ocean and lake plankton, and pollen are some of the best-known and best-developed proxy sources of past climate going back centuries and millennia. Networks of tree ring width and density chronologies are used to decipher past temperature and other environmental factors based on comprehensive comparisons with overlapping instrument data. Distributions of pollen and plankton from sediment cores are used to derive quantitative estimates of past climate (e.g., temperatures, salinity, and precipitation) using statistical methods calibrated against their modern distribution and associated climate parameters.

Geochemistry of several biological and physical entities reflects well-understood thermodynamic processes that can be transformed into estimates of climate parameters such as temperature. Key examples include: oxygen isotope ratios (^{18}O and ^{16}O) in coral and foraminiferal carbonate to infer past temperature and salinity; magnesium/calcium (Mg/Ca) and strontium/calcium (Sr/Ca) ratios in carbonates for temperature estimates; alkenone (highly resistant organic compounds) saturation indices from marine organic molecules to infer past sea surface temperature (SST); and oxygen and hydrogen isotopes and combined nitrogen and argon isotope studies in ice cores to infer temperature and atmospheric transport.

Many physical systems (e.g., sediments and aeolian deposits) change in predictable ways that can be used to infer past climate change. There is ongoing work on further development and refinement of methods, and there are remaining research issues concerning the degree to which the methods have spatial and seasonal biases. Therefore, in many recent paleoclimatic studies, a combination of methods is applied since multi-proxy series provide more rigorous estimates than a single proxy approach, and the multi-proxy approach may identify possible seasonal biases in the estimates. No paleoclimatic method is foolproof, and knowledge of the underlying methods and processes is required when using paleoclimatic data.

The field of paleoclimatology depends heavily on replication and cross-verification between paleoclimate records from independent sources in order to build confidence in inferences about past climate variability and change. In this chapter, the most weight is placed on those inferences that have been made with particularly robust or replicated methodologies.

19.2 Historical Records

Historical records go back as far as drawings on the walls of caves. Most useful climatic records, however, are observations found in farmer's logs, diaries, old newspaper accounts, and other written records. These records are largely anecdotal and give only an overview or a general sense of climate prior to instrumental recordings in the 1880s.

Paleoclimatologists also use documentary data (e.g., in the form of specific observations and crop harvest data) for reconstructions of past climates.

19.3 Ice Cores

Ice cores have been taken from drilling into glaciers and ice caps in many parts of the world and those from Greenland and Antarctica are especially well known.

Recent studies (2010–2012) have shown that ice also forms by melt water from the glacial ice re-freezing at the bottom of glaciers. This does not affect data that are obtained above the re-freezing zone.

As glacial ice forms from snow which accumulates year after year, it entraps part of the environment from which it forms such as dust from volcanic eruptions and air trapped in atmospheric bubbles preserved in the ice. Thus, glacial ice cores tell scientists a great deal about Earth history at the time the ice was formed, especially the volcanic eruptions and composition of the atmosphere. Atmospheric concentrations of such atmospheric constituents as carbon dioxide, methane, and volcanic dust can be read directly from these ice cores. Other ice core constituents, such as certain stable isotopes, may also be important.

Reliable modern instrument records of climate only began in the 1880s and to obtain climate readings prior to then requires the use of proxies.

19.4 Stable Isotope Analysis

Oxygen and carbon stable isotopes are the two most used for environmental and climate change applications, although others are sometimes useful. They were discussed in detail in Chap. 14.

19.5 Ice Cores and Proxies

Ice cores are retrieved from glaciers and ice caps by a special coring or drilling method. The methods of obtaining and analyzing data from ice cores are discussed in Chap. 14.

19.6 Dating Ice Cores

Near the top of glacial ice, it is usually possible to identify annual layers of alternating light- and dark-colored bands. The light-colored bands represent summer and the dark-colored bands represent winter. The light- and dark-colored bands together represent 1 year.

Deeper below the ice surface, the original snow is recrystallized and the annual layers are indistinguishable. Dating the deeper ice becomes a much more difficult problem. Methods of dating ice cores are discussed in more detail in Chap. 14.

Gas synchronization uses records of gases that are well mixed in the atmosphere to link ice core records. This has been used with $\delta^{18}O$ to compare the timing of deglacial changes recorded in Greenland and Antarctica. The rapid variations in atmospheric methane concentrations has allowed more accurate comparisons of the relationship between Dansgaard-Oeschger events in Greenland and warming events in Antarctica.

Tephrochronology uses the elemental composition and geochemical signature of volcanic ash (tephra) found in ice cores as stratigraphic markers. If the age of the volcanic eruption is known, tephra offer a means to date an ice core with radioisotopes and to correlate between ice cores in different parts of the world.

Correlation with other dated records allows researchers to establish relative chronologies between ice cores and with marine sediments.

19.7 Dendroclimatology

The study of the annual growth of trees and the consequent assembling of long, continuous chronologies for use in dating wood is called dendrochronology. The study of the relationships between annual tree growth and climate is called dendroclimatology. Dendroclimatology offers a high resolution (annual) form of paleoclimate reconstruction for most of the Holocene and Anthropocene.

The annual growth of a tree is the net result of many complex and interrelated biochemical processes. Trees interact directly with the microenvironment of the leaf and the root surfaces. The fact that there exists a relationship between these extremely localized conditions and larger scale climatic parameters offer the potential for extracting some measure of the overall influence of climate on growth from year to year. Growth may be affected by many aspects of the microclimate: sunshine, precipitation, temperature, wind speed and other factors.

A cross section of most forest tree trunks found in temperate regions will reveal an alternation of lighter and darker bands, each of which is usually continuous around the tree circumference (Fig. 19.1). Each seasonal increment consists of a couplet of early wood (a light growth band from the early part of the growing season) and denser late wood (a dark band produced towards the end of the growing season), and collectively they make up the tree ring. The mean width of the tree ring is a function of many variables, including the species, age, soil nutrients, and a host of other climatic factors. The problem facing the dendroclimatologist is to extract whatever climatic signal is available in the tree-ring data from the remaining background "noise." Figure 19.1 below shows the variability in widths of the tree rings.

19.8 Ocean Sediments

Billions of tons of sediment are carried off the land and accumulate in the ocean basins every year, and these sediments may be indicative of climatic conditions near the ocean surface or on the adjacent continents. Sediments are composed of both biogenic (organic) and terrigenous (inorganic, land derived) materials. The biogenic component includes the remnants of planktonic (ocean surface-dwelling) and benthic (deep-water- or

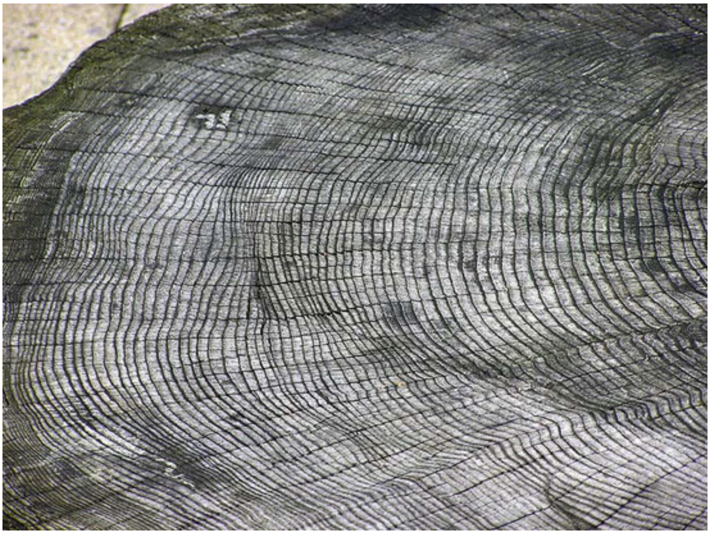


Fig. 19.1 Tree rings in a tree trunk in the Bristol Zoo, Bristol, England (Public Domain)

sea floor-dwelling) organisms which provide a record of past climate and oceanic circulation. Such records may reveal information about past surface water temperatures, salinity, dissolved oxygen and nutrient availability. By contrast, the nature and abundance of terrigenous materials may provide information about continental humidity-aridity variations, and the intensities and directions of winds. Ocean sediment records have been used to reconstruct paleoclimate changes over a range of time scales, from thousands of years to millions and even tens of millions of years.

19.9 Paleoclimate Reconstruction from Biogenic Material

Biogenic sea floor sediments are called oozes, and are usually either calcareous or siliceous in nature. Calcareous oozes consist mainly of the carbonate tests (hard parts) of millions of marine organisms, while siliceous oozes are made up of millions of silicate sources. For paleoclimatic purposes, the most important materials are the tests of foraminifera (calcareous zooplankton; Fig. 19.2), coccoliths (calcareous algae; Fig. 19.3), radiolarians and silicoflagellates (siliceous zooplankton; Fig. 19.4), and diatoms (siliceous algae; Fig. 19.5).

Paleoclimate reconstruction from the study of calcareous and siliceous tests has resulted from basically three types of analysis:

- Oxygen isotope composition of calcium carbonate ($CaCO_3$);
- Relative abundance of warm- and cold-water species; and
- Morphological variations in particular species resulting from environmental factors.

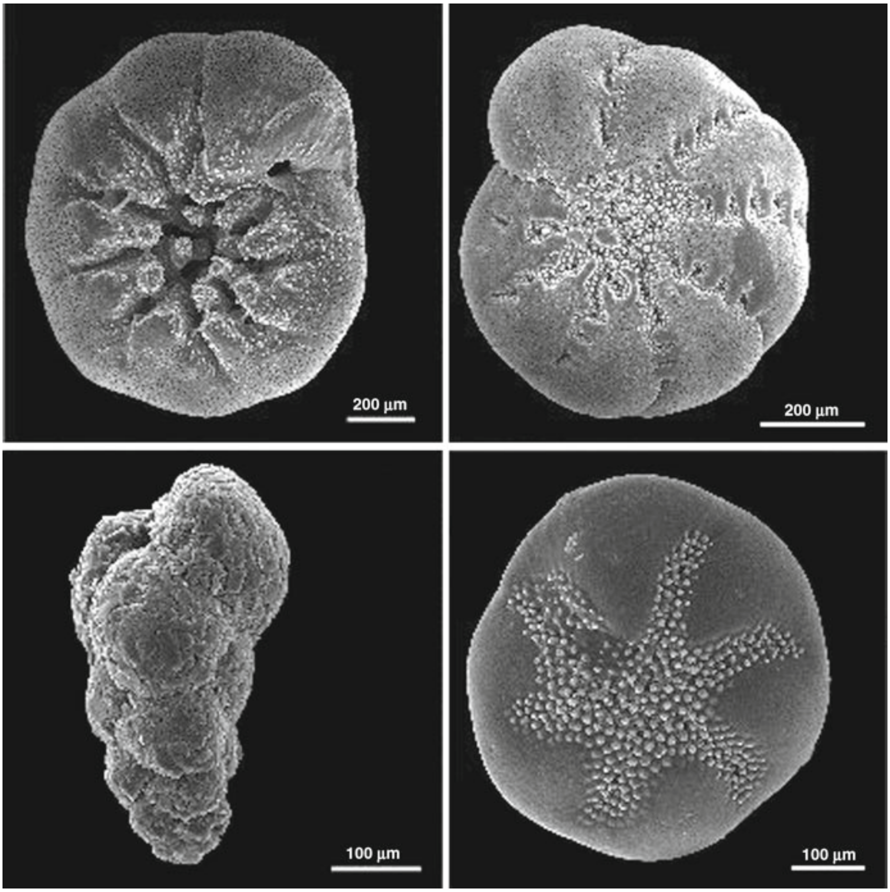


Fig. 19.2 Scanning electron microscope (SEM) images of tests (calcareous skeletons) of foraminifera (USGS, Public Domain)

Most work has concentrated on the study of the foraminifera, in particular oxygen isotopic analyses. Foraminifera ("forams" for short) are abundant and the oxygen content of their shells can be readily analyzed.

If calcium carbonate of a marine organism is crystallized slowly in water, the ^{18}O is slightly concentrated in the precipitate relative to that remaining in the water. This fractionation process is temperature dependent, with the concentrating effect diminishing as temperature increases. When the organism dies, the test sinks to the sea bed and is laid down, with millions of other tests, as biogenic sea floor sediment (calcareous ooze), thus preserving a temperature signal (in the form of an oxygen isotopic ratio) from a time when the organism lived. If a record of oxygen isotope ratios is built up from cores of ocean sediment, and the cores can be accurately dated, this provides paleoclimatologists with a method of paleoclimate reconstruction.

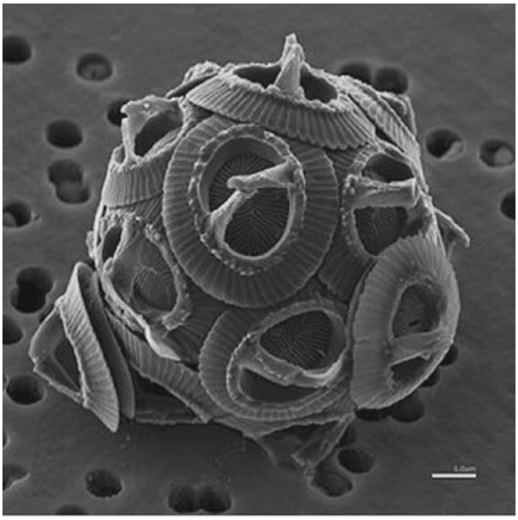


Fig. 19.3 Coccolith, calcareous algae (From Wikipedia, Licensed under the Creative Commons Attribution-Share Alike 2.5 Generic License, by Richard Bartz)

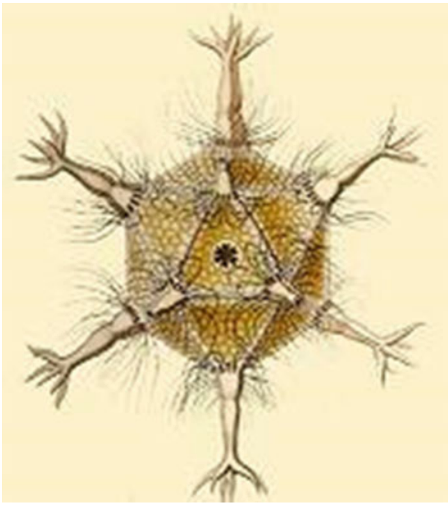


Fig. 19.4 A radiolarian from siliceous zooplankton ooze (Public Domain)

As for isotope ratios from ice cores, the oxygen isotopic composition of a sample is generally expressed as a departure, $\delta^{18}O$, from the $^{18}O/^{16}O$ ratio of an arbitrary standard, $^{18}O/^{16}O_{SMOW}$. SMOW is "standard mean ocean water" according to the following formula:

$$d^{18}O = \left({}^{18}O/{}^{16}O\right)_{\text{sample}} - \left({}^{18}O/{}^{16}O\right)_{\text{SMOW}} \times 10^3 \,\tfrac{0}{00} \div \left({}^{18}O/{}^{16}O\right)_{\text{SMOW}}$$

The fractionation effect is much smaller than that which occurs during evaporation/condensation of water, and typically, $\delta^{18}O$ values are no more than a few parts per mille (‰) above or below the SMOW isotopic ratio.

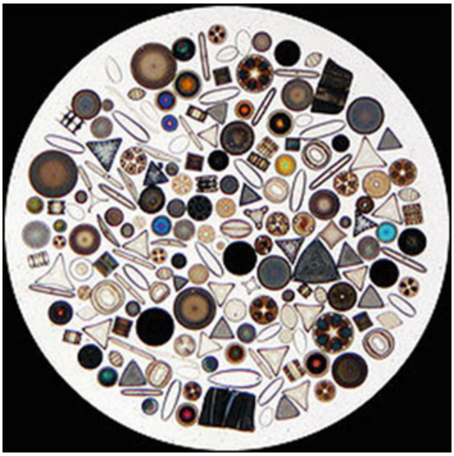


Fig. 19.5 Photomicrograph of diatoms on a slide (From Wikipedia, Licensed under the Creative Commons Attribution-Share Alike 2.5 Generic License)

Empirical studies relating the isotopic composition of calcium carbonate deposited by marine organisms to the temperature at the time of deposition have demonstrated the following relationship:

$$\mathrm{T} = 16.9 - 4.2(\delta_c - \delta_w) + 0.13(\delta_c - \delta_w)^2$$

where T is the water temperature (°C), δ_c is departure from SMOW of the carbonate sample and δ_w is the departure from SMOW of the water in which the sample precipitated. For modern analyses, δ_w can be measured directly in ocean water samples; in fossil samples, however, the isotopic composition of sea water is unknown and cannot be assumed to have been the same as it is today. In particular, during glacial times, sea water was isotopically heavier (i.e., enriched in ^{18}O) compared to today; large quantities of isotopically lighter water were land-locked as huge ice sheets. Thus, the expected increase in δ_c due to colder sea surface temperatures during glacial times is complicated by the increase in δ_w at these times.

By analyzing isotopic records of deep water organisms, it is possible to resolve how much of the increase in δ_c for surface organisms was due to decreases in surface temperature and how much was due to continental ice sheet formation. It is expected that bottom water temperatures (≈1–2°C) have changed very little since glacial times (the last glacial maximum being 20,000–18,000 ka) and increases in δ_c for deep water organisms would reflect only changes in the isotopic composition of the glacial ocean. On this basis, some scientists have concluded that 70% of the changes in the isotopic composition of surface dwelling organisms were due to changes in the isotopic composition of the oceans, and only 30% due to temperature variations.

Unfortunately, changes in the isotopic composition of the ocean reservoirs are not the only complications affecting a simple temperature interpretation of δ_c variations. The assumption that marine organisms precipitate calcium carbonate from sea water in equilibrium is sometimes invalidated. Certain vital effects of marine organisms, such as the incorporation of metabolically produced carbon dioxide, may cause a departure from the thermodynamic equilibrium of carbonate precipitation. However, by careful selection of species either with no vital effects or where the vital effects may be quantified, this problem can be avoided.

In addition to stable isotope analyses, the reconstruction of paleoclimates can also be achieved by studying the relative abundances of species, or species assemblages, and their morphological variations. In the case of the latter, test coiling directions (either right-coiling (dextral) or left-coiling (sinistral)) often reveal useful proxy information about paleotemperatures of the oceans. Other variations include differences in test size, shape and surface structure.

19.10 Paleoclimate Reconstruction from Terrigenous Material

Terrigenous material comes from land or continental areas. It is material picked up and transported by streams, mass wasting, or glaciers which finds its way into ocean waters and sinks to the bottom.

Weathering and erosion processes in different climatic zones on the continental land masses may produce characteristic sedimentary products. When these sediments (inorganic particles) are carried to the oceans (by wind, rivers, or ice) and deposited on the ocean floor, they may contain clues to the climate of their origin or transportation at the time of deposition.

Terrestrial sediment dilutes the relatively constant precipitation of calcium carbonate in warm waters; calcareous ooze shows an inverse relationship with the influx of terrestrial material. Because terrestrial sediment is related to climatic factors, the mixture of calcareous sediments with terrigenous sediment provides a paleoclimatic indicator. Therefore, times of high carbonate abundance indicate low terrestrial influx, i.e., low rates of continental weathering, transportation, and deposition. Conversely, less carbonate deposition may correspond to increased levels of continental weathering, erosion, and deposition which occur when the climate of the source region becomes warmer and wetter. Grain sizes and shapes may also be indicative of environments in which the particles originated or were deposited.

19.11 Terrestrial Sediments

Terrestrial sediments are those that come to rest on the continents or other land areas of the world. Streams (fluvial), lakes (lacustrine), wind (aerial), and ice (glacial) all show deposits on land where they are or have been active. Fluvial deposits occur along streams on the inside of meanders, as sand bars, and as deltas. Lacustrine deposits are characterized by annual alternating layers of light- and dark-colored material (varves); the light material is deposited in the warm summer months and the dark material in the winter months, the couplet marking a year's deposit. Aerial or wind deposits are such things as dunes and loess (pronounced “lurss”). Glacial deposits are found where glaciers have receded or at the terminus or ends of glaciers and are called moraines.

19.12 Periglacial Features

Deposits and other features which occur around glaciers are known as periglacial features. Periglacial features are morphological features which are associated with continuous (permafrost) or discontinuous (diurnal or seasonal freezing) periods of sub-zero Celsius temperatures. Such features on which paleoclimatic inferences can be based include: fossil ice wedges; pingos; polygons; and periglacial involutions formed by multiple years of freezing and thawing. As the soil freezes and thaws over many hundreds of years in regions of permafrost, it is cracked and buckled to create ice wedges, polygons, thermo-karst lakes, and pingos.

Unfortunately, paleoclimate reconstructions based on such phenomena are subject to a fair degree of uncertainty. First, the occurrence of periglacial activity during the past can only indicate an upper limit on paleotemperatures, not a lower one. Second, periglacial features are generally difficult to date accurately; dating of the sediments with which they are associated provides only a maximum age estimate. Also periglacial features are destroyed when the glacier advances and are only found as the glacial ice recedes. But they are at best temporary features of the Earth’s surface. Subsequent to their formation, soil creep and erosion often destroy them.

19.13 Glacial Fluctuations

Glacial ice moves either under the influence of gravity or under its own weight. It recedes when ablation exceeds accumulation (Fig. 14.10) and expands when the opposite is true. When the two, ablation and accumulation, are equal the terminus or end of the glacier remains in place while the glacial ice within the glacier continues to move under the influence of gravity or its own weight. The material carried by the moving glacial ice piles up at the end of the glacier and forms an end moraine. A terminal moraine forms at the terminus or furthermost extent of the glacial ice and represents a period of equilibrium as the glacier begins to recede.

19.14 Lake-Level Fluctuations

The study of lakes is limnology. Climate is a major factor in the study of lakes as well as the lake water composition. Lakes in arid regions tend to be higher in salt content than lakes in humid areas due to the high rate of evaporation in arid regions (e.g., Great Salt Lake, Utah). The condition of a lake at a given time is the result of the interaction of many factors: its watershed, climate, geology, human influence, and characteristics of the lake itself. With constantly expanding databases and increased knowledge, limnologists and hydrologists are able to better understand problems that develop in particular lakes, and further develop comprehensive models that can be used to predict how a lake might change in the future.

Lake levels fluctuate with the seasons of the year and with the amount of sediment carried into them. Lakes are temporary parts of the landscape in a geologic sense because streams flowing in carry sediment that will eventually fill up the lake. Also, if evaporation exceeds the amount of water being fed to the lake it will eventually dry up.

Lake levels fluctuate depending on the amount of water flowing into them and the amount of water flowing from them.

Lakes are by definition dammed structures, either man-made or natural. Dams fail, are overtopped or undercut and water flows from the lake.

Shorelines of ancient lakes are found in various parts of the world and are indicators of past climates. Sediment deposited in these lakes may also provide clues to ancient climates. Unfortunately with time, lake sediments are removed from Earth's surface quite readily and as a result are rare beyond a few thousand years in age. An exception is the lake discussed below.

19.14.1 Russia's Lake El'gygytgyn (Lake E)

During the week of June 17th, 2012, *Science* published a paper concerning first analysis of the longest sediment core ever collected on land in the Arctic that provides dramatic, "astonishing" documentation that intense warm intervals, warmer than scientists thought possible, occurred there over the past 2.8 million years at the beginning of the Pleistocene Epoch. This Russian lake, known colloquially as "Lake E" for rather obvious reasons, was created by a meteor impact around 3.6 million years ago and has been receiving terrigenous sediment almost continuously ever since. The core retrieved from the lake bed measured 318 m at which depth they encountered 3.6 million-year old impact rock.

The lead U. S. scientist, Julie Brigham-Grette of the University of Massachusetts Amherst, is quoted by *Science News* (June 21, 2012) as saying "What we see is astonishing. We had no idea that we'd find this. It's astonishing to see so many intervals when the Arctic was really warm, enough so forests were growing where today we see tundra and permafrost. And the intensity of warming is completely unexpected. The other astounding thing is that we were able to determine that during many times when the West Antarctic ice sheet disappeared, we see a corresponding warm period following very quickly in the Arctic. Arctic warm periods cluster with periods when the Western Antarctic ice sheet is gone."

These extreme inter-glacial warm periods correspond closely with times when parts of Antarctica were ice-free and also warm, suggesting strong inter-hemispheric climate connectivity, between the two Polar Regions.

The team of scientists has been analyzing sediment cores collected in 2009 from under ice-covered Lake El'gygytgyn in the northeast Russian Arctic. "Lake E" was formed 3.6 million years ago when a huge meteorite hit Earth and blasted out an 11-mile (18 km) wide crater. This crater has been collecting layers of sediment ever since. Fortunately it is located in one of the few areas in the Arctic not eroded by continental glaciers, leaving the thick sediment record remarkably undisturbed and continuous. Cores from Lake E reach back in geologic time nearly 30 times farther than Greenland ice cores covering the past 110,000 years.

The June 17th, 2012 paper in *Science* discusses four warm phases in detail; two of the oldest warm interglacials from about 1.1 million years ago and 400,000 years ago, and two of the youngest from 125,000 and about 12,000 years ago.

Pollen-based climate reconstructions (Table 19.1) suggest that summer temperatures and annual precipitation during the exceptional interglacials were about 4–5°C warmer and about 12 in. (300 mm) wetter than in other interglacials. Modeling and sensitivity tests for these warm periods also suggest it is virtually impossible for Greenland's ice sheet to have existed in its present form at those times.

Scientists using a state-of-the-art climate model show that the high temperature and precipitation during the "super interglacials" cannot be explained by Earth's orbital parameters or variations in atmospheric greenhouse gases alone, which geologists typically see driving the glacial/interglacial pattern during ice ages. This suggests that perhaps additional climate feedbacks were at work. The Lake E researchers suspect the trigger for intense interglacials might be in Antarctica. Earlier work in Antarctica by the international ANDRILL (Antarctic Geological Drilling; more information may be obtained at the following website: http://www.andrill.org/node/192) program discovered recurring intervals when the West Antarctic Ice Sheet melted. The Lake E study shows that some of these events match remarkably well with the super interglacials in the Arctic.

Brigham-Grette and colleagues discuss two scenarios for future testing that could explain inter-hemispheric climate coupling. First, reduced glacial ice cover and loss of ice shelves in Antarctica could have limited formation of cold water masses that flow into the north Pacific and well up to the surface, resulting in warmer surface waters, higher temperatures and increased precipitation on nearby land. Alternatively, disintegration of the West Antarctic Ice Sheet likely led to a significant global sea level rise and allowed more warm surface water into the Arctic Ocean through the Bering Strait.

Not only do results shed light on natural variability of the Arctic climate, but this view of the past may be a key to understanding climate in future centuries, the researchers said. "We have a lot more to learn," says Brigham-Grette. "But our results mesh with what glaciologists are seeing today. Seven of the 12 major ice shelves around the Antarctic are melting or are gone. We suspect the tipping point for the gradual de-glaciation of Greenland and the Arctic may be lower than glaciologists once thought."

The international Lake El'gygytgyn Drilling Project was funded by the International Continental Drilling Program (ICDP), the U.S. National Science Foundation's Division of Earth Sciences and Office of Polar Programs, the German Federal Ministry for

Table 19.1 Pollen zones recognized worldwide from the youngest (IX) on top to the oldest (Ia) at the bottom

Pollen Zones Recognized Worldwide					
Zone	Biostratigraphic division	Dates	Dominate plant type	Archeological periods	Geological stage
IX	Sub-Atlantic	500 BC to present	Spread of grasses and pine and beech woodland	Present iron age	Flandrian
VIII	Sub-Boreal	3000–500 BC	Mixed oak forest	Bronze age and iron age	Flandrian
VII	Atlantic	5500–3000	Mixed oak forest	Neolithic and bronze age	Flandrian
V and VI	Boreal	c. 7700–5500 BC	Pine/birch forest and increasing mixed forest	Mesolithic	Flandrian
IV	Pre-Boreal	c. 8300–7700 BC	Birch forest	Late upper paleolithic and early – mid mesolithic	Devensian
III	Younger dryas	c. 8800–8300 BC	Tundra	Late upper paleolithic	Devensian
II	Allerød oscillation	c. 9800–8800 BC	Tundra park tundra and birch forest	Late upper paleolithic	Devensian
Ic	Older dryas	c. 10000–9800 BC	Tundra	Late upper paleolithic	Devensian
Ib	Bølling oscillation	c. 10500–10000 BC	Park tundra	Late upper paleolithic	Devensian
Ia	Oldest dryas	c. 13000–10500 BC	Tundra	Late upper paleolithic	Devensian

Education and Research, Alfred Wegener Institute, GeoForschungsZentrum-Potsdam, the Russian Academy of Sciences Far East Branch, the Russian Foundation for Basic Research and the Austrian Ministry for Science and Research.

19.15 Pollen Analysis

The study of pollen is palynology. Pollen (Fig. 19.6) is plant material that has the consistency of ground up flour. It consists of microgametophytes of vascular seed plants that produce sperm cells. They have a resistant outer shell that protects them and is probably the main reason they are commonly found as fossils. Pollen is often discussed with spores, which are reproductive parts of lower plants, such as club mosses, horsetails, and ferns.

Pollen preserves best if the sedimentary environment lacks oxygen or is acidic, conditions unfavorable for the organisms that decompose pollen. Fossil pollen is an important kind of data for reconstructing past vegetation. Because vegetation is sensitive to climate, fossil pollen is a very important kind of proxy data for reconstructing past climates.

Pollen is widely dispersed by the wind and often occurs as fossils. It is useful for correlation purposes in the fossil record.

Pollen found in sediment cores are good indicators of the types of vegetation living at that particular time in Earth history and it is used to correlate horizons between deep-sea cores. It is possible to obtain high-resolution records of vegetation change with decadal resolution and to document plant community changes over the past few thousand years.

Palynologists also study orbicules, dinoflagellate cysts, acritarchs, chitinozoans, particulate organic matter, kerogen, and scolecodonts. These can all be found online or in textbooks of palynology. Palynology does not include diatoms, foraminiferans or other organisms with siliceous or calcareous exoskeletons.

Reasons why pollen is used in reconstructing past climates are as follows:

- Natural lakes contain abundant fossil pollen which is easily found. A cubic centimeter of lake sediment will typically contain tens or hundreds of thousands of pollen grains;
- Pollen is released to the air and is dispersed great distances and is representative of the vegetation from the region around the site;
- The pollen assemblage will represent a wide variety of plants from the region; and
- Pollen accumulates continuously year after year and can be used to reconstruct climate changes in the region in the past.

Peat deposits also contain abundant pollen and can be used to reconstruct past climatic conditions.

In the years before the First World War (WWI) a Swedish palynologist, Lennart von Post, analyzed pollen in core samples from peat bogs and noticed that different plant species were represented by bands throughout the cores. These bands offered a glimpse of past climates based on the differing species and quantities of the same species.

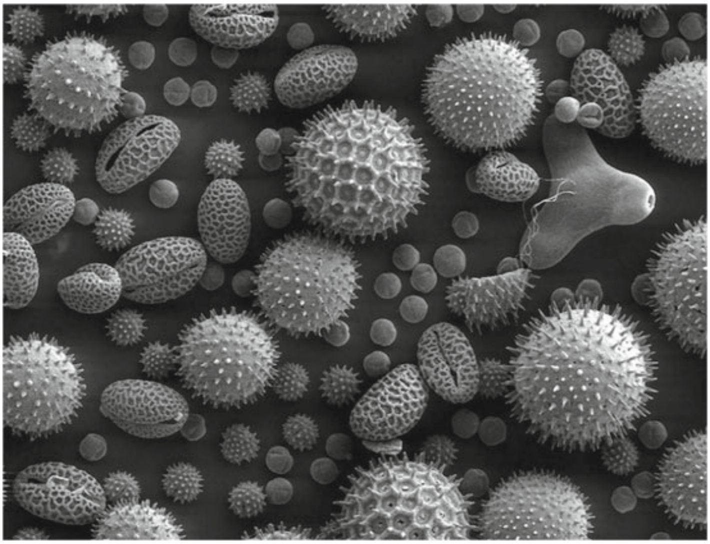


Fig. 19.6 Scanning electron microscope image of pollen grains from a variety of common plants (Magnification ×500, from Dartmouth Electron Microscope Facility, Public Domain)

In 1940, von Post's methods were applied to cores from the British Isles which produced the wider European pollen sequence stratigraphy used today. Von Post's method spread to the Western Hemisphere after WWII. Currently nine zones are recognized, numbered I–IX. They represent climatic and biological zones in the fairly recent geologic past from the present to 13,000 years ago. The table (Table 19.1) below lists the pollen zones with the youngest at the top (IX) to the oldest at the bottom (Ia).

19.16 Sedimentary Rocks

Certain types of sedimentary rocks provide clues as to the climatic conditions under which they formed. For example, limestone (made mainly of the mineral calcite [$CaCO_3$]) is formed only under warm, shallow sea environments where it is forming today. It indicates those conditions in the past.

Coal is a sedimentary rock that forms under oxygen-free conditions in areas that have abundant vegetation. The vegetation and coal itself indicate past climatic conditions.

Paleoclimatic conditions can often be determined by a study of paleogeography which involves identifying ancient geographic positions of shorelines, shallow seas, and delta deposits, for example. Sizes, shapes, and composition of particles making up sedimentary rocks may also indicate the climatic conditions under which a rock has formed.

The weathering processes result in different types of material ending up as sediment and these sediments may be indicators of climate in the geologic record.

The sedimentary rock record may show signs of sea level rise and fall. Features such as “fossilized” sand dunes can be identified. Scientists can get a grasp of long term climate by studying sedimentary rock going back thousands, millions, and billions of years. The division of Earth history into separate periods is largely based on visible changes in sedimentary rock layers that are based on major changes in conditions. Often these include major shifts in climate.

Additional Readings

Bradley, R. S. (1985). *Quaternary paleoclimatology: Methods of paleoclimatic reconstruction*. Boston: Allen & Unwin. ISBN 0-04-551067-9.

Came, R. E., et al. (September 2007). Coupling of surface temperatures and atmospheric CO_2 concentrations during the Palaeozoic era. *Nature, 449*(7159), 198–201. doi:10.1038/nature06085. PMID 17851520.

Crowley, T. J., & North, G. R. (1996). *Paleoclimatology* (Oxford monographs on geology and geophysics. 18). Oxford: Clarendon Press. ISBN 0-19-510533-8.

Drummond, C. N., & Wilkinson, B. H. (2006). Interannual variability in climate data. *Journal of Geology, 114*(3), 325–339. doi:10.1086/500992. Bibcode 2006JG....114..325D.

Gould, S. J. (1989). *Wonderful life, the story of the Burgess Shale*. New York: W.W. Norton. ISBN 0-393-02705-8.

Imbrie, J. (1986, c1979). *Ice ages: Solving the mystery*. Cambridge, MA: Harvard University Press. ISBN 0-674-44075-7.

Ludwig, K -H. (2006). *Eine kurze Geschichte des Klimas. Von der Entstehung der Erde bis heute* [A short history of climate, From the evolution of earth till today] Herbst 2006, ISBN 3-406-54746.

Margulis, L., & Sagan, D. (1986). *Origins of sex: Three billion years of genetic recombination* (The bio-origins series). New Haven: Yale University Press. ISBN 0-300-03340-0.

Melles, M., et al. (2012). 2.8 million years of arctic climate change from lake El’gygytgyn, NE Russia. *Science, 337*, 315–320. doi:10.1126/science.1222135.

Ruddimann, W. F. (2008). *Earth’s climate: Past and future* (2nd ed.). New York: W. H. Freeman and Company. ISBN 10: 0-7167-8490-4.

Sahney, S., & Benton, M. J. (2008). Recovery from the most profound mass extinction of all time. *Proceedings of the Royal Society: Biological, 275*(1636), 759–765. doi:10.1098/rspb.2007.1370. PMC 2596898. PMID 18198148.

University of Massachusetts at Amherst. (2012, June 21). Arctic climate more vulnerable than thought, maybe linked to Antarctic ice-sheet behavior. *ScienceDaily*. Retrieved June 22, 2012, from http://www.sciencedaily.com/releases/2012/06/120621151506.htm

Windley, B. (1984). *The evolving continents*. New York: Wiley Press.

Chapter 20
Climates of the Recent Past

Abstract Scientists know the most about the most recent climate changes and events. The more time that passes, the less we know about Earth history. We know more about climate changes in the Holocene than we do in the Pliocene; more about the Pleistocene than the Paleocene. We know more about the Wisconsin glaciation than we know about the Kansan, and more about the Kansan that the Nebraskan. The Tibetan Plateau began to be uplifted with the collision of the Indian Plate with the Eurasian plate about 58 million years ago and began to affect the climate of Southeast Asia. The high standing plateau and the Himalayan Mountains caused the severe monsoons that affect the area today.

Keywords Holocene • Anthropocene • Glacial • Interglacial • Milankovitch • Sangamon • Eemian • 100,000 • Paleolithic • Mesolithic • Neolithic • Boreal • Atlantic • Bronze • Age • *Dryas* • *Octopetalia* • Iron • Aftonian • Wisconsin • Ice • Stadial • Interstadial • Nebraskan • Kansan • Bølling/Allerød • Wurm • LIA • MWP • Forcings • Thermal • Maximum • HTM • Tibetan • Plateau

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_20,

Things to Know	
Pleistocene	Yarmouth interglacial
Obliquity	IETM
Paleocene-Eocene thermal maximum	Günz glaciation
41,000-year cycle	Weichselian
Laurentide	PETM
Start of Antarctic glaciation	30% of Earth's surface
Carbon-13	Würm glaciation
Clathrate gun hypothesis	Isthmus of Panama
Ocean's biological pump	Shelf-nutrient hypothesis
Eemian	$BaSO_4$
Cordilleran	Possible cause of arctic Freezing
Riss	Iron fertilization hypothesis
Wisconsin glaciation	3,900 m
MIS1	2.5 million years
Mid-Miocene climatic optimum	ACEX

20.1 Introduction

Climates of the past are known mainly by the methods of paleoclimatology, as we saw in the previous chapter (Chap. 19). To introduce past climates and to treat them in any order, it is necessary to know and understand the geologic time scale as shown in Appendix I. The evidence for past climates and scientists' confidence in the evidence decrease the further one goes back in geologic time, e.g., from Holocene to Pleistocene, or from Silurian to Cambrian. Scientists know the most about the most recent and less and less as we go back in time.

20.2 Holocene Climates

The Holocene Epoch began about 11,700 years ago, about 10,000 BC. Many scientists consider the Holocene to continue to the present day, but others have proposed the Anthropocene to reflect mankind's impact on Earth's climate system. The Anthropocene would constitute a new geologic Epoch, beginning about 10,000 years Before Present (BP) (about 8,000 years BC) The Anthropocene begins when mankind first starts to affect the climate by beginning to use agriculture to feed himself; and this began about 10,000 years BP, or 8,000 BC.

The last maximum extent of the continental glacial ice occurred at about 20,000 to 18,000 years ago (ka; kiloannum), just prior to the beginning of the Holocene. By about 14 ka, most of the ice had retreated and by 10 ka most of it had disappeared.

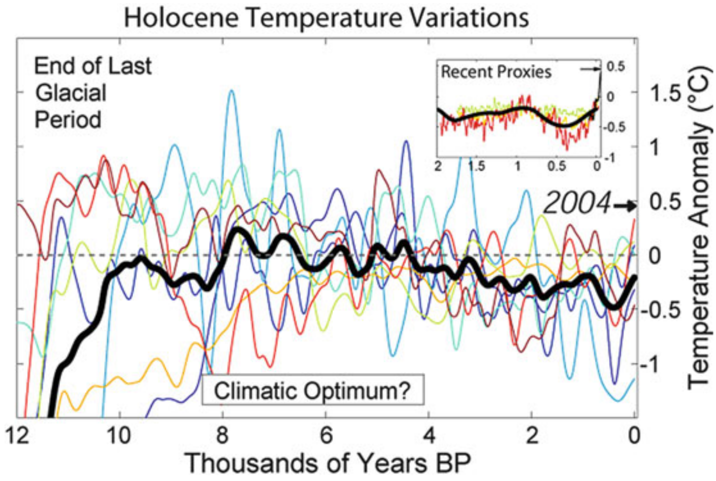


Fig. 20.1 Temperature variations during the Holocene from the end of the last glacial period to 2004 (indicated by *arrow*) Eight data sources were used in the construction of this figure. The following data sources were used in the figure – 1. (*dark blue*) Sediment core ODP 658, interpreted sea surface temperature, Eastern Tropical Atlantic: 2. (*blue*) Vostok ice core, interpreted paleotemperature, Central Antarctica: 3. (*light blue*) GISP2 ice core, interpreted paleotemperature, Greenland: 4. (*green*) Kilimanjaro ice core, $\delta^{18}O$, Eastern Central Africa: 5. (*yellow*) Sediment core PL07-39PC, interpreted sea surface temperature, North Atlantic: 6. (*orange*) Pollen distributions, interpreted temperature, Europe: 7. (*red*) EPICA ice core, δDeuterium, Central Antarctica: 8. (*dark red*) Composite sediment cores, interpreted sea surface temperature, Western Tropical Pacific (From Richard Rohde, Global Warming Art, Wikipedia)

By 6 ka, the Earth had reached a thermal maximum (Holocene Thermal Maximum – HTM). The thermal maximum consisted of temperatures of up to 4°C warmer at the North Pole than at present. At lower latitudes there was very little warming. The Southern Hemisphere experienced cooling and the global average temperature during the HTM was cooler than the present.

The illustration above (Fig. 20.1) shows the temperature trends beginning about 11,700 years ago with the last glacial episode showing what has been called the climatic optimum, or the Mid-Holocene Thermal Maximum (MHTM). The insert shows the temperature record for the last 2,000 years based on proxies, with the 2004 date using instruments. Of course, the warming has continued since 2004.

The main figure in the plots above (Fig. 20.1) shows eight records of local temperature variability on multi-centennial scales throughout the course of the Holocene, and an average of these (thick dark line). The data graphed are for the period from 10000 BC to 2000 CE, which is from 12000 BP to the present time. The records are plotted with respect to the mid twentieth century average temperature, and the global average temperature in 2004 is indicated. The inset plot compares the most recent two millennia of the average to other recent reconstructions.

At the far right of this plot it is possible to observe the emergence of climate from the last glacial period of the current ice age. During the Holocene itself, there is general scientific agreement that temperatures on the average have been quite stable compared to fluctuations during the preceding glacial period. The above average curve supports this belief. However, there is a slightly warmer period in the middle which might be identified with the proposed Holocene climatic optimum. The magnitude and nature of this warm event is disputed, and it may have been largely limited to high northern latitudes. The illustration is by Richard Rohde and is part of "Global Warming Art" available in Wikipedia.

The Holocene Epoch is often divided into the following subdivisions (oldest to youngest):

- Pre-boreal (10.3 ka–9 ka), followed the end of the Younger Dryas cooling;
- Boreal (9 ka–7.5 ka);
- Atlantic (7.5 ka–5 ka);
- Sub-boreal (5 ka–2.5 ka);
- Sub-Atlantic (2.5 ka–present)

The Holocene may also be divided into periods of human technological development (oldest to youngest):

- Paleolithic (2.6 Ma–10,000 BP)
- Mesolithic (?10,000–9,500 BP)
- Neolithic (?9,500–3,500 BP)

These subdivisions represent what is known as the Stone Age. After the Neolithic, the Bronze Age began, which is a transitional period between the Stone Age and the Iron Age.

- Bronze Age (3,500–300 BC)
- Iron Age (300 BC–500 AD)
- Middle Ages (500 AD–1346 AD)

All of the above subdivisions of the Holocene overlap and the dates are not to be taken literally. Some consider the Middle Ages to have begun around 395 AD. Some consider the end of the Middle Ages to be as late as 1516 with the death of King Ferdinand of Spain, who financed, in part, the voyages of Christopher Columbus.

20.3 Younger Dryas Cooling

The Younger Dryas cooling was a geologically brief period of cold temperatures between about 12.8 and 11.5 ka BP. It is named after an alpine-tundra wildflower, *Dryas octopetalia*. This cooling event is also referred to as a stadial, which follows an interstadial or warm period. The interstadial or warm period preceding the Younger Dryas was the Bølling/Allerød interstadial (Fig. 20.2).

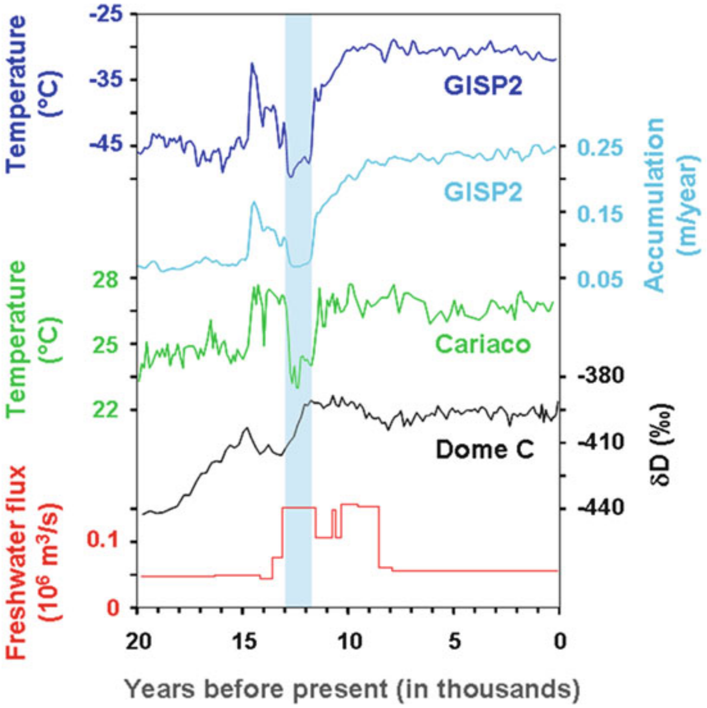


Fig. 20.2 Climate changes associated with the Younger Dryas, highlighted here by the *light blue bar*, include (from *top* to *bottom*): cooling and decreased snow accumulation in Greenland, cooling in the tropical Cariaco Basin, and warming in Antarctica. Also shown is the flux of meltwater from the Laurentide Ice Sheet down the St. Lawrence River (Sources: Alley (2000), Lea et al. (2003), EPICA (2004), Licciardi et al. (1999))

The end of the Younger Dryas, about 11,500 years ago, was particularly abrupt. In Greenland, temperatures rose 10°C (18°F) in a decade.

20.4 Mid-Holocene Thermal Maximum

The Mid-Holocene Thermal Maximum (MHTM) occurred between 9,000 and 5,000 years before the present (BP). Temperatures near the North Pole were as much as 4°C warmer than today's temperatures (June 2012). The MHTM may have been restricted to the Northern Hemisphere although the Great Barrier Reef's ocean surface temperature about 5,350 years BP was about 1°C warmer than at present.

20.5 Late Holocene Neoglaciation

The Late Holocene Neoglaciation was a period of cooling after the retreat of the Wisconsin glaciation in the Northern Hemisphere. It followed the thermal maximum mentioned above. Neoglaciation saw the western mountain glaciers of North America, many of which had receded completely during the MHTM, begin to expand again.

20.6 Little Ice Age

The Little Ice Age (LIA) was a cooling period that occurred just after the Medieval Warm Period. It was a period extending from the sixteenth to the nineteenth centuries (1500s–1800s). There is evidence of glacier expansion during this period from Alaska, New Zealand, and Patagonia. Some scientists think that this cooling was only regional, not global. Current evidence supports the regional-only extent of the LIA. There are a few scientists who think that Earth is now coming out of the LIA, but there is overwhelming evidence that suggests the current warming is due to greenhouse gases and is not natural.

20.7 Medieval Warm Period

The Medieval Warm Period (MWP) was a period of warmth from 950 to 1150 in the North Atlantic, China, New Zealand, and other countries. It was followed by the Little Ice Age. Some scientists think that the warmest temperatures in the last 2,000 years before the twentieth century were during the MWP. Evidence suggests that the Medieval Warm Period was in fact warmer than today in many parts of the globe such as in the North Atlantic. This warming allowed Vikings to travel further north than had been previously possible because of reductions in sea ice and land ice in the Arctic. However, evidence also suggests that some places were very much cooler than the present including the tropical pacific. When the warm places are averaged out with the cool places, it becomes clear that the overall warmth was likely similar to early- to mid-twentieth century warming. Since that early century warming, temperatures have risen well beyond those achieved during the Medieval Warm Period across most of the globe. This has been confirmed by the U. S. National Academy of Sciences Report on Climate Reconstructions. Further evidence suggests that even in the Northern Hemisphere where the Medieval Warm Period was the most visible, temperatures are now beyond those experienced during medieval times.

The Medieval Warm Period has known causes which explain both the scale of the warmth and the pattern. It has now become clear to scientists that the Medieval Warm Period occurred during a time which had higher than average solar radiation and less volcanic activity, both resulting in warming. New evidence is also suggesting

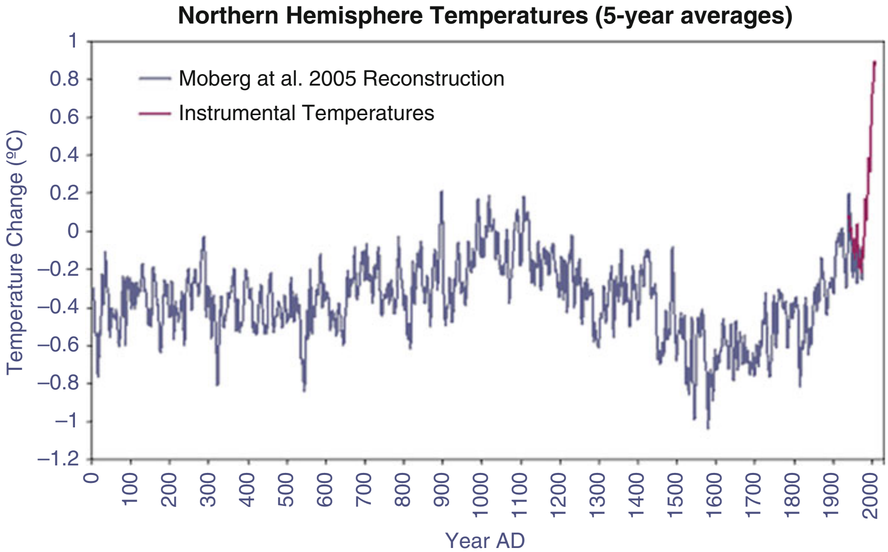


Fig. 20.3 Reconstructed temperature for the last 2,000 years of Earth history showing the Medieval Warm Period and the Little Ice Age. Also shown is the instrumental record in red (After Moberg 2005)

that changes in ocean circulation patterns played a very important role in bringing warmer seawater into the North Atlantic. This explains much of the extraordinary warmth in that region. These causes of warming contrast significantly with today's warming which cannot be caused by the same mechanisms.

The illustration above (Fig. 20.3) shows Northern Hemisphere temperatures (i.e., 5-year averages) over the last 2,000 years with recent temperatures measured by instruments shown in red.

20.8 Holocene Climate Forcing Mechanisms

Holocene forcing mechanisms are solar irradiance, volcanism, and internal ocean dynamics. These forcing mechanisms controlled climate until greenhouse gases began to increase due to the burning of fossil fuels.

Variations in the amount of solar irradiance cause the Earth to warm and cool as a direct result. It is thought that increased solar activity was the cause of the Medieval Warm Period and that decreased solar activity caused the Little Ice Age. Other factors may have been involved such as Milankovitch cycles, oceanic and atmospheric circulation, and the increase or decrease in volcanic activity, but the primary forcing was solar.

20.9 Coupled Internally-Externally Driven Climate Change

Changes in insolation (externally-driven climate change) at high latitudes of the Northern Hemisphere is thought to have begun the cyclical nature of the Pleistocene glacial-interglacial episodes by Milankovitch-type orbital variations which regulated the complex non-linear internal variations within the climate system. Such internal variations include the advance and retreat of continental and mountain glaciers, changes in oceanic circulation, and CO_2 forcing.

It is most likely that a Milankovitch trigger began the first glacial advance when the CO_2 level was about 180 ppm; then a rise in CO_2 caused an interglacial. The rise in CO_2 might have been caused by the drop in sea level resulting in the exposure of methane clathrates. The 100,000 year interval between glacial advances is thought to have been caused by the Milankovitch cycle, the Earth's eccentricity with a periodicity of nearly a 100,000 years. Although this is a weak signal, perhaps eccentricity in combination with a low level of CO_2 in the atmosphere was enough to trigger the first glacial advance. Throughout the glacial advances and retreats, there is a strong correlation between carbon dioxide levels and temperature but there had to be an initial process to start the periodicity.

The main problem with the Malinkovitch scenario is that it would affect Northern Hemisphere insulation and not the Southern Hemisphere. Climate change scientists know that the Southern Hemisphere also experienced glaciation during the last ice age (Pleistocene) but this was perhaps due to global cooling as opposed to cooling of just the Northern Hemisphere.

Climate has varied rapidly, as has been seen, over the course of Earth's history. The Earth has gone through the ice ages of the Pleistocene, the intervening interglacial periods, the cyclical nature of glacials and interglacials, possibly a "snowball Earth" or more than one, and variations between hot ("hothouse") and cold ("icehouse") periods for the past few thousands of years (Fig. 20.4). It seems that climate is always changing but over different time frames. It was a billion years or so, or millions of years, or thousands of years between glacial episodes. The longest interglacial episode of the Cenozoic was the last interglacial (before the current one) which began about 131,000 (131 ka) years ago and ended about 114,000 (114 ka) years ago with the advance of the Wisconsin glacier in North America and the Würm glacier in Europe. This glacial period lasted for about 17,000 years. The interglacial is known in Europe and Greenland as the Eemian and in North America as the Sangamon or Sangamonian.

20.10 Contemporary Climate Change

Contemporary climate change is what is happening now and what has been happening in the most recent past to bring Earth's climate to its present state and the present global climate is warming.

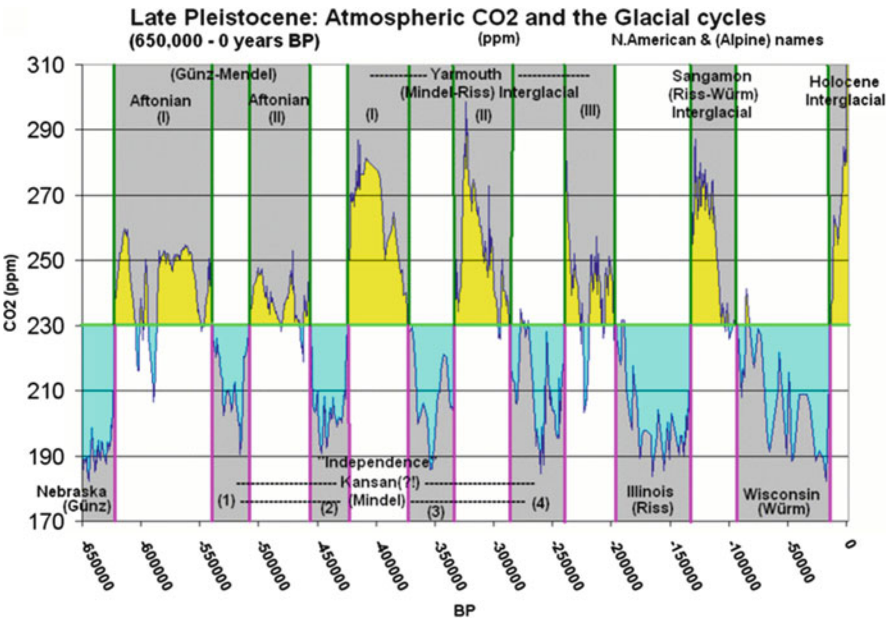


Fig. 20.4 Pleistocene glaciations and interglacials during the past 650,000 years showing the variations in CO_2 in parts per million (ppm) (Public Domain)

March 2012 was notable for the extraordinary early spring heat wave that affected the eastern two thirds of the U.S. and southern and eastern portions of Canada. It was one of the most anomalous temperature events on record for anywhere in the world. March heat records were set in Scotland, Iceland, Norway, the Summit station on the peak of Greenland's ice cap, and Perth, Australia. A massive tornado outbreak in the U.S. killed 39 people. Cyclone Irina resulted in 72 deaths in Madagascar and severe storms with flooding rains occurred in Hawaii and eastern Australia.

The heat wave and inordinately warm weather in the U.S. has been attributed to large meanders of the Jet Stream bringing warmer air further north over the eastern U.S. Of course, all modern weather is the result of global warming of the planet. No single weather event can be directly attributed to global warming but all of the current climate events are the result of a new average global temperature which is steadily rising.

The 'summer in March' across the eastern two thirds of the U.S. resulted in a nationwide average temperature of 51.1°F, some +8.6°F above the normal March average of 42.5°F, and thus the second most anomalously warm month in U.S. history (only January 2006 was even more above the average). A large section of the upper Midwest experienced temperatures more than 15°F above normal.

Figures 20.5 and 20.6 show temperature highs recorded compared to lows (Fig. 20.5) and extreme climate events (tornadoes, hurricanes, deadly heat waves, devastating floods, etc. (Fig. 20.6)).

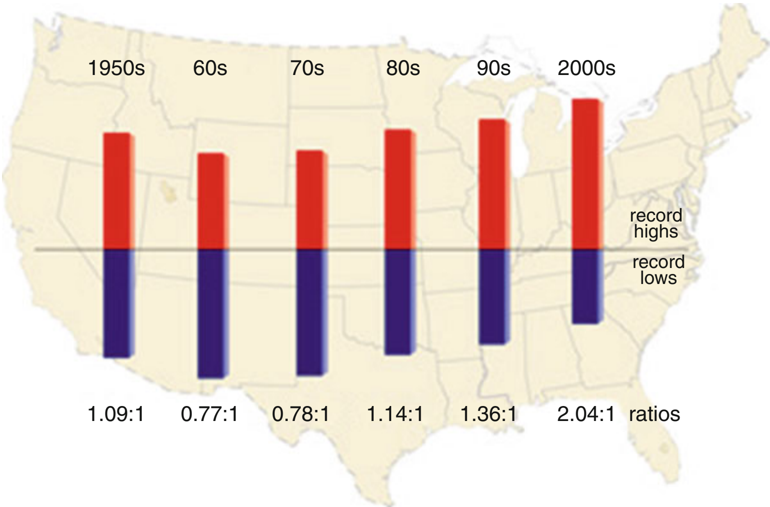


Fig. 20.5 Record highs outpace record lows 2:1. The ratio of record daily high temperatures to record daily lows observed at about 1,800 weather stations in the 48 contiguous United States from January 1950 through September 2009 (From Meehl et al. 2009)

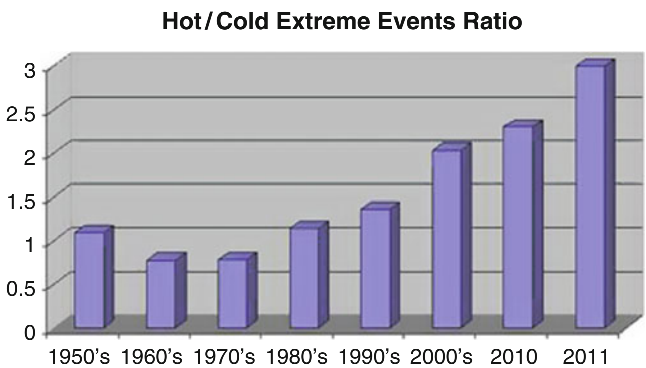


Fig. 20.6 Extreme climate events from the 1950s through August 2011. A report from Climate Communication Science and Outreach, a project of the Aspen Global Change Institute (September 2011)

There is awareness of a new normal in contemporary weather patterns.

The past decade (2002–2012) has been one of unprecedented weather extremes. Scientists have noted that the high incidence of weather extremes is not accidental. From the many single events that have occurred over the past decade, a pattern has emerged. At least for extreme rainfall and heat waves the link with human-caused global warming is clear. Less clear is the link between warming and storms, despite the observed increase in the intensity of hurricanes. However, with a higher rate of evaporation and more water vapor in the atmosphere due to global warming there is a high probability that a link will be found.

In 2011 alone the U.S. was hit by 14 extreme weather events which caused damages exceeding one billion dollars each – in several states the months of January to October were the wettest ever recorded. Japan also registered record rainfalls, while the Yangtze River basin in China suffered a record drought. In 2010, Western Russia experienced the hottest summer in centuries, while in Pakistan and Australia record-breaking amounts of rain fell. The year 2003 saw Europe's hottest summer in at least half a millennium. And in 2002, the weather station of Zinnwald-Georgenfeld measured more rain in 1 day than ever before recorded anywhere in Germany – what followed was the worst flooding of the Elbe River for centuries.

Scientists base their analysis on three scientific pillars: (1) basic physics, (2) statistical analysis and (3) computer simulations. Elementary physical principles already suggest that a warming of the atmosphere leads to more extremes. For example, warm air can hold more moisture than colder air. Secondly, clear statistical trends can be found in temperature and precipitation data. And thirdly, detailed computer simulations also confirm the relation between warming and records in both temperature and precipitation.

With warmer ocean temperatures and a higher rate of evaporation, tropical storms, called typhoons or hurricanes depending on the region, should increase in intensity and possibly in number. In the past decade, several record-breaking storms occurred, for example hurricane Wilma in 2005. Hurricane Wilma was the most intense tropical cyclone ever recorded in the Atlantic basin. But the dependencies are complex and not yet fully understood. The observed strong increase in the intensity of tropical storms in the North Atlantic between 1980 and 2005, for example, could be caused not just by surface warming but by a cooling of the upper atmosphere. Furthermore, there are questions about the precision and reliability of historical storm data.

Overall, cold extremes decrease with global warming. But this does not compensate for the increase in heat extremes. There are many more heat records broken than cold records (Fig. 20.5). Some scientists are predicting that soon the ratio of warm to cold records will reach 20 to one.

Climate scientists have long predicted that global warming would result in a greater number of record highs than record lows. One such "high temperature episode" was the monster summer heat wave centered near Moscow, Russia in 2010, where temperatures soared well above their normal summertime maximum and were so record-shattering they may have been the warmest in almost 1,000 years.

A statistical model has been developed and using the model scientists have found that record-breaking extremes depend on the ratio of trend (warming or cooling) to the year-to-year variability in the record of observations. They have tested this model by analyzing global temperatures and have found that warming increased the odds of record-breaking. When applied to the July 2010 temperatures in Moscow, they

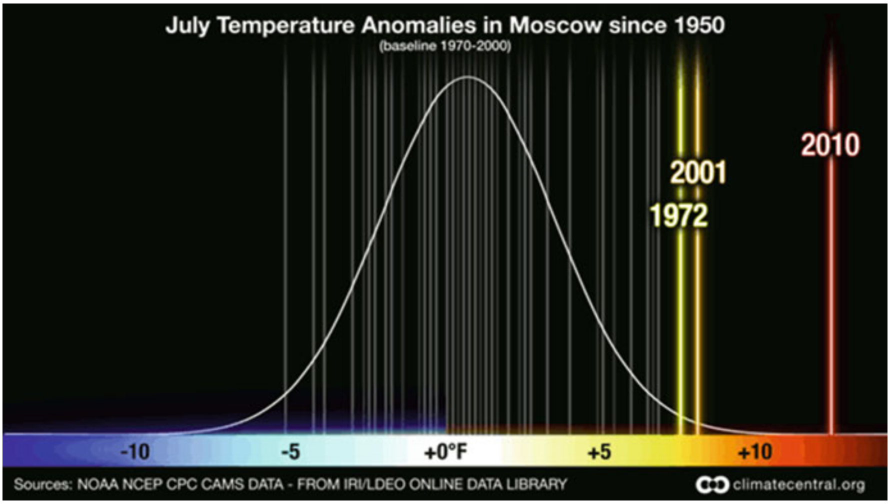


Fig. 20.7 Probability of July average temperature anomalies in Moscow, Russia since 1950. This image shows that the average temperature in Moscow for July 2010 was significantly hotter than in any year since 1950 (Credit: Claudia Tebaldi and Remik Ziemlinski. From ClimateCentral.org)

estimated a 80% probability that the heat record would not have occurred without climate warming. Figure 20.7 above shows the normal curve for temperatures in July from a baseline 1970–2000 and the anomalies for 1972, 2001, and 2010.

Earlier statistical work on record-breaking events has shown that for any time series that is stationary (i.e., no trend), the probability of record-breaking falls with each subsequent observation. This is known as the $1/n$ rule, where n equals the previous number of data in the series. For example, the first observation has a 1-in-1 chance of being the record extreme (100%), the second has a 1-in-2 chance (50%), the third a 1-in-3 chance (33%), and so on.

The illustration (Fig. 20.8) shows temperature fluctuations in the deep ocean from (a) 65.5 million years, (b) 5.33 million years, and (c) 0.5 million years. Beginning around 58 million years ago, the Indian plate began to collide with the Eurasian plate forming the Himalayan Mountains and the Tibetan Plateau. This event began a long interval that continues today of uplift of land and exposure of new rocks to erosion which had a major impact on climate regimes worldwide, but especially in southern Asia and India. The plateau is probably the largest and highest area ever to exist in Earth history, with an average elevation exceeding 5,000 m (16,400′) and it has a direct causal relationship with the monsoons of Southeast Asia.

Monsoons are periods of heavy rainfall that result from different rates of heating between the ocean and land areas due to different heat capacities of land and sea. In summer, land heats more rapidly than ocean water and warms the overlying atmosphere. The warm air over land draws more moisture from the Indian Ocean to the south and the Himalayan Mountains at the southern edge of the Tibetan Plateau cause

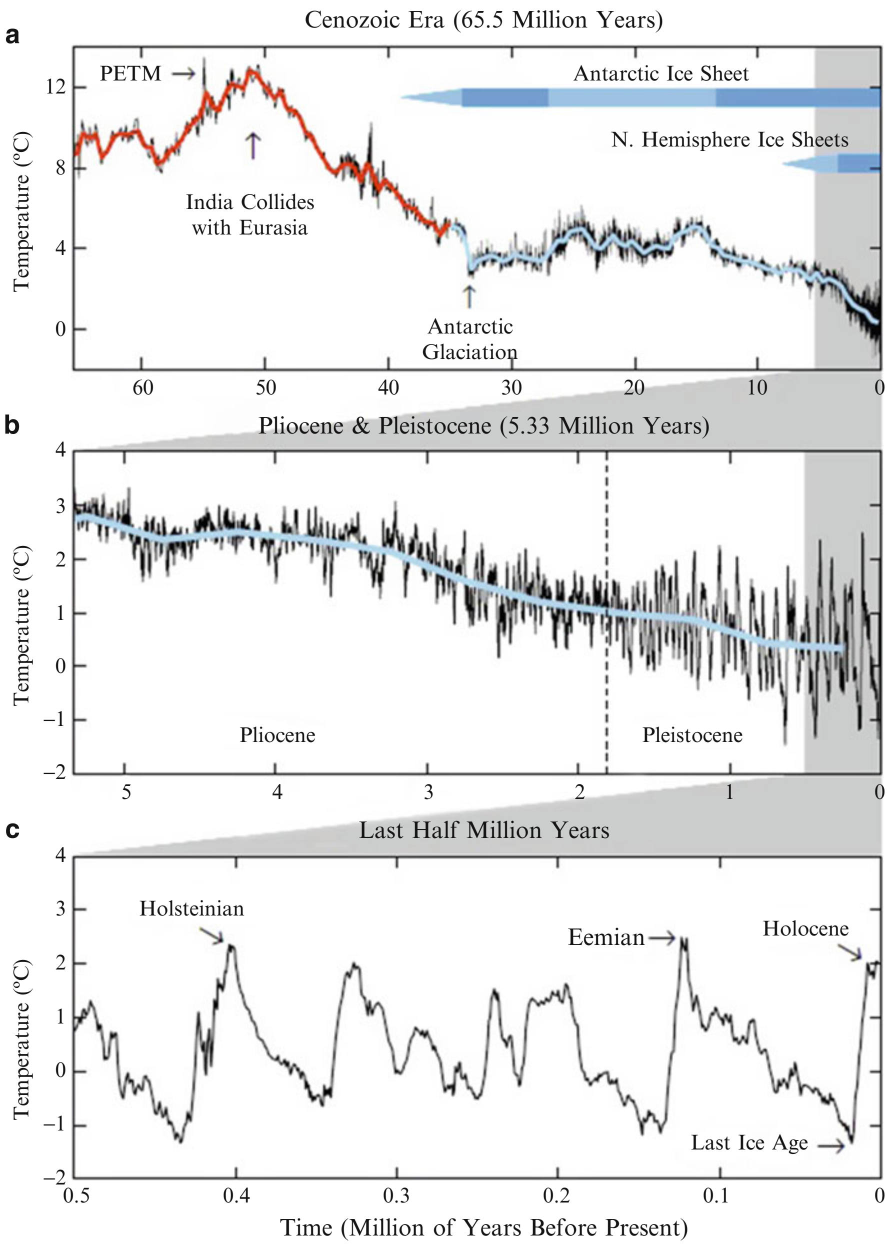


Fig. 20.8 (**a**) Estimated Cenozoic global deep ocean temperature. Pliocene/Pleistocene is expanded in (**b**) and the last half million years in (**c**). High frequency variations (*black*) are 5-point running means of original data (Zachos et al. 2001); red and blue curves have 500 ka resolution. PETM is the Paleocene-Eocene Thermal Maximum. *Blue bars* indicate ice sheet presence, with *dark blue* for ice sheets near full size. Holsteinian and Eemian are known in paleoclimate literature as Marine Isotope Stages 11 and 5e (From Hansen and Sato 2011) (Used with permission)

the warm moist air to rise, cooling the air and causing it to drop its moisture. The steep slopes of the Himalayas get strong summer monsoonal rains. These ascending moisture-laden clouds release heat causing even stronger monsoonal conditions.

The severe monsoons of Southeast Asia are thought to have been caused by uplift of the Tibetan Plateau beginning around 58 million years ago.

Additional Readings

Barnett, T. P., et al. (2008). Human-induced changes in the hydrology of the Western United States. *Science, 319*, 1080–1083. doi:10.1126/science.1152538.

Cook, B. I., et al. (2011). Irrigation induced surface cooling in the context of modern and increased greenhouse gas forcing. *Climate Dynamics, 37*, 1587–1600. doi:10.1007/s00382-010-0932-x.

Hansen, J., et al. (1988). Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. *Journal of Geophysical Research, 93*, 9341–9364. doi:10.1029/JD093iD08p09341.

Hansen, J., et al. (2010). Global surface temperature change. *Reviews of Geophysics, 48*, RG4004. doi:10.1029/2010RG000345.

Held, I. M., & Soden, B. J. (2006). Robust responses of the hydrologic cycle to global warming. *Journal of Climate, 19*, 5686–5699.

Hoerling, M. (2012) On the Increased Frequency of Mediterranean Drought. *Journal of Climate, 25*, 2146–2161.

Levi, B. G. (2008). Trends in the hydrology of the western U.S. bear the imprint of manmade climate change. *Physics Today, 61*(4), 16.

Meehl, G. A., et al. (2009). Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods. *Nature Climate Change, 1*, 360–364.

Nigam, S., et al. (2011). Key role of the Atlantic Multidecadal Oscillation in 20th century drought and wet periods over the Great Plains. *Geophysical Research Letters, 38*, L16713. doi:10.1029/2011GL048650.

Palmer, M. D., et al. (2011). Importance of the deep ocean for estimating decadal changes in Earth's radiation balance. *Geophysical Research Letters, 38*, L13707, doi:10.1029/2011GL047835.

Rahmstorf, S., & Coumou, D. (2011). *Increase of extreme events in a warming world*. www.pnas.org/cgi/doi/10.1073/pnas.1101766108.

Ruddiman, W. F. (2008). *Earth's climate: Past and future* (2nd ed.). New York: W.H. Freeman and Company.

Chapter 21
Pleistocene Glaciations

Abstract The Pleistocene glaciations are unique in geologic history as far as is known at present. The periodicity appears to be the result of the interaction of Milankovitch cycles and carbon dioxide. The 100,000 year cycles appear to have initiated the major glacial advances and carbon dioxide releases, perhaps as methane, appear to have resulted in interglacial episodes. As glaciers advanced, ocean and atmospheric currents were affected and carbon dioxide levels were lowered. As glaciers retreated, ocean and atmospheric currents returned to their previous paths and carbon dioxide levels increased. In order to place the periodicity of the Pleistocene in the proper time perspective, climate conditions leading up to the Pleistocene are outlined in this chapter.

Keywords Pleistocene • Glaciers • Milankovitch • Carbon-13 • PETM • Obliquity • Oscillation • Eccentricity • Yarmouth • Sangamonian • Laurentide • Cordilleran • IETM • Wisconsin • Clathrate • Würm • Kansan • Illinoian • Riss • Weichselian • Eemian • MI5

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_21,

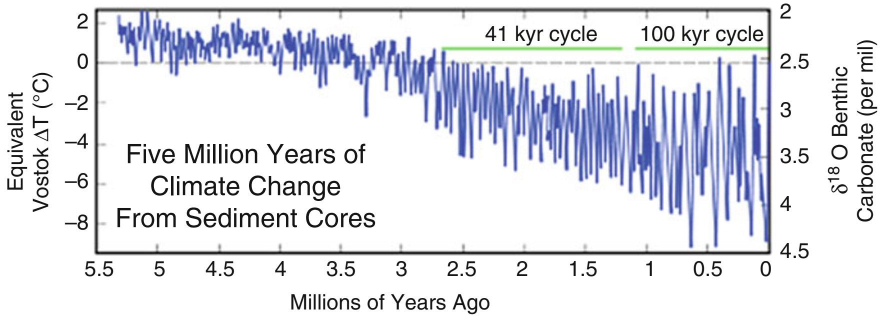


Fig. 21.1 Temperatures based on $\delta^{18}O$ during the last 5.5 million years (From Wikipedia, GNU Free Documentation License)

Things to Know	
Pleistocene	Yarmouth Interglacial
Obliquity	IETM
Paleocene-Eocene Thermal Maximum	Günz Glaciation
41,000-Year Cycle	Weichselian
Laurentide	PETM
Start of Antarctic Glaciation	30% of Earth's Surface
Carbon-13	Würm Glaciation
Clathrate Gun Hypothesis	Isthmus of Panama
Ocean's Biological Pump	Shelf-Nutrient Hypothesis
Eemian	$BaSO_4$
Cordilleran	Possible Cause of Arctic Freezing
Riss	Iron Fertilization Hypothesis
Wisconsin Glaciation	3,900 m
MIS1	2.5 million years
Mid-Miocene Climatic Optimum	ACEX

The Pleistocene geological record provides evidence of at least 20 cycles of advancing and retreating continental glaciers (see Fig. 21.1). Much of this glaciation occurred at high latitudes and high altitudes, especially in the Northern Hemisphere.

Glaciers covered up to 30% of the Earth's surface which was glaciated periodically during the Pleistocene. Large portions of Europe, North America (including Greenland), South America, all of Antarctica, and small sections of Asia were entirely covered by ice. In North America during the peak of the Wisconsin Glaciation approximately 20,000–18,000 years ago, there were two massive yet independent ice sheets. Both the eastern Laurentide and the western Cordilleran ice sheets were over 3,900 m (2.4 miles) thick. In Europe, ice covered Scandinavia, extended south and east across Germany and western Russia, and southwest to the British Isles. Another ice sheet covered most of Siberia. In South America, Patagonia and the southern Andes mountains were beneath part of the Antarctic ice sheet.

Because so much water was taken up as ice, global sea level dropped approximately 140 m (448 ft), exposing a great deal of the present-day continental shelf.

The causes of the Pleistocene cycle of glacial and interglacial episodes are still being debated. It appears that continental positions, oceanic circulation, solar-energy fluctuations, and Earth's orbital cycles combined to generate these glacial conditions, so perhaps it is inappropriate to pinpoint any single cause. However, a trigger for the first glacial episode was probably an orbital one and the apparent 100,000-year periodicity of the major advances strongly suggests an astronomical cause. However, the 100,000 year cycle, as we've seen, is the weakest of the astronomical cycles and many scientists think that it must have been a combination of factors that initiated the glaciation (Nebraskan in North America) about 680,000 years ago.

There are other periodicities found in the ice core records from both Antarctica and Greenland.

Some climate change scientists have calculated that changes in the concentration of greenhouse gases were a partial reason for large (5–7°C) global temperature swings between glacial advances and interglacial periods. This is the reason given for the rather abrupt changes between glacial and interglacial episodes. In all cases during the glacial-interglacial episodes, there was rapid warming and relatively slow cooling.

21.1 Glacials and Interglacials

Continental ice sheets expanded southward from Canada into the Eastern and Central United States ten or more (possibly as many as 50) times during the past 680,000 years (the latter part of the Pleistocene that began 2.588 million years ago). The area covered by ice varied from one glaciation to another. The glaciations were geologic events, and the events were recorded by deposits left behind by the glaciers. However, the subsequent glacial advance obliterated most evidence from the previous glacial advance and retreat. So the best evidence left is from the last glacial advance and retreat (the Wisconsin in North America, the Würm glaciation in the Alps, Devensian and Midlandian glaciation in Britain and Ireland, and the Weichselian glaciation in Scandinavia and the continent of Europe).

Table 21.1 gives the names of glacial events, the glacial index (from youngest at the top to oldest at the bottom), whether the event is a glacial or an interglacial, the period in thousands of years ago, the Marine Isotope Stage (MIS), and the Epoch.

The time interval between 35,000 and 11,150 calendar years ago is referred to informally as "late Wisconsin time" in North America. Late Wisconsin glaciation occurred during late Wisconsin time. During late Wisconsin glaciation, the ice sheet margin reached its maximum southern extent in many parts of the United States between 24,700 and 18,000 years ago, and it had retreated into Canada by about 11,400 years ago. The ice sheet margin fluctuated (retreated and re-advanced) during southward advances and northward retreats, and the extents of re-advances and retreats varied in different regions.

Table 21.1 Glacial events during the Pleistocene and Holocene Epochs

	Interglacial						
Glacial Index	Alps	N. American	N. European	Great Britain		MIS	Epoch
				Flandrian	Interglacial	1	Holocene
1st	Würm	Wisconsin	Weichselian or Vistulian	Devensian	Glacial period	2–4 & 5a–d	Pleistocene
	Riss-Würm	Sangamonian	Eemian	Ipswichian	Interglacial	5e (7, 9?)	
2nd	Riss	Illinoian	Saalian	Wolstonianor Gipping	Glacial period	6	
	Mindel-Riss	Yarmouth	Holstein	Hoxnian		200–300/380	
3rd–5th	Mindel	Kansan	Elsterian	Anglian	Glacial period	12	
	Günz-Mindel	Aftonian		Cromerian	Interglacial	13–15	
7th	Günz	Nebraskan	Menapian	Beestonian	Glacial period	16	

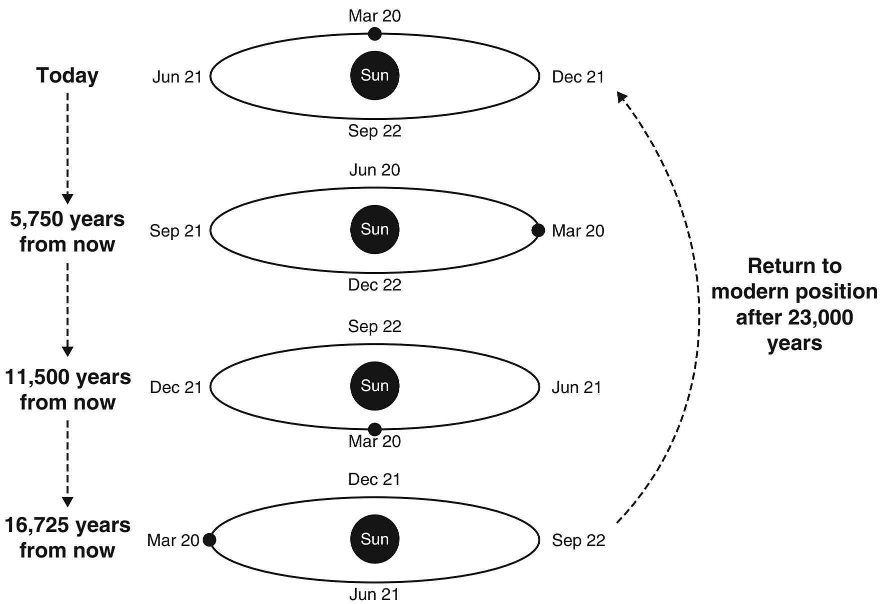


Fig. 21.2 Precession of the equinoxes caused by the slow turning of Earth's elliptical orbit and its wobble on its axis. Both the solstices and equinoxes move slowly around the orbital plane in cycles of 23,000 years (Credit: John Cook, based on Imbrie and Imbrie, Ice Ages: Solving the Mystery, 1979)

21.2 Causes of Glacial Advances and Retreats

The Pleistocene glaciations had their beginning in geologic events much earlier. The cooling that led to this glaciation was accompanied by an almost continuous loss of atmospheric CO_2, which dropped from a concentration of around 2,000 ppm at the beginning of the epoch to just under 300 ppm during the last million years. Figure 21.1 shows the temperature decline into the Pleistocene beginning at the end of the Mid-Miocene Climatic Optimum and this was accompanied by a similar drop in CO_2.

21.3 Paleocene-Eocene Thermal Maximum

The Paleocene-Eocene Thermal Maximum was a global warming event which lasted around 12 million years and had an enormous influence on the evolution of animal and plant life. The episode coincided with a major wave of extinctions among the existing fauna, both on the continents and in the oceans, and is coincident with the emergence of many new mammalian orders which have dominated the animal kingdom ever since. Flora adapted by changing the structure of their leaves and by migrating to higher latitudes, as is happening today.

Land temperatures, already high, rose again by between 5 and 7°C. In the ocean, the temperature of coastal surface waters in the Antarctic rose from 13 to 20°C, and in the Arctic, they reached as high as 24°C. Although the waters of subtropical regions also became warmer, the effect was much more noticeable in the higher latitudes. Today, the higher latitudes in the Northern Hemisphere are warming more rapidly than other parts of the planet.

Deep water temperatures also rose to around 12°C higher than the current-day mean. This was probably due to a change in the principal location at which deep waters were formed, which moved from the cold seas of the southern hemisphere to the warmer ones of the northern hemisphere. Carbon-13 analyses of sediments provide evidence pointing to this abrupt circulatory change.

It is believed that the Paleocene-Eocene Thermal Maximum (PETM) peak may have been caused by a sudden increase in methane or carbon dioxide release. The most reliable evidence of this sudden increase in methane seems to lie in an abrupt high-low oscillation of sedimentary carbon-13, since methane, due to its biological origin, is very poor in this isotope.

The sudden release of methane into the atmosphere would have come from the methane enclosed in ice crystals located in the sediments of the ocean floor (the Clathrate Gun Hypothesis). The eruption of the gas may have occurred after the temperature of ocean's deep waters passed a specific heat threshold, thus enabling the release of methane clathrates. It is possible that a change in ocean circulation triggered this process.

Nevertheless, the abundance of methane may also have been the result of intense bacterial production in either the wetlands that covered vast areas of tropical and mid-level regions during that period or the peat bogs which formed in higher latitudes. However, the suddenness of the episode seems to support the theory of the release of clathrates frozen in the marine substrate.

21.4 Initial Eocene Thermal Maximum (IETM)

Following the temperature peak at the end of the Paleocene, the temperature dropped, although it remained high throughout the whole first part of the Eocene, until around 48 million years ago. Particularly striking is the situation of the Arctic, which remained free of ice and enjoyed much milder winters than today. Recent studies carried out by the ACEX (Arctic Coring Expedition) project indicate the existence of sedimentary microfossils near the North Pole which are typical of waters with a temperature of 20°C.

21.5 The Cooling Begins

About 50 million years ago, following the initial Paleocene-Eocene Thermal Maximum, the climatic trend took a downturn and temperatures began to drop. Throughout the rest of the Eocene, in almost all of Europe and Asia, the climate became considerably colder and drier. This was the beginning of what was to be (on a long geological time scale and from the beginning of the Oligocene onwards) an ice-house period; namely a period in which abundant ice sheets and mountain glaciers can be found any season of the year. We are still in an ice-house period today, although ice is melting throughout the world.

One of the most significant characteristics of this downwards cooling trend is the evolution of the temperature of deep ocean waters, which dropped from around 12°C 48 million years ago to just 6°C at the end of the Eocene, 35 million years ago. Today, deep ocean waters have a temperature of just over 2°C.

There is evidence that the initial cause of this cooling trend was the reduction of CO_2 concentrations in the atmosphere during the warm climate of the Paleocene and early Eocene. A recent study (2005) of alkenones present in marine sediments registered a constant drop (with the occasional ups and downs) in CO_2 concentrations, which decreased from 1,500 ppm at the beginning of the Eocene to just 500 ppm by the middle of the Oligocene.

Research into the crystallization of different varieties of sodium carbonates has also come to the same conclusion. The precipitation of trona, instead of nacolite (another variant of carbonate) indicates a decrease in atmospheric CO_2 concentrations throughout the course of the Eocene.

According to this theory, the preceding warm Epoch came to an end because a major increase in oceanic plankton caused absorption of a large percentage of atmospheric CO_2. The existence of a vast accumulation of barite (barium sulphate, $BaSO_4$), a mineral of biological origin, in numerous marine sediments, seems to indicate a high level of oceanic productivity during the initial stages of the Cenozoic Era.

Other cooling factors also accompanied this drop in CO_2 levels, such as a decrease in water vapor and a rise in the albedo, triggered mainly by the formation of sea ice.

It is also possible that the warm climate itself, which would have been accompanied by higher humidity levels, accelerated the loss of atmospheric CO_2 through the weathering of silicate rocks.

Nevertheless, some oceanographers believe that more important than the drop in CO_2 levels were the changes in ocean circulation caused by large-scale geological movements, which in turn triggered changes in atmospheric circulation. One of these major modifications to ocean circulation contributed to the formation of the Antarctic ice sheet, which increased the planet's albedo and played an important part in global cooling.

21.6 Formation of the Isthmus of Panama and the Freezing of the Arctic

The flow of ocean currents was drastically modified at the end of the Pliocene when all communication between the Atlantic and the Pacific through Central America was closed off. The geological closure of the channel was a gradual process which began 13 million years ago and probably ended around 4 million years ago, when the gap between the two Americas, North and South, finally closed, allowing land mammals to emigrate in both directions.

The closure had an immediate effect on the world's oceans and probably changed the climate of the North Atlantic, sending the whole equatorial current flow northward and reinforcing the Gulf Stream.

According to a paradoxical theory, the warm water transported by the Gulf Stream actually helped to begin the glaciations which occurred in the higher latitudes of the Northern Hemisphere. Although one might logically assume that the redirection of tropical water to the North Atlantic should have provoked just the opposite effect, it seems that what it in fact triggered was the formation of the large North American and Northern European ice sheets.

According to this theory, the temperature increase in the North Atlantic increased evaporation. This in turn rendered the Atlantic air masses more humid which the westerly winds from mid-level latitudes transported towards the inland areas of the Eurasian continent and the rivers flowing into the Arctic Ocean added fresh water. The fresh water freezes, increases Earth's albedo and eventually forms an ice cap over the Northern Hemisphere.

At the beginning of the Pleistocene glacial advances and retreats, climatic oscillations followed cycles of around 40,000 years, which appear to coincide with the cycle of variation in the Earth's axial tilt. The ice masses which formed on the continents were not, at that time, particularly large.

Between 1.5 million and 680,000 years ago, the length of the cycles started to increase, and from 680,000 years ago onwards, glacial cycles have occurred at intervals of between 80,000 and 120,000 years, averaging around 100,000 years. The length of recent cycles is similar to that of the cycle of variation in the Earth's orbital eccentricity (Milankovitch cycle), which is around 100,000 years.

The periodicities reflected in Pleistocene glacial deposits, ice cores, and sediments are compared to Milankovitch cycles that were discussed earlier. Eccentricity has a periodicity of roughly 100,000 years but its effects on the climate system are the weakest of the cycles. However, the 100,000 year cycle stands out at the beginning of the major continental advances and may have been due to a combination of factors which coincided at 100,000-year intervals.

As Earth travels around the Sun in an elliptical orbit, the orbital plane changes and it moves about the plane on a cycle of 23,000 years.

Precession has the following components:

- An axial precession, in which the torque of the other planets exerted on the Earth's equatorial bulge causes the rotational axis to gyrate like a spinning top.
- An elliptical precession, in which the elliptical orbit of the Earth itself rotates about one focus.
- The net effect describes the precession of the equinoxes with a period of 22,000 years. This term is modulated by eccentricity which splits the precession into periods 19,000 and 23,000 years.

Like obliquity, precession does not affect the total amount of solar energy received by the Earth, but only its hemispheric distribution over time. If the perihelion

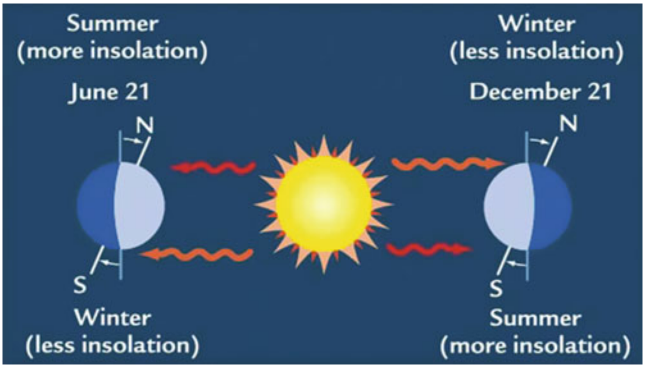


Fig. 21.3 The effect of Earth's obliquity on insolation, the amount of energy received by the Earth at different seasons of the year (summer and winter (Source: John Cook)

occurs in mid-June i.e., when the Northern Hemisphere is tilted toward the Sun, then the receipt of summer solar radiation in the Northern Hemisphere will increase. Conversely, if the perihelion occurs in December, the Northern Hemisphere will receive more solar radiation in winter. It should be clear that the direction of changes in solar radiation receipt at the Earth's surface is opposite in each hemisphere.

The illustration (Fig. 21.2) shows the precession of the equinoxes (so called because twice a year, the length of day and night is equal).

Precession has a periodicity of between 19,000 and 23,000 years and obliquity has a periodicity of 41,000 years. Do any of these periodicities show up in the geologic record?

From the present day to 700,000 years ago, the dominant periodicity is 100,000 years. From 700,000 years ago to 2.8 million years ago, the dominant periodicity was 40,000 years. This suggests a major change at 700,000 years.

The effect of obliquity on Earth's seasons is shown in the illustration above (Fig. 21.3). The obliquity of Earth's axis of rotation causes the seasons of the year and it regulates the amount of the Sun's energy hitting various parts of the Earth.

21.7 Other Influences and Possible Causes of Ice Ages

There are other natural cycles which may strengthen the 100,000-year Milankovitch cycle:

- Ice-sheet growth and retreat appears to have a 100,000 cycle and provides a positive feedback loop, i.e., as glaciers advance, they reflect sunlight and further cause cooling. As glaciers retreat, less sunlight is reflected reducing albedo and exposed ground absorbs more sunlight and causes further warming.
- Residence time of carbon in the ocean appears to be about 100,000 years. The atmospheric CO_2 concentration is in equilibrium with the surface CO_2 concentration. Scientists have conceived of a biological pump in the ocean that cycles CO_2

from the ocean surface to the deeper ocean waters where upwelling brings carbon back to the surface as nutrients.

- Shelf-nutrient Hypothesis: nutrient balance in the ocean reflects rates of supply and sediment burial; as glaciers grow, sea level is lowered exposing continental shelves rich in organic matter and nutrients like PO_4 to weathering and river transport to the ocean. This results in a feedback loop that enhances reduction of atmospheric CO_2 during glaciation. Nutrient supply to the surface ocean increases productivity which removes atmospheric CO_2 and causes cooling. Residence time of phosphate in the ocean is 40,000–100,000 years.
- Iron Fertilization Hypothesis: in cold upwelling of the oceans, iron limits primary productivity. Nitrogen fixation by cyanobacteria requires large amounts of Fe to build the enzyme that catalyzes N-fixation. In an oxygen-rich ocean Fe is brought to the sea by wind-derived particulates. When glaciers advance there is less moisture in the atmosphere, winds are stronger and carry more dust to the ocean and increasing primary productivity.

The illustration below (Fig. 21.4) summarizes information about major events that took place since the extinction of the dinosaurs and during the Cenozoic Era. The temperature-dependent isotopes of carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$), and the climatic, tectonic, biotic events, and temperature variations are summarized in the illustration below.

21.8 Maximum Extent and Characteristics of Continental Glaciers

Continental glaciation is happening now in Greenland and Antarctica, although Greenland is not considered a continent and much of the glacial ice occupies valleys. By studying these glaciers it is possible to better understand the continental glaciers that covered up to 30% of the land area of Earth during the maximum glacial extent about 18,000 years ago during the Pleistocene "ice age." There were two major continental glaciers covering the northern part of North America during the Pleistocene, the Laurentide and Cordilleran ice sheets, and they coalesced and formed the North American Ice Line at their southernmost terminus.

The ice reached a maximum thickness of about 2 miles at its center and thinned toward its edges. It affected the global climate and disrupted the Jet Stream, increasing rainfall in areas that are now dry such as the southwestern United States. The ice sheets over Europe and Siberia also acted to increase rainfall in dry areas such as present day Iran and Afghanistan.

The increased rainfall periods in dry areas are referred to as pluvial periods and remnants today are Salt Lake, Utah, which is a remnant of the Pleistocene glacial Lake Bonneville. Lake Bonneville is estimated to have been 1,000 ft deep when it was at its maximum extent. The shoreline is seen in the photograph below (Fig. 21.5) identified by the wave-cut terraces on the hillside.

Pluvial lakes occurred throughout the southwestern United States and those in the Mojave Desert Region are shown in the reconstruction below in Fig. 21.7.

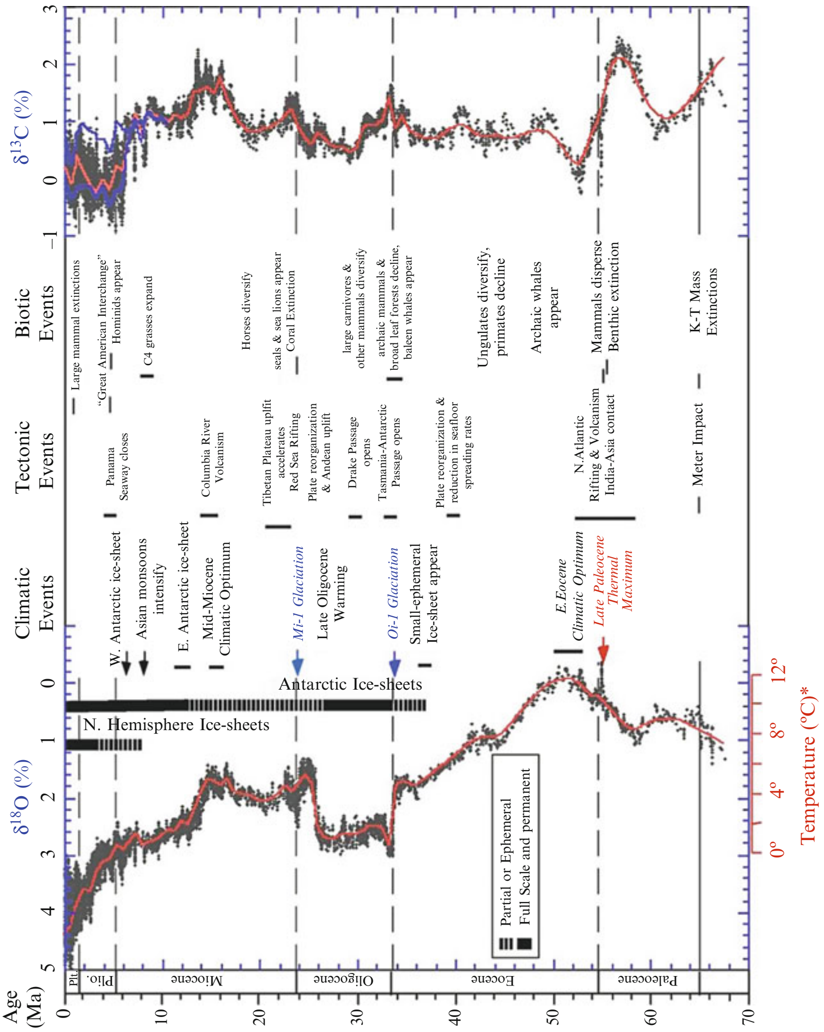


Fig. 21.4 Summary or composite timeline and events for the Cenozoic Era showing ages in millions of years, Epochs, carbon and oxygen isotopes, tectonic and biotic events. (used with permission)

Fig. 21.5 Wave-cut terraces of former Lake Bonneville above the bank of Great Salt Lake, Utah (Public Domain)

About 8,200 years before present, glacial lake Agassiz was the largest lake in the world. It covered over 840,000 km^2 in Canada (Manitoba, Saskatchewan, and Ontario) and the U. S. (North and South Dakota and Minnesota).

There were some very large glacial lakes throughout the Northern Hemisphere during the Pleistocene that formed from the meltwater as the ice receded. One of these was Lake Agassiz (Fig. 21.6), an immense glacial lake located in the geographical center of the continent of North America. It covered an area larger than the present Great Lakes and was equivalent to about 15 Lake Superiors in the amount of fresh water it held. This water was released rather suddenly into the Arctic Ocean and northern Atlantic through the Mackinzie River basin about 8,700 years ago and was probably witnessed by early North American settlers.

The draining of Lake Agassiz raised sea level world-wide almost 2 m (6 ft) and some scientists think that this caused a migration inland across Europe which greatly expanded agriculture in post-glacial Europe by Neolithic people (Fig. 21.7).

Another large glacial lake was Lake Bonneville as seen below (Fig. 21.8) with other glacial lakes in the northwestern U.S. The Great Salt Lake in Utah is a remnant of glacial Lake Bonneville.

Remnants of the Laurentide ice sheet are still found in northern Canada, such as the ice on Baffin Island as shown in the picture below (Fig. 21.9).

The extent of the ice during the Pleistocene is shown in the illustration below (Fig. 21.10) as well as the extent of the sea ice in the Northern Hemisphere as compared to their presence today.

21.8.1 The North American Ice Line

The southernmost extent of the Laurentide glacier in North America is marked by the terminus of the last glaciation (Wisconsin) as evidenced by the glacial deposits that it left behind as it receded. This lobate line is called the North American Ice Line and runs from Long Island in the east, westward to the Ohio River, irregularly through Pennsylvania, along the Ohio River to the Mississippi River, then to the

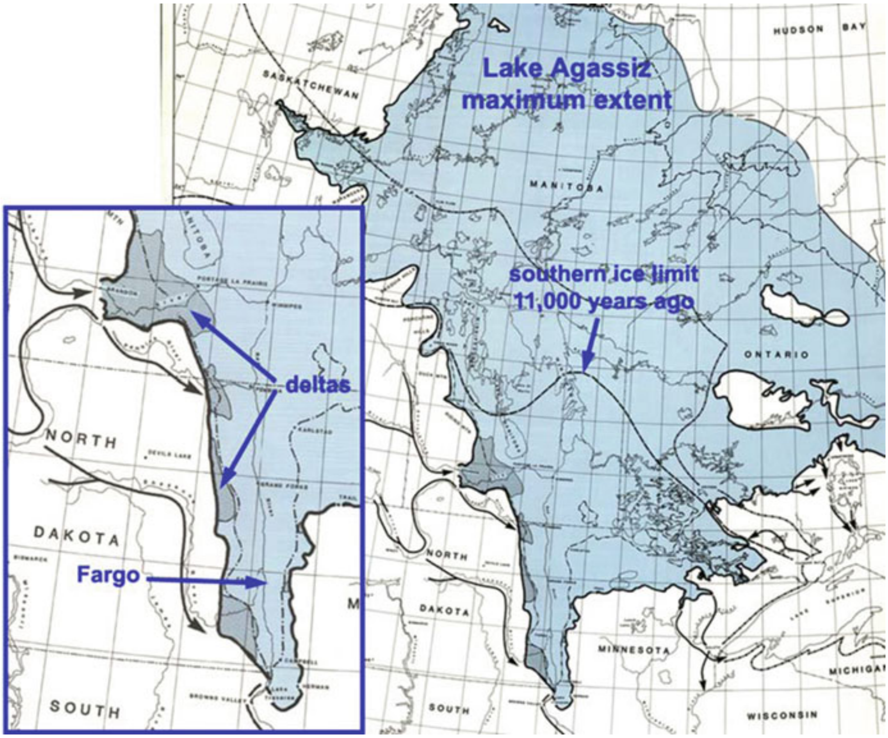


Fig. 21.6 The outbreak from Lake Agassiz about 8,700 years ago caused a world-wide rise in sea level (From the Geological Association of Canada)

Missouri River, along the Missouri River until it joins with the Cordilleran Ice Sheet (Fig. 21.11).

21.8.2 Europe and Asia's Continental Glaciation

Continental glaciation affected Europe and Asia during the Pleistocene as shown in the illustration below (Fig. 21.12).

The Great Lakes of North America were also formed during the Pleistocene (Figs. 21.13 and 21.14). The Laurentide Great Lakes were formed nearly 20,000 years ago when the Earth's climate warmed and the last glacial continental ice sheet retreated. But this was not a continuous retreat, as we've seen with the Interstadials and the rapid warming of the Greenland area.

During its retreat, the ice moved from time to time as the temperature went below freezing and the glacier, up to 2 miles thick, was so powerful that it gouged out the Earth's surface to create the lake basins. Meltwater from the retreating glacier filled the newly created basins. Approximately 3,500–4,000 years ago, the Great Lakes attained their modern levels and areal extent. The Finger Lakes of New York State were also formed at this time

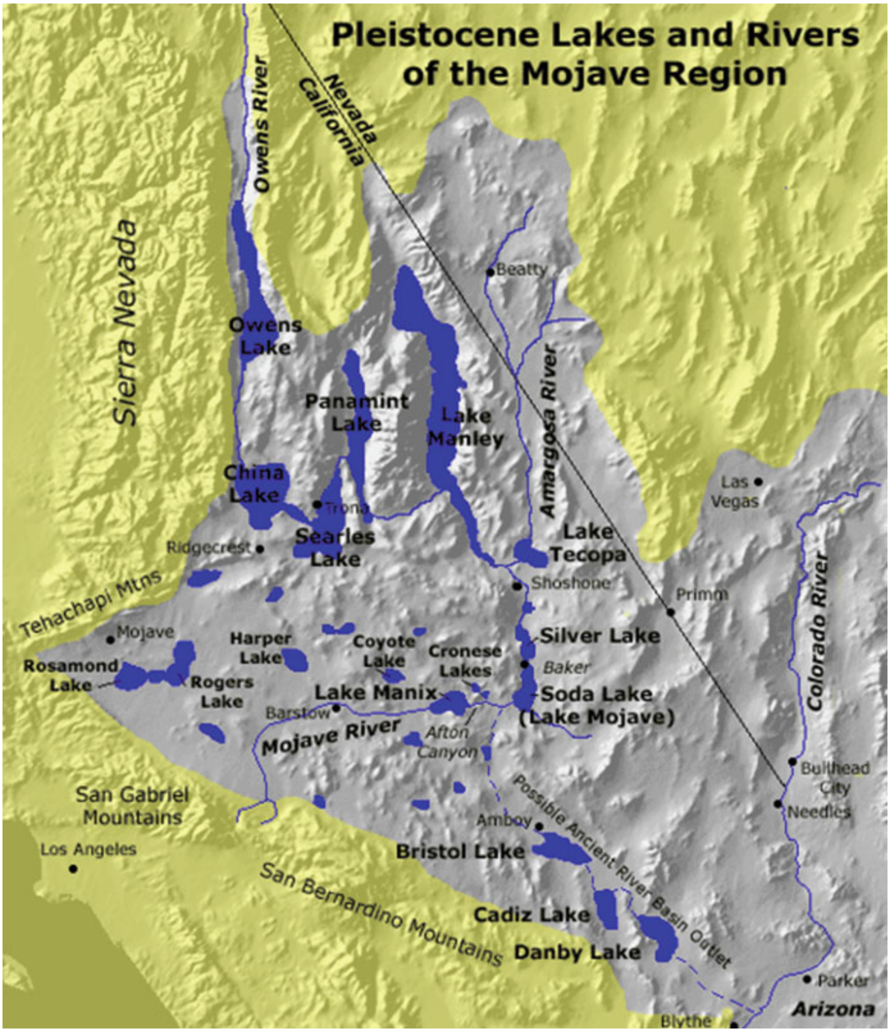


Fig. 21.7 Pluvial lakes and rivers of the Mojave region (National Park Service and USGS, Public Domain)

21.8.3 Southern Hemisphere Glaciation

One of the greatest unanswered paleoclimatic questions is why both the northern and southern hemispheres entered the last (Wisconsin) glaciation almost simultaneously, since the Earth's orbital geometry 115,000 years ago, which gave rise to cool northern summers, did not have the same effect in the southern latitudes, where solar radiation levels tended to fall in spring, rather than in summer.

According to the classic Milankovitch theory, the glaciation should have begun in the northern hemisphere. However, paleoclimatic sites in the southern hemisphere

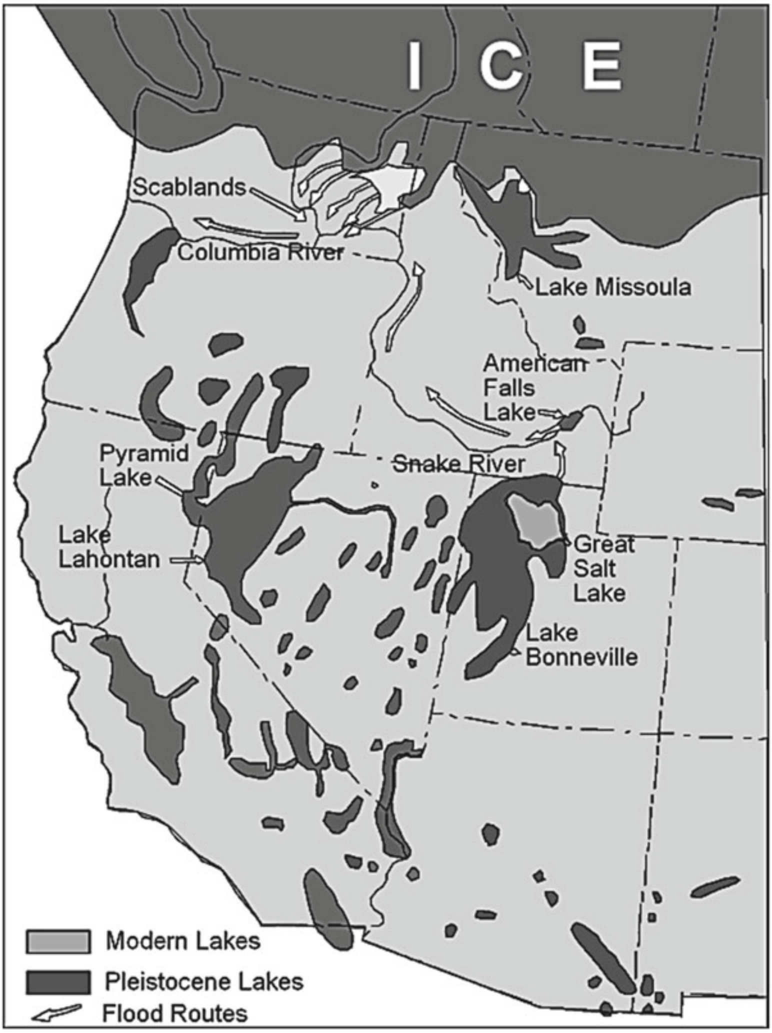


Fig. 21.8 Glacial and modern lakes in the northwestern U.S (From http://geology.isu.edu/Digital_Geology_Idaho/Module14/mod14.htm)

indicate that in this region also temperatures plummeted around 115,000 years ago, almost precisely at the same time as in the northern hemisphere, with the advance of glaciers from the southern Andes and Patagonia and the growth of sea ice that surrounded Antarctica.

The mechanism by which glaciation spread from one hemisphere to the other is still largely unknown. There are even indications that, in the southern seas, the cooling which marked the end of the Eemian (Sangamonian) began several thousand years earlier than 115,000 years ago; or in other words, before the conditions conducive to the start of the glaciation arose in the northern hemisphere. Similarly,

Fig. 21.9 A remnant of the Laurentide ice sheet on Baffin Island, Canada (NASA, Public Domain)

a comparison of ice measurements from Greenland and Antarctica offers no firm evidence that the northern glaciation predates the southern one. Only when we achieve time resolutions of less than 500 years for the interval in which the last glaciation began will we be able to determine the exact nature of the connection between the two hemispheres.

If the glaciation did begin in the high latitudes of the northern hemisphere, then it is possible that a drop in the thermohaline ocean circulation triggered the cooling of the Antarctic land mass. During warm interglacial eras, such as the one in which

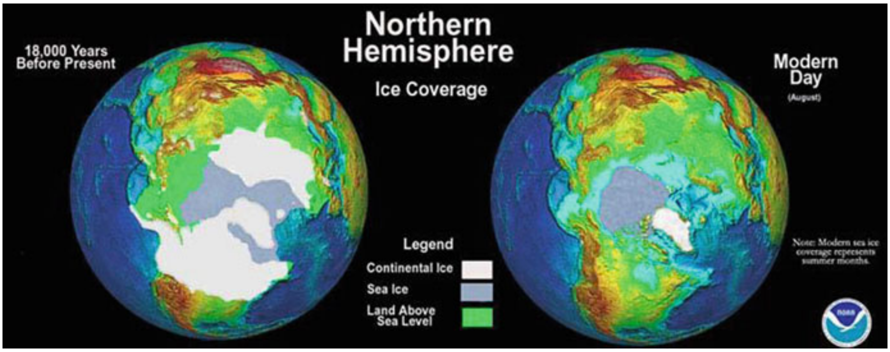


Fig. 21.10 Northern hemisphere ice coverage 18,000 years ago and today (August) (NOAA, Public Domain)

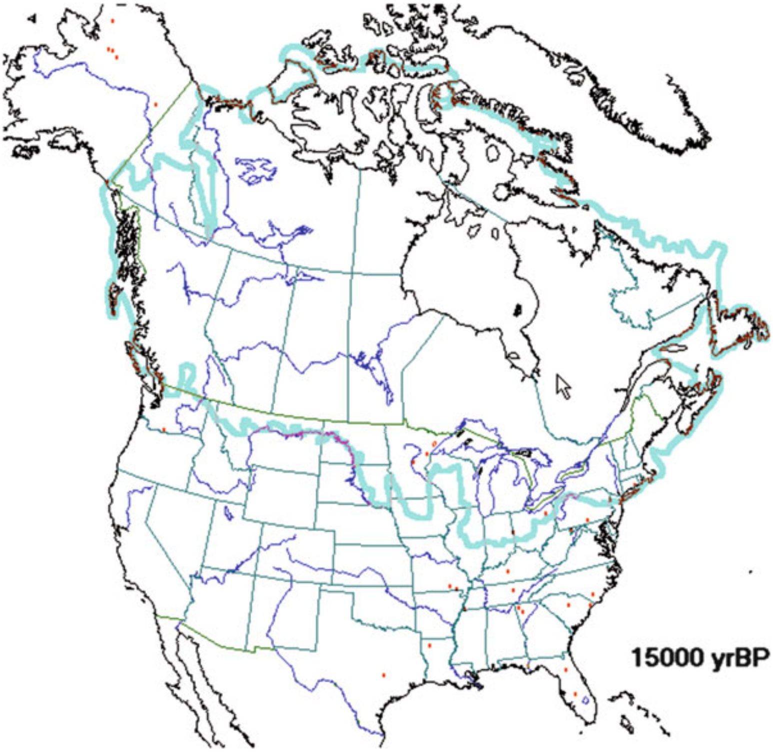


Fig. 21.11 The extent of the Laurentide and Cordilleran glaciers outline by the aqua line. The land north of this line was covered by continental glaciers (From NOAA, Public Domain)

we are living now, part of the NADW (North Atlantic Deep Water) upwelling in the Southern Ocean after crossing the whole Atlantic Ocean at both deep and intermediate levels. This mass of upwelling water, although cold, is not as cold as that formed

Fig. 21.12 A North Polar view showing the major Pleistocene ice sheets, the Laurentide, Inuitian, and Cordilleran in North America, the Greenland and Iceland ice sheets, and the Scandinavian and Kara ice sheets in Europe and Asia. Directions of ice movement are shown by the *arrows*

along the Antarctic Coast (known as AABW, Antarctic Bottom Water; Fig. 21.15), and as a result moderates the intense cold of the air which surrounds the coastline of the southern continent. However, once glaciation begins in the northern hemisphere, the Atlantic thermohaline circulation is weakened and this upwelling decreases, rendering the water layers of the Southern Ocean more stratified and colder. As a consequence, Antarctica also becomes colder.

Another hypothesis, which places the emphasis more on the southern hemisphere, is that an increase in the winter sea ice surrounding Antarctica (which is highly sensitive to air temperature changes), coupled with an increase in water salinity, may have triggered a greater production of AABW. This mass of very cold

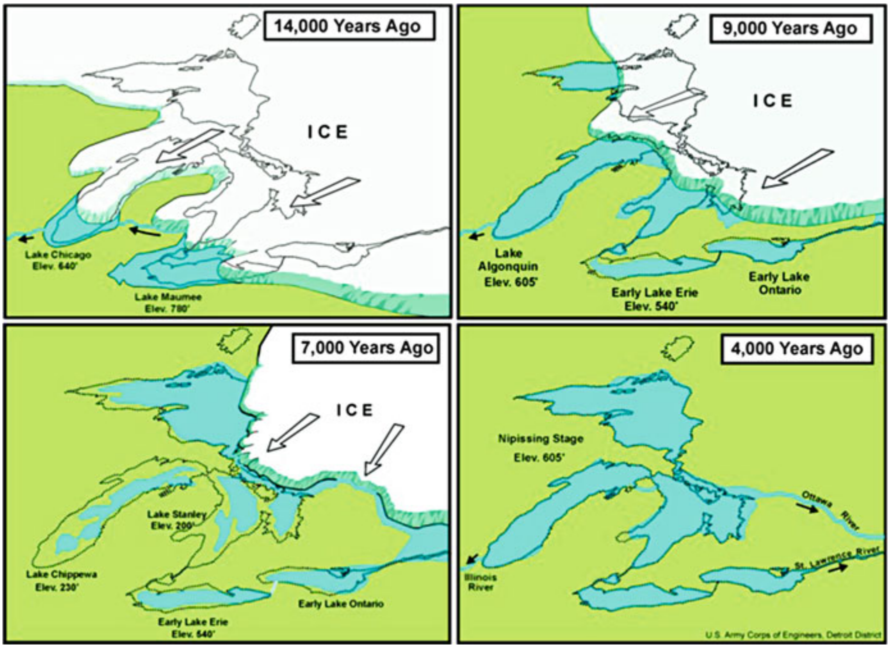


Fig. 21.13 Stages in the formation of the Great Lakes (NOAA, Public Domain)

Fig. 21.14 The glacial Great Lakes of Canada and the United States as they are today (SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE. Image taken 24 April 2000, Public Domain)

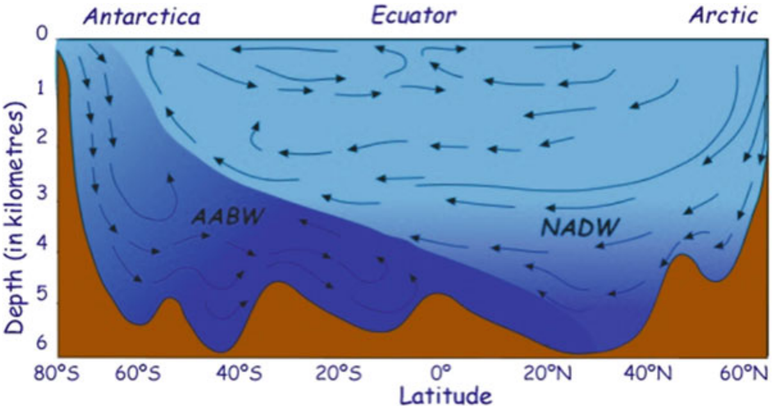


Fig. 21.15 Vertical, schematic cross-section of the deep waters and currents in the modern-day Atlantic. In the thermohaline circuit, surface water sinks in high latitudes. In the vicinity of the Arctic, the mass of water known as NADW (North Atlantic Deep Water) is formed, and in the vicinity of Antarctica, the even denser water mass known as AABW (Antarctic Bottom Water) is formed

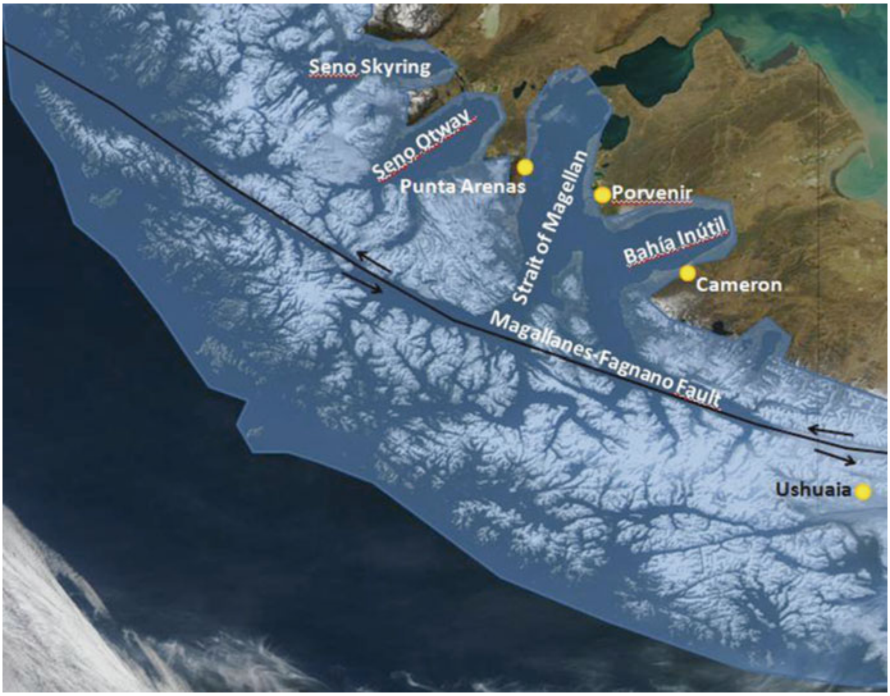


Fig. 21.16 Patagonian ice sheet (NASA, Public Domain)

water, which would have moved through the deep ocean layers towards the North Atlantic, may have increased the vertical stability of the water upon arriving in the north, thus reducing the production of NADW and slowing up the thermohaline circulation. This in turn would have accentuated the global drop in temperature.

In the Southern Hemisphere the Patagonian ice sheet (see Fig. 21.16) covered the southern one-third of Chile and adjacent areas of Argentina. On the western side of the continent the ice reached sea level as far north as 41° North latitude. The Straights of Magellan were iced over. Small glaciers formed in the Middle East and Africa and the Sahara, Gobi, and other smaller deserts were greatly expanded.

During the Last Glacial Maximum (LGM), around 18,000 years ago, the world was cold, dry, and inhospitable, with frequent storms and a dust-laden atmosphere. The massive sheets of ice locked away water, lowering sea level, exposing continental shelves, joining land masses together with land bridges, and creating extensive coastal plains. It has been estimated that sea level was lowered about 180 ft during the LGM exposing vast areas of what is today submerged continental shelf areas.

Additional Readings

Alley, R. B., & Clark, P. U. (1999). The deglaciation of the Northern Hemisphere: A global perspective. *Annual Review of Earth and Planetary Sciences, 27*, 149–182.

Alley, R. B., et al. (1993). Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. *Nature, 362*, 527–529.

Dyke, A. S., et al. (2003) *Deglaciation of North America* (Geological Survey of Canada Open File, 1574). Ottawa: Natural Resources Canada. (Thirty-two digital maps at 1:7000000 scale with accompanying digital chronological database and one poster (two sheets) with full map series.)

Ehlers, J., & Gibbard, P. L. (2004a). *Quaternary glaciations: Extent and chronology 2: Part II North America*. Amsterdam: Elsevier. ISBN 0-444-51462-7.

Ehlers, J., & Gibbard, P. L. (2004b). *Quaternary glaciations: Extent and chronology 3: Part III: South America, Asia, Africa, Australia, Antarctica*. Amsterdam: Elsevier. ISBN 0-444-51593-3.

Gillespie, A. R., et al. (2004) *The Quaternary Period in the United States*. Developments in Quaternary Science no. 1. Amsterdam: Elsevier. ISBN 978-0-444-51471-4.

Lisiecki, L. E., & Raymo, M. E. (2005). A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records, *Paleoceanography*, 20, PA1003. doi:10.1029/2004PA001071; data: doi:10.1594/PANGAEA.704257.

Lowell, T. V., et al. (1995). Interhemispheric correlation of late Pleistocene glacial events. *Science, 269*, 1541–1549.

Mangerud, J., et al. (2004). *Quaternary glaciations: Extent and chronology 1: Part I. Europe*. Amsterdam: Elsevier. ISBN 0-444-51462-7.

Marden, C. J. (1997). Late-glacial fluctuations of South Patagonia icefield, Torres del Paine National Park, Southern Chile. *Quaternary International, 38/39*, 61–68.

Petit, J. R., et al. (1999). Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature, 399*, 429–436. doi:10.1038/20859.

Sibrava, V., et al. (1986). Quaternary glaciations in the northern hemisphere. *Quaternary Science Reviews, 5*, 1–514.

Part IX
Future Climates and Mitigation

Chapter 22
Projections of Future Climates

Abstract Climate projections are not the same as climate predictions. Climate change scientists can't predict the future but with knowledge of past climates and detected climate trends, it is feasible to project climate change into the future using various scenarios. The IPCC did several projections in their AR4 2007 report and these are discussed in this chapter. What will happen in a hotter, flatter, and more crowded world is something inhabitants of this planet should be concerned about. There are conditions that we can be fairly confident about as we gaze into a virtual future. The political climate is separate from the temperature but has a great deal to do with the future of Earth and its inhabitants. Some politicians are famous or notorious for their stance on climate change and their contribution to environmental issues (both positive and negative) and some are discussed in this and the following chapters. Mitigation of climate change is to slow things down and thereby improve the global temperature rise or to stop it entirely. Is it already too late to stop the globe from further warming and, if it is not, what should or can we do?

Keywords Internet • World-Wide • Web • Computers • Laptops • Hotter • Flatter • Crowded • Digital • Billion • Projections • EPRI • IPCC • IPods • Royal • Nixon • Obama • Reagan • Inhofe • EPA • Mitigation • Carbon sequestration

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_22,

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
Hotter	GHGs
Flatter	Niger
14.5°C	EPRI
More crowded	Internet
IPods	11.5°F
EPA	Digital age
$GtCO_{2\text{-eq}}$	0.2°C
Mitigation	350 ppm
IPCC 2007 projections	Royal society
200 billion	14.5°F
Future climate scenarios	Population projections for mid-twenty-first century

22.1 Introduction

Projections of current climatic conditions into the future are not the same as predicting the future. The future is impossible to predict but projecting into the future climate conditions that exist today and have been trending a certain way can be a very useful exercise.

Civilization has only recently completed the first decade of the twenty-first century. The world is a much different place than it was at the beginning of the last century. And there are already projections for the next century. Those projections do not inspire optimism as some things need to be accomplished soon or it will be too late for the planet's inhabitants, or at least too expensive to contemplate at this time.

Earth is becoming hotter, flatter, and more crowded. It is becoming hotter due to global warming caused appreciably by greenhouse gas increases which are due mainly to the burning of fossil fuels. It is becoming flatter because of the internet, the world-wide web and the use of personal computers, cell phones, tablets, and other means of world-wide communication. It is becoming more crowded because the population of human beings is growing out of control. There are ways that human beings can choose to change or mitigate the worst-case scenarios that we can see playing out in the near future of planet Earth or we can do nothing and gamble on the future of the species and other life on Earth.

22.2 Hotter – Global Warming

Since the beginning of the Industrial Revolution in the mid-1700s, the Earth's temperature has been raised approximately 0.8°C (1.4°F) and it continues to climb. About 66% (0.53°C) of the temperature increase has been since 1980. Estimates of a temperature rise up to a 10°C increase by the end of this century have been projected into the future if certain conditions are not met, one of which is to significantly reduce the emissions of greenhouse gases.

The Intergovernmental Panel on Climate Change (IPCC) in their 2007 report state that during the twenty-first century the global surface temperature is likely to rise an additional 1.1–2.9°C (2–5.2°F) for their lowest emissions scenario and 2.4–6.4°C (4.3–11.5°F) for their highest. It is likely to rise higher and unlikely to be lower by the end of this century (the twenty-first century).

The global average temperature in 2011 was 14.52°C (58.14°F). According to NASA scientists, 2011 was the ninth warmest year in 132 years of recordkeeping since 1879, despite the cooling influence of the La Niña atmospheric and oceanic circulation pattern and relatively low solar irradiance. Since the 1970s, each subsequent decade has gotten hotter, and 9 of the 10 hottest years on record have occurred in the twenty-first century. There is no doubt, despite what the deniers are saying, the thermometers, Agro floats, climate models, and satellites worldwide are not lying; the Earth is warming and global warming is real.

22.3 Flatter – The Digital Age

The internet and the world-wide web (www) have made almost instantaneous global communication available to nearly everyone on the planet; and this, combined with web browsers and smart phones, has made the world flatter. Within the last decade of the twentieth century and the first in the twenty-first, technological innovation in the form of communication and economy has caused a globalization and a fundamental change in the way that humans communicate that has been a revolution. No longer does humanity depend on airmail, snail mail, pony express, long-distance land-line telephones or other means of slow communication when we can receive stock market reports, environmental study reports, email, instant messages; spy satellite downloads all in a matter of seconds. The world is flatter.

By stating that the Earth is getting flatter, it is obviously not intended to convey that the planet is physically getting flatter. Earth remains a globe, an oblate spheroid that circles the Sun in 1 year and rotates on its axis in 1 day. But the global economy is allowing more and more people to join the middle class, to join in the advances that are impacting the middle class, such as being able to purchase personal computers, laptops, cell phones, a family residence, and other personal items that were out of their reach before the twenty-first century. Global communications and a global economy are making the world flatter.

The personal computer has been a symbol of the new middle class. For the first time in the history of the world, it has allowed individuals to partake in the world economy and to join a world community. It has allowed individuals to obtain information that previous generations could not even dream of obtaining. And this has come about only in the last couple of decades, with the advent of the Internet, the World-Wide Web, the web browser, and the digital age in general. Humans now live in a world of 1 and 0s, a digital world and a flatter world.

Along with the personal computer, the Internet and the World-Wide Web, was a revolution in the use of software transmission protocols that improved workflow. People could work on the same projects in different parts of the world; for example an industrial engineer in California could work with a scientist in Japan and a software engineer in New York to devise a new program to assist a manufacturing project in Montreal. Report writers in Moscow and Philadelphia could work with writers in Harrisonburg, Virginia to complete a report for the soccer team in Manchester, England. Computer programmers could share code (open source) throughout the world and thousands of people could make suggestions and improve the software. The world was becoming even flatter.

22.4 More Crowded – Population Increase

The illustration below (Fig. 22.1) shows the planet's growth in population from 1800 to the present and projected growth to 2100. The rapid increase in the world's population has been supported by science and technology; Watt's coal-fired steam engine, Haber and Bosch synthesizing nitrogen fertilizer, Fleming's discovery of penicillin and these science and technology advances continue today as the world's population expands at the rate of 78 million people per year. As birth rates increase in many parts of the world, people's increasing life span, and improving health care for millions of humans, the world's population increase is a cause for concern.

Rapid and widespread changes in the world's human population, coupled with unprecedented levels of consumption present profound challenges to human health and wellbeing, and the natural environment as well as for the future of the planet.

The combination of these factors is likely to have far reaching and long-lasting consequences for our finite planet and will impact on future generations as well as the present one. These impacts raise serious concerns and challenge us to consider the relationship between people and the planet. It is not surprising then, that debates about population have tended to inspire controversy.

The Royal Society (London) in an April 28, 2012 report entitled "People and the Planet" made the following recommendations:

Key recommendations include:

- The international community must bring the 1.3 billion people living on less than \$1.25 per day out of absolute poverty, and reduce the inequality that persists in the world today. This will require focused efforts in key policy areas including economic development, education, family planning and health;

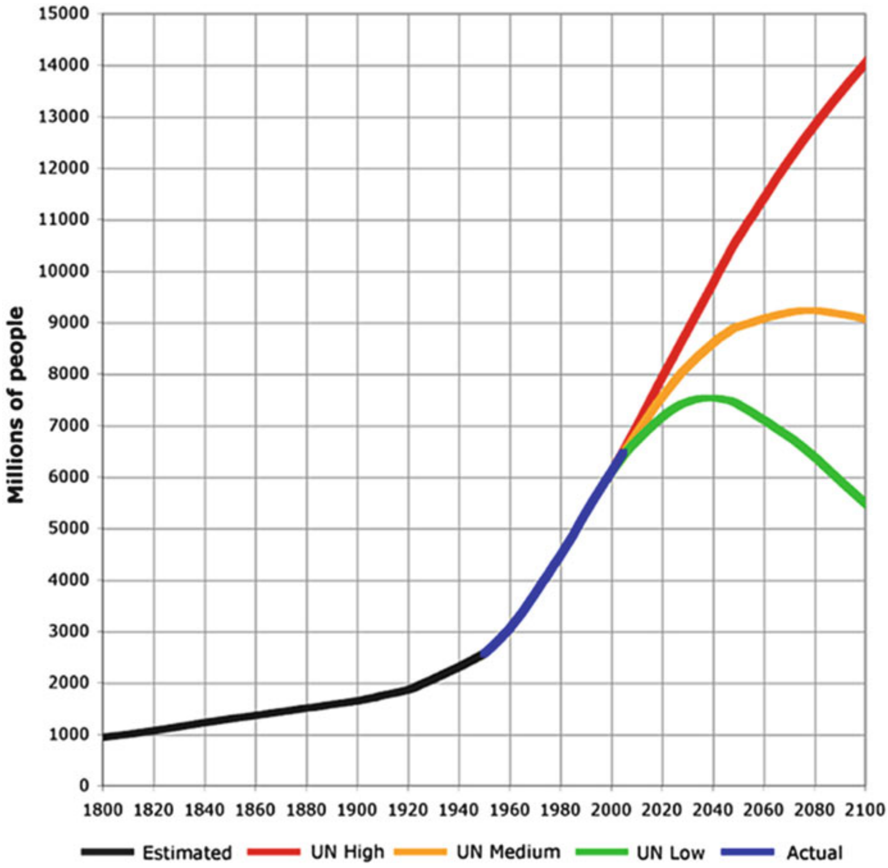


Fig. 22.1 World population from 1800 to 2100 based on United Nations 2004 projections and U.S. Census Bureau historical estimates (From Wikipedia, Loren Cobb (User: Aetheling), GNU Free Documentation License)

- The most developed and the emerging economies must stabilize and then reduce material consumption levels through dramatic improvements in resource use efficiency, including: reducing waste; investment in sustainable resources, technologies and infrastructures; and systematically decoupling economic activity from environmental impact;
- Reproductive health and voluntary family planning programs urgently require political leadership and financial commitment, both nationally and internationally. This is needed to continue the downward trajectory of fertility rates, especially in countries where the unmet need for contraception is high;
- Population and the environment should not be considered as two separate issues. Demographic changes, and the influences on them, should be factored into economic and environmental debate and planning at international meetings, such as

the Rio+20 Conference on Sustainable Development and subsequent meetings (the first of which recently completed in June 2012).

Other recommendations made in the report focus on:

- The potential for urbanization to reduce material consumption;
- Removing barriers to achieve high-quality primary and secondary education for all;
- Undertaking more research into the interactions between consumption, demographic change and environmental impact;
- Implementing comprehensive wealth measures;
- Developing new socio-economic systems.

22.4.1 Population and Demographics

The advances in technology during the last half of the twentieth century and the beginning of the twenty-first, the collapse of the Soviet Union, and the fall of the Berlin Wall freed about 200 million people from the clutches of economic and social depression and brought them into the global marketplace. These advances allowed more millions to buy and sell more goods than ever before and have contributed to the advancement of obtaining a middle class existence for themselves and their families. They wanted cell phones, iPods, laptops, cars, houses, air conditioning, televisions, and anything else that would help them attain the "American dream." Thus society became the "throw away" society, increasing the size of landfills and other deleterious impacts on human services. They also became part of the "instant gratification society" and contributed to the age of the "sound bite."

The American diet of McDonalds, Burger King, Kentucky Fried Chicken (KFC), and fast food in general expanded globally which led to obesity as a world-wide problem with its plethora of adverse health effects. Additional health effects from increased groundwater contamination, inadequate sewerage treatment, and the direct effects of global warming, such as floods and droughts and the spread of tropical diseases will cause further impacts on the well being of the human race.

The United Nations Population Division, in a report issued March 13, 2007, stated that the world population was approaching seven billion (which it attained in October 2011) and it would likely increase by 2.5 billion in the next 13 years reaching 9.5 billion by 2050. This increase is equal to the total global population in 1950. The majority of these new people will be in the less developed countries whose population is projected to rise from 5.4 billion in 2007 to 7.9 billion by 2050. The population of the more developed countries will remain largely unchanged.

Urbanization will have to accommodate the large majority of the population increase and they are not prepared for it; they do not have the resources, transportation systems, or other infrastructure necessary for the increased number of inhabitants.

In 2008 more than half of humanity lived in cities. In 1800, London was the world's largest city with one million people. On April 28, 2012 the world's population was 7,009,819,056 and over 300 cities had over a million people.

Megacities are defined as those with over ten million inhabitants. According to the United Nations, there were five megacities in 1975, 14 in 1995, and their number is expected to reach 26 by 2015. By 2030 the number of city dwellers is projected to be five billion.

Most of the population growth will take place in cities of around 500,000, according to the United Nations. These cities do not have the infrastructure to handle such rapid growth. Water, sewer, health services, food, shelter, and other services will be overwhelmed. Classical methods of urban planning will be obsolete as these smaller cities grow beyond their capacity. Modern transportation will also become obsolete as more and more people will use public transportation as the cities grow.

The most rapid population growth will occur in underdeveloped countries that can least afford it. According to the U.S. Central Intelligence Agency (CIA), poor and fragile states like Afghanistan, Niger, Liberia, the Sudan, and the Democratic Republic of the Congo will have rapidly growing populations, some estimates calling for a tripling of their populations by mid-century. The populations in countries like Ethiopia, Nigeria, and Yemen are projected to double in size. A large percentage of the increasing population will be younger people in search of food, housing, education, jobs. If the needs of these younger people are not met, there is a great chance they will resort to violence, civil unrest, and religious extremism.

Thomas L. Friedman, in his 2008 book entitled "Hot, Flat, and Crowded," quoted David Douglas, a vice president of Sun Microsystems, who commented that when the newest billion people arrived, we give each of them a 60-W incandescent light bulb, as follows:

"Each bulb doesn't weigh much – roughly 0.7 ounces with the packaging – but a billion of them together weigh around 20,000 metric tons, or about the same as 15,000 Priuses. Now let's turn them on. If they are all on at the same time it would be 60,000 MW. Luckily, they will only use their bulbs 4 h/day, so we're down to 10,000 MW at any moment. Yikes! Looks like we'll still need twenty or so new 500-MW coal-burning power plants" just so the next billion people can turn a light on.

Coal-burning power plants are among the planet's greatest sources of carbon dioxide emissions to the atmosphere. The advertisements by coal companies and the Electric Power Research Institute (EPRI) about "clean coal" are misleading. "Clean coal" is an oxymoron; it doesn't exist. Use of the term is a lie and the advertisements using the term are lies and the general public and good citizens of this planet need to know this. Coal is one of the dirtiest fuels on the planet, only exceeded by oil sands and lignite and the majority of coal throughout the world is strip-mined in the Appalachians in the eastern United States. The total cost of mining coal is astronomical when the cost of health effects, mine explosions and deaths, damage to the local ecology, and stream and groundwater contamination are factored into the process.

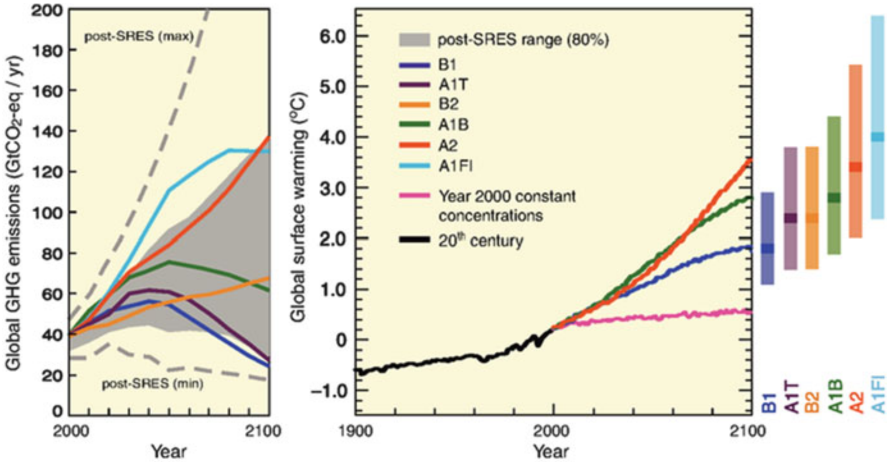


Fig. 22.2 *Left Panel*: Global GHG emissions (in $GtCO_2$-eq) in the absence of climate policies: six illustrative SRES marker scenarios (*colored lines*) and the 80th percentile range of recent scenarios published since SRES (post-SRES) (*gray shaded area*). *Dashed lines* show the full range of post-SRES scenarios. The emissions include CO_2, CH_4, N_2O and F-gases. *Right Panel*: Solid lines are multi-model global averages of surface warming for scenarios A2, A1B and B1, shown as continuations of the twentieth-century simulations. These projections also take into account emissions of short-lived GHGs and aerosols. The pink line is not a scenario, but is for Atmosphere-Ocean General Circulation Model (AOGCM) simulations where atmospheric concentrations are held constant at year 2000 values. The bars at the right of the figure indicate the best estimate (*solid line* within each bar) and the likely range assessed for the six SRES marker scenarios at 2090–2099. All temperatures are relative to the period 1980–1999 (Figures 3.1and 3.2 of the IPCC AR4, 2007 Report)

22.5 IPCC Projections of Future Climate Change

The IPCC AR4 2007 report's projections for the future are based on the four scenarios given above (Fig. 22.2). For the next two decades a warming of about 0.2°C per decade is projected for a range of scenarios in their report *Special Report on Emissions Scenarios* (*SRES*). Even if the concentrations of all GHGs and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. Afterwards, temperature projections increasingly depend on specific emissions scenarios.

For the six SRES marker scenarios, IPCC (2007) gave a "best estimate" of global mean temperature increase (2090–2099 relative to the period 1980–1999) that ranged from 1.8 to 4.0°C. Over the same time period, the "likely" range (greater than 66% probability, based on expert judgment) for these scenarios was for a global mean temperature increase of between 1.1 and 6.4°C.

The SRES scenarios were admittedly conservative. If the Greenland and Antarctic ice sheets substantially diminish as they are now showing signs of doing, the decrease in Earth's albedo will be substantial and greater warming will take place. Land and water generally have a lower albedo than ice.

Climate change projections done by scientists other than those on the IPCC have been made using several different emission scenarios. In a scenario where global emissions start to decrease by 2010 and then decline at a sustained rate of 3% per year, the likely global average temperature increase was predicted to be 1.7°C above pre-industrial levels by 2050, rising to around 2°C by 2100. In a projection designed to simulate a future where no efforts are made to reduce global emissions, the likely rise in global average temperature was predicted to be 5.5°C by 2100; a rise as high as 7°C was thought possible but less likely (Fig. 22.3).

The IPCC AR4 2007 report also produced the table given below (Table 22.1). Scientists now are in general agreement that these temperatures and projected sea-level rise are conservative projections.

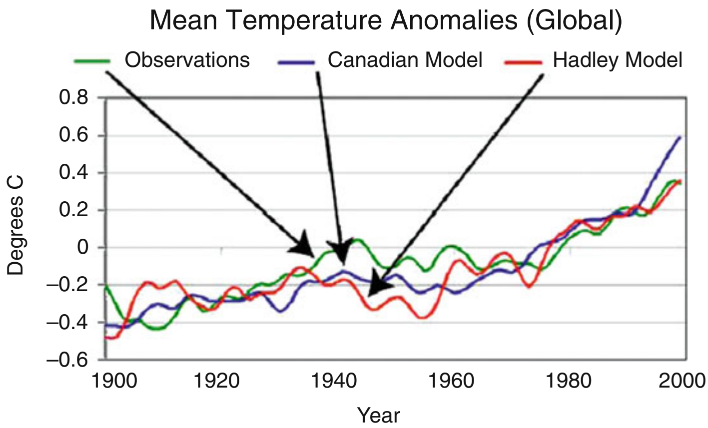


Fig. 22.3 Mean global temperatures from observations and two climate models. Trends of global temperature from observations, the United Kingdom's Hadley Centre Global Climate Model, and the Canadian Climate Center's Global Climate Model. Trends have been smoothed to remove year-to-year high frequency variations (Public Domain)

Table 22.1 Projected global average surface warming and sea level rise at the end of the twenty-first century

Case	Temperature change (°C at 2090–2099 relative to 1980–1999)[a,b] Best estimate	*Likely* range	Sea level rise (m at 2090–2099 relative to 1980–1999) Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations[c]	0.6	0.3–0.9	Not available
B1 scenario	1.8	1.1–2.9	0.18–0.38
A1T scenario	2.4	1.4–3.8	0.20–0.45
B2 scenario	2.4	1.4–3.8	0.20–0.43
A1B scenario	2.8	1.7–4.4	0.21–0.48

(continued)

Table 22.1 (continued)

Case	Temperature change (°C at 2090–2099 relative to 1980–1999)[a,b] Best estimate	*Likely* range	Sea level rise (m at 2090–2099 relative to 1980–1999) Model-based range excluding future rapid dynamical changes in ice flow
A2 scenario	3.4	2.0–5.4	0.23–0.51
A1FI scenario	4.0	2.4–6.4	0.26–0.59

From IPCC AR4 Report, SRES Table 3.1, 2007
Notes:
[a]Temperatures are assessed best estimates and likely uncertainty ranges from a hierarchy of models of varying complexity as well as observational constraints
[b]Temperature changes are expressed as the difference from the period 1980–1999. To express the change relative to the period 1850–1899 add 0.5°C
[c]Year 2000 constant composition is derived from Atmosphere-Ocean General Circulation Models (AOGCMs) only
[d]All scenarios above are six SRES marker scenarios. Approximate CO_2-eq concentrations corresponding to the computed radiative forcing due to anthropogenic GHGs and aerosols in 2100 (see p. 823 of the Working Group I TAR) for the SRES B1, AIT, B2, A1B, A2 and A1FI illustrative marker scenarios are about 600, 700, 800, 850, 1,250 and 1,550 ppm, respectively

22.6 Politics and Global Warming

Politicians usually go into politics because they crave power. Not all do, as witness the Kennedy family in the U.S. Some feel that they have gained so much from a political system or from a system of government that they decide that they should give back to that system. But these politicians are in a minority, in the U.S. as in many other parts of the world.

22.6.1 Politicians and Their Views

A politician's views are usually determined by their constituency, their religious convictions, or their social views. A prime example is given by the senior Senator from Oklahoma, Senator James Inhofe. Senator Inhofe has claimed to be an expert on climate change and global warming but he has proven to have little if any understanding of the subject and has had no training in any of the Earth sciences. He is the perfect example of someone with no expertise in a subject claiming to be an expert. Senator Inhofe has as his terminal degree a bachelor's degree in economics from the University of Tulsa, hardly qualifying him as an expert in climate science.

Amidst mounting worldwide concern from scientists, governments, and citizens, Inhofe glibly dismisses global warming as propaganda, as "the poster child of the Left," and, incredibly, as "the greatest hoax ever perpetrated on the American people."

22.6.2 Ronald Reagan

Ronald Reagan was the 40th president of the United States. He was previously a member of the Democratic Party, turned Republican, became governor of California, had a background as an actor, and was president of the Screen Actors Guild (SAG). He was ignorant of scientific issues and made no attempt to educate himself in any of them. He surrounded himself with scientists who supported weapons of mass destruction during the "cold war," such as S. Fred Singer (a notorious denier of global warming and an annual contributor to the discredited Heartland Institute's anti-environmental meetings in Washington, DC), and were not knowledgeable of or did not care about environmental issues. It was during the Reagan administration that the U.S. Republican Party's anti-science movement began. Reagan died of Alzheimer's disease that almost certainly had its beginnings while he was president. It was rumored that others made the decisions of the presidency in his stead while he was still occupying the Oval Office in the U.S. White House.

22.6.3 Richard Nixon

Richard Nixon was the 37th president of the United States. He established the U.S. Environmental Protection Agency in 1970. The initiatives supported by Nixon included the Clean Air Act of 1970 and Occupational Safety and Health Administration (OSHA); the National Environmental Policy Act required environmental impact statements for many Federal projects. Nixon vetoed the Clean Water Act of 1972—objecting not to the policy goals of the legislation but to the amount of money to be spent on them, which he deemed excessive. After Congress overrode his veto, Nixon impounded the funds he deemed unjustifiable.

22.6.4 Barak Obama

Barak Obama is the 44th President of the United States. During his campaign in 2008 he mentioned climate change numerous times but has accomplished little during his first term. He postponed approval of the XL pipeline, a proposed pipeline extending from Alberta, Canada to Houston, Texas to transport oil from tar sands, one of the dirtiest sources of petroleum on Earth. There is hope for more environmental accomplishments during his 2nd term, if he is re-elected in November 2012 and relatively no hope for environmental regulations mitigating global warming prior to 2016. The longer the delay, the more severe the consequences and the greater the cost.

Additional Readings

"Atmospheric Model Intercomparison Project". The program for climate model diagnosis and intercomparison, Lawrence Livermore National Laboratory, Livermore. Information about this project may be found at the following web site: http://www-pcmdi.llnl.gov/projects/amip/index.php

Friedman, T. L. (2008). *Hot, flat, and crowded: Why we need a green revolution and how it can renew America* (438 pp). New York: Farrar, Straus and Giroux.

McGuffie, K., & Henderson-Sellers, A. (2005). *A climate modelling primer* (p. 188). New York: Widely. ISBN 978-0-470-85751-9.

Meehl, G. A., et al. (2007). Climate change 2007, Chapter 10: Global climate projections, in IPCC AR4 WG1. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Climate change 2007: The physical science basis*, *contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press, ISBN 978-0-521-88009-1 (pb: 978-0-521-70596-7).

Soden, B. J., & Held, I. M. (2006). An assessment of climate feedbacks in coupled ocean–atmosphere models. *Journal of Climate, 19*, 3354–3360. doi:10.1175/JCLI3799.1.

Sokolov, A. P., et al. (2009). Probabilistic forecast for 21st century climate based on uncertainties in emissions (without policy) and climate parameters. *Journal of Climate, 22*(19), 5175–5204. doi:10.1175/2009JCLI2863.1.

Wang, W. C., & Stone, P. H. (1980). Effect of ice-albedo feedback on global sensitivity in a one-dimensional radiative-convective climate model. *Journal of the Atmospheric Sciences, 37*(3), 545–552. Bibcode 1980JAtS…37..545W. doi:10.1175/1520-0469(1980)037<0545:EOIAFO>2.0.CO;2. ISSN 1520-0469.

Part X
Understanding Climate Change Denial

Chapter 23
Understanding Climate Change Denial

Abstract At its heart, climate denial is the rejection of the scientific consensus that humans are disrupting the climate. Denial of a consensus can be identified by five telltale characteristics: fake experts, cherry picking, logical fallacies, impossible expectations and conspiracy theories. These techniques are observed in the tactics and strategies of the climate denial movement, disseminated by ideological think-tanks, some conservative governments and vested interests through a range of media streams. The key to responding to climate misinformation is to provide alternative narratives that are more compelling than the myths they replace.

Keywords Climate denial • Denier • Consensus • Peer-review • Uncertainty • Fake experts • Cherry picking • Logical fallacies • Impossible expectations • Conspiracy theories "Climategate" • Intergovernmental Panel on Climate Change, IPCC • Conservative ideology • Media balance-as-bias • Conservative think tanks • Government • Corporate vested interests • Internet • Misinformation • Refutation • Backfire effect

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_23,

Things to Know	
Consensus of evidence	Consensus of scientific organizations
Denialism versus skepticism	Consensus of scientists
Conservative ideology	Media balance-as-bias
Conservative think tanks	Government and vested interests
Internet role in misinformation	Backfire effects
Alternative narratives	Fake experts
Cherry picking	Logical fallacies
Impossible expectations	

23.1 Introduction

There is actually no such thing as a climate change denier. No one denies that climate changes (in fact, most climate change deniers will argue that past climate change is evidence that current global warming is also natural). What 'climate deniers' reject is the scientific consensus that humans are disrupting the climate. A more appropriate term would be 'consensus denier' (but for convention's sake, we will adopt 'climate denier').

The term 'denier' is also controversial, with connotations that climate denial is akin to Holocaust denial. It's important to stress that the term denier should not be used as a pejorative term equating climate denial to Holocaust denial. Climate change and the Holocaust are not equivalent. However, it is appropriate and instructive to examine the rhetorical tactics and psychological processes at play involved in the denial of climate science. The climate denial movement has employed numerous strategies and rhetorical tactics to cast doubt or distract from the consensus. These efforts have been successful, as illustrated by the increase in public confusion about climate change at the same time that the scientific consensus has strengthened. This chapter will examine the various strategies, rhetorical arguments and driving forces of climate denial.

23.2 Basis for the Scientific Consensus on Climate Change

To understand climate denial, we need to understand first what is being denied. Climate denial is the rejection of the scientific consensus that human activity is disrupting our climate. Scientific consensus is typically thought of as the agreement among the scientific community and most popularly expressed as the near-unanimous agreement between actively researching climate scientists. Numerous surveys of the climate science community have been conducted since the early 1990s to determine the level of consensus that humans were causing global warming. Over time, the percentage of climate scientists who agreed that humans are causing global warming has increased steadily, demonstrating a strengthening consensus (Fig. 23.1).

Two of the most recent studies adopting different methodologies have arrived at strikingly consistent results. One study led by Peter Doran et al. in 2009 surveyed

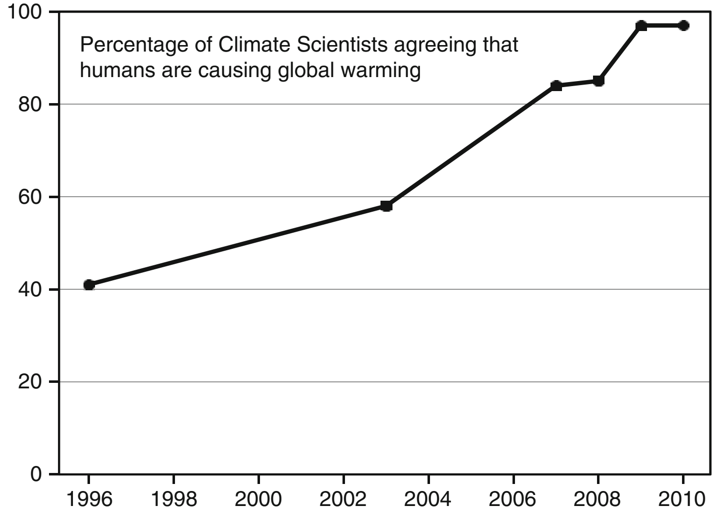


Fig. 23.1 Percentage of climate scientists agreeing that humans are causing global warming (Adapted from Bray (2010) with addition of Anderegg et al. (2010))

over 3,000 Earth scientists and found that for areas of expertise more relevant to climate change, the agreement about human-caused global warming was higher. For the most qualified experts, climate scientists actively publishing peer-reviewed research, there was 97% agreement.

This result is echoed in a separate study that compiled a database of scientists from public declarations on climate change, both supporting and rejecting the consensus. The publishing record of each scientist was then scanned to determine their level of expertise on climate change. Among scientists who had published peer-reviewed papers, there was 97% agreement. The authors tested the robustness of this result by employing different thresholds for the number of climate papers published. For varying thresholds, agreement varied between 97 and 98%, strikingly consistent with the Doran survey (Anderegg et al. 2010).

The consensus on climate change also manifests in the published statements of prestigious scientific organizations throughout the world. Academies of Science from many countries endorse the consensus view, as do many prestigious scientific organizations such as NASA, the National Oceanic and Atmospheric Administration (NOAA) and the Royal Society of the UK. The Academies of Science from the following countries have all endorsed the consensus:

Australia	Ireland	Sénégal
Brazil	Italy	South Africa
Belgium	Japan	Sudan
Cameroon	Kenya	Sweden
Canada	Madagascar	Tanzania

(continued)

(continued)

China	Malayasia	Turkey
France	Mexico	Uganda
Germany	New Zealand	United Kingdom
Ghana	Nigeria	USA
India	Poland	Zambia
Indonesia	Russia	Zimbabwe

However, a scientific consensus is not decided by majority vote. This is articulated concisely by John Reisman in the ironically titled *'Exposing the Climate hoax: It's all about the economy'* (Reisman 2011):

> Science is not a democracy. It is a dictatorship. It is evidence that does the dictating.

While individual scientists may have their personal views on climate change, they must back up their opinions with empirical evidence and robust analysis that withstands the scrutiny of the peer-review process and then must survive the test of time. Thus the peer-reviewed literature is a robust indicator of the state of the scientific consensus. Naomi Oreskes conducted the seminal study of peer-reviewed climate research in 2004, surveying the abstracts of papers from 1993 to 2003 matching the search "global climate change" (Oreskes 2004). The startling result from this survey is that out of the 928 papers surveyed, none were found that rejected the consensus position that humans caused most of global warming over the last 50 years.

This is not to say no rejection papers exist. A broader survey of peer-reviewed papers was conducted (coordinated by John Cook) of 12,465 papers spanning 1991–2011, matching the searches "global climate change" and "global warming". This broader survey compared the number of papers that endorse the consensus versus the number of papers that reject the consensus to find a widening gap between the two, with the number of papers endorsing the consensus increasing at an accelerating rate (Fig. 23.2).

Thus the scientific consensus on climate change manifests in a multitude of ways, just as there are many lines of evidence for human-caused global warming. It is important to appreciate this multi-faceted nature of consensus in order to understand how climate deniers reject the consensus.

Why is consensus important? When people understand that there is consensus among climate scientists, they are more likely to support climate policy. Conversely, if the public thinks that scientists disagree on global warming, they're less certain that global warming is happening and show less support for climate action (Ding et al. 2011). Consequently, a key strategy of the climate denial movement has been to cast doubt on the scientific consensus. A striking example of this strategy is articulated in a memo by political strategist Frank Luntz who provided the following advice to Republicans in 2002:

> Voters believe that there is no consensus about global warming in the scientific community. Should the public come to believe that the scientific issues are settled, their views about global warming will change accordingly. Therefore, you need to continue to make the lack of scientific certainty a primary issue in the debate.

This strategy has been quite successful in persuading the public that there is much disagreement among the scientific community. Public opinion polls conducted

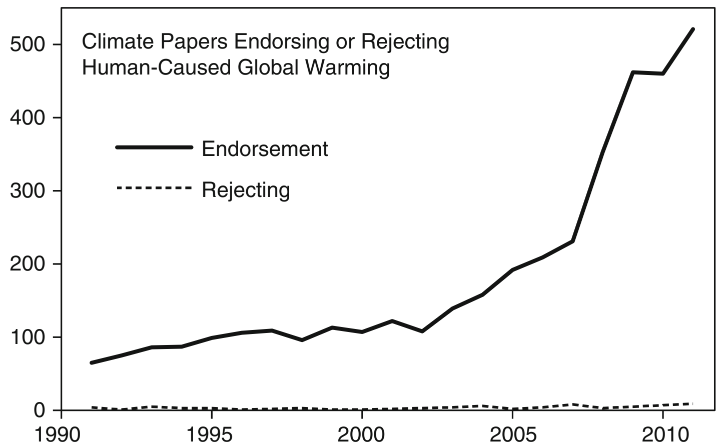


Fig. 23.2 Peer-reviewed papers from the Web of Science matching the searches 'global warming' or 'global climate change' from 1991 to 2011. *Solid line* represents the number of papers per year endorsing human-caused global warming while dashed line represents rejection papers

from 1997 to 2007 have shown that over this period, around 60% of the public thought there was a lot of disagreement between scientists about whether global warming was happening (Nisbet and Myers 2007). While the scientific consensus has been steadily strengthening, the public continues to erroneously think there is significant disagreement.

23.3 Characteristics of Denial

How does one distinguish between climate denial and genuine scientific skepticism? Mark and Chris Hoofnagle identified five tell-tale characteristics of science denial (Hoofnagle and Hoofnagle 2007). They use the following definition for science denial:

> Denialism is the employment of rhetorical tactics to give the appearance of argument or legitimate debate, when in actuality there is none. These false arguments are used when one has few or no facts to support one's viewpoint against a scientific consensus or against overwhelming evidence to the contrary.

Simply put, denialism is the attempt to deny a scientific consensus based on rhetorical argument. A subsequent analysis by Diethelm and McKee (2009) examined a number of different movements that deny a scientific consensus, including climate denial, the denial of the link between smoking and cancer and evolution denial. They identified that the five characteristics of denial appear in each movement. They are:

1. Fake Experts
2. Cherry Picking
3. Logical Fallacies

4. Impossible Expectations
5. Conspiracy theories

These characteristics shall now be examined in more detail with a number of applications relating to climate misinformation.

23.3.1 Fake Experts

Most people aren't in a position to directly investigate complex scientific issues and rely on experts to inform their views. When people think there is a consensus among climate scientists about global warming, this strongly informs their views on global warming itself. One tactic to prevent the public from correctly perceiving the consensus is to invoke dissenting non-experts who appear to be highly qualified while not having published any actual climate research. This paints the picture of a scientific community still in strong disagreement, with both sides possessing roughly equal numbers. This tactic has a long history:

- An early example of this strategy comes from 1992, when S. Fred Singer released a "Statement by Atmospheric Scientists on Greenhouse Warming", featuring 47 signatories comprising mostly of weather forecasters and physicists.
- In 1995, Singer also published the "Leipzig Declaration" that claimed to refute that there was a scientific consensus about the importance of greenhouse warming. It featured 80 scientists and 25 TV weather forecasters. An investigation by Øjvind Hesselage found that 12 of the signatories denied signing the declaration while many worked in fields unrelated to climate (Jensen 1998).
- In 2007, Dennis Avery (a journalist and senior fellow at the Hudson Institute) published a paper "500 Scientists Whose Research Contradicts Man-Made Global Warming Scares" on the Heartland Institute website (Avery 2007). A number of scientists on the list expressed outrage and dismay at being included in such a list (Hoggan 2009). Avery is yet to apologize to objecting scientists for their inclusion.

In 2008, political lobbyist Marc Morano published a U.S. Senate Minority Report (working for Senator James Inhofe) titled "More Than 650 International Scientists Dissent over Man-Made Global Warming Claims" (Morano 2008). An investigation by the Office of Public Policy found that the "vast majority are neither climate scientists, nor have they published in fields that bear directly on climate science" (Kurtz et al. 2009).

The largest example of the fake expert (and best demonstration of the strategy) is The Petition Project by the Oregon Institute of Science and Medicine, featuring over 31,000 scientists claiming that there is no evidence that humans are disrupting climate (OISM 1999). Around 99.9% of the scientists are not climate scientists. The Petition Project will be examined in more detail in the next chapter.

A variation of the Fake Expert strategy is to take the handful of remaining dissenting climate scientists and magnify their voices to give the impression of more significant disagreement then there actually is.

A 1998 strategy memo by oil company representatives and conservative think tank members illustrates this strategy (Hoggan 2009). They suggested a "National Media Relations Program" to "identify, recruit and train" a team of five new 'independent' scientists to participate in media outreach on climate science. A key element of the strategy was the targeting of mainstream media with a steady stream of material to "undercut the 'conventional wisdom' on climate science". The goal was to ensure that "media coverage reflects a balance on climate science". The issue of media balance will be shortly examined in more detail.

The 2002 Luntz memo also explored the idea of amplifying the role of dissenting scientists. He recommended Republicans should "…be even more active in recruiting experts who are sympathetic to your view and much more active in making them part of your message… If you wish to challenge the prevailing wisdom about global warming, it is more effective to have professionals making the case than politicians."

23.3.2 Cherry Picking

The consensus on climate change is based on the full body of evidence that has led to the conclusion that human activities are having a significant effect on Earth's climate. Consequently, a common technique in climate change denial is to focus on select pieces of data, often out of context, whilst excluding any data that conflicts with the desired conclusion.

Of course, it is usually not practical to present the full body of evidence on most occasions so how does one distinguish between misleading cherry picking and appropriate selection of data? Cherry picking occurs when the conclusion derived from a small selection of data differs from the conclusion arising from the full body of evidence. Common examples of this technique involve:

- **Short periods of time**. Focusing on short periods in a time series to argue a long-term trend. This is readily achievable with highly variable data such as the surface temperature record, by selecting a short period of time that starts at one extreme and ends at the opposite extreme, amidst a long-term trend. This may take the form of calculating trends over a short period where a statistically significant trend is not possible. The most egregious application of this form of cherry pick is to compare single data points in a noisy dataset.
- **Isolated examples**. Selecting isolated examples while ignoring others that lead to the opposite result. For example, although glaciers are retreating globally at an accelerating rate, there remain a small number of isolated glaciers that are growing. Using a few growing glaciers as an argument against global warming is ignoring the full body of evidence.
- **Specific locations**. Focusing on a specific location or region to the exclusion of broader regional data. A common example is selecting a temperature

reconstruction of a single location to argue that the Medieval Warm Period was warmer than current temperatures. However, when one includes data from across the world to build a global temperature reconstruction, one finds cooler temperatures at one location balance warmer temperatures from elsewhere. The result is that global average temperature over the past few decades are warmer than any period over the last 1,000 years, including the Medieval Warm Period.

- **Isolated papers**. Selecting isolated research papers that provide a "denial" viewpoint while ignoring climate papers that come to the opposite conclusion or that refute the denial paper. A commonly mentioned paper by Richard Lindzen purports to find low climate sensitivity using satellite data (Lindzen and Choi 2009). However, rarely mentioned are the numerous papers that find high climate sensitivity, even using the same satellite data as Lindzen, or the papers that point out the flaws in Lindzen's methodology. Conversely, critics of Michael Mann's 1998 hockey stick paper typically ignore the fact that over a decade's worth of research has since independently confirmed Mann's conclusions.
- **Quote mining**. Taking quotes out-of-context from research or correspondence to paint a misleading picture in contrast to what the full context provides. Climategate emails (see Conspiracy Theories) were frequently quote-mined to paint the impression of scientists engaging in nefarious behavior when the full context (and understanding of the science being discussed) revealed scientists merely discussing their trade in technical terms.

23.3.3 Logical Fallacies

Logical fallacies are logically false arguments leading to an invalid conclusion. Logical fallacies are based on erroneous logic, misdirection or false characterizations. It is useful to be aware of common logical fallacies used by climate deniers in order to effectively identify poorly constructed arguments:

- ***Ad hominem* attacks**. These dismiss a person's arguments by attacking the person. Climate scientists routinely face personal attacks, particularly scientists who publish prominent research highlighting the human influence on climate change. Michael Mann labels this the Serengeti Strategy, referring to predators at the Serengeti National Park that target animals at the edge of the herd (Mann 2012). In a similar fashion, individual scientists are subjected to personal attacks with the intent to discredit climate science in general.
- **Straw man arguments**. This involves misrepresenting your opponent so that their position is easier to argue against. For example, aspects of climate science are mischaracterized presenting false positions that are easily refuted. The claim that 'climate scientists say carbon dioxide is the only driver of climate' is an oversimplification of the science; whereas in reality climate scientists consider many different forcings that drive climate (it just happens that carbon dioxide is currently the dominant climate forcing). Another misrepresentation is the myth

'there was a consensus about global cooling in the 1970s' which was shown to be false by a survey of peer-reviewed papers in the 1970s which found the vast majority of published research predicted warming.

- **Red Herring**. These pose a distraction with a statement that is easy to support but has nothing to do with the final argued conclusion. For example, the argument that carbon dioxide isn't a problem because it's a colorless, odorless gas. However, carbon dioxide is a problem not because it's smelly or visually unattractive but because it traps heat. In fact, it's because CO_2 is colorless (e.g., invisible) that it is a greenhouse gas. It's invisible to sunlight but traps infrared radiation as it is on its way to escaping out to space. Similarly, another climate myth is that carbon dioxide is plant food and hence good for plants. In isolation, carbon dioxide is good for plant growth. But plants also need water and a certain temperature range to thrive. Global warming disrupts the climate's water cycle, causing more intense droughts and floods and also increases heat waves that cause heat stress among plants.
- **False Analogy**. This is an argument made by analogy where the analogy is not a valid comparison. A good example is the Galileo fallacy, where climate deniers liken themselves to Galileo who defied the consensus that the Sun revolves around the Earth. The irony is that Galileo was suppressed not by scientists but by religious and political forces. Galileo's conclusions were based on observation and logic, which later came to be known as the scientific method. In contrast, climate denial is driven by ideology while climate scientists employ the scientific method pioneered by Galileo. The analogy is not only inappropriate, it is an inversion of reality.
- **Association Fallacy**. This argues that because two things share a property, they are the same. For example, the Heartland Institute, a conservative think-tank that generates climate misinformation, displayed a billboard featuring a photo of terrorist Ted Kaczynski (the Unabomber) with the text "I still believe in global warming. Do you?" This argued that climate science is invalid because a terrorist believed in global warming. This is the logical equivalent to arguing that vegetarianism is invalid because Hitler was a vegetarian. It also implies that climate scientists are equivalent to terrorists.
- ***Non Sequitor***. This is Latin for "it does not follow" and applies to arguments where the stated conclusion is not supported by its premise. The most common example of this (in fact, the most popular climate myth) is "climate has changed naturally in the past therefore current warming must be natural". This is equivalent to arguing that people have died from natural causes in the past so no one ever gets murdered now. Ironically, the main lesson from past climate change is that our climate is highly sensitive due to reinforcing feedbacks. Past climate change is not a cause for comfort but a cause for concern.
- **False Dilemma**. This is the case where only two alternatives are considered, while there may be another alternative or both options may be simultaneously viable. For example, the argument "The ice core record shows CO_2 lags temperature thus proving temperature drives CO_2, not the other way around". The fallacy here is the assumption that one must choose between either CO_2 driving temperature

or temperature driving CO_2. In reality, both occur. The result is a reinforcing feedback, amplifying the modest warming from planetary orbital changes to bring our planet out of an ice age.

Note – some logical fallacies such as argument from authority (fake experts) or cherry picking are so common, they have been elevated to one of the five main characteristics of denial.

23.3.4 Impossible Expectations

Impossible expectations involve demanding unrealistic standards of proof before acting on the science. Uncertainty is an important element to the scientific method, which is often probabilistic rather than deterministic. However, opponents to the scientific consensus misrepresent the nature of science by perpetuating the misconception that science is about providing absolute proof. This technique of using uncertainty as an attack point is labeled by sociologist William Freudenburg as "Scientific Certainty Argumentation Methods" (with the apt acronym SCAM). The SCAM strategy is remarkably effective even in cases were scientific results are robust with a clear consensus (Freudenburg et al. 2008).

A leading pioneer of the SCAM strategy was the tobacco industry who attacked the scientific consensus that cigarette smoking caused cancer. A key element to their strategy was summed up by one tobacco executive: "Doubt is our product". Their goal was to highlight the uncertainty and obscure the fact that a consensus existed (as documented by Oreskes and Conway 2010).

An articulation of impossible expectations regarding climate science is found in the Luntz memo to Republicans which suggests that:

> Should the public come to believe that the scientific issues are settled, their views about global warming will change accordingly. Therefore, you need to continue to make the lack of scientific certainty a primary issue in the debate…

This strategy misrepresents the nature of science, arguing that we should wait for 100% proof before acting. This is not how science operates and is especially not how we operate in real life when managing risk. To wait for 100% certainty is to never act. Greater uncertainty means a higher chance that the climate response will be larger than expected. In the case of climate change, uncertainty is not our friend.

23.3.5 Conspiracy Theories

A conspiracy is a secret plan among a number of people, generally to implement a nefarious scheme of some sort. The fact that the world's experts, scientific organizations and peer-reviewed journals find agreement requires explanation and a convenient alternative is the accusation of corruption or a conspiracy among scientists.

One identifying feature of a conspiracy theory is exaggerated claims about the power of the conspirators. The more widespread and powerful the conspiracy, the more implausible that such a conspiracy could remain undetected. Thus the notion of a conspiracy among scientific organizations across the globe and thousands of scientists in dozens of countries pushes the realms of credibility.

Claims of climate conspiracy theories have been around for many years. In 1996, the Intergovernmental Panel on Climate Change released their Second Assessment Report (SAR), concluding that 'the balance of evidence suggests a discernible human influence on climate'. Within one month, retired scientist Frederick Seitz published an op-ed in the Wall Street Journal, accusing the IPCC of a "major deception on global warming" (Seitz 1996). Seitz made no scientific arguments but attacked the IPCC's procedures, successfully shifting much of the public discussion from the science to issues of personalities and motivations.

An often-attacked figure is Michael Mann who was lead author of the hockey stick graph in 1998. Since then, Mann has endured relentless attacks on his research and credibility, as documented in his book "The Hockey Stick and the Climate Wars". One of Mann's major public critics has been Senator James Inhofe, who published his conspiracy theories in the 2012 book "The Greatest Hoax" (Inhofe 2012).

Climate conspiracy theories achieved mainstream consciousness in late 2009 when a server at the Climate Research Unit at the University of East Anglia was hacked with years of private email correspondence posted on the web. This led to an international scandal that the media dubbed "Climategate". Climate deniers quote-mined selected emails as evidence that scientists were engaged in a conspiracy to falsify climate data to exaggerate the warming trend.

Since 'Climategate', nine (9) independent investigations across the globe have concluded there is no evidence of data falsification or wrongdoing by climate scientists. To the conspiracy theorists, however, investigations that find no wrongdoing are only further evidence that there is a conspiracy. This is the world that the conspiracy theorist inhabits – where every piece of evidence that opposes their worldview is further confirmation of the conspiracy.

A survey of American adults was conducted to determine the impact of Climategate (Leiserowitz et al. 2010). Around 13% of Americans reported becoming more certain that global warming was not happening and to have less trust in scientists. However, a key finding of the survey was that conservatives already predisposed to disbelieve climate science were the most likely to report lost trust in climate scientists. Meanwhile liberals did not lose trust in scientists. Political ideology was a strong predictor in whether Americans lost trust in scientists or not. This underscores the important role of political ideology in shaping public views on climate change.

The unlikelihood of a climate conspiracy is apparent when one considers the global nature of the climate consensus. Academies of Science from countries all over the world endorse the consensus. A survey of 12,465 papers found scientists from all over the world endorsing the consensus. This would require a conspiracy of such scope, human history would never before have seen its equal.

There are several variations of conspiracy theory to be aware of:

- **Religious orthodoxy**. A more subtle form of climate conspiracy theory is not the accusation of a cabal of deception but that of a mainstream orthodoxy suppressing a minority view. The Galileo fallacy feeds into this conspiracy theory. This narrative is often couched in religious terms, referring to climate scientists as dogmatic priests while endorsement of the consensus is framed as faith and belief. This is of course an inversion of reality where climate scientists are driven by evidence and the scientific method.
- **Funding Gravy Train**. An alternative version of the conspiracy theory is the myth that scientists who endorse the consensus are motivated by funding. Again, this inverts reality. Research grants and papers aren't accepted for merely repeating accepted knowledge. On the contrary, scientific research is only accepted (and funded) if it expands our knowledge and understanding.
- **Inversionism**. Another variation of conspiracy theory is explored by Diethelm and McKee in their paper on science denialism, "in which some of one's own characteristics and motivations are attributed to others" (Diethelm and McKee 2009). Psychologically, this is known as projection. This is seen in accusations of climate deniers that climate scientists are politically motivated (whereas much evidence has been produced that climate denial is ideologically driven). Climate deniers accuse scientists of being motivated by money when much of the funding and even leading voices of the climate denial movement are funded by the fossil fuel industry.

23.3.6 Denial Characteristics at a Psychological Level

While the five characteristics of denial are manifested as misleading, rhetorical arguments need not be always deliberately deceptive. Science denial can operate at a psychological level and bias how one processes evidence. The behavior resulting from unconscious, psychological bias can be indistinguishable from deliberately misleading rhetorical techniques. Thus it is possible for deniers to display the five characteristics of denial while genuinely believing these false rhetorical arguments.

- **Fake Experts**. The reliance on fake experts can derive from the way people form their beliefs about expert opinion. Greater expertise is attributed to people who agree with one's existing beliefs and values (Kahan et al. 2011). When confronted with the term 'scientific consensus', people perform a mental survey of the experts they have observed, more readily recalling experts who are consistent with their own beliefs. This leads to a distorted view of the state of consensus, with the group of experts they agree with taking on a magnified role.
- **Cherry picking**. This can derive from the psychological phenomenon of confirmation bias. This is the process where people attribute greater weight to information that confirms prior beliefs while downplaying any disconfirming

evidence. We remember the hits but tend to forget the misses. This is observed in experiments where people with different prior beliefs are shown the same information and yet their beliefs update in different directions. One experiment presented information about a nuclear breakdown to both supporters and opponents of nuclear power. The nuclear supporters concentrated on the fact that that the safeguards worked while nuclear opponents focused on the fact that the breakdown happened at all. Both parties strengthened their original belief.

- **Logical fallacies**. These can also arise from cognitive bias (Correia 2011). For example, the straw man fallacy, where one misrepresents an opponent's position, can result from focusing on an opponent's weaker arguments while ignoring their stronger arguments (Talisse and Aikin 2006). In many cases, the arguer is unaware of the logical fallacy and the unconscious biases that cause them.
- **Impossible Expectations**. The demand for impossible expectations can arise from disconfirmation bias. This is the flip side of confirmation bias, which is the uncritical acceptance of confirming evidence. In the case of disconfirmation bias, threatening evidence is vigorously opposed. The result is that presenting evidence to correct a person's false beliefs can often have a backfire effect. A non-climate example is an experiment where participants who believed Saddam Hussein was linked to the 9/11 terrorist attacks were shown conclusive evidence that there was no link, including a quote from George W. Bush (Prasad et al. 2009). One response to the evidence was counter arguing or directly rebutting the information, which resulted in participants holding to their false beliefs stronger than ever.
- **Conspiracy Theories**. People who deny a scientific consensus are more likely to distrust science. However, science denial has further implications than just conspiracy theories about scientists. Climate deniers are more likely to hold to a number of conspiracy theories. This includes not just conspiracy theories about climate science but also related to non-climate issues such as the 9/11 terrorist attacks and the 'faked' moon landing (Lewandowsky et al. in press).

23.4 Drivers of Climate Denial

In 1988, global warming was a bi-partisan issue. Republican George H. W. Bush pledged to "fight the greenhouse effect with the White House effect" (Boykoff and Boykoff 2004). However, within a few years, the mainstream media was portraying climate change as an unresolved issue, giving climate deniers equal voice with the consensus views of the climate science community. While the scientific consensus strengthened, public opinion on climate change stagnated with a growing divergence between scientists and the general public. There is also an increasing gap between liberals and conservatives, with liberals becoming more accepting of the science while more conservatives are rejecting the science. We shall now explore the driving forces behind the climate denial movement and the growing polarization.

23.4.1 *Conservative Ideology*

Belief that humans are not causing global warming is closely associated with free-market ideology (Heath and Gifford 2006). This ideology opposes the government regulation of industry, insisting that the market should be free of government intervention. In the case of climate change, the industries most affected are related to the burning of fossil fuels, emitting greenhouse gases that cause global warming. Rather than seek solutions to the problem of global warming, many choose not to believe there is a problem in the first place, denying the scientific evidence.

Over the period 1998 to 2008, overall public opinion about climate change has shifted very little. This is not to say there hasn't been any change. Opinion has been shifting but for two different groups, they're shifting in opposite directions. In the U.S., the percentage of Democrats who agree that global warming is happening has increased from 47 to 76%. At the same time, the percentage of Republicans agreeing has dropped from 46 to 41% (Hamilton 2009).

The polarization between Democrat and Republican is not just over time but also across education levels. As Republicans and Democrats become more educated, their concern about climate change moves in opposite directions. More educated Republicans are less concerned about climate change while more educated Democrats have a greater concern. This startling result undermines the intuitive view that more education is the answer to reducing climate denial. For a significant percentage of the general public, denial is not due to a deficit of information but is rooted in ideology.

In a series of Gallup surveys from 2001 to 2010, conservative white males were significantly more likely than other adults to report denialist views (McCright and Dunlap 2011). For instance, 59% of conservative white males deny there's a scientific consensus compared to 35% of all other adults. Similarly, 58% of conservative white males deny that recent temperature increases are primarily caused by human activities, nearly double the percentage of all other adults.

The other striking statistic from these surveys is that a greater percentage of conservative white males (30.4%) report that they understand global warming very well compared to all other adults (18.0%). In fact, among conservative white males, the higher they rate their own understanding of climate, the more likely they are to deny the science. Thus there is strong evidence for a conservative white male effect that has them both confident that they understand climate science and more likely to deny the scientific consensus on climate change.

23.4.2 *Conservative Think Tanks*

Significant responsibility for the growth of climate denial is attributable to conservative think tanks. These are non-profit, advocacy organizations that promote core conservative ideals such as 'free enterprise' and 'limited government'. Funded by wealthy conservative foundations and corporations (often from the fossil fuel industry), they act as a means of influencing public opinion and policy makers. They began to take form in the 1970s but increased in activity in the early 1990s (Jacques et al. 2008).

Their primary tactic is to cast doubt on environmental science, alleging that the science is corrupt and either fabricated or exaggerated. Underlying the attack on science is the campaign against government regulation. A survey of online news media from 1995 to 2000 searching for the term 'junk science' (a common phrase used by conservative think tanks) found the overwhelming majority of articles also contained an anti-regulatory message.

Conservative think tanks promote their anti-regulatory, anti-science message through a constant stream of published content ranging from books to newspaper editorials, coupled with TV and radio appearances. From 1972 to 2005, 92% of English-language books that promoted environmental skepticism had a clear link to conservative think tanks.

Another successful outcome of the misinformation campaign has been to establish their in-house "experts" as having equal legitimacy to qualified climate scientists in the eyes of the media and public. This is especially significant considering most of their 'experts' are economists, policy analysts and legal scholars rather than scientists.

While advancing non-experts, they have also campaigned aggressively to bring down the actual experts, intimidating or threatening climate scientists. Throughout the 1990s, members of conservative think tanks regularly labeled mainstream climate scientists as 'junk scientists.' The goal was to sully the image of mainstream climate science by association.

Having ready access to the media, conservative think tanks have effectively exploited the journalistic norm of balance, achieving a disproportionate amount of media attention for skeptical non-experts. They have also achieved the same amount of representation as climate scientists at Congressional hearings on climate change.

Thus conservative think tanks have been a significant influence in the campaign to confuse the public about the science and delay climate policy.

23.4.3 Mainstream Media's Balance-as-Bias

The general public obtains most of its scientific information from mainstream media such as newspapers, radio and television. Consequently, the handling of climate science by the media is crucial to the shaping of public opinion. The journalistic norm of balance requires that the views of conflicting sides are both presented with roughly equal attention. The conservative movement has exploited this 'balancing norm' by promoting a handful of climate deniers to national prominence. This has allowed a small, vocal minority to have their views amplified.

Thus, despite the fact that there is agreement among the scientific community, the media have granted equal time to climate deniers alongside mainstream climate scientists. From 1988 to 2002, just over half (52%) of news reports covering climate change granted equal attention to denialist and mainstream views, while 6% exclusively presented the denialist viewpoint. Only 41% of media portrayed climate change as predominantly anthropogenic. This skewed presentation has led to a perception of continued division among the scientific community that doesn't actually exist. The so-called balanced media coverage actually presents a distorted, inaccurate picture, characterized by the term 'balance-as-bias' (Boykoff and Boykoff 2004).

One experiment tested the impact of giving climate deniers equal weight with scientists by measuring the effect of showing (1) a news story with only a mainstream scientist (2) compared to a news story with a mainstream scientist followed by a skeptical scientist. Including the skeptic in the news report significantly reduced the number of people who believed that scientists agreed about climate change from 48 to 36% (Malka et al. 2009).

The fragmentation of mainstream media, with the development of cable TV and specialized radio shows, has further contributed to climate polarization. Specialized media sources allow people to select information sources consistent with their beliefs, reinforcing their pre-existing attitudes (Hamilton 2009).

23.4.4 Government

Significant opposition to climate science has originated from government. There is a significant body of literature documenting cases where the George W. Bush administration censored scientists and distorted scientific evidence while promoting fringe science that conflicted with the scientific consensus (McCright and Dunlap 2010). Some examples of government intervention in climate science include:

- **Editing Scientific Reports**. A prominent example of government distortion of scientific results is that of Philip Cooney, chief of staff for the White House Council on Environmental Quality under George W. Bush. Cooney made a number of edits to the Environmental Protection Agency's 2003 'State of the Environment' report, editing out references to a 2001 National Academy of Science (NAS) report and inserting references to a discredited paper by two climate deniers.
- **Magnifying uncertainty**. The George W. Bush White House mischaracterized the 2001 NAS report by placing the focus on any mention of uncertainty. In justifying why the U.S. would not be party to the Kyoto Protocol, President Bush characterized the report as saying "we do not know how much our climate could, or will change in the future. We do not know how fast change will occur, or even how some of our actions could impact it."
- **Intimidating scientists**. Various government representatives have attempted to intimidate or threaten sanctions on individual scientists. Congressman Joe Barton targeted Michael Mann and other authors of the 1998 hockey stick graph, demanding that they turn over their data and research materials for the previous 15 years. Both Joe Barton and Senator James Inhofe have convened Congressional

hearings where invited witnesses associated with conservative think tanks testified against the scientists.

- **Censoring scientists**. Scientists from government agencies have been silenced or censored by members of the George W. Bush administration. Dr. James Hansen, renowned climate scientist from NASA, had his public statements and media interviews filtered by NASA public affairs officials in order to prevent him from airing any views conflicting with the government's position on climate (Hansen 2009).

23.4.5 Corporate Vested Interests

While the driving force behind climate denial is ideology, the denial movement has received significant financial support from corporate vested interests. Specifically, this involves fossil fuel industries whose profits are threatened by regulation of carbon dioxide emission. Vested interests have funded the dissemination of climate misinformation, by funding a number of conservative think tanks responsible for producing climate denial material (Jacques et al. 2008).

In 1991, the Western Fuels Association combined with a number of other fossil fuel related associations and institutes to produce a series of campaigns casting doubt on climate science (Hoggan 2009). These included a video extolling the positive benefits of carbon dioxide, with hundreds of free copies distributed to public and university libraries.

In the decade after the Kyoto Protocol was introduced in 1997, Exxon-Mobil invested more than $20 million in think tanks that promoted climate denial. This inspired the Royal Society of London to challenge Exxon-Mobil to stop funding organizations that disseminated climate denial.

An investigation by Greenpeace has revealed that from 1997 to 2008, the oil, chemical and polluting corporations of Koch Industries has contributed over $48 million to front groups that cast doubt on climate science (Greenpeace 2011). Ironically, they also funded the Berkeley Earth Surface Temperature (BEST) study, an independent project that purported to check other surface temperature records by NASA and HadCRUT. The BEST results confirmed the other temperature records, finding a nearly identical global warming trend.

23.4.6 Internet

The Internet has facilitated the quick and easy dissemination of climate misinformation across the globe. Some of the negative effects of the Internet are as follows.

- **Cyber ghettos**. The Internet contributes to the polarization surrounding public opinion on climate change. It provides an environment where individuals can selectively source their information from websites that support their existing views. This leads to the development of 'cyber-ghettos' where 'people go to support

their own opinions and attack opposing ones' (Johnson et al. 2009). This creates pockets of denial that can become significant sources of misinformation. One of the highest trafficked climate blogs is wattsupwiththat.com, a website that publishes climate misinformation on a daily basis.
- **Expedient publishing of misinformation**. The Internet also enables expedient publishing of information without the rigorous quality controls in the peer-reviewed system. This places the peer-reviewed system, which can take months to process, at a severe disadvantage. What makes peer-review so strong is a weakness in terms of communication, where myths can propagate and take hold in the public consciousness before scientists can even draft a response to submit to a journal.
- **Instant dissemination**. Winston Churchill once said "*A lie gets halfway around the world before the truth has a chance to get its pants on.*" This was before the existence of the Internet where a catchy myth can go viral instantly via social media websites such as Twitter and Facebook. A tweet can propagate the globe in seconds in stark contrast to scientific research which often requires months of peer-review and subsequent months before publication. Social media features many tools enabling readers to quickly and easily share information with their network of contacts.

Of course the Internet is a two-edged sword. It also enables scientists and communicators to rebut myths and communicate the science. Thus it is imperative that scientists and communicators make use of the technologies available on the Internet and social media to communicate science to the general public as a counterbalance to the climate denial online machine.

23.5 Responding to Climate Denial

Once misinformation takes root, it is notoriously difficult to dislodge. In fact, debunking a myth runs the danger of actually making matters worse and reinforcing the myth! Scientists and communicators need to be aware of the numerous psychological processes that come into play when correcting misinformation. However, once all the various backfire effects have been successfully navigated, the psychology of misinformation reveals that debunking myths presents an opportunity to educate.

Educators are beginning to discuss misinformation in the classroom in order to educate students about the nature of scientific consensus and strengthen critical thinking (Bedford 2010).

The next section summarizes research into the most effective ways of refuting misinformation and avoiding backfire effects that reinforce the myth.

23.5.1 Familiarity Backfire Effect

When refuting a myth, one runs the risk of making people more familiar with the myth. However, the more familiar people are with information, the more likely they are to accept it as true. Thus debunking misinformation runs the risk of provoking a

'Familiarity Backfire Effect', with people remembering the myth more clearly after the debunking. This can be avoided by placing the emphasis on the facts you wish to communicate rather than the myth. Communicate your core fact in your headline and opening text before mentioning the myth.

Also, explicit warnings prior to mentioning misinformation ensure that people are 'cognitively on guard' when exposed to the myth. This reduces influence from the misinformation.

23.5.2 Overkill Backfire Effect

While it is tempting to include as much information as possible, overloading people with too many facts can backfire. Generating just a few arguments is more successful in reducing misperceptions than generating a large number of arguments. This is because processing many arguments takes more effort than some people are willing to give. A simple myth is cognitively more attractive than an over-complicated correction. To avoid the 'Overkill Backfire Effect', communicators need to make their content easy to process using simple language, short sentences and subheadings. End on a strong and simple message that is memorable and easy to pass on. Graphics have been shown to be more effective in refuting misinformation than text so if appropriate, use graphics to illustrate your points.

23.5.3 Worldview Backfire Effect

As seen earlier, climate denial is driven by ideology and worldview. One consequence is that presenting evidence that threatens a person's worldview can often have the result of strengthening false beliefs. The cognitive process that contributes to this is confirmation bias, where people selectively seek out information that supports their pre-existing views. The flip side is disconfirmation bias, where people spend significant time and thought actively arguing against arguments that contradict their beliefs.

If evidence and arguments cannot correct a person's false beliefs, what can one do? The Worldview Backfire Effect is greatest among those strongly fixed in their views. One stands a greater chance of correcting misinformation among those not as firmly fixed in their views. This suggests effort should be directed towards the undecided majority rather than the unswayable minority.

A promising approach to presenting evidence to those whose worldview is threatened is to frame information in a way that is less threatening, or even affirms a person's worldview. Climate change science is more acceptable to conservatives when accompanied with calls for nuclear power compared to calls to regulate carbon pollution. It's important to stress that these techniques aren't about manipulating people but about giving the facts a fighting chance (Kahan et al. 2007).

23.5.4 Alternative Explanation

When people assimilate misinformation, they build a mental model with the myth providing part of the explanation. When you refute a myth, you create a gap in their mental model. If this gap isn't filled, people can still be influenced by the original misinformation, even if they know it to be untrue. In the absence of a better explanation, they opt for the wrong explanation.

The solution is to provide an alternative explanation. Consider what gaps are created by your refutation and fill them with an explanation that is plausible and explains all the observed features of the event/phenomenon.

This practice is summed up concisely by Chip and Dan Heath in their book '*Made to Stick*' which explores the concept of "sticky ideas" and how to communicate ideas that capture attention and stick in the memory. When they address the question of how to unstick a sticky idea (e.g., debunk a myth), they recommend:

> Fight sticky ideas with an even stickier idea.

This is simple advice that is difficult to implement. Not only must a debunking provide an alternative narrative, the idea presented must be simple, compelling, engaging: stickier than the myth being debunked.

23.5.5 Summary

In summary, when responding to misinformation, one must emphasize the facts but not too many facts. One must create a gap by removing the myth then fill the gap with an alternative explanation. Here lies the educational opportunity. The process of creating gaps by raising questions then answering them is a standard communication tool used to provoke curiosity and interest, making the message 'stickier'. Scientists and other communicators can use refutations to communicate the facts of climate science in a 'create gap/fill gap' structure to provoke curiosity.

The next chapter will refute some of the most common climate myths, adopting the principles outlined in this section. Look for the emphasis on core facts and alternative explanations.

Additional Readings

Anderegg, W. R. L., Prall, J. W., Harold, J., & Schneider, S. H. (2010). Expert credibility in climate change. *Proceedings of the National Academy of Science, 107*, 12107–12109.

Avery, D. (2007). *500 scientists whose research contradicts man-made global warming scares*, Heartland Institute website. Captured on 1 June 2012 from http://heartland.org/sites/all/modules/custom/heartland_migration/files/pdfs/21977.pdf

Bedford, D. (2010). Agnotology as a teaching tool: Learning climate science by studying misinformation. *Journal of Geography, 109*(4), 159–165.

Boykoff, M. T., & Boykoff, J. M. (2004). Balance as bias: Global warming and the US prestige press. *Global Environmental Change, 14*, 125–136.
Bray, D. (2010). The scientific consensus of climate change revisited. *Environmental Science & Policy, 13*(5), 340–350.
Cook, J., & Lewandowsky, S. (2011). *The debunking handbook*. St. Lucia: University of Queensland. Nov 5. ISBN 978-0-646-56812-6. http://sks.to/debunk
Correia, V. (2011). Biases and fallacies: The role of motivated irrationality in fallacious reasoning. *Cogency, 3*(1), 107–126.
Diethelm, P., & McKee, M. (2009). Denialism: What is it and how should scientists respond? *European Journal of Public Health, 19*, 2–4.
Ding, D., Maibach, E., Zhao, X., Roser-Renouf, C., & Leiserowitz, A. (2011). Support for climate policy and societal action are linked to perceptions about scientific agreement. *Nature Climate Change, 1*, 462–466.
Doran, P. T., & Zimmerman, M. K. (2009). Examining the scientific consensus on climate change. *EOS, 90*(3), 21–22.
Freudenburg, W. R., Gramling, R., & Davidson, D. J. (2008). Scientific certainty argumentation methods (SCAMs): Science and the politics of doubt. *Sociological Inquiry, 78*(2), 5.
Greenpeace (2011). *Koch industries secretly funding the climate denial machine*. Captured on 5 June from http://www.greenpeace.org/usa/Global/usa/report/2010/3/koch-industries-secretly-fund.pdf
Hamilton, L. (2009). *Education, politics and opinions about climate change evidence for interaction effects*. Springer Science+Business Media B.V. doi 10.1007/s10584-010-9957-8.
Hansen, J. (2009). *Storms of my grandchildren*. New York: Bloomsbury. p. 304.
Heath, Y., & Gifford, R. (2006). Free-market ideology and environmental degradation: The case of belief in global climate change. *Environment and Behavior, 38*, 48–71.
Hoggan, J. (2009). *Climate cover-up*. Vancouver: Greystone Books.
Hoofnagle, C., & Hoofnagle, M. (2007). What is denialism?. Captured on 16 Apr 2012 from http://scienceblogs.com/denialism/about.php
Inhofe, J. (2012). *The Greatest Hoax: How the Global Warming Conspiracy Threatens Your Future* (WND Books, Washington, DC).
Jacques, P. J., Dunlap, R. E., & Freeman, M. (2008). The organisation of denial: Conservative think tanks and environmental scepticism. *Environmental Politics, 17*, 349–385.
Jensen, C. (1998). *How many climate researchers support the "Leipzig Declaration"?*. Captured on 4 June from http://naturalscience.com/ns/letters/ns_let08.html
Johnson, T. J., Bichard, S. L., & Zhang, W. (2009). Communication communities or "cyberghettos?": A path analysis model examining factors that explain selective exposure to blogs. *Journal of Computer-Mediated Communication, 15*, 60–82.
Kahan, D., Braman, D., Gastil, J., Slovic, P., & Mertz, C. K. (2007). Culture and identity-protective cognition: Explaining the white-male e_ect in risk perceptions. *Journal of Empirical Legal Studies, 4*, 465–505.
Kahan, D., Jenkins-Smith, H., & Braman, D. (2011). Cultural cognition of scientific consensus. *Journal of Risk Research, 14*, 147–174.
Kurtz, P., et al. (2009). *The credibility project*. Captured on 1 June 2012 from http://www.centerforinquiry.net/opp/news/senate_minority_report_on_global_warming_not_credible/
Leiserowitz, A., Maibach, E., Roser-Renouf, C., & Smith, N. (2010). Climate change in the American Mind: Americans' global warming beliefs and attitudes in June 2010. Yale University and George Mason University. New Haven, CT: Yale Project on Climate Change Communication. Available at: http://environment.yale.edu/climate/files/ClimateBeliefsJune2010.pdf
Lewandowsky, S., Oberauer, K., & Gignac, C. E. (in press). NASA faked the moon landing-therefore (climate) science is a hoax: An anatomy of the motivated rejection of science. Psychological Science.
Lindzen, R. S., & Choi, Y. S. (2009). On the determination of climate feedbacks from ERBE data. *Geophysical Research Letters, 36*, L16705. doi:10.1029/2009GL039628.

Malka, A., et al. (2009). *Featuring skeptics in news media stories about global warming reduces public beliefs in the seriousness of global warming*. Palo Alto: Woods Institute for the Environment, Stanford University.

Mann, M. (2012). *The hockey stick and the climate wars: Dispatches from the front lines*. New York: Columbia University Press.

McCright, A. M., & Dunlap, R. E. (2010). Anti-reflexivity: The American conservative movement's success in undermining climate science and policy. *Theory Culture & Society, 27*, 100–133.

McCright, A. M., & Dunlap, R. E. (2011). Cool dudes: The denial of climate change among conservative white males in the United States. *Global Environmental Change, 21*, 1163–1172.

Morano, M. (2008). *More than 650 international scientists dissent over man-made global warming claims*. Captured on 1 June 2012 from http://epw.senate.gov/public/index.cfm?FuseAction=Minority.Blogs&ContentRecord_id=2158072e-802a-23ad-45f0-274616db87e6

Nisbet, M. C., & Myers, T. (2007). The polls – trends – twenty years of public opinion about global warming. *Public Opinion Quarterly, 71*, 444–470.

OISM (1999). Captured on 1 June 2012 from http://www.petitionproject.org/

Oreskes, N. (2004). Beyond the ivory tower. The scientific consensus on climate change. *Science*, 306:1686.

Oreskes, N., & Conway, E. M. (2010). *Merchants of doubt*. London: Bloomsbury.

Prasad, M., Perrin, A. J., Bezila, K., Hoffman, S. G., Kindleberger, K., Manturuk, K., et al. (2009). "There must be a reason": Osama, Saddam, and inferred justification. *Sociological Inquiry, 79*, 142–162.

Reisman, J. P. (2011). *Exposing the climate hoax: It's all about the economy*. Lyra Books (http://www.lyrabooks.com/about/).

Seitz, F. (1996). Major deception on global warming. *Wall Street Journal*, 12 June.

Talisse, R., & Aikin, S. (2006). Two forms of the straw man. *Argumentation, 20*(3), 345–352.

Part XI
Specific Declarations Against Climate Science and Climate Scientists

Chapter 24
Rebuttals to Climate Myths

Abstract Virtually all climate misinformation can be divided into five categories: fake experts, cherry picking, logical fallacies, impossible expectations and conspiracy theories. The most common climate myths are grouped into these five categories, examining the rhetorical techniques employed to mislead and explaining the science that puts the myths in proper context.

Keywords Climate denial • Fake experts • Petition Project • Oregon Institute of Science and Medicine • Scientific consensus • Climate sensitivity • Richard Lindzen • Cherry picking • Total heat content • Planetary energy imbalance • 1998 • HadCRUT • Hockey stick • Paleoclimate • Solar activity • Atmospheric CO_2 • Carbon cycle • Ice age • Non sequitor • Past climate change • CO_2 lag • Ice cores • Feedback • False dilemma • 1970s • Trace gas • Greenhouse effect • Climate models • James Hansen • Settled science • Uncertainty • Conspiracy theories • Climategate • Mike's trick • Hide the decline • Kevin Trenberth • Missing heat

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the "Things to Know" should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8_24,

Things to Know	
Scientific Consensus	OISM Petition Project
Climate Sensitivity	Planetary Energy Imbalance
Hockey Stick	Solar Activity
Carbon Cycle	Past Climate Change
CO_2 Lag	1970s Predictions
Trace Gas Greenhouse Effect	Climate Models
Settled Science	Uncertainty
Climategate	

24.1 Introduction

This chapter is divided into five sections representing the five characteristics of climate denial. We examine a selection of the more popular climate myths on offer (with a much broader selection available at http://sks.to/args). As well as explaining the science that puts each myth into a broader context, we will also examine the rhetorical techniques associated with each myth. It is hoped the reader will adopt the critical thinking skills required to identify other myths employing the same rhetorical techniques.

24.2 Fake Experts

The tactic of fake experts is designed to prevent the public from correctly perceiving the scientific consensus. It is employed by citing dissenting non-experts who appear to be highly qualified while not having published any actual climate research or by magnifying the voices of a small minority of dissenting climate scientists. The goal is to give the impression of a scientific community still in strong disagreement.

24.2.1 A Petition of Tens of Thousands of Non-experts

As discussed in Sect. 23.2, there is scientific consensus that humans are disrupting our climate in various ways. There is an abundance of evidence with a strengthening consensus found in the peer-reviewed literature. There is a consensus among the world's most prestigious scientific organizations with agreement among National Academies of Science all over the world. There is a consensus among the climate science community with 97% agreement among actively publishing climate scientists.

Given such agreement among an overwhelming majority of climate scientists, one way to portray a false picture of a divided community is to highlight scientists with supposedly impressive credentials who actually possess scant expertise in climate science.

The most prominent (and prolific) example of this strategy is the Petition Project, first published in 2008 by the Oregon Institute of Science and Medicine (OISM 2008). This petition lists over 31,000 scientists who dispute that human activity is disrupting our climate and is cited frequently, including by prominent conservative politicians such as U.S. Congressman Dana Rohrabacher, a Republican.

With 97% consensus among climate scientists, how is it 31,000 scientists disagree with the consensus? This is because around 99.9% of the signatories on the Petition Project are not climate scientists. Anyone with a Bachelor of Science or higher can be listed. This includes graduates of computer science, mechanical engineering, zoology and other fields unrelated to climate science. Given the lack of climate expertise, the Petition Project is a transparent ploy to foster the impression of ongoing debate among the climate science community where none exists.

24.2.2 A Contrarian Take on Climate Sensitivity

Climate sensitivity is a measure of how much global temperature will increase if atmospheric carbon dioxide is doubled from the pre-industrial concentration of approximately 280 ppm. There are many lines of evidence from Earth's history over the last 700,000 years indicating that climate sensitivity is around 3°C. In other words, the direct warming effect from CO_2 before feedbacks is 1°C but reinforcing feedbacks amplify this initial warming so that the total amount of global warming is 3°C; thus the sensitivity of the Earth's climate to a doubling of CO_2 is an increase in temperature of 3°C.

The consensus of 3°C on climate sensitivity is often denied by contrarians and skeptics by their focusing on the work of a single scientist to the exclusion of the full body of research conducted by the rest of the scientific community. This is despite the fact that the work of the particular scientist involved has been refuted repeatedly in the peer-reviewed literature.

The scientist is MIT's Richard Lindzen who analyzed satellite data of surface temperature and outgoing radiation in the tropics (Lindzen and Choi 2009). Examining surface warming over short periods, Lindzen found more outgoing radiation escaped to space after the surface temperature increased. He concluded that net feedback was negative, with a climate sensitivity of 0.5°C. This is significantly less than the scientific consensus of mainstream scientists that the climate sensitivity is 3°C.

However, numerous studies have examined Lindzen's research and found fatal flaws in his methodology. His low sensitivity result is heavily dependent on the choice of start and end points in the time periods analyzed (Trenberth et al. 2010). One can tweak the start and end points to obtain any feedback one wishes. Lindzen also restricted his data to only tropical measurements. However, to calculate global climate sensitivity, one needs global data. Several independent studies have found that the tropics do not provide an adequate data set from which to calculate global climate sensitivity; using a global dataset calculated higher climate sensitivity consistent with mainstream estimates (Chung et al. 2010; Murphy 2010). A more complete picture of climate sensitivity can be found by considering the entire body of research by the scientific community, not just a single scientist, especially one with discredited methods and results.

24.3 Cherry Picking

As many lines of evidence lead to the inevitable, consistent conclusion that humans are causing climate change, one way to circumvent the full body of evidence is cherry picking. This involves focusing on select pieces of data while excluding any data that conflicts with the desired conclusion.

24.3.1 Warming at Over Two Hiroshima Bombs per Second

When scientists add up all the heat building up in the oceans, warming the land and atmosphere and melting ice on land and in the sea, they find that our planet has been building up heat at a rate of over two (2) Hiroshima bombs per second. This rate of heat build-up has continued past 1998 (when some skeptics say global warming stopped) with our planet continuing to accumulate heat into the twenty-first century. Over 90% of global warming is going into the oceans (Fig. 24.1).

To deny the inevitable fact of a planetary energy imbalance, the technique of cherry picking is employed by deniers, skeptics, and contrarians to focus on narrow pieces of data at the exclusion of the full body of evidence. For example, some argue that global warming stopped in 1998 by selecting temperature records that find 1998 is the hottest year on record (Fig. 24.2).

How could 1998 be the hottest year on record if the planet is still accumulating and storing heat? It is possible for surface temperature to drop over a few years even during a longer period of global warming. This is because surface temperature shows much variability from year to year as heat is exchanged between the ocean and the atmosphere. Nevertheless, the long-term trend in the temperature record is that of warming due to the steady build-up and storage of heat content in the World Ocean.

Most surface temperature records actually show either 2005 or 2010 as the hottest years on record. The most cited record by climate deniers was an earlier version

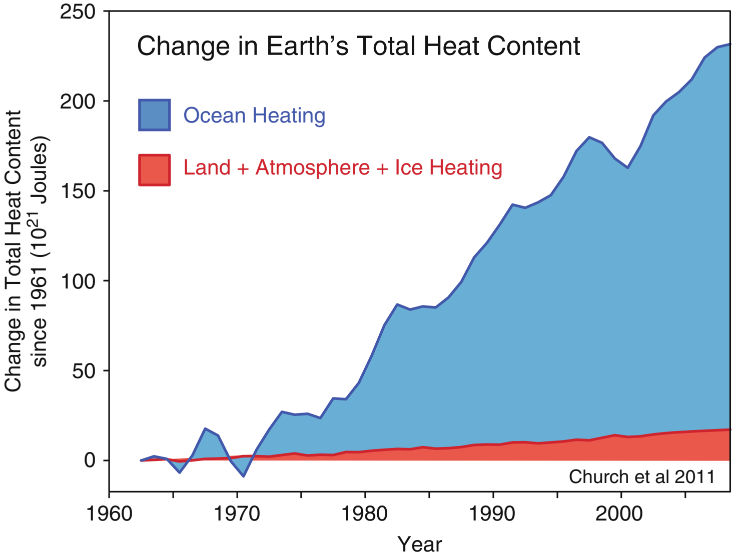


Fig. 24.1 Total heat content accumulating in the ocean (*blue*) and warming the land, atmosphere and melting the ice (*red*) (Figure adapted from Church et al. 2011)

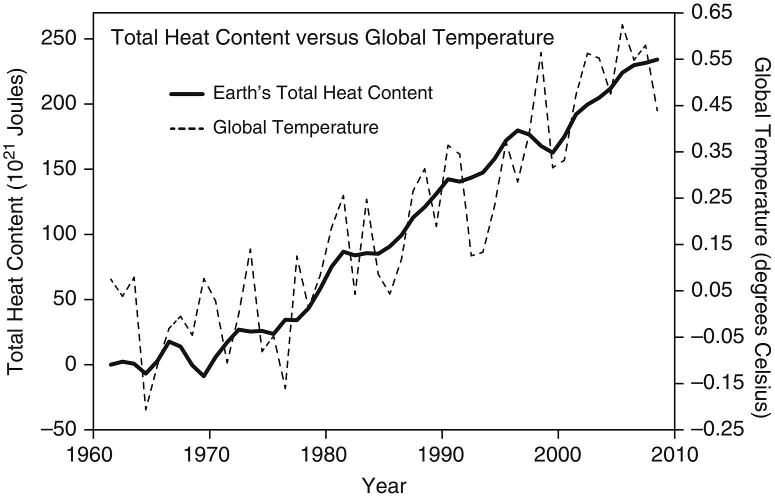


Fig. 24.2 Total ocean heat content (Church et al. 2011) versus global surface temperature (NASA/GISS 2012, Public Domain)

of the HadCRUT temperature record (HadCRUT3), which did show 1998 as the hottest year on record. However, this was due to the fact that the HadCRUT record didn't include regions such as the Arctic where warming is three times faster than

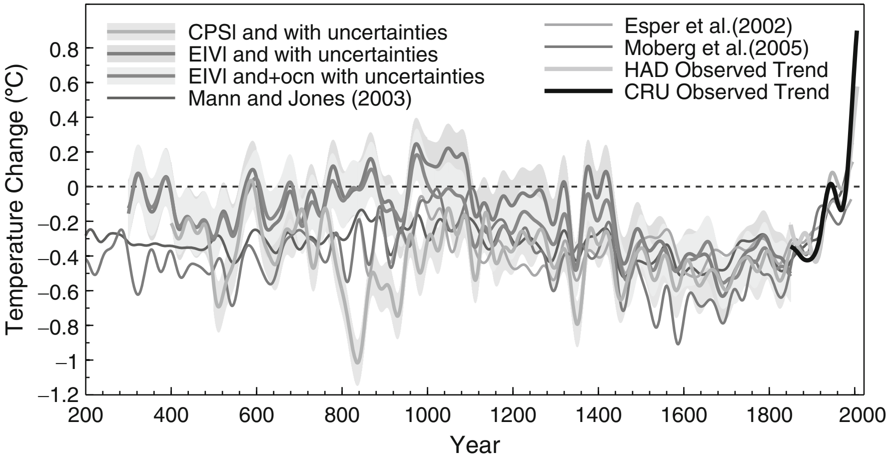


Fig. 24.3 Composite Northern Hemisphere land and land plus ocean temperature reconstructions and estimated 95% confidence intervals (Mann et al. 2008)

the rest of the planet. The latest version of the HadCRUT record (HadCRUT4) includes more data from the Arctic and consequently finds the hottest years on record are 2005 and 2010.

24.3.2 Hockey Stick Versus Hockey Team

Over a decade of paleoclimate research has produced a series of independent studies finding that the last few decades are the hottest in at least the last 1,000 years. The research employs a variety of sources including ice cores, ocean sediments, cave deposits, tree-rings and boreholes. A number of independent statistical techniques have been employed to analyze the data, arriving at the consistent conclusion that current global warming is unusual over the past millennium. The temperature record is often referred to as the 'hockey stick' but a more appropriate characterization of this body of evidence is a "hockey team" (Fig. 24.3).

While the evidence for anthropogenic global warming does not depend on the paleoclimate record, the 'hockey stick' is a compelling visual tool and has been much attacked by climate change deniers. But how does one attack over a decade's worth of research by scientists all over the world? The deniers accomplish this by concentrating their attack on the very first 'hockey stick' diagram and paper, published in 1998 by Michael Mann, Ray Bradley and Malcolm Hughes.

The original 'hockey stick' research reconstructed temperatures over the last 600 years (Mann et al. 1998) and a follow-up paper extended the analysis to the past 1,000 years (Mann et al. 1999). The IPCC Third Assessment Report (TAR) published in 2001 reproduced the Mann et al. 'hockey stick' and as a result, it reached a much larger audience than it would have otherwise. A critique of the 'hockey stick' was published in 2004, falsely claiming that the 'hockey stick' shape was an artifact of the Mann et al. statistical method of principal component analysis (McIntyre and McKitrick 2005).

However, an independent assessment of the 1998 'hockey stick' method by the National Center for Atmospheric Research (NCAR) used several different statistical techniques (with and without principal component analysis) to confirm the principal results of the original 'hockey stick' (Wahl and Ammann 2007). Since then, a number of studies using independent methods and data have confirmed that temperatures over the last few decades are unprecedented over at least the last 600 years.

24.3.3 Sun and Climate Moving in Opposite Directions

Over the last few decades of global warming, solar activity and climate have been moving in opposite directions. While global temperatures have been increasing and the planet has been building up heat, solar activity has shown a slight cooling trend. In 2009 during an unusually deep solar minimum, solar activity reached its lowest levels in over a century. Thus, while changes in the Sun's brightness have a strong impact on Earth's climate, any effect from the Sun currently would be a slight cooling (Lockwood 2008) (Fig. 24.4).

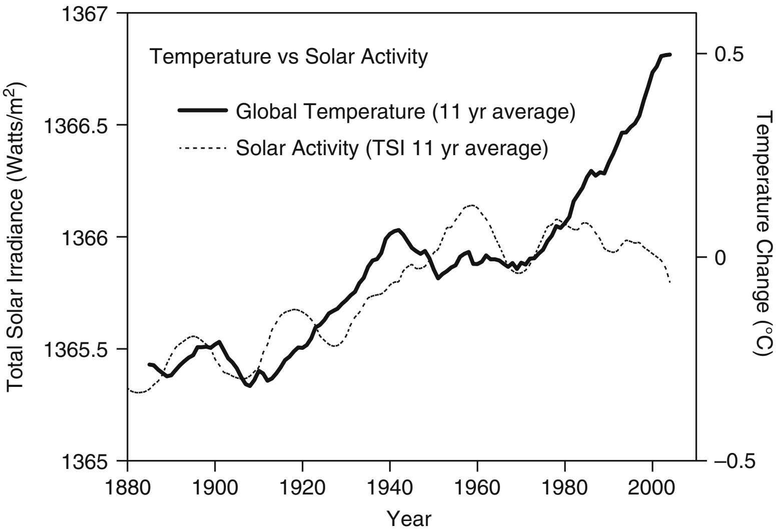


Fig. 24.4 Change in annual global temperature (NASA GISS 11 year moving average) and total solar irradiance (11 year moving average from Krivova et al. 2007 and Frohlich 2006)

Despite these facts, many denialists ignore the last few decades of divergence between solar activity and climate and argue that the Sun is the major cause of recent global warming. They argue this by highlighting the fact that during the twentieth century, the Sun was at its highest levels for the past 1,150 years (Usoskin et al. 2005). However, this argument ignores the divergence between Sun and climate since 1975, leading the authors of Usoskin and colleagues in 2005 to conclude that "this most recent warming episode must have another source."

The patterns observed in the current global warming trend indicate what that other source must be. Warming caused by the Sun predicts a warming trend throughout the atmosphere, in both the upper (stratosphere) and lower (troposphere) atmosphere. Instead, we see cooling in the upper atmosphere and warming in the lower atmosphere. This is the pattern expected from greenhouse warming. Similarly, solar warming would cause summers to warm faster than winters. Instead, we see winters warming faster than summers – another fingerprint of greenhouse warming. The observed patterns in the current global warming not only rule out the Sun as the major cause, they also provide additional evidence for greenhouse warming.

24.3.4 Human Emissions Upsetting the Natural Balance

Over the last 10,000 years, atmospheric CO_2 levels remained relatively steady until the industrial revolution in the mid-1700s. At that point, humans began emitting significant amounts of CO_2, upsetting the natural carbon cycle where natural emissions (sources) were roughly balanced by natural absorptions (sinks). Since pre-industrial times, atmospheric CO_2 levels have increased by around 40%. Current levels are close to 400 ppm, the highest in over 3 million years.

Carbon isotope fingerprints provide more evidence that human activity is responsible for the rise in CO_2. Nevertheless, some deny even the fundamental fact that humans are responsible for the dramatic rise in carbon dioxide seen in Fig. 24.5. This is accomplished by the deniers 'cherry picking' the data and arguing that human CO_2 emissions are only 3% of natural CO_2 emissions (Fig. 24.6).

Annual human emissions are around 9 tonnes of carbon. This is small compared to natural CO_2 emissions from plant decomposition, plant respiration and the ocean which add up to 210 tonnes of carbon. However, natural emissions are balanced by natural absorptions with plants and oceans absorbing around 215 tonnes of carbon each year. By failing to consider natural absorptions, this act of 'cherry picking' distracts from the fact that human CO_2 emissions have upset the natural balance.

24.4 Logical Fallacies

Logical fallacies are false arguments that lead to an invalid conclusion. They are based on erroneous logic, misdirection or false characterization. There are a number of different logical fallacies, such as non sequitor, misrepresentation and false dilemma.

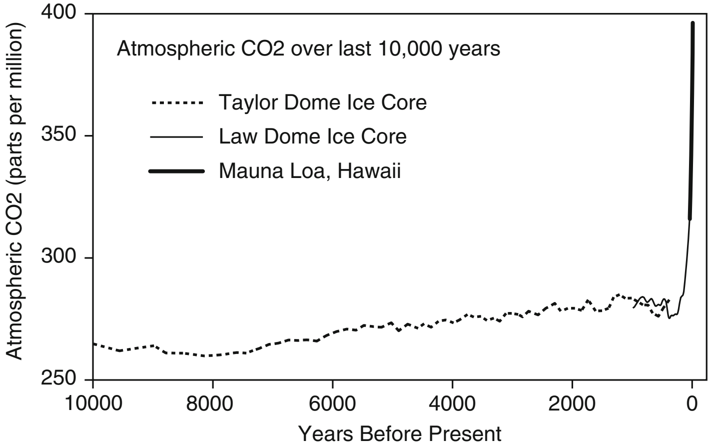


Fig. 24.5 Atmospheric CO_2 levels taken from Antarctic ice core records (Taylor Dome and Law Dome) and Mauna Loa instrumental measurements

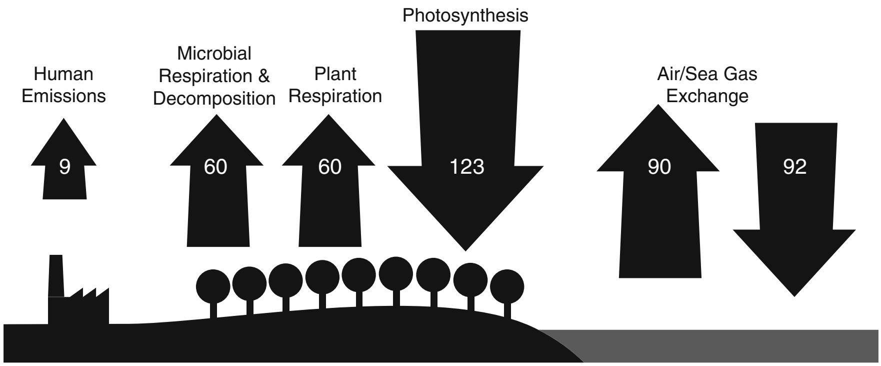


Fig. 24.6 Carbon flux amounts in units of carbon (from skepticalscience.com, 2012)

24.4.1 What Does Past Climate Change Tell Us?

Throughout Earth's history, we see dramatic changes in global temperature. Slow, subtle changes in the Earth's energy balance cause dramatic climate change, including the plunging in and out of ice ages. Our sensitive climate is best characterized by paleoclimatologist Wallace ("Wally") Broeker who said "The paleoclimate record shouts out to us that, far from being self-stabilizing, the Earth's climate system is an ornery beast which overreacts to even small nudges."

Some succumb to the logical fallacy of non sequitor (Latin for "it does not follow") in coming to the opposite conclusion of the paleoclimatologists who study past climate change. They assume that because climate has changed naturally in the past, then current climate change must be natural also. This is equivalent to examining a dead body with a knife protruding from its back and concluding "people have died naturally in the past therefore this death must also be caused by natural causes."

The overall influence from natural forcings over the last few decades has been a slight cooling. If the planet was in its natural equilibrium state, the forcings that are currently acting on Earth's global climate should and would cause the Earth to be cooling. Solar activity has been dropping, the Earth's orbit is configured to have a cooling influence and volcanic activity has been relatively active in the latter twentieth century, again imposing a cooling effect. At the same time, human activity is now the dominant driving force of climate, outpacing natural drivers. We've seen from the geologic past that climate reacts strongly to small nudges but our current nudging is much stronger than a small nudge. Past climate change is not a cause for comfort but a cause for concern.

24.4.2 CO_2 Lag – The Chicken and Egg Dilemma

Of course as every paleontologist and evolutionary biologist knows, the amniote egg preceded the chicken by millions of years, having freed the first amphibians from the aquatic environment and allowed them to become reptiles. However, it is a useful analogy to use as a "which came first" analogy. Most people get the message even though those most erudite already know the answer.

Over the past half million years, the Earth has cycled between ice ages and warm periods called interglacials. The main driving force behind the "ice age" glacial and interglacial cycles appears to be subtle changes in Earth's orbit. The ice core record shows that the small temperature changes from orbital variations are magnified by reinforcing feedbacks. One of the dominant feedbacks is carbon dioxide, which outgases from the oceans, amplifies the initial warming and spreads warming across the planet. We have previously identified carbon dioxide as the "Earth's thermostat."

However, the ice core records are misunderstood by those who commit the logical fallacy of false dilemma. In the Antarctic ice core records, temperature rises first followed by an increase in CO_2 around 800 years later. The logical fallacy is to assume that one must choose between either CO_2 driving temperature or temperature driving CO_2. This is the logical equivalent of observing a chicken hatching from an egg and concluding "chickens come from eggs therefore eggs cannot come from chickens."

In reality, we observe both CO_2 driving warming and warming driving CO_2. The evidence that CO_2 causes warming is provided by satellites and many other lines of evidence. The ice core record also indicates that warming causing an increase in atmospheric CO_2. When the Southern Ocean warms, it outgases carbon dioxide into the atmosphere. When we put the two together, the result is a reinforcing feedback that magnifies the small warming effect of orbital changes and brings our planet out of an ice age.

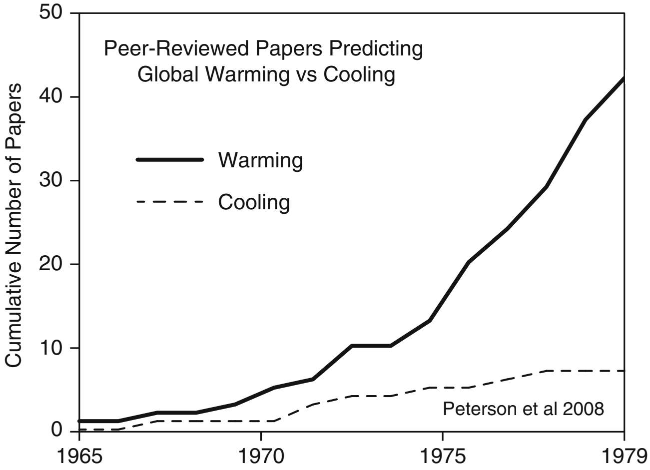


Fig. 24.7 Number of papers classified as predicting global warming (*solid line*) versus cooling (*dotted line*). In no year were there more cooling papers than warming papers (Peterson et al. 2008)

24.4.3 What Were Scientists Predicting in the 1970s?

The best indication of what scientists were saying about climate change in the 1970s is found in the peer-reviewed literature. A survey of peer-reviewed papers from 1965 to 1979 found that significantly more papers (42) predicted global warming than the minority that predicted cooling (7) as shown in the illustration above (Fig. 24.7). The majority of climate research in the 1970s predicted global warming as a consequence of greenhouse gas emissions.

However, some deniers misrepresent the state of the science in the 1970s by claiming that the scientific consensus at the time was that of imminent cooling. This is achieved by citing media articles from the 1970s, misrepresenting them as the scientific consensus at the time. Cited examples are a 1974 *Time* magazine article ‘Another Ice Age?’ or a 1975 Newsweek article ‘The Cooling World’ that suggested global cooling may cause a “drastic decline for food production.”

However, the most comprehensive study in the 1970s was the 1975 report by the U.S. National Academy of Sciences and National Research Council that concluded, “… we do not have a good quantitative understanding of our climate machine and what determines its course.” This qualified statement is in strong contrast with the current position of the U.S. National Academy of Science: “The scientific understanding of climate change is now sufficiently clear to justify nations taking prompt action.” To compare the handful of cooling predictions in the 1970s (predominantly from media sources, not peer-reviewed literature) to the current scientific consensus endorsing human-caused global warming, is both inappropriate and misleading.

24.4.4 How a Trace Gas Has Such a Significant Effect

The warming effect of CO_2 has been empirically confirmed by multiple lines of evidence. Airplanes and satellites measure heat escaping to space, observing a significant ‘hole’ in outgoing radiation at the wavelengths that carbon dioxide absorbs energy. Surface measurements also measure downward infrared radiation emitted by the atmosphere and record heat returning to Earth at those same wavelengths. The greenhouse effect is an empirical reality and without it we would not be able to live on Earth’s surface.

Nevertheless, the drive to deny the human influence on climate change is strong and leads some to reject even basic physics and physical phenomena like the greenhouse effect. One argument employs the logical fallacy of non sequitor, arguing that as CO_2 comprises such a small percentage of the atmosphere, it cannot have a significant effect.

Atmospheric CO_2 currently comprises around 400 ppm or around 0.04% of the atmosphere. How can such a small percentage cause such a significant effect? Over 99% of the atmosphere consists of nitrogen and oxygen, both of which are not greenhouse gases. It is like holding an election in a town of 10,000 people where less than 10 people vote. The few people who vote will have a significant impact on the outcome of the election, even though they are a small fraction of the entire population.

24.5 Impossible Expectations

Impossible expectations involve the demand of unrealistic standards of proof before acting on the science. This often involves shifting the discussion away from what we know and focusing instead on uncertainty and areas of low understanding.

24.5.1 What Lessons Do We Learn from Past Model Predictions?

Climate models simulate many aspects of climate change and observations provide the opportunity to test model performance and glean insights from the comparison. A good example of testing model performance was the Mount Pinatubo volcanic eruption in 1991. The aerosol particles thrown into the atmosphere by the volcano had a cooling effect and the models forecast subsequent global cooling of 0.5°C. The temperature response as well as radiative, water vapor and dynamical feedbacks predicted by the models were matched by observations (Hansen et al. 2007).

Nevertheless, climate model uncertainties are often used as an excuse to reject both models and empirical evidence for human-caused global warming. Any discrepancy between model predictions and observations is used to argue that model results are worthless, when a more appropriate and enlightening approach is to discern what lessons can be learned from past model predictions.

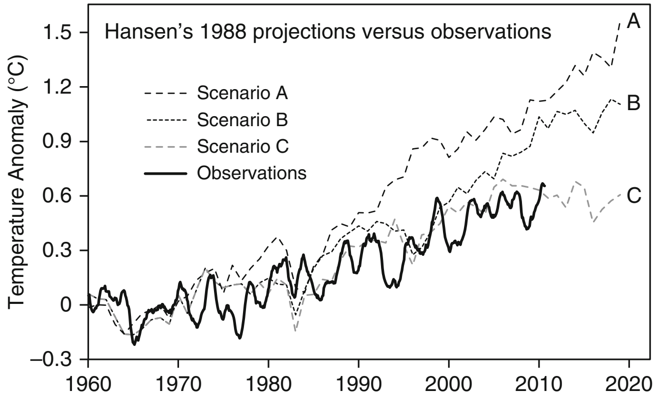


Fig. 24.8 Projections for Scenarios A (*black dashed line*), B (*dotted line*) and C (*grey dashed line*) by Hansen et al. (1988) compared to 12 month running average of NASA GISS global temperature (*thick black line*)

An example of using models to try and see future climate conditions is the 1988 projections used by James Hansen in a presentation before the U.S. Congress in 1988. Hansen used three (3) different greenhouse gas emission scenarios in his presentation (Hansen et al. 1988). Scenario A assumed accelerating greenhouse gas emissions, Scenario B assumed a slowing rate of growth and Scenario C assumed a rapid decline in emissions. Critics have pointed out that Hansen's scenarios overestimated future warming and concluded that his climate model is invalid. However, this fails to ask the crucial question – why did Hansen's model overestimate the warming trend? (Fig. 24.8).

The scenario that most closely matches actual greenhouse emissions is Scenario B. The reason that Hansen's Scenario B overestimated the warming trend is because the model used a climate sensitivity of around 4°C for doubled CO_2. However, if Hansen's model had used a climate sensitivity of just over 3°C, it would have accurately predicted global warming since 1988. Hansen's 1988 model projections are actually evidence for climate sensitivity consistent with current mainstream estimates (i.e., 3°C for a doubling of CO_2).

24.5.2 Science Is Never Settled

Various areas of science are understood with different levels of understanding. For example, scientists understand how greenhouse gases trap heat with a high degree of certainty and can accurately calculate the radiative forcing from greenhouse gases. However, our understanding of how aerosols cool climate, by reflecting sunlight and contributing to cloud formation, is not as well understood. This contrast is reflected in Fig. 24.9.

Climate deniers presume that poor understanding in one area invalidates strong understanding in other areas. This is like arguing that if we don't understand everything,

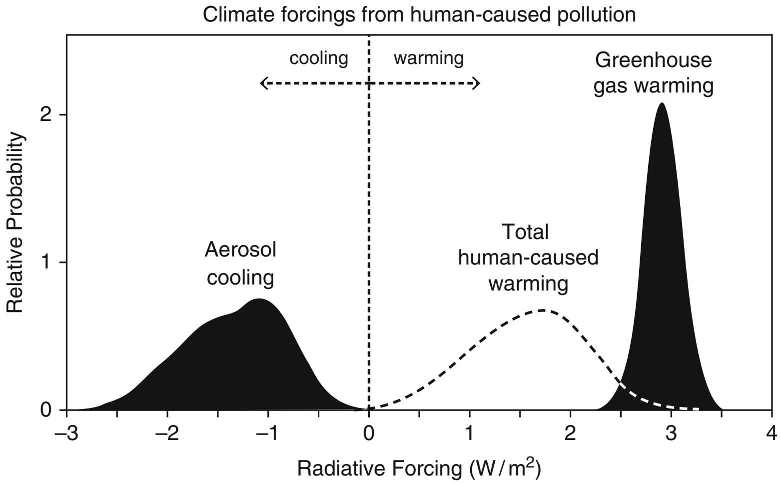


Fig. 24.9 Probability distribution function from human-caused forcings (Solomon et al. 2007). Relative probability is a measure of the level of confidence, indicating that greenhouse warming has a higher level of understanding than aerosol cooling

we understand nothing. Thus, areas of uncertainty in climate science such as the cooling effect of aerosols are used to argue "the science isn't settled" and that we don't know enough to act.

However, science is not about absolute proof, which is the domain of mathematics and logic. There is no invisible line where the science suddenly becomes 'settled.' Instead, science provides a range of estimated values and progresses by gradually reducing the range of uncertainty. Areas of climate science that are less understood do not invalidate the well understood areas, such as the warming effect of greenhouse gas emissions.

24.5.3 Uncertainty Is Not Our Friend

To scientists, uncertainty is related to calculating a best estimate within a likely range of values. For example, the climate response to doubled CO_2 is estimated to be anywhere between 2 and 4.5°C with a most likely value of 3°C. While there is a significant chance that the climate response will be less than 3°C, it is more likely that the response will be greater than expected. This is known as the "fat tail" of climate sensitivity, the inevitable consequence of a climate system with net positive feedback (Fig. 24.10).

In an ironic twist, climate deniers invoke scientific uncertainty to conclude with "certainty" that there isn't a problem or at the least, we should act as if there is no problem. But inaction is not an option - we are already emitting billions of tonnes of carbon dioxide into the atmosphere every year. The logic behind "don't act until we

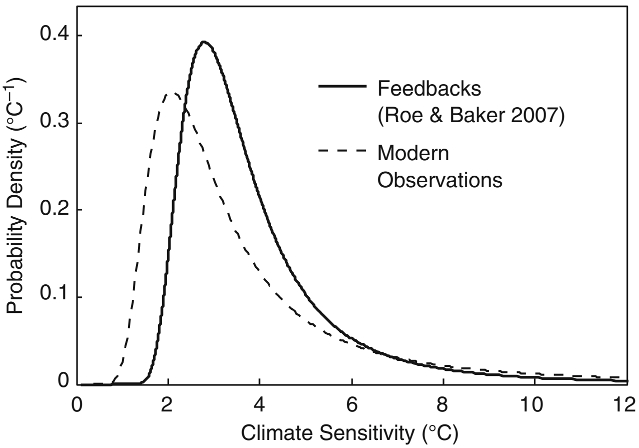


Fig. 24.10 Probability Density Function from Roe and Armour (2011) for climate sensitivity estimated from model-based climate feedbacks (*solid line*) and modern instrumental observations (*dashed line*)

have more certainty" is like being informed there are a range of possible side-effects from drinking poison, from slight illness to death – but persisting in taking the poison until the uncertainty range is further narrowed.

Intrinsic to climate science is the unavoidable fact that climate uncertainty is asymmetrical and more likely to be worse than expected. Another key point to realize is that higher uncertainty means the probability distribution in Fig. 24.10 is spread over a greater range leading to an increased chance of higher climate responses. A greater the range of possible climate responses means more likelihood of serious consequences. Uncertainty is not our friend.

24.6 Conspiracy Theories

Two identifying features of a conspiracy theorist are exaggerated claims about the power of the conspirators and immunity to new facts by claiming any counter evidence is all part of the conspiracy.

24.6.1 Nine Climategate Investigations Across Two Countries

In November 2009, emails were stolen from servers at the University of East Anglia and published on the Internet. A number of suggestive quotes were focused on as supposed evidence of a conspiracy among climate scientists, dubbed 'Climategate' by the news media. To determine if there was any wrongdoing, nine separate investigations across two countries have independently investigated the 'Climategate' emails. This includes the House of Commons Science and Technology Committee, the University of East Anglia's Scientific Assessment Panel in consultation with the Royal Society, Pennsylvania State University, the U.S. Environmental Protection Agency, the U.K. Government, the U.S. Department of Commerce and the U.S. National Science Foundation. These government and educational bodies have unanimously concluded that nothing in the 'Climategate' emails affect the science.

Movements that deny a scientific consensus are prone to conspiracy theories and 'Climategate' presented an ideal opportunity for climate change deniers to indulge their fantasies (or tin foil hat tendencies). Emails were quote mined in order to accuse scientists of suppressing inconvenient results ("hide the decline," Trenberth's travesty) or corrupting data ("Mike's trick"). Little effort was made to put the quotes in context or understand the science discussed in the emails. After all, journalists are not required to have knowledge of science or the scientific method.

Two features of conspiracy theorists were apparent among 'Climategate' proponents. A characteristic of conspiracy theorists is immunity to contrary facts – any evidence against the conspiracy theory is assumed to be part of the plot. When investigation after investigation found no evidence of wrongdoing, each subsequent exoneration was assumed to be a whitewash. Another characteristic of conspiracy theorists is ascribing omnipresent, omnipotent powers to the conspirators. The climate conspiracy is so powerful that climate scientists have managed to engineer evidence for global warming in surface temperature records, glaciers, ice sheets, sea levels, ocean heat, atmospheric patterns, and the timing of the seasons. Even thousands of animal species and tree lines that are shifting towards cooler regions appear to be in on the conspiracy.

24.6.2 Confusing 'Mike's Trick' with 'Hide the Decline'

The most quoted phrase from the 'Climategate' emails comes from an email by Phil Jones of the U.K.'s Hadley Centre's Climate Research Unit discussing reconstructions of past temperatures, where Jones states:

> I've just completed Mike's Nature trick of adding in the real temps to each series for the last 20 years (i.e. from 1981 onwards) and from 1961 for Keith's to hide the decline.

In this email, "Mike's Nature trick" and "hide the decline" refer to two separate techniques. The 'trick' is a technique employed by Michael Mann plotting recent instrumental data in the same graph as reconstructed temperatures predating the instrumental record (Mann et al. 1998). This places recent global warming trends in the context of temperature changes over longer time scales.

The first misconception about Phil Jones' email is that the "decline" refers to declining temperatures. It actually refers to a decline in tree-ring growth at certain high-latitude locations since the 1960s. This is known as the 'divergence problem', where tree-ring proxies diverge from the instrumental record after 1960. Rather than a secret climate conspiracy, the decline in tree-ring growth is an issue that has been publicly discussed in the peer-reviewed literature since 1995 (Jacoby and D'Arrigo 1995).

The second and most common misconception about this email is the conflation of "Mike's trick" with "hide the decline." Many climate change deniers believe that hiding the decline was a technique employed by Michael Mann. However, there were no declining tree-rings in Mann's 1998 'hockey stick' and the decline had nothing to do with "Mike's trick." Despite the obsession with the word 'trick', it merely refers to the technique (as in 'trick of the trade') of plotting instrumental data in the same graph as reconstructed paleotemperatures.

24.6.3 Tracking Down Trenberth's 'Missing Heat'

The second most cited 'Climategate' email is from climate scientist Kevin Trenberth (a Distinguished Scientist at UCAR) who stated that:

> The fact is that we can't account for the lack of warming at the moment and it is a travesty that we can't.

Trenberth is referring to a paper he had recently published that examined the planetary energy budget, how much energy is flowing into our climate system and where it's going (Trenberth 2009). It is a frankly worded paper that laments the limitations of our observation systems that are unable to comprehensively track all the energy flowing through our climate.

Trenberth's email was quote-mined so that the one sentence about 'lack of warming' was quoted out of context, thus hiding the fact that Trenberth was merely summarizing the conclusions of a published paper. Critics characterized the quote as if Trenberth was secretly admitting that global warming wasn't happening or that observations didn't match theoretical expectations.

However, the issues Trenberth raised are openly discussed in his published paper. Moreover, the conflict Trenberth discusses is not a discrepancy between observations and models. Rather, it is a discrepancy between two sets of observations. Satellite measurements indicate our planet is suffering an energy imbalance but observations are unable to track where all this energy is going. Once again, taking isolated quotes out of context without taking the time to or being able to understand the science being discussed have fed conspiracy theories when in reality, scientists are simply emailing about technical issues that have been discussed in publicly available peer-reviewed papers.

In any case, the illegal stealing of the emails, their selective editing and posting on internet sites frequented by skeptics, deniers, and contrarians about climate change has had a significant impact on the general public's confidence in science in general and climate science in particular.

Additional Readings

Chung, E.-S., Soden, B. J., & Sohn, B.-J. (2010). Revisiting the determination of climate sensitivity from relationships between surface temperature and radiative fluxes. *Geophysical Research Letters, 37*, L10703. doi:10.1029/2010GL043051.

Church, J. A., White, N. J., Konikow, L. F., Domingues, C. M., Cogley, J. G., Rignot, E., Gregory, J. M., van den Broeke, M. R., Monaghan, A. J., & Velicogna, I. (2011). Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters, 38*, L18601.

Frohlich, C. (2006). Solar irradiance variability since 1978: Revision of the PMOD composite during solar cycle 21. *Space Science Reviews, 125*, 53–65. ftp://ftp.pmodwrc.ch/pub/data/irradiance/composite/DataPlots/composite_d41_62_0906.dat

Hansen, J., et al. (1988). Global climate changes as forecast by Goddard Institute for space studies 3-dimensional model. *Journal of Geophysical Research-Atmospheres, 93*, 934–9364.

Hansen, J, et al. (2007). Climate simulations for 1880–2003 with GISS Model *E. Clim. Dyn, 29*, 661–696.

Jacoby, G., & D'Arrigo, R. (1995). Tree ring width and density evidence of climatic and potential forest change in Alaska. *Global Biogeochemical Cycles, 9*, 227–234.

Krivova, N., Balmaceda, L., & Solanki, S. (2007). Reconstruction of solar total irradiance since 1700 from the surface magnetic flux. *Astronomy & Astrophysics, AA 467*, 335–346. http://www.mps.mpg.de/projects/sun-climate/data/tsi_1611.txt

Lindzen, R. S., & Choi, Y.-S. (2009). On the determination of climate feedbacks from ERBE data. *Geophysical Research Letters, 36*, L16705.

Lockwood, M. (2008). Recent changes in solar output and the global mean surface temperature. III. Analysis of the contributions to global mean air surface temperature rise. *Proceedings of the Royal Society A, 464*, 1–17.

Mann, M., Bradley, R., & Hughes, M. (1998). Global-scale temperature patterns and climate forcing over the past six centuries. *Nature, 392*, 779–787.

Mann, M., Bradley, R., & Hughes, M. (1999). Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters, 26*(6), 759–762.

Mann, M., Zhang, Z., Hughes, M., Bradley, R., Miller, S., Rutherford, S., & Ni, F. (2008). Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences, 105*(36), 13252–13257.

McIntyre, S., & McKitrick, R. (2005). Hockey sticks, principal components, and spurious significance. *Geophysical Research Letters, 32*(3), L03710.

Murphy, D. M. (2010). Constraining climate sensitivity with linear fits to outgoing radiation. *Geophysical Research Letters, 37*, L09704. doi:10.1029/2010GL042911.

NASA GISS Temperature Index. (2012). *GLOBAL land-ocean temperature index by the Goddard Institute of Space Studies at NASA*. Captured on 15 June 2012 from http://data.giss.nasa.gov/gistemp/graphs_v3/Fig.A2.txt

OISM. (2008). Petition project. *Oregon Institute of Science and Medicine*. http://www.petition-project.org/ Accessed on 14 June 2012.

Peterson, T. C., Connolley, W. M., & Fleck, J. (2008). The myth of the 1970s global cooling scientific consensus. *Bulletin of the American Meteorological Society, 89*(9), 1325–1337.

Roe, G. H., & Armour, K. C. (2011). How sensitive is climate sensitivity? *Geophysical Research Letters, 38*, L14708.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & Miller, H.L. (2007) *The Physical Science Basis*, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge UK.

Trenberth, K. (2009). An imperative for climate change planning: Tracking Earth's global energy. *Current Opinion in Environmental Sustainability, 1*(1), 19–27.

Trenberth, K. E., Fasullo, J. T., O'Dell, C., & Wong, T. (2010). Relationships between tropical sea surface temperature and top-of-atmosphere radiation. *Geophysical Research Letters, 37*, L03702.

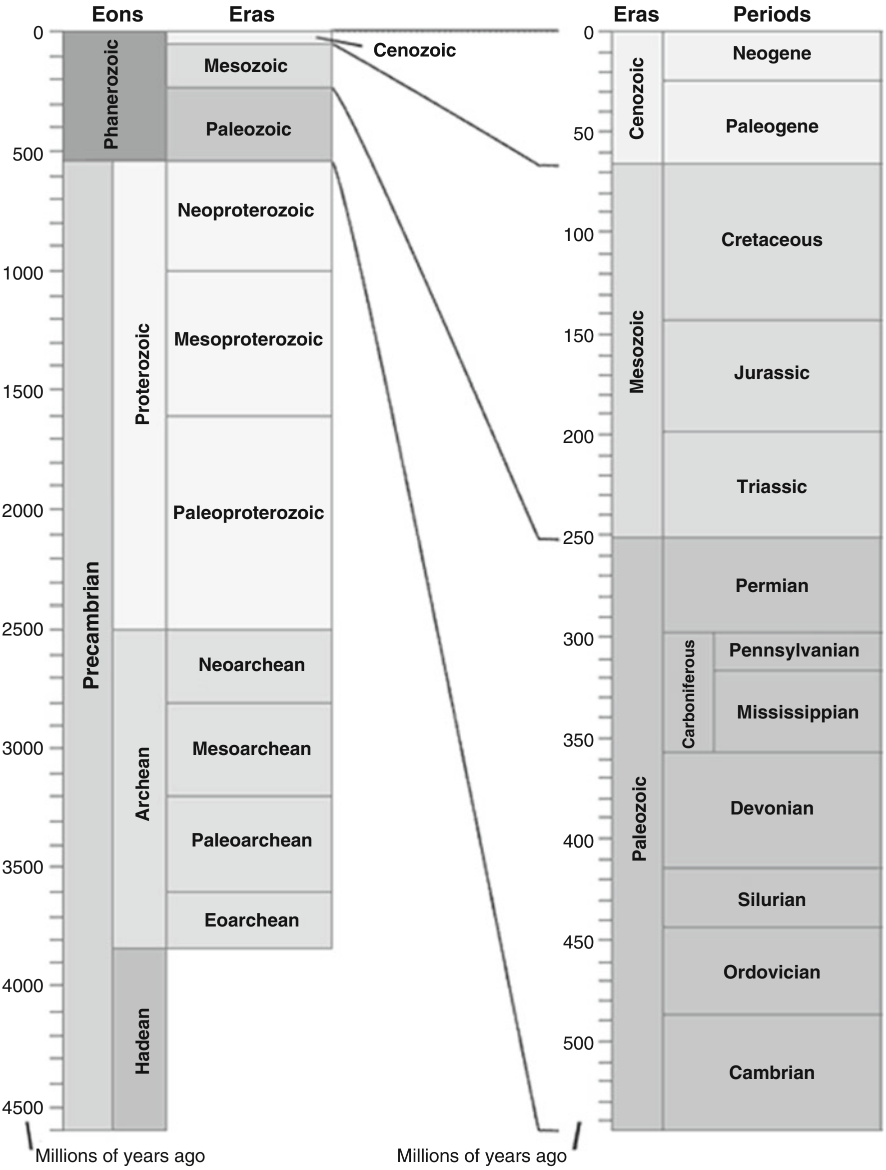
Usoskin, I., Schüssler, M., Solanki, S., & Mursula, K. (2005). Solar activity over the last 1150 years: Does it correlate with climate? In F. Favata, G. Hussain, & B. Battrick (Eds.), *Proceedings of the 13th Cambridge workshop on cool stars, stellar systems and the sun, ESA SP-560*. Paris: European Space Agency.

Wahl, E., & Ammann, C. (2007). Robustness of the Mann, Bradley, Hughes reconstruction of northern hemisphere surface temperatures: Examination of criticisms based on the nature and processing of proxy climate evidence. *Climatic Change, 85*(85), 33–69.

Appendices

Appendix I: Geological Time Scale

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8,



Geological Time Scale

Appendix II: Metric Weights and Measures

Tables of Metric Weights and Measures

Linear Measure

10 millimeters (mm) =	1 centimeter (cm)	
10 centimeters =	1 decimeter (dm)	= 100 millimeters
10 decimeters =	1 meter (m)	= 1,000 millimeters
10 meters =	1 dekameter (dam)	
10 dekameters =	1 hectometer (hm)	= 100 meters
10 hectometers =	1 kilometer (km)	= 1,000 meters

Area Measure

100 square millimeters =	1 sq centimeter
10,000 square centimeters =	1 sq meter
=	1,000,000 sq millimeters
100 square meters =	1 are (a)
100 ares =	1 hectare (ha)
=	10,000 sq meters
100 hectares =	1 sq kilometer
=	1,000,000 sq meters

Volume Measure

10 milliliters (ml) =	1 centiliter (cl)	
10 centiliters =	1 deciliter (dl)	= 100 milliliters
10 deciliters =	1 liter (l)	= 1,000 milliliters
10 liters =	1 dekaliter (dal)	
10 dekaliters =	1 hectoliter (hl)	= 100 liters
10 hectoliters =	1 kiloliter (kl)	= 1,000 liters

Cubic Measure

1,000 cubic millimeters =	1 cubic centimeter
1,000 cubic centimeters =	1 cubic decimeter
=	1,000,000 cubic millimeters
1,000 cubic decimeters =	1 cubic meter
=	1 stere
=	1,000,000 cubic centimeters
=	1,000,000,000 cubic millimeters

Weight

10 milligrams (mg) =	1 centigram (cg)	
10 centigrams =	1 decigram (dg)	= 100 milligrams
10 grams =	1 dekagram (dag)	
10 dekagrams =	1 hectogram (hg)	= 100 grams
10 hectograms =	1 kilogram (kg)	= 1,000 grams
1,000 kilograms =	1 metric ton (t)	

Multiply	By	To Calculate
Centimeters	0.0328	Feet
Centimeters	0.3937	Inches
Feet	30.4801	Centimeters
Feet/minute	0.507	Centimeters/second
Gallons	3,785.4	Cubic Centimeters
Gallons	3.7853	Liters
Grams	0.0353	Ounces
Grams	0.0022	Pounds
Inches	2.54	Centimeters
Inches	0.0833	Feet
Kilograms	2.2046	Pounds
Kilometers	3,280.833	Feet
Kilometers	0.6214	Miles
Kilometers/hour	54.68	Feet/minute
Kilometers/hour	0.6214	Miles/hour
Knots	1.8532	Kilometers/hour
Liters	1.0567	Quarts
Meters	3.2808	Feet
Meters	39.37	Inches
Meters	1.0936	Yards
Meter-kilograms	7.2307	Foot-pounds
Meters/minute	1.667	Centimeters/second
Meters/minute	0.0547	Feet/second
Miles	1.6093	Kilometers
Miles/hour	0.8684	Knots
Miles/hour	1.6093	Kilometers/hour
Miles/hour	0.447	Meters/second
Ounces	28.3495	Grams
Ounces	2.8349×10^2	Kilograms
Pounds	453.5924	Grams
Pounds	0.4536	Kilograms
Quarts	0.946	Liters
Quarts (dry)	67.2	Cubic inches
Quarts (liquid)	57.75	Cubic inches
Square centimeters	0.0011	Square feet
Square kilometers	0.3861	Square miles
Square kilometers	1.196×10^6	Square yards
Square meters	10.7639	Square feet
Square meters	1.196	Square yards
Square miles	2.59	Square kilometers
Square yards	0.8361	Square meters
Yards	91.44	Centimeters
Yards	0.9144	meters

Appendix III: Measures and Statistics of the Earth

Measures and Statistics of the Earth

- Surface Gravity: 9.78 m/s^2
- Diameter: 12,753 km (7,926 miles)
- Equatorial Radius: 6,378 km
- Mean radius: 6,371 km (3,981 miles)
- Rotation Period with respect to Sun (Length of Day): 24 h
- Average distance from Sun: 149.6 million km (93 million miles)
- Closest to Sun (perihelion): 147.1 million km (91.5 million miles) about Jan. 3
- Farthest from Sun (aphelion): 152.1 million km (94.5 million) miles about July 4
- Mass: $5.98x10^{e24}$ kg (6.5^{e21} tons)
  Of the Earth's mass:
  About 1/3 is in the core, 2/3 in the mantle, 4/1,000 in the crust, 2/10,000 in the oceans, 1/1,000,000 in the atmosphere, and 1/100,000 in ice caps
- Rotation Period with respect to stars (Sidereal Day): 23 h 56 min
- Density: 5,515 kg/m^3
- Revolution Period about the Sun (Length of a Year): 365 days 5 h
- Minimum Distance from Sun: 146 million km (91 million miles)
- Tilt of Axis: 23° 27"
- Maximum Distance from Sun: 152 million km (94.5 million miles)
- Temperature: −89 to 57.7°C (−128 to 136°F)
- Orbital Semimajor Axis: 1.0 AU
- Average Surface Temperature (K): 287 K = 14°C

Abbreviations

$\delta^{13}C$	Ratios of environmental isotopes, such as $^{18}O/^{16}O$ and $D/^{1}H$ from waters are displayed using delta notation $\delta^{18}O$ and δD, respectively. A temperature dependent isotope of carbon
$\delta^{18}O$	A temperature dependent isotope of oxygen using delta notation
δD	Changes in deuterium using delta notation
*.edu	An educational website or at least one from an educational institution.
*.gov	A government website.
µm	one millionth of a meter

A

A1	An IPCC scenario that describes a future world of very rapid economic growth, global population that peaks in mid-Century and declines thereafter, and the rapid introduction of new and more efficient technologies.
A1B	An IPCC scenario that describes a future world where there is a balance across all sources.
A1F1	An IPCC scenario that describes a future world where it is fossil fuel-intensive.
A1T	An IPCC scenario that describes a future world that is not fossil fuel-intensive.
A2	The A2 scenario describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other scenarios.
AABW	Antarctic Bottom Water
ACC	Anthropogenic Climate Change
ACEX	Arctic Coring Expedition
ACRIM I	Active Cavity Radiometer Irradiance Monitor I

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8,

ACRIM-Sat	Active Cavity Radiometer Irradiance Monitor I Satellite
AD	Anno Domini, Latin for "Year of our Lord"
AER	Aerosols only
Af	Tropical rainforests in the Köppen-Geiger climate classification
AGAGE	Advanced Global Atmosphere Gas Experiment
AGU	American Geophysical Union
ALE	Atmospheric Lifetime Experiment
ALL	Anthropogenic and Natural Forcings
AMO	Atlantic Meridional Oscillation
AMOC	Atlantic Meridional Overturning Circulation
AMS	American Meteorological Society
AO	Arctic Oscillation
AOGCMs	Atmospheric-Ocean General Circulation Models
API	American Petroleum Institute
AR3	IPCC Third Assessment Report
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
ARGO	Ocean temperature measurement device
ARM	Atmospheric Radiation Measurement
Aw	A tropical savanna grassland in the Köppen-Geiger climate classification.
AZ	Arizona

B

B1	An IPCC scenario that describes a convergent world with the same global population that peaks in mid-Century and declines thereafter, as in the A1 scenario, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.
B2	An IPCC scenario that describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 scenarios. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.
BC	Before Christ
BEST	Berkeley Earth Surface Temperature project
BP	British Petroleum
BW	A warm desert climate in the Köppen-Geiger climate classification.
BWh	A hot desert climate in the Köppen-Geiger climate classification.

C

CA	California
CanESM2	A Canadian Climate Model
CC	CC Attribution-Share Alike 3.0 Unported License
CCDG	NASA/GSFC Coupled Climate Dynamics Group
CCN	Cloud Condensation Nuclei
CCSM	NCAR Community Climate System Model
CDAT	Climate Data Analysis Tools
CDC	Center for Disease Control
CDML	XML representation (CDML) for datasets
CE	Current or Common Era
CIA	Central Intelligence Agency
CRU	Climate Research Unit of the University of East Anglia
CRUTEM's	Climate Research Unit of the University of East Anglia's Temperature Analysis
CSM	NCAR Climate Systems Model
Cwa	The humid subtropical climate zone (Cfa, Cwa) is where winter rainfall (and sometimes snowfall) is associated with large storms that the westerlies steer from west to east.

D

DC	District of Columbia
Dfa	A humid continental climate in the Köppen-Geiger climate classification
DI	Dryness Index
DKRZ	German Climate Science Computing Center
DNA	Deoxyribonucleic Acid
DOD	Department of Defense
DOE	Department of Energy
DSOW	Denmark Strait Overflow Water

E

e.g.	For Example
EBMs	Energy Balance Models
ECMWF	European Centre for Medium-Range Weather Forecasts
EIA	Energy Information Administration
$E = MC^2$	Energy equals mass times the speed of light squared.
EMR	Electromagnetic Radiation
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
EPICA	European Project for Ice Coring in Antarctica
EPRI	Electric Power Research Institute
ERBE	A space platform. Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Satellite
ERSST	NOAA Extended Reconstructed Sea Surface Temperature

ESRI	Earth Sciences and Resources Institute
ESRL	Earth System Research Laboratory
ET	Evapotranspiration
et al.	And others
EUROCS	EUROpean Cloud Systems

F

FAR	IPCC First Assessment Report

G

Ga	Giga Annum, a billion years
GAGE	Global Atmospheric Gas Experiment
GCM	General Circulation Model
GCMs	General Circulation Models
GCOS	Global Climate Observing System
GCSM	Global Climate Systems Model
GCSS	Global Cloud System Study
GEWEX	Global Energy and Water cycle Experiment
GFDL	Geophysics Fluid Dynamics Laboratory
GHCN	Global Historical Climatology Network
GHCN-M	Global Historical Climatology Network Monthly
GHG	Greenhouse Gas
GHGs	Greenhouse Gases
GHRSST	U.S. Group for High Resolution Sea Surface Temperatures
GISP2	Greenland Ice Sheet Project 2. GISP2 produced an ice core 3,053.44 m in depth, the deepest ice core recovered in the world at the time (July 1993).
GISS	Goddard Institute of Space Studies.
GISTEMP	GISS Temperature Analysis
GLOFs	Glacial Lake Outbreak Floods
GMD	Global Monitoring Division of NOAA
GMSL	Global Marine Sea Level
GNU	"GNU" is a recursive acronym that stands for "GNU's Not Unix."
GODAE	Global Ocean Data Assimilation Experiment
GOE	Great Oxygenation Event
Gpc	A gigaparsec (Gpc) is equal to a billion parsecs.
GPP	Gross Primary Production
GPS	Global Positioning System
GRACE	NASA's Gravity and Recovery Climate Experiment satellite system
GRL	Geophysical Review Letters
GSFC	Goddard Space Flight Center
Gt CO_2	Gigatons of Carbon Dioxide
GtC	Gigatons of Carbon
GTP	Global Temperature Potential
GWP	Global Warming Potential

H

HadCRU	Hadley Centre Climate Research Unit
HCFCs	hydrochlorofluorocarbons
HI	Humidity Index
HTM	Holocene Thermal Maximum
http	The Hypertext Transfer Protocol (HTTP) is an application protocol for distributed, collaborative, hypermedia information systems.

I

i.e.	*id est.*, that is
ICESat	NASA's Ice, Cloud and Elevation satellite
ICOADS	International Comprehensive Ocean-atmosphere Data Set
IEA	International Energy Agency
IETM	Initial Eocene Thermal Maximum
IGY	International Geophysical Year
IMO	International Meteorological Organization
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
IR	Infrared longwave radiation
IRBM	Intermediate Range Ballistic Missile
ITCZ	Intertropical Convergence Zone

J

JMA	Japanese Meteorology Agency
JPL	Jet Propulsion Laboratory

K

ka	A thousand years ago
KFC	Kentucky Fried Chicken

L

LAS	An integrated Climate Data Analysis Tool
LGM	Last Glacial Maximum
LHC	Large Hadron Collider
LIA	Little Ice Age
LIDAR	Light Detection and Ranging
LNG	Liquid Natural Gas

M

M.I.T.	Mass. Institute of Technology
m/s	Meters per second
Ma	A million years ago
MBH	Mann, Bradley, and Hughes
MECCA	Model Evaluation Consortium for Climate Assessment
MECCA.html	Model Evaluation Consortium for Climate Assessment html website
MHTM	Mid-Holocene Thermal Maximum

MI	Moisture Index
MIS	Marine Isotope Stage
MISR	The Multi-angle Imaging SpectroRadiometer (MISR) is a scientific instrument on the Terra satellite launched by NASA on December 18, 1999.
MJO	Madden-Julian Oscillation
MODIS	Moderate Resolution Imaging Spectroradiometer (MODIS) on
NASA	's Aqua satellite
MOHC	The U. K. Meteorological Office Hadley Centre-
MSFC	NASA's Marshall's Space Flight Center
MSU	Microwave Sounding Unit
MWP	Medieval Warm Period
MYD28M	http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=MYD28M

N

NADW	North Atlantic Deep Water
NAM	Northern Annular Mode
NAMO	North Atlantic Multidecadal Oscillation
NAO	North Atlantic Oscillation
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NAT	Near-surface air temperature
NCAR	National Center for Atmospheric Research
NCDC	National Climate Data Center
NDBC	National Data Buoy Center
NO	Nitric oxide
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrogen oxides
NP	Northern Pacific
NPOESS	In October 2011 a satellite, NPOESS Preparatory Project (NPP) delivered a scanning radiometer called VIIRS into orbit that measures aerosol content in the atmosphere.
NPP	In October 2011 a satellite, NPOESS Preparatory Project (NPP) delivered a scanning radiometer called VIIRS into orbit that measures aerosol content in the atmosphere.
NRC	National Research Council
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
NY	New York

O

°C	Degrees Centigrade or Celsius
ODSs	Ozone depleting substances
°F	Degrees Fahrenheit
OH	Ohio

OPeNDAP	Open Data Package
ORBIMAGE	GeoEye Inc. (NASDAQ: GEOY) (formerly Orbital Imaging Corporation or ORBIMAGE) is a commercial satellite imagery company based in Herndon, Virginia that is the world's largest space imaging corporation.
OSHA	Occupational Safety and Health Administration
OSTM	The Ocean Surface Topography Mission (OSTM) on the Jason-2 satellite is an international Earth observation satellite mission that continues the sea surface height measurements begun in 1992 by the joint NASA/CNES TOPEX/Poseidon mission and followed by the NASA/CNES Jason-1 mission launched in 2001.

P

PA	Pennsylvania
PBL	Planet boundary layer
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PDO	Pacific Decadal Oscillation
PE	Potential evapotranspiration
PETM	Paleocene-Eocene Thermal Maximum
Ph.D.	Doctor of Philosophy
PIOMAS	The University of Washington's Pan-Arctic Ice Ocean Modeling and Assimilation System (**PIOMAS**) model. Arctic sea ice volume anomaly from PIOMAS updated once a month. Daily Sea Ice volume anomalies for each day are computed relative to the 1979–2010 average for that day of the year.
PMOD	Physikalisch-Meteorologisches Observatorium Davos
ppb	Parts per billion
ppm	Parts per million
ppt	Parts per thousand
pptv	Parts per thousand volume

Q

QA	Quality assessment
QC	Quality control
QDO	Quasi-Decadal Oscillation

R

RCMs	Radiative-Convective Models
RF	Radiative forcing
RSS	Remote Sensing Systems

S

SAG	Screen Actors Guild
SAR	Second assessment report (IPCC)
SAT	Satellite and Terrestrial RF Spectrum Monitoring, Interference and Geolocation
SDMs	Statistical Dynamical Models

SeaWifs A now defunct satellite (SeaWifs) provided three decades and longer satellite data on aerosols which is the longest single-satellite record of aerosols to date (July 2011).
SIO Scripps Institution of Oceanography
SMM The Solar Maximum Mission (SMM) was launched on 14 February 1980 to, primarily, study the Sun during the high part of the solar cycle. The payload included the Active Cavity Radiometer Irradiance Monitor (ACRIM), the Gamma-Ray Spectrometer (GRS), the Hard X-Ray Burst Spectrometer (HXRBS), the soft X-Ray Polychromator (XRP), the Hard X-ray Imaging Spectrometer (HXIS), and the Ultraviolet Spectrometer and Polarimeter (UVSP).
SMOW Standard Marine Ocean Water
SOHO NASA's Solar and Helispheric Observatory
SOI Southern Oscillation Index
SPECMAP Detailed charting of glacial cycles over the last million years, according to isotopic oxygen analyses of foraminifera (SPECMAP project).
SRES Special Report on Emissions Scenarios
SSC Spatial Synoptic Classification System (SSC) is based on the Bergeron classification scheme.
SSEC University of Wisconsin-Madison Space Science and Engineering Center (SSEC) (USA)
SSTs Sea surface temperatures
SSU Seasonal anomalies of global average temperature (°C), 1958–2000, relative to 1979–1990 for the lower stratosphere, as observed from satellites (MSU 4 and SSU 15X) and balloons (UKMO 4). The times of the major explosive eruptions of the Agung, El Chichón and Mt. Pinatubo volcanoes are marked and the lower stratosphere warms. Image adapted from IPCC TAR 2001. (From http://www.atmosphere.mpg.de/enid/20c.html)

T

T Temperature
T/ET Temperature/Evapotranspiration
TAR IPCC Third Assessment Report
TOA Top of the atmosphere
TOPEX Launched in 1992, **TOPEX/Poseidon** was a joint satellite mission between NASA, the U.S. space agency, and CNES, the French space agency, to map ocean surface topography. The first major oceanographic research vessel to sail into space, TOPEX/Poseidon helped revolutionize oceanography by proving the value of satellite ocean observations. The distinguished oceanographer Walter Munk described TOPEX/Poseidon as "the most successful ocean experiment of all times." A malfunction ended normal satellite operations January 2006.
TSI Total Solar Irradiance (or Total Solar Index)

U

U.K.	United Kingdom
U.S.	United States
UAH	University of Alabama Huntsville
UARS	Upper Atmosphere Research Satellite
UC	University of California
UCAR	University Corporation for Atmospheric Research
UEA	University of East Anglia
UKMO	United Kingdom Met Office
UM	University of Michigan
UNFCCC	United Nations Framework Convention on Climate Change
URL	Uniform Resource Locator it is the global address of documents and other resources on the World Wide Web.
USA	United States of America
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UV	Ultraviolet shortwave radiation

V

VA	Virginia
VCDAT	Graphical user interface for climate data analysis called CDAT (Climate Data Analysis Tools)
VCS	Visualization system for CDAT.
VIIRS	In October 2011 a new satellite, NPOESS Preparatory Project (NPP) delivered a scanning radiometer called VIIRS into orbit that measures aerosol content in the atmosphere.
VIRGO	Radiometers measuring the Total Solar Irradiance (TSI) on different space platforms since November 1978: HF on Nimbus7, ACRIM I on SMM, ERBE on ERBS, ACRIM II on UARS, VIRGO on SOHO, and ACRIM III on ACRIM-Sat.
VOCs	Volatile organic carbons or Volatile organic compounds

W

W	Watt
W/m^2	Watts per square Meter
W·s	Watts per second
WGI	The World Glacier Inventory (WGI) contains information for over 130,000 glaciers. Inventory parameters include geographic location, area, length, orientation, elevation, and classification. The WGI is based primarily on aerial photographs and maps with most glaciers having one data entry only. Hence, the data set can be viewed as a snapshot of the glacier distribution in the second half of the 20th century. It is based on the original WGI (WGMS 1989) from the World Glacier Monitoring Service (WGMS).
WMO	World Meteorological Organization

WWI	World War I
WWII	World War II
WWR	World Weather Records
www.	The World Wide Web (abbreviated as WWW or W3, commonly known as the Web, or the "Information Superhighway"), is a system of interlinked hypertext documents accessed via the Internet.

X

XML	Extensible Markup Language

Z

ZAMS	Zero-age main sequence

Glossary

.edu Web site from an educational institution.
.gob A government web site.
μm One millionth of a meter
4.5 billion years ago Age of Earth
540 million years ago Beginning of the Paleozoic Era
65.5 million years ago Beginning of the Cenozoic Era
2.5 million years ago Beginning of the Pleistocene Epoch
8.2 ka event Following the last post-glacial warming, a rapid climate oscillation with a cooling lasting about 400 years that occurred about 8.2 ka. This event is also referred to as the 8.2 k year event.

A

A1 A growth scenario that describes a future world of very rapid economic growth, global population that peaks in mid-century and declines afterward, with the rapid introduction of new and more efficient technologies. The A1 scenario includes a balance of growth and technology.
A1B A growth scenario where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies.
A1FI A growth scenario that is fossil fuel-intensive with new non-fossil energy sources.
A1T A growth scenario that is a balance across all sources where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies.
A2 The A2 scenario describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other scenarios.
Ablation Surface removal of ice or snow from a glacier or snowfield by melting, sublimation, and/or calving.

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8,

Abrupt climate change Sometimes called rapid climate change, abrupt events or even surprises. Abrupt often refers to time scales faster than the typical time scale of the responsible forcing. However, not all abrupt climate changes need be externally forced. Some possible abrupt events that have been proposed include a dramatic reorganization of the thermohaline circulation, rapid deglaciation and massive melting of permafrost or increases in soil respiration leading to fast changes in the carbon cycle. Others may be truly unexpected, resulting from a strong, rapidly changing forcing of a nonlinear system (IPCC).

Ablation Zone Region in a glacier where there is a surface net removal of snow and/or ice by melting, sublimation, and/or calving.

Absolute Zero Temperature of −273.15°C. At this temperature atomic motion stops.

Absorption (1) Process of taking in and being made part of an existing amount of matter. (2) Interception of electromagnetic radiation or sound.

Absorption (Atmospheric) Atmospheric absorption is defined as a process in which solar radiation is retained by a substance and converted into heat energy. The creation of heat energy also causes the substance to emit its own radiation. In general, the absorption of solar radiation by substances in the Earth's atmosphere results in temperatures that no higher than 1,800°C. According to Wien's Law, bodies with temperatures at this level or lower would emit their radiation in the longwave band (IPCC).

Abyss Deep water in the ocean.

Abyssal Plain Ocean floor in deep water.

Accumulation Surface addition of snow to a glacier or snowfield.

Accumulation Zone (1) Region in a glacier where there is a surface net addition of snow. (2) Part of a hillslope that has a net gain of material leading to a progressive raising of the slope's surface.

Acid (1) Substance having a pH less than 7. (2) Substance that releases hydrogen ions ($H+$). (3) Sialic rocks.

Acid Deposition Atmospheric deposition of acids in solid or liquid form on the Earth's surface. Also see acid precipitation

Acidic Any substance with a pH below 7 Sialic rocks.

Acid Precipitation Atmospheric precipitation with a pH less than 5.6. Normal pH of precipitation is 5.6.

Acid Rain Rain with a pH less than 5.6. Normal pH of precipitation is 5.6.

Active Layer Upper zone of soil in higher latitude locations that experiences daily and seasonal freeze-thaw cycles.

Adiabatic A process in which heat does not enter or leave a system. In the atmospheric sciences, adiabatic processes are often used to model internal energy changes in rising and descending parcels of air in the atmosphere. When a parcel of air rises it expands because of a reduction in pressure. If no other non-adiabatic processes occur (like condensation, evaporation and radiation), expansion causes the parcel of air to cool at a set rate of 0.98°C per 100 m. The opposite occurs when a parcel of air descends in the atmosphere. The air in a descending parcel becomes compressed. Compression causes the temperature within the parcel to increase at a rate of 0.98°C per 100 m. An adiabatic process is a process in which no external heat is gained or lost by the system. The opposite is called a diabatic process (IPCC).

Adiabatic Cooling The cooling of a rising parcel of air due to adiabatic processes.

Advection Advection involves the transfer of heat energy by means of horizontal mass motions through a medium. Advection transport of water or air along with its properties (e.g., temperature, chemical tracers) by the motion of the fluid. Regarding the general distinction between advection and convection, the former describes the predominantly horizontal, large-scale motions of the atmosphere or ocean, while convection describes the predominantly vertical, locally induced motions (IPCC).

Aeolian Geomorphic process involving wind. Alternative spelling *eolian*.

Aeolian Landform A landform originating from the erosion or deposition of weathered surface materials by wind. This includes landforms with some of the following geomorphic features: sand dunes, deflation hollows, and desert pavement.

Aerobic (1) Presence of molecular oxygen. (2) Occurring only in the presence of molecular oxygen. (3) Growing in the presence of molecular oxygen.

Aerosols A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 μm that reside in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: directly through scattering and absorbing radiation, and indirectly by acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds (see indirect aerosol effect) (IPCC).

Agronomy Field of science that studies phenomena related to agriculture.

Air Mass A widespread body of air, the approximately homogeneous properties of which (1) have been established while that air was situated over a particular region of the Earth's surface, and (2) undergo specific modifications while in transit away from the source region (AMS 2000). A body of air whose temperature and humidity characteristics remain relatively constant over a horizontal distance of hundreds to thousands of kilometers. Air masses develop their climatic characteristics by remaining stationary over a source region for a number of days. Air masses are classified according to their temperature and humidity characteristics (IPCC).

Air Pollution Toxification of the atmosphere through the addition of one or more harmful substances in the air. Substance must be in concentrations high enough to be hazardous to humans, other animals, vegetation, or materials. Also see primary pollutant and secondary pollutant.

Air Pressure See atmospheric pressure.

Albedo Is the reflectivity of a surface. The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the surface albedo of soils ranges from high to low, and vegetation-covered surfaces and oceans have a low albedo. The Earth's planetary albedo varies mainly through varying cloudiness, snow, ice, leaf area and land cover changes (IPCC).

Albedo feedback A climate feedback involving changes in the Earth's albedo. It usually refers to changes in the cryosphere, which has an albedo much larger

(~0.8) than the average planetary albedo (~0.3). In a warming climate, it is anticipated that the cryosphere would shrink, the Earth's overall albedo would decrease and more solar radiation would be absorbed to warm the Earth still further (IPCC).

Aleutian Low Subpolar low pressure system found near the Aleutian Islands most developed during the winter season. This large-scale pressure system gives rise to mid-latitude cyclones.

Algae A simple photosynthetic plant that usually lives in moist or aquatic environments. The bodies of algae can be unicellular or multicellular.

Alkaline (1) Having a pH greater than 7. (2) Substance that releases hydroxyl ions (OH-).

Alpha Particle Particle of matter that is positively charged. This particle consists of two neutrons and two protons and is emitted as a form of radioactivity from the nuclei of some radioisotopes. Also see beta particle and gamma rays.

Alpine Glacier Small glacier that occupies a U-shaped valley on a mountain. Also called mountain glacier and valley glacier. Glaciers that flow together at the foot of mountains are called piedmont glaciers.

Alpine Permafrost Form of permafrost that exists at high altitudes in mountainous environments.

Alpine Tundra High altitude biome dominated by a few species of small shrubs, a few grasses, sedges, lichens, and mosses. Productivity is low because of the extremes of climate. Similar to tundra.

Altimetry A technique for measuring the height of the sea, lake or river, land or ice surface with respect to the center of the Earth within a defined terrestrial reference frame. More conventionally, the height is with respect to a standard reference ellipsoid approximating the Earth's oblateness, and can be measured from space by using radar or laser with centimetric precision at present. Altimetry has the advantages of being a geocentric measurement, rather than a measurement relative to the Earth's crust as for a tide gauge, and of affording quasi-global coverage (IPCC).

Altitude Vertical distance above sea-level. Usually expressed in feet, inches, millimeters, or centimeters.

Altocumulus Clouds Middle altitude cloud that is from white to gray in color, composed of a mixture of water droplets and ice crystals. It appears in the atmosphere as layers or patches that are well rounded and commonly wavelike. Found in an altitude range from 2,000 to 8,000 m.

Altostratus Clouds Gray-looking middle altitude cloud composed of water droplets and ice crystals. Appears in the atmosphere as dense sheet- like layers. Can be distinguished from stratus clouds by the fact that the Sun can be seen through it. Found in an altitude range from 2,000 to 8,000 m.

Anaerobic (1) Absence of molecular oxygen. (2) Occurring only in the absence of molecular oxygen. (3) Growing in the absence of molecular oxygen.

Anemometer Mechanical instrument used to measure wind speed. These instruments commonly employee three methods to measure this phenomenon: (1) A device with three or four open cups attached to a rotating spinal. The speed of rotation is then converted into a measurement of wind speed; (2) A pressure plate that measures the force exerted by the moving wind at right angles; (3) An instrument consisting of a heated-wire where electrical resistance (temperature of the wire) is adjusted to account for heat lost by air flow (IPCC).

Angle of Incidence Angle at which the Sun's rays or insolation strike the Earth's surface. If the Sun is positioned directly overhead or 90° from the horizon, the incoming insolation strikes the surface of the Earth at right angles and is most intense (IPCC).

Antarctic High A region of high pressure that occupies central Antarctic throughout the year. This pressure system is responsible for very cold temperatures and extremely low humidity.

Anthropogenic Resulting from or produced by human beings.

Aphelion The point in the Earth's orbit when it is farthest from the Sun (152.5 million kilometers). Aphelion occurs on the 3rd or 4th of July.

Archean Geologic Eon that occurred from 2,500 to 3,800 million years ago. During this time period, the first single-celled prokaryote organisms evolved and developed.

Archipelago A group of islands that have an arc shaped distribution. These islands are usually of volcanic origin and are associated with subduction zones.

Atlantic Multi-decadal Oscillation (AMO) A multi-decadal (65–75 year) fluctuation in the North Atlantic, in which sea surface temperatures showed warm phases during roughly 1860–1880 and 1930–1960 and cool phases during 1905–1925 and 1970–1990 with a range of order 0.4°C (IPCC).

Atmosphere The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium and radiatively active greenhouse gases such as carbon dioxide (0.035% volume mixing ratio) and ozone. In addition, the atmosphere contains the greenhouse gas water vapor, whose amounts are highly variable but typically around 1% volume mixing ratio. The atmosphere also contains clouds and aerosols (IPCC).

Atmospheric boundary layer The atmospheric layer adjacent to the Earth's surface that is affected by friction against that boundary surface, and possibly by transport of heat and other variables across that surface (AMS 2000). The lowest 10 m or so of the boundary layer, where mechanical generation of turbulence is dominant, is called the surface boundary layer or surface layer (IPCC).

Atmospheric lifetime See Lifetime.

Attribution See Detection and attribution.

B

Barometer An Instrument that measures atmospheric pressure.

Base (1) Substance having a pH greater than 7. (2) Substance that releases hydroxide ions (OH-).

Basic Substance having a pH greater than 7 Simatic rocks.

Bay A body of sheltered water found in a crescent shaped coastal configuration of land.

Beach The terrestrial interface area in between land and a water body where there are accumulations of unconsolidated sediments like sand and gravel.

Bedrock Rock at or near the Earth's surface that is solid and relatively unweathered

Benthos The plants and animals that live on the sea floor. Often divided into two categories: deep-sea benthos, below 200 m and the littoral benthos, from 200 m to the high-water spring tide level.

Bermuda High High pressure system that develops over the western subtropical North Atlantic. Also called the Azores High.

Beta Particle Electron emitted from the nucleus of a radioactive isotope. Also see alpha particle and gamma rays.

Biome Largest recognizable assemblage of animals and plants on Earth. The distribution of the biomes is controlled mainly by climate.

Biosphere Part of the Earth where life is found. The biosphere consists of all living things, plant and animal. This sphere is characterized by life in profusion, diversity, and clever complexity. Also called the ecosphere.

Biotic (1) Referring to life. (2) Influences caused by living organisms.

Black Body (or blackbody) An object that emits electromagnetic radiation, at any temperature, at the maximum possible rate per unit surface area. A black body also absorbs all electromagnetic radiation that is intercepted by it.

Black carbon (BC) Operationally defined aerosol material based on measurement of light absorption and chemical reactivity and/or thermal stability; consists of soot, charcoal and/or possible light-absorbing refractory organic matter (IPCC) (Charlson and Heintzenberg, 1995, p. 401).

Boreal Forest High to mid-latitude biome dominated by coniferous forest. Predominant vegetation of this biome is various species of spruce, fir, pine, and cedars. Also called Taiga.

Brackish Environment that is influenced by sea water with a salinity less than 35 parts per thousand (usually caused by the presence of an inflow of fresh water).

Breccia Coarse-grained sedimentary rock composed of cemented angular rock fragments.

C

^{13}C Stable isotope of carbon having an atomic weight of approximately 13. Measurements of the ratio of $^{13}C/^{12}C$ in carbon dioxide molecules are used to infer the importance of different carbon cycle and climate processes and the size of the terrestrial carbon reservoir (IPCC).

^{14}C Unstable isotope of carbon having an atomic weight of approximately 14, and a half-life of about 5,700 years. It is often used for dating purposes going back some 40 ka. Its variation in time is affected by the magnetic fields of the Sun and Earth, which influence its production from cosmic rays (see Cosmogenic isotopes) (IPCC).

Calcite A mineral consisting of calcium carbonate ($CaCO_3$)**.** The major constituent of limestone.

Calcium Carbonate A compound consisting of calcium, carbon and oxygen. Calcium carbonate has the following chemical formula, $CaCO_3$ and is he major constituent of limestone.

Calving Literally, to give birth to a calf. Used as a term to refer to the breaking up of glacial ice sometimes giving rise to icebergs.

Cambrian Geologic Period that occurred from 540 to 488.3 million years ago. During this period, invertebrates (animals without backbones) become common in the oceans and the Burgess Shale was formed. The Cambrian is known as the "Age of Trilobites."

Cambrian Explosion Great diversification of multicellular life forms in the Earth's oceans that started during the Period about 540 million years ago.

Carbonate A compound consisting of a single atom of carbon and three atoms of oxygen. Carbonate has the following chemical formula (CO_3^{2-}).

Carbonation (1) A form of chemical weathering where carbonate and bicarbonate ions react with minerals that contain calcium, magnesium, potassium, and sodium. (2) The dissolving of carbon dioxide in water.

Carbon Cycle Storage and cyclic movement of organic and inorganic forms of carbon between the biosphere, lithosphere, hydrosphere, and atmosphere.

Carbon Dioxide Gas found naturally occurring in the atmosphere. Has the ability to selectively absorb radiation in the longwave band. This absorption by carbon dioxide and other chemicals in the atmosphere causes the greenhouse effect. The concentration of this gas has been steadily increasing in the atmosphere over the last three centuries mainly due to the burning of fossil fuels, deforestation, and land-use changes. Most scientists and a majority of the general public believe higher concentrations of carbon dioxide and other greenhouse gases will result in an enhancement of the greenhouse effect and increase global warming. It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. I t is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1. The chemical formula for carbon dioxide is CO_2.

Carbon Monoxide A colorless, odorless, and tasteless gas that is produced by the incomplete burning of fossil fuels. The chemical formula for carbon monoxide is CO.

Cascading System A system where energy and/or matter flows from one form to another including the processes that cause this movement.

Catastrophism General theory of Earth history that suggests that certain phenomena on the Earth are the result of catastrophic events. For example, that the "Biblical Flood" is responsible for sedimentary rock formations and the extinction of the dinosaurs.

Celsius temperature scale One of the three scales commonly used in climate science for measuring temperature. In this scale, water boils at 100° and freezes at 0°. The Celsius scale is the same as the centigrade scale. The term Celsius if used by scientists while centigrade is used by non-scientists.

Cenozoic Geologic Era that occurred from 65.5 million years ago to today.

Centripetal Force Force required to keep an object moving in a circular pattern around a center of rotation. This force is directed towards the center of rotation. Common in meteorological phenomena like tornadoes and hurricanes.

Chalk A form of limestone. This is a sedimentary rock composed of the shells and skeletons of marine microorganisms.

Chaos theory Chaos theory deals with a dynamical system such as the climate system, governed by nonlinear deterministic equations (see Nonlinearity), may exhibit erratic or chaotic behaviour in the sense that very small changes in the initial state of the system in time lead to large and apparently unpredictable changes in its temporal evolution. Such chaotic behaviour may limit the predictability of nonlinear dynamical systems (IPCC).

Chemical Energy Energy consumed or produced in chemical reactions.

Chemical Reaction Reaction between chemicals where there is a change in the chemical composition of the elements or compounds involved.

Chemical Weathering Breakdown of rock and minerals into smaller-sized particles through chemical decomposition.

Chlorofluorocarbons (CFCs) Artificially created gases that have become concentrated in the Earth's atmosphere. These very strong greenhouse gases are released from aerosol sprays, refrigerants, and the production of foams. The basic chemical formula for chlorofluorocarbons is CFx Clx .

Chronology Arrangement of events according to dates or times of occurrence.

Circle of Illumination A line that bisects areas on the Earth receiving sunlight and those areas in darkness. The circle of illumination cuts the spherical Earth into lighted and dark halves. The line is not a sharp one as the light gradually turns into dark.

Circum-Pacific Belt (or "Ring of Fire") A zone circling the edge of the Pacific Ocean basin where tectonic subduction causes the formation of volcanic island arcs and trenches.

Cirrocumulus Clouds Patchy white high altitude clouds composed of ice crystals. Found in an altitude range from 5,000 to 18,000 m.

Cirrostratus Clouds High altitude sheet like clouds composed of ice crystals. These thin clouds often cover the entire sky. Found in an altitude range from 5,000 to 18,000 m.

Cirrus Clouds High altitude cloud composed of ice crystals. The appearance of these clouds is white feather like patches, filaments or thin bands. Found in an altitude range from 5,000 to 18,000 m.

Clathrate (methane) A partly frozen mix of methane gas and ice, usually found in sediments.

CLIMAP Project Multi-university research project that reconstructed the Earth's climate for the last million years by examining proxy data from ocean sediment cores.

Climate General pattern of weather conditions for an area or region over at least 30 years. Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (WMO). The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate change Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. See also Climate variability; Detection and Attribution (IPCC).

Climate feedback An interaction mechanism between processes in the climate system is called a climate feedback when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it (IPCC).

Climate Feedback Parameter A way to quantify the radiative response of the climate system to a global surface temperature change induced by a radiative forcing (units: W m^{-2} $°C^{-1}$). It varies as the inverse of the effective climate sensitivity. Formally, the Climate Feedback Parameter (Λ) is defined as: $\Lambda = (\Delta Q - \Delta F)/\Delta T$, where Q is the global mean radiative forcing, T is the global mean air surface temperature, F is the heat flux into the ocean and Δ represents a change with respect to an unperturbed climate.

Climatic Optimum Warmest period during the Holocene Epoch. The Holocene Climatic Optimum is dated from about 5,000–3,000 BC. During this time average global temperatures were 1–2°C warmer than they are today.

Climate model (spectrum or hierarchy) A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parameterizations are involved. Coupled Atmosphere-ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology (see

Chap. 9). Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and interannual climate predictions (IPCC).

Climate prediction A climate prediction or climate forecast is the result of an attempt to produce an estimate of the actual evolution of the climate in the future, for example, at seasonal, interannual or long-term time scales. Since the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature. See also Climate projection; Climate scenario; Predictability (IPCC).

Climate projection A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty IPCC.

Climate scenario A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate (IPCC).

Climate sensitivity In the IPCC reports, equilibrium climate sensitivity refers to the equilibrium change in the annual mean global surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration. Due to computational constraints, the equilibrium climate sensitivity in a climate model is usually estimated by running an atmospheric general circulation model coupled to a mixed-layer ocean model, because equilibrium climate sensitivity is largely determined by atmospheric processes. Efficient models can be run to equilibrium with a dynamic ocean. The effective climate sensitivity is a related measure that circumvents the requirement of equilibrium. It is evaluated from model output for evolving non-equilibrium conditions. It is a measure of the strengths of the climate feedbacks at a particular time and may vary with forcing history and climate state. The climate sensitivity parameter (units: $°C\ (W\ m^{-2})^{-1}$) refers to the equilibrium change in the annual mean global surface temperature following a unit change in radiative forcing. The transient climate response is the change in the global surface temperature, averaged over a 20-year period, centered at the time of atmospheric carbon dioxide doubling, that is, at year 70 in a 1% $year^{-1}$ compound carbon dioxide increase experiment with a global coupled climate model. It is a measure of the strength and rapidity of the surface temperature response to greenhouse gas forcing (IPCC).

Climatology Scientific study of the Earth's climate over long time spans. May also involve an investigation of climate's influence on flora and fauna, and other aspects of climate's influence on the environment.

Climate shift or climate regime shift An abrupt shift or jump in mean values signaling a change in regime. Most widely used in conjunction with the 1976/1977 climate shift that seems to correspond to a change in El Niño-Southern Oscillation (ENSO) behavior (IPCC).

Climate system The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface (geosphere) and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land use change (IPCC).

Climate variability Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See also Climate change (IPCC).

Closed System A system that transfers energy, but not matter, across its boundary to the surrounding environment. The Earth has often been erroneously viewed as a closed system.

Cloud A collection of tiny particles of liquid or solid water occurring above the Earth's surface. Clouds are classified accord to their height of occurrence and shape. The major types of clouds include: Cirris, Cirrocumulus, Cirrostratus, Altocumulus, Altostratus, Nimbostratus, Stratocumulus, Stratus, Cumulus, and Cumulonimbus.

Cloud condensation nuclei (CCN) Airborne particles that serve as an initial site for the condensation of liquid water, which can lead to the formation of cloud droplets. See also Aerosols.

Cloud feedback A climate feedback involving changes in any of the properties of clouds as a response to other atmospheric changes. Understanding cloud feedbacks and determining their magnitude and sign require an understanding of how a change in climate may affect the spectrum of cloud types, the cloud fraction and height, and the radiative properties of clouds, and an estimate of the impact of these changes on the Earth's radiation budget. At present, cloud feedbacks remain the largest source of uncertainty in climate sensitivity estimates. See also Cloud radiative forcing; Radiative forcing IPCC.

Cloud radiative forcing Cloud radiative forcing is the difference between the all-sky Earth's radiation budget and the clear-sky Earth's radiation budget (units: W m^2) (IPCC).

CO_2-equivalent See Equivalent carbon dioxide.

Coal A sedimentary (bituminous) or metamorphic rock (anthracite) composed of compacted lithified and in the case of anthracite, altered remains of plants. Coal is a solid, combustible mixture of organic compounds, hydrocarbons, with 30–98% carbon by weight, mixed with various amounts of water and small amounts of sulphur and nitrogen compounds. It is formed in several stages as the remains of plants are subjected to heat and pressure over millions of years. It is an extremely dirty fuel and is one of the main causes in increasing concentrations of carbon dioxide in the atmosphere. "Clean coal" is an oxymoron.

Coastline The line that separates a land surface from an ocean or sea.

Cold Desert A desert found in the high latitudes and at high altitudes where precipitation is low. Surface air temperatures are generally cold in these dry environments. The continent of Antarctica is a cold desert.

Comet A large mass of ice and dust that has an orbit around a star.

Compound A compound consists of the atoms of different elements bonded together.

Condensation The change in state of matter from vapor to liquid that occurs with cooling. The term is used in meteorology when discussing the formation of liquid water from vapor. This process releases latent heat energy to the surroundings.

Condensation Nuclei Microscopic particle of dust, smoke or salt that allows for condensation of water vapor to water droplets in the atmosphere. Nucleus for the formation of a rain drop. Condensation normally occurs on these particles when relative humidity becomes 100%. Some condensation nuclei, like salt, are hygroscopic and water can condense on them at relative humidities lower than 100%.

Conduction Conduction consists of energy transfer directly from atom to atom and represents the flow of energy along a temperature gradient.

Coniferous Vegetation Cone-bearing vegetation of middle and high latitudes that are mostly evergreen and that have needle-shaped or scale like leaves. Compare with deciduous vegetation.

Confidence The level of confidence in the correctness of a result. See also Likelihood; Uncertainty (IPCC).

Convection Vertical motion driven by buoyancy forces arising from static instability, usually caused by near-surface cooling or increases in salinity in the case of the ocean and near-surface warming in the case of the atmosphere. At the location of convection, the horizontal scale is approximately the same as the vertical scale, as opposed to the large contrast between these scales in the general circulation. The net vertical mass transport is usually much smaller than the upward and downward exchange (IPCC).

Continental Arctic Air Mass An air mass that forms over extensive landmass areas of the high latitudes in the Northern Hemisphere. In the Northern Hemisphere, these systems form only in winter over Greenland, northern Canada, northern Siberia, and the Arctic Basin. Continental Arctic air masses are very cold and extremely dry. These air masses are also very stable.

Continental Crust The granitic portion of the Earth's crust that makes up the continents. Thickness of the continental crust varies between 20 and 75 km. See sial.

Continental Drift Theory that suggests that the Earth's continents have migrated to their current positions across the globe. First proposed by A. Snider in 1858 and developed by F.B. Taylor (1908) and Alfred Wegener (1915).

Continental Effect The effect that continental surfaces have on the climate of locations or regions. This effect results in a greater range in surface air temperature at both daily and annual scales. Also see maritime effect.

Continental Glacier Largest type of glacier with a surface coverage in the order of 5 million km^2.

Continental Ice Sheet See continental glacier.

Continental Margin The area between a continent's shoreline and the beginning of the ocean floor. It includes the continental shelf, continental rise, and continental slope.

Continental Plate A rigid, independent segment of the lithosphere composed of mainly granite that "floats" on the viscous plastic asthenosphere and moves over the surface of the Earth. T he Earth's continental plates are an average 125 km thick and were formed more than 3 billion years ago. Also see oceanic plate.

Continental Polar Air Mass (cP) An air mass that forms over extensive landmass areas of middle to high latitudes. In North America, these system form over northern Canada. Continental Polar air masses are cold and very dry in the winter and cool and dry in the summer. These air masses are also atmospherically stable in both seasons.

Continental Rise Thick layers of sediment found between the continental slope and the ocean floor or abyssal plain.

Continental Shelf Shallow submerged margin of the continents that lies between the edge of the shoreline and the continental slope. This nearly level area of the continental crust has surface layers composed of sediment or sedimentary rock.

Continental Slope Steeply sloping portion of continental crust found between the continental shelf and the continental rise.

Convection Convection involves the transfer of heat energy by means of vertical mass motions through a medium, in the case of meteorology or climate, through the atmosphere.

Convection Current The movement of a gas or a fluid in chaotic vertical mass motions because of heating.

Convectional Lifting The vertical lifting of parcels of air through convective heating of the atmosphere. This process can initiate adiabatic processes inside the air parcel.

Convectional Precipitation The formation of precipitation due to surface heating of the air at the ground surface. If enough heating occurs, the mass of air becomes warmer and lighter than the air in the surrounding environment, and just like a hot air balloon it begins to rise, expand and cool. When sufficient cooling has taken place saturation occurs forming precipitation. This process is active in the interior of continents and near the equator forming cumulus clouds and possible later thunderstorms. Rain is usually the precipitation type that is formed, and in most cases this moisture is delivered in large amounts over short periods of time in extremely localized areas.

Convergence Horizontal inflow of wind into an area. Once at the area, the wind then travels vertically.

Convergence Precipitation The formation of precipitation due to the convergence of two air masses. In most cases, the two air masses have different climatological characteristics. One is usually warm and moist, while the other is cold and dry.

The leading edge of the latter air mass acts as an inclined wall or front causing the moist warm air to be lifted. Of course the lifting causes the warm moist air mass to cool due to expansion resulting in saturation. This precipitation type is common at the mid-latitudes where cyclones form along the polar front. Also known as frontal precipitation.

Coral Simple marine animals that live symbiotically with algae. In the symbiotic relationship, algae provide the coral with nutrients, while the coral provides the algae with a support structure in which to live. Coral animals secrete calcium carbonate ($CaCO_3$) to produce a hard external skeleton (exoskeleton).

Coral Bleaching When coral lose their colorful symbiotic algae. Thought to be caused by unusually warm water, changes in salinity of ocean waters, excessive exposure to ultraviolet radiation, or ocean acidification.

Coral Reef A reef or ridge of limestone found generally below the ocean surface (except in the case of fossil coral reefs). This marine feature is produced by numerous colonies of tiny coral animals, called polyps that create calcium carbonate structures around themselves for protection. When the corals die, their vacant exterior skeletons form layers of limestone that new polyps use as a substrate upon which to grow. Coral reefs are found in the coastal zones of warm tropical and subtropical oceans where waters are clean and well aerated.

Coriolis Force An apparent force due to the Earth's rotation. Causes moving objects to be deflected to the right in the Northern Hemisphere and to the left in the Southern hemisphere. Coriolis force does not exist on the equator. This force is responsible for the direction of flow in meteorological phenomena like mid-latitude cyclones, hurricanes and anticyclones.

Craton Stable core of Earth's various plates of continental crust. Composed of the shield and platform.

Cretaceous The Cretaceous Period of geologic time that occurred roughly 65.5–145.5 million years ago. During this interval, the first flowering plant species appear and dinosaurs are at their greatest diversity. Dinosaurs die out at the end of the Cretaceous.

Crevasse (1) Opening on a levee that allows for the drainage of water from the floodplain to the stream channel. (2) Fracture on the brittle surface of a glacier.

Crust Earth's outer most layer of solid rock. Between 7 and 70 km thick. Two types of crust exist: oceanic crust and continental crust.

Cryosphere The component of the climate system consisting of all snow, ice and frozen ground (including permafrost) on and beneath the surface of the Earth and ocean. See also Glacier; Ice sheet (IPCC).

Cumulus Cloud Puffy clouds with relatively flat bases. Cumulus clouds form when moist warm air bubbles vertically escape from the Earth's surface. Found in an altitude range from 300 to 2,000 m.

Cumulonimbus Cloud A well developed vertical cloud that often has a top shaped like an anvil. These clouds are very dense with condensed and deposited water. Weather associated with this cloud includes: strong winds; hail; lightning; tornadoes; thunder; and heavy rain. When this weather occurs, these events are then thunderstorms. These clouds can extend in altitude from a few hundred meters above the surface to more than 12,000 m.

Cyclogenesis Process of cyclone formation, maturation, and death.

Cyclone Area of low pressure in the atmosphere that displays circular inward movement of air. In the Northern Hemisphere circulation is counterclockwise, while Southern Hemisphere cyclones have clockwise wind patterns.

D

Dansgaard-Oeschger events Abrupt warming events followed by gradual cooling. The abrupt warming and gradual cooling is primarily seen in Greenland ice cores and in paleoclimate records from the nearby North Atlantic, while a more general warming followed by a gradual cooling has been observed in other areas as well, at intervals of 1.5–7 kyear during glacial times.

December Solstice Date during the year when the declination of the Sun is at 23.5° South of the equator. During the December solstice, locations in the Northern Hemisphere experience their shortest day. The December solstice is also the first day of winter in the Northern Hemisphere. Locations in the Southern Hemisphere have their longest day on the June solstice. This date also marks the first day of summer in the Southern Hemisphere.

Deciduous Vegetation Type of vegetation that sheds its leaves during winter or dry seasons. Compare with coniferous vegetation.

Decomposition (1) To chemically or physically breakdown a mass of matter into smaller parts or chemical elements. (2) Breakdown of organic matter into smaller parts or inorganic constituents by decomposing organisms.

Deduction Inference in which the conclusion about particulars follows necessarily from general theory. In a science, deductive reasoning would involve stating a theory or hypothesis first and then trying to find facts that reject this idea.

Deforestation Removal of trees from a habitat dominated by forest. Conversion of forest to non-forest. For a discussion of the term forest and related terms such as afforestation, reforestation, and deforestation see the IPCC Special Report on Land Use, Land-Use Change and Forestry (IPCC, 2000). See also the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).

Density (of Matter) Refers to the quantity of mass per unit volume. For gases, density involves the number of atoms and molecules per unit volume.

Deoxyribonucleic Acid (DNA) Form of nucleic acid that is organized int o a double-helix molecule. DNA is used by most organisms to chemically code their genetics and to direct the development and functioning of cells. This direction requires RNA which represents a copy of a portion of DNA. Found in the nucleus of cells.

Deposition (1) The change in state of matter from gas to solid that occurs with cooling. Usually used in meteorology when discussing the formation of ice from water vapor. This process releases latent heat energy to the environment. (2) Laying down of sediment transported by wind, water, or ice.

Desert (1) Biome that has plants and animals adapted to survive severe drought conditions. In this habitat, evaporation exceeds precipitation and the average amount of precipitation is less than 25 cm a year. (2) Area that receives low precipitation.

Desertification Conversion of marginal rangeland or cropland to a more desert- like land type. Desertification can be caused by overgrazing, soil erosion, prolonged drought, or climate change. Land degradation in arid, semi-arid, and dry sub-humid areas may result from various factors, including climatic variations and human activities. The United Nations Convention to Combat Desertification defines land degradation as a reduction or loss in arid, semi-arid, and dry sub-humid areas, of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical and biological or economic properties of soil; and (iii) long-term loss of natural vegetation (IPCC).

Detection and attribution Climate varies continually on all time scales. Detection of climate change is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change. Attribution of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence (IPCC).

Deuterium An isotope of hydrogen, with a nucleus containing one proton and one neutron, and an atomic number of 2.

Devonian Geologic Period that occurred roughly 360–408 million years ago. During this period, the first amphibians and trees appear.

Diatoms Silt-sized algae that live in surface waters of lakes, rivers and oceans and form shells of opal. Their species distribution in ocean cores is often related to past sea surface temperatures (IPCC).

Direct Solar Radiation Solar radiation received by the Earth's atmosphere or surface which has not been modified by atmospheric scattering.

Discontinuous Permafrost Form of permafrost that contains numerous scattered pockets of unfrozen ground.

Dispersal A group of organisms leaving their place or birth or activity for another location.

Dissolution The process of a substance dissolving and dispersing into a liquid.

Disturbance (1) Partial or complete alteration of a community or an ecosystem by a biotic or abiotic factor. (2) A cyclonic low pressure system.

Diurnal temperature range The difference between the maximum and minimum temperature during a 24-h period.

Dobson unit (DU) A unit to measure the total amount of ozone in a vertical column above the Earth's surface (total column ozone). The number of Dobson units is the thickness in units of 10^{-5} m that the ozone column would occupy if compressed into a layer of uniform density at a pressure of 1,013 hPa and a temperature of 0°C. One DU corresponds to a column of ozone containing $2.69 \times 1{,}020$ molecules per square meter. A typical value for the amount of ozone in a column of the Earth's atmosphere, although very variable, is 300 DU (IPCC).

Doldrums Area of low atmospheric pressure and calm westerly winds located at the equator. Similar to Intertropical Convergence zone.

Downdraft Downward movement of air in the atmosphere.

Drought In general terms, drought is a 'prolonged absence or marked deficiency of precipitation', a 'deficiency that results in water shortage for some activity or for some group', or a 'period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance' (Heim, 2002). Drought has been defined in a number of ways. Agricultural drought relates to moisture deficits in the topmost 1 m or so of soil (the root zone) that affect crops, meteorological drought is mainly a prolonged deficit of precipitation, and hydrologic drought is related to below-normal stream flow, lake and groundwater levels. A megadrought is a long-drawn out and pervasive drought, lasting much longer than normal, usually a decade or more.

Dry Adiabatic Lapse Rate (DALR) The rate of decline in the temperature of a rising parcel of air before it has reached saturation. This rate of temperature decline is 9.8° Celsius per 1,000 m because of adiabatic cooling.

Dry-Bulb Thermometer Thermometer on a psychrometer used to determine current air temperature. This measurement and the reading from a wet-bulb thermometer are then used for the determination of relative humidity or dew point from a psychrometric table.

Dune (1) Stream bed deposit found in streams whose channel is composed mainly of sand and silt. Dunes are about 10 or more centimeters in height and are spaced a meter or more apart and are common in streams with high velocities. (2) Terrestrial deposit of sand that resembles a mound or ridge that was formed from aeolian processes. Also see sand dune.

Dynamical system A process or set of processes whose evolution in time is governed by a set of deterministic physical laws. The climate system is a dynamical system. See Abrupt climate change; Chaos; Nonlinearity; Predictability.

E

Ecosystem A system of living organisms interacting with each other and their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth (IPCC).

El Niño-Southern Oscillation (ENSO) The term **El Niño** was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Perú, disrupting the local fishery. It has since become identified with a basin-wide warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled atmosphere-ocean phenomenon, with preferred time scales of 2 to about 7 years, is collectively known as the El Niño-Southern Oscillation (ENSO). It is often measured by the surface pressure anomaly difference between Darwin and Tahiti and the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections. The cold phase of ENSO is called **La Niña** (IPCC).

Equivalent carbon dioxide (CO_2) emission The amount of carbon dioxide emission that would cause the same integrated radiative forcing, over a given time horizon, as an emitted amount of a well mixed greenhouse gas or a mixture of well mixed greenhouse gases. The equivalent carbon dioxide emission is obtained by multiplying the emission of a well mixed greenhouse gas by its Global Warming Potential (GWP) for the given time horizon. For a mix of greenhouse gases it is obtained by summing the equivalent carbon dioxide emissions of each gas. Equivalent carbon dioxide emission is a standard and useful metric for comparing emissions of different greenhouse gases but does not imply exact equivalence of the corresponding climate change responses (IPCC).

Evapotranspiration The combined process of evaporation from the Earth's surface and transpiration from vegetation.

External forcing External forcing refers to a forcing agent outside the climate system causing a change in the climate system. Volcanic eruptions, solar variations and anthropogenic changes in the composition of the atmosphere and land use change are external forcings.

Extreme weather event An extreme weather event is an event that is rare at a particular place and time of year. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. Single extreme events cannot be simply and directly attributed to anthropogenic climate change, as there is always a finite chance the event in question might have occurred naturally. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).

F

Faculae Bright patches on the Sun. The area covered by faculae is greater during periods of high solar activity.

Feedback See Climate feedback.

Fingerprint The climate response pattern in space and/or time to a specific forcing is commonly referred to as a fingerprint. Fingerprints are used to detect the presence of this response in observations and are typically estimated using forced climate model simulations (IPCC).

Fossil fuel emissions Emissions of greenhouse gases (in particular carbon dioxide) resulting from the combustion of fuels from fossil carbon deposits such as oil, gas and coal.

Framework Convention on Climate Change See United Nations Framework Convention on Climate Change (UNFCCC).

G

General circulation The large-scale motions of the atmosphere and the ocean as a consequence of differential heating on a rotating Earth, which tend to restore the energy balance of the system through transport of heat and momentum.

General Circulation Model (GCM) See Climate model.

Geologic time time from the beginning of Earth through 4.5 billion years of its history.

Geostrophic winds or currents A wind or current that is in balance with the horizontal pressure gradient and the Coriolis force, and thus is outside of the influence of friction. Thus, the wind or current is directly parallel to isobars and its speed is inversely proportional to the spacing of the isobaric contours.

Glacial isostatic adjustment See Post-glacial rebound.

Glacier A mass of land ice that flows downhill under gravity (through internal deformation and/or sliding at the base) and is constrained by internal stress and friction at the base and sides. A glacier is maintained by accumulation of snow at high altitudes, balanced by melting at low altitudes or discharge into the sea (IPCC).

Global dimming Global dimming refers to perceived widespread reduction of solar radiation received at the surface of the Earth from about the year 1961 to around 1990 (IPCC).

Global warming A positive (upward) trend in Earth's average temperature throughout the world. Some areas may show a negative trend (cooling) but the average global temperature has been increasing since 1880 with slight cooling during the 1970s.

Ground temperature The temperature of the ground near the surface (often within the first 10 cm). It is often called soil temperature (IPCC).

Global surface temperature The global surface temperature is an estimate of the global mean surface air temperature. However, for changes over time, only anomalies, as departures from a climatology, are used, most commonly based on the area-weighted global average of the sea surface temperature anomaly and land surface air temperature anomaly (IPCC).

Global Warming Potential (GWP) An index, based upon radiative properties of well-mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation. The Kyoto Protocol is based on GWPs from pulse emissions over a 100-year time frame (IPCC).

Greenhouse Effect Greenhouse gases effectively absorb thermal infrared radiation, emitted by the Earth's surface, by the atmosphere itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth's surface. Thus, greenhouse gases trap heat within the surface-troposphere system. This is called the greenhouse effect. Thermal infrared radiation in the troposphere is strongly coupled to the temperature of the atmosphere at the altitude at which it is emitted. In the troposphere, the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, −19°C, in balance with the net incoming solar radiation, whereas the Earth's surface is kept at a much higher temperature of, on average, +14°C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing that leads to an enhancement of the greenhouse effect, the so-called enhanced greenhouse effect (IPCC).

Greenhouse gas (GHG) Greenhouse gases (GHGs) are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) (IPCC).

Gyre Basin-scale ocean horizontal circulation pattern with slow flow circulating around the ocean basin, closed by a strong and narrow (100–200 km wide) boundary current on the western side. The subtropical gyres in each ocean are associated with high pressure in the centre of the gyres; the subpolar gyres are associated with low pressure (IPCC).

H

Hadley Circulation A direct, thermally driven overturning cell in the atmosphere consisting of poleward flow in the upper troposphere, subsiding air into the subtropical anticyclones, return flow as part of the trade winds near the surface, and with rising air near the equator in the so-called Inter-Tropical Convergence Zone (IPCC).

Halocarbons A collective term for the group of partially halogenated organic species, including the chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), halons, methyl chloride, methyl bromide, etc. Many of the halocarbons have large Global Warming Potentials. The chlorine- and bromine-containing halocarbons are also involved in the depletion of the ozone layer (IPCC).

HCFC See Halocarbons.

HFC See Halocarbons.

Holocene The Holocene geological Epoch is the latter of two Quaternary epochs, extending from about 11.6 ka to and including the present.

Hydrosphere The component of the climate system comprising liquid surface and subterranean water, such as oceans, seas, rivers, fresh water lakes, underground water, etc.

I

Ice age An ice age or glacial period is characterized by a long-term reduction in the temperature of the Earth's climate, resulting in growth of continental ice sheets and mountain glaciers (glaciation) (IPCC).

Ice cap A dome shaped ice mass, usually covering a highland area, which is considerably smaller in extent than an ice sheet (IPCC).

Ice core A cylinder of ice drilled out of a glacier or ice sheet.

Ice sheet A mass of land ice that is sufficiently deep to cover most of the underlying bedrock topography, so that its shape is mainly determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base). An ice sheet flows outward from a high central ice plateau with a small average surface slope. The margins usually slope more steeply, and most ice is discharged through fast-flowing ice streams or outlet glaciers, in some cases into the sea or into ice shelves floating on the sea. There are only three large ice sheets in the modern world, one on Greenland and two on Antarctica, the East and West Antarctic Ice Sheets, divided by the Transantarctic Mountains. During glacial periods there were others (IPCC).

Ice shelf A floating slab of ice of considerable thickness extending from the coast (usually of great horizontal extent with a level or gently sloping surface), often filling embayments in the coastline of the ice sheets. Nearly all ice shelves are in Antarctica, where most of the ice discharged seaward flows into ice shelves (IPCC).

Indirect aerosol effect Aerosols may lead to an indirect radiative forcing of the climate system through acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds. Two indirect effects are distinguished:

- Cloud albedo effect
- A radiative forcing induced by an increase in anthropogenic aerosols that cause an initial increase in droplet concentration and a decrease in droplet size for fixed liquid water content, leading to an increase in cloud albedo. This effect is also known as the first indirect effect or Twomey effect.
- Cloud lifetime effect
- A forcing induced by an increase in anthropogenic aerosols that cause a decrease in droplet size, reducing the precipitation efficiency, thereby modifying the liquid water content, cloud thickness and cloud life time. This effect is also known as the second indirect effect or Albrecht effect.

Apart from these indirect effects, aerosols may have a semi-direct effect. This refers to the absorption of solar radiation by absorbing aerosol, which heats the air and tends to increase the static stability relative to the surface. It may also cause evaporation of cloud droplets (IPCC).

Industrial Revolution A period of rapid industrial growth with far-reaching social and economic consequences, beginning in Britain during the second half of the eighteenth century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The Industrial Revolution marks the beginning of a strong increase in the use of fossil fuels and emission of, in particular, fossil carbon dioxide (IPCC).

Infrared radiation See Thermal infrared radiation.

Insolation The amount of solar radiation reaching the Earth by latitude and by season. Usually insolation refers to the radiation arriving at the top of the atmosphere. Sometimes it is specified as referring to the radiation arriving at the Earth's surface. See also: Total Solar Irradiance (IPCC).

Interglacials The warm periods between ice age glaciations. The previous interglacial, dated approximately from 129 to 116 ka, is referred to as the Last Interglacial (AMS, 2000).

Inter-Tropical Convergence Zone (ITCZ) The Inter-Tropical Convergence Zone is an equatorial zonal belt of low pressure near the equator where the northeast trade winds meet the southeast trade winds. As these winds converge, moist air is forced upward, resulting in a band of heavy precipitation. This band moves seasonally.

IPCC The Intergovernmental Panel on Climate Change, part of the United Nations Environmental Program. The IPCC assesses the scientific, technical and socio-economic information relevant for the understanding of the risk of human-induced climate change.

Isostatic or Isostasy Isostasy refers to the way in which the lithosphere and mantle respond visco-elastically to changes in surface loads. When the loading of the lithosphere and/or the mantle is changed by alterations in land ice mass (glaciers), ocean mass, sedimentation, erosion or mountain building, vertical isostatic adjustment results, in order to balance the new load (IPCC).

K

Kyoto Protocol The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1997 in Kyoto, Japan, at the Third Session of the Conference of the Parties (COP) to the UNFCCC. It contains legally binding commitments, in addition to those included in the UNFCCC. Countries included in Annex B of the Protocol (most Organization for Economic Cooperation and Development countries and countries with economies in transition) agreed to reduce their anthropogenic greenhouse gas emissions (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride) by at least 5% below 1990 levels in the commitment period 2008–2012. The Kyoto Protocol entered into force on 16 February 2005. The United States of America was not a party to the Kyoto Protocol.

L

Land use and Land use change Land use refers to the total of arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction and conservation). Land use change refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land use change may have an impact on the surface albedo, evapotranspiration, sources and sinks of greenhouse gases, or other properties of the climate system and may thus have a radiative forcing and/or other impacts on climate, locally or globally. See also the IPCC Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000).

La Niña See El Niño-Southern Oscillation.

Land surface air temperature The surface air temperature as measured in well-ventilated screens over land at 1.5 m above the ground (IPCC).

Lapse rate The rate of change of an atmospheric variable, usually temperature, with height. The lapse rate is considered positive when the variable decreases with height.

Last Glacial Maximum (LGM) The Last Glacial Maximum refers to the time of maximum extent of the ice sheets during the last glaciation, approximately 21 ka. This period has been widely studied because the radiative forcings and boundary conditions are relatively well known and because the global cooling during that period is comparable with the projected warming over the 21st century (IPCC).

Last Interglacial (LIG) See Interglacial.

Lithosphere The upper layer of the solid Earth, both continental and oceanic, which comprises all crustal rocks and the cold, mainly elastic part of the uppermost mantle. Volcanic activity, although part of the lithosphere, is not considered as part of the climate system, but acts as an external forcing factor (IPCC). See Isostatic.

Little Ice Age (LIA) An interval between approximately AD 1400 and 1900 when temperatures in the Northern Hemisphere were generally colder than today's, especially in Europe (IPCC).

M

Mean sea level See Relative sea level.

Medieval Warm Period (MWP) An interval between AD 1000 and 1300 in which some Northern Hemisphere regions were warmer than during the Little Ice Age that followed.

Meridional Overturning Circulation (MOC) Meridional (north-south) overturning circulation in the ocean quantified by zonal (east-west) sums of mass transports in depth or density layers. In the North Atlantic, away from the Subpolar regions, the MOC (which is in principle an observable quantity) is often identified with the **Thermohaline Circulation (THC)**, which is a conceptual interpretation. However, it must be borne in mind that the MOC can also include shallower, wind-driven overturning cells such as occur in the upper ocean in the tropics and subtropics, in which warm (light) waters moving poleward are transformed to slightly denser waters and subducted equatorward at deeper levels (IPCC).

Metadata Information about meteorological and climatological data concerning how and when they were measured, their quality, known problems and other characteristics (IPCC).

Metric A consistent measurement of a characteristic of an object or activity that is otherwise difficult to quantify.

Mitigation A human intervention to reduce the sources or enhance the sinks of greenhouse gases (IPCC).

Mixing ratio See Mole fraction.

Model hierarchy See Climate model (spectrum or hierarchy).

Modes of climate variability Natural variability of the climate system, in particular on seasonal and longer time scales, predominantly occurs with preferred spatial patterns and time scales, through the dynamical characteristics of the atmospheric circulation and through interactions with the land and ocean surfaces. Such patterns are often called regimes, modes or teleconnections. Examples are the North

Atlantic Oscillation (NAO), the Pacific-North American pattern (PNA), the El Niño-Southern Oscillation (ENSO), the Northern Annular Mode (NAM; previously called Arctic Oscillation, AO) and the Southern Annular Mode (SAM; previously called the Antarctic Oscillation, AAO). Many of the prominent modes of climate variability are discussed in Section 3.6, of the IPCC AR4, 2007. See also Patterns of climate variability.

Mole fraction Mole fraction, or mixing ratio, is the ratio of the number of moles of a constituent in a given volume to the total number of moles of all constituents in that volume. It is usually reported for dry air. Typical values for long-lived greenhouse gases are in the order of μmol mol^{-1} (parts per million: ppm), nmol mol^{-1} (parts per billion: ppb), and fmol mol^{-1} (parts per trillion: ppt). Mole fraction differs from volume mixing ratio, often expressed in ppmv etc., by the corrections for non-ideality of gases. This correction is significant relative to measurement precision for many greenhouse gases. (Schwartz and Warneck 1995) (IPCC).

Monsoon A monsoon is a tropical and subtropical seasonal reversal in both the surface winds and associated precipitation, caused by differential heating between a continental-scale land mass and the adjacent ocean. Monsoon rains occur mainly over land in summer.

Montreal Protocol The Montreal Protocol on Substances that Deplete the Ozone Layer was adopted in Montreal in 1987, and subsequently adjusted and amended in London (1990), Copenhagen (1992), Vienna (1995), Montreal (1997) and Beijing (1999). It controls the consumption and production of chlorine- and bromine-containing chemicals that destroy stratospheric ozone, such as chlorofluorocarbons, methyl chloroform, carbon tetrachloride and many others (IPCC).

Microwave Sounding Unit (MSU) A satellite-borne microwave sounder that estimates the temperature of thick layers of the atmosphere by measuring the thermal emission of oxygen molecules from a complex of emission lines near 60 GHz. A series of nine MSUs began making this kind of measurement in late 1978. Beginning in mid 1998, a follow-on series of instruments, the Advanced Microwave Sounding Units (AMSUs), began operation (IPCC).

MSU See Microwave Sounding Unit.

N

Nonlinearity A process is called nonlinear when there is no simple proportional relation between cause and effect. The climate system contains many such nonlinear processes, resulting in a system with a potentially very complex behaviour. Such complexity may lead to abrupt climate change. See also Chaos; Predictability (IPCC).

North Atlantic Oscillation (NAO) The North Atlantic Oscillation consists of opposing variations of barometric pressure near Iceland and near the Azores. It therefore corresponds to fluctuations in the strength of the main westerly winds across the Atlantic into Europe, and thus to fluctuations in the embedded cyclones with their associated frontal systems (IPCC).

Northern Annular Mode (NAM) A winter fluctuation in the amplitude of a pattern characterized by low surface pressure in the Arctic and strong mid-latitude westerlies. The NAM has links with the northern polar vortex into the stratosphere. Its pattern has a bias to the North Atlantic and has a large correlation with the North Atlantic Oscillation (IPCC).

O

Ocean acidification A decrease in the pH of sea water due to the uptake of anthropogenic carbon dioxide (IPCC).

Organic aerosol Aerosol particles consisting predominantly of organic compounds, mainly carbon, hydrogen, oxygen and lesser amounts of other elements. (Charlson and Heintzenberg, 1995, p. 405) (IPCC). See Carbonaceous aerosol.

Ozone Ozone, the tri-atomic form of oxygen (O_3), is a gaseous atmospheric constituent. In the troposphere, it is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Tropospheric ozone acts as a greenhouse gas. In the stratosphere, it is created by the interaction between solar ultraviolet radiation and molecular oxygen (O_2). Stratospheric ozone plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the ozone layer (IPCC).

Ozone hole See Ozone layer.

Ozone layer The stratosphere contains a layer in which the concentration of ozone is greatest, the so-called ozone layer. The layer extends from about 12–40 km above the Earth's surface. The ozone concentration reaches a maximum between about 20 and 25 km. This layer is being depleted by human emissions of chlorine and bromine compounds. Every year, during the Southern Hemisphere spring, a very strong depletion of the ozone layer takes place over the Antarctic region, caused by anthropogenic chlorine and bromine compounds in combination with the specific meteorological conditions of that region. This phenomenon is called the ozone hole (IPCC). See Montreal Protocol.

P

Pacific decadal variability Coupled decadal-to-inter-decadal variability of the atmospheric circulation and underlying ocean in the Pacific Basin. It is most prominent in the North Pacific, where fluctuations in the strength of the winter Aleutian Low pressure system co-vary with North Pacific sea surface temperatures, and are linked to decadal variations in atmospheric circulation, sea surface temperatures and ocean circulation throughout the whole Pacific Basin. Such fluctuations have the effect of modulating the El Niño-Southern Oscillation cycle. Key measures of Pacific decadal variability are the North Pacific Index (NPI), the Pacific Decadal Oscillation (PDO) index and the Inter-decadal Pacific Oscillation (IPO) index.

Paleoclimate Climate during periods prior to the development of measuring instruments, including historic and geologic time, for which only proxy climate records are available.

Parameterization In climate models, this term refers to the technique of representing processes that cannot be explicitly resolved at the spatial or temporal resolution of the model (sub-grid scale processes) by relationships between model-resolved larger-scale flow and the area- or time-averaged effect of such sub-grid scale processes (IPCC).

Permafrost Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years (Van Everdingen, 1998).

pH pH is a dimensionless measure of the acidity of water (or any solution) given by its concentration of hydrogen ions (H^+). pH is measured on a logarithmic scale where $pH = -\log_{10}(H^+)$. Thus, a pH decrease of 1 unit corresponds to a ten-fold increase in the concentration of H^+, or acidity (IPCC).

Philosophy of science Philosophy of science is the study of general and fundamental problems, such as those connected with existence, knowledge, values, reason, mind, and language and how these relate to science.

Photosynthesis The process by which plants take carbon dioxide from air (or bicarbonate in water) to build carbohydrates, releasing oxygen in the process. There are several pathways of photosynthesis with different responses to atmospheric carbon dioxide concentrations. See Carbon dioxide fertilization; C3 plants; C4 plants (IPCC).

Plankton Microorganisms living in the upper layers of aquatic systems. A distinction is made between phytoplankton, which depend on photosynthesis for their energy supply, and zooplankton, which feed on phytoplankton.

Pleistocene The earlier of two Quaternary Epochs, extending from the end of the Pliocene, about 1.8 Ma, until the beginning of the Holocene about 11.6 ka.

Pollen analysis A technique of both relative dating and environmental reconstruction, consisting of the identification and counting of pollen types preserved in peat, lake sediments and other deposits. See Proxy (IPCC).

Post-glacial rebound The vertical movement of the land and sea floor following the reduction of the load of an ice mass, for example, since the Last Glacial Maximum (21 ka). The rebound is an isostatic land movement (IPCC).

Precursors Atmospheric compounds that are not greenhouse gases or aerosols, but that have an effect on greenhouse gas or aerosol concentrations by taking part in physical or chemical processes regulating their production or destruction rates.

Predictability The extent to which future states of a system may be predicted based on knowledge of current and past states of the system. Since knowledge of the climate system's past and current states is generally imperfect, as are the models that utilize this knowledge to produce a climate prediction, and since the climate system is inherently nonlinear and chaotic, predictability of the climate system is inherently limited. Even with arbitrarily accurate models and observations, there may still be limits to the predictability of such a nonlinear system (AMS 2000)

Projection A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasize that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised, and are therefore subject to substantial uncertainty. See also Climate projection; Climate prediction.

Proxy A proxy climate indicator is a local record that is interpreted, using physical and biophysical principles, to represent some combination of climate-related variations back in time. Climate-related data derived in this way are referred to as proxy data. Examples of proxies include pollen analysis, tree ring records, characteristics of corals and various data derived from ice cores.

Q

Quaternary The period of geological time following the Tertiary (65–1.8 Ma). Following the current definition (which is under revision at present) the Quaternary extends from 1.8 Ma until the present. It is formed of two epochs, the Pleistocene and the Holocene.

R

Radiative forcing Radiative forcing is the change in the net, downward minus upward, irradiance (expressed in W m^{-2}) at the tropopause due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun. Radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. For the purposes of this report, radiative forcing is further defined as the change relative to the year 1750 and, unless otherwise noted, refers to a global and annual average value. Radiative forcing is not to be confused with cloud radiative forcing, a similar terminology for describing an unrelated measure of the impact of clouds on the irradiance at the top of the atmosphere.

Radiative forcing scenario A plausible representation of the future development of radiative forcing associated, for example, with changes in atmospheric composition or land use change, or with external factors such as variations in solar activity. Radiative forcing scenarios can be used as input into simplified climate models to compute climate projections.

Reanalysis Reanalyses are atmospheric and oceanic analyses of temperature, wind, current, and other meteorological and oceanographic quantities, created by processing past meteorological and oceanographic data using fixed state-of-the-art weather forecasting models and data assimilation techniques. Using fixed data assimilation avoids effects from the changing analysis system that occurs in operational analyses. Although continuity is improved, global reanalyses still suffer from changing coverage and biases in the observing systems.

Reconstruction The use of climate indicators to help determine (generally past) climates.

Reforestation Planting of forests on lands that have previously contained forests but that have been converted to some other use. For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation, see the IPCC Report on Land Use, Land-Use Change and Forestry (IPCC, 2000). See also the Report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003)

Regime A regime is preferred states of the climate system, often representing one phase of dominant patterns or modes of climate variability.

Region A region is a territory characterized by specific geographical and climatological features. The climate of a region is affected by regional and local scale forcings like topography, land use characteristics, lakes, etc., as well as remote influences from other regions. See Teleconnection.

Relative sea level Sea level measured by a tide gauge with respect to the land upon which it is situated. Mean sea level is normally defined as the average relative sea level over a period, such as a month or a year, long enough to average out transients such as waves and tides. See Sea level change.

Reservoir A component of the climate system, other than the atmosphere, which has the capacity to store, accumulate or release a substance of concern, for example, carbon, a greenhouse gas or a precursor. Oceans, soils and forests are examples of reservoirs of carbon. Pool is an equivalent term (note that the definition of pool often includes the atmosphere). The absolute quantity of the substance of concern held within a reservoir at a specified time is called the stock.

Response time The response time or adjustment time is the time needed for the climate system or its components to re-equilibrate to a new state, following a forcing resulting from external and internal processes or feedbacks. It is very different for various components of the climate system. The response time of the troposphere is relatively short, from days to weeks, whereas the stratosphere reaches equilibrium on a time scale of typically a few months. Due to their large heat capacity, the oceans have a much longer response time: typically decades, but up to centuries or millennia. The response time of the strongly coupled surface-troposphere system is, therefore, slow compared to that of the stratosphere, and mainly determined by the oceans. The biosphere may respond quickly (e.g., to droughts), but also very slowly to imposed changes. See lifetime for a different definition of response time pertinent to the rate of processes affecting the concentration of trace gases.

S

Scenario A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline. See also SRES scenarios; Climate scenario; Emission scenario.

Sea ice Any form of ice found at sea that has originated from the freezing of seawater. Sea ice may be discontinuous pieces (ice floes) moved on the ocean surface by wind and currents (pack ice), or a motionless sheet attached to the coast (land-fast ice). Sea ice less than 1 year old is called first-year ice. Multi-year ice is sea ice that has survived at least one summer melt season.

Sea level change Sea level can change, both globally and locally, due to (i) changes in the shape of the ocean basins, (ii) changes in the total mass of water and (iii) changes in water density. Sea level changes induced by changes in water density are called steric. Density changes induced by temperature changes only are called thermosteric, while density changes induced by salinity changes are called halosteric. See also Relative Sea Level; Thermal expansion.

Sea surface temperature (SST) The sea surface temperature is the temperature of the subsurface bulk temperature in the top few metres of the ocean, measured by ships, buoys and drifters. From ships, measurements of water samples in buckets were mostly switched in the 1940s to samples from engine intake water. Satellite measurements of skin temperature (uppermost layer; a fraction of a millimetre thick) in the infrared or the top centimetre or so in the microwave are also used, but must be adjusted to be compatible with the bulk temperature.

Sink Any process, activity or mechanism that removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere.

Snow line The lower limit of permanent snow cover, below which snow does not accumulate.

Soil moisture Water stored in or at the land surface and available for evaporation.

Solar activity The Sun exhibits periods of high activity observed in numbers of sunspots, as well as radiative output, magnetic activity and emission of high-energy particles. These variations take place on a range of time scales from millions of years to minutes. See Solar cycle.

Solar ('11 year') cycle A quasi-regular modulation of solar activity with varying amplitude and a period of between 9 and 13 years.

Solar radiation Electromagnetic radiation emitted by the Sun. It is also referred to as shortwave radiation. Solar radiation has a distinctive range of wavelengths (spectrum) determined by the temperature of the Sun, peaking in visible wavelengths. See also: Thermal infrared radiation, Insolation.

Source Any process, activity or mechanism that releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol into the atmosphere.

Southern Oscillation See El Niño-Southern Oscillation (ENSO).

Spatial and temporal scales Climate may vary on a large range of spatial and temporal scales. Spatial scales may range from local (less than 100,000 km^2), through regional (100,000–10 million km^2) to continental (10–100 million km^2). Temporal scales may range from seasonal to geological (up to hundreds of millions of years).

SRES scenarios SRES scenarios are emission scenarios developed by Nakićenović and Swart (2000) and used, among others, as a basis for some of the climate projections shown in Chap. 11 of this report. The following terms are relevant for a better understanding of the structure and use of the set of SRES scenarios:

Scenario family Scenarios that have a similar demographic, societal, economic and technical change storyline. Four scenario families comprise the SRES scenario set: A1, A2, B1 and B2.

- Illustrative Scenario
- A scenario that is illustrative for each of the six scenario groups reflected in the Summary for Policymakers of Nakićenović and Swart (2000). They include four revised scenario markers for the scenario groups A1B, A2, B1, B2, and two additional scenarios for the A1FI and A1T groups. All scenario groups are equally sound.
- Marker Scenario
- A scenario that was originally posted in draft form on the SRES website to represent a given scenario family. The choice of markers was based on which of the initial quantifications best reflected the storyline, and the features of specific models. Markers are no more likely than other scenarios, but are considered by the SRES writing team as illustrative of a particular storyline. They are included in revised form in Nakićenović and Swart (2000). These scenarios received the

closest scrutiny of the entire writing team and via the SRES open process. Scenarios were also selected to illustrate the other two scenario groups.

Stratosphere The highly stratified region of the atmosphere above the troposphere extending from about 10 km (ranging from 9 km at high latitudes to 16 km in the tropics on average) to about 50 km altitude.

Subduction Ocean process in which surface waters enter the ocean interior from the surface mixed layer through Ekman pumping and lateral advection. The latter occurs when surface waters are advected to a region where the local surface layer is less dense and therefore must slide below the surface layer, usually with no change in density.

Sunspots Small dark areas on the Sun. The number of sunspots is higher during periods of high solar activity, and varies in particular with the solar cycle.

Surface temperature See Global surface temperature; Ground temperature; Land surface air temperature; Sea surface temperature.

T

Thermal expansion In connection with sea level, this refers to the increase in volume (and decrease in density) that results from warming water. A warming of the ocean leads to an expansion of the ocean volume and hence an increase in sea level. See Sea level change.

Thermal infrared radiation Radiation emitted by the Earth's surface, the atmosphere and the clouds. It is also known as terrestrial or longwave radiation, and is to be distinguished from the near-infrared radiation that is part of the solar spectrum. Infrared radiation, in general, has a distinctive range of wavelengths (spectrum) longer than the wavelength of the red colour in the visible part of the spectrum. The spectrum of thermal infrared radiation is practically distinct from that of shortwave or solar radiation because of the difference in temperature between the Sun and the Earth-atmosphere system.

Thermocline The layer of maximum vertical temperature gradient in the ocean, lying between the surface ocean and the abyssal ocean. In subtropical regions, its source waters are typically surface waters at higher latitudes that have subducted and moved equatorward. At high latitudes, it is sometimes absent, replaced by a halocline, which is a layer of maximum vertical salinity gradient.

Thermohaline circulation (THC) Large-scale circulation in the ocean that transforms low-density upper ocean waters to higher-density intermediate and deep waters and returns those waters back to the upper ocean. The circulation is asymmetric, with conversion to dense waters in restricted regions at high latitudes and the return to the surface involving slow upwelling and diffusive processes over much larger geographic regions. The THC is driven by high densities at or near the surface, caused by cold temperatures and/or high salinities, but despite its suggestive though common name, is also driven by mechanical forces such as wind and tides. Frequently, the name THC has been used synonymously with Meridional Overturning Circulation.

Tide gauge A device at a coastal location (and some deep-sea locations) that continuously measures the level of the sea with respect to the adjacent land. Time averaging of the sea level so recorded gives the observed secular changes of the relative sea level.

Total solar irradiance (TSI) The amount of solar radiation received outside the Earth's atmosphere on a surface normal to the incident radiation, and at the Earth's mean distance from the Sun.

Aljwhsd Reliable measurements of solar radiation can only be made from space and the precise record extends back only to 1978. The generally accepted value is 1,368 W m^{-2} with an accuracy of about 0.2%. Variations of a few tenths of a percent are common, usually associated with the passage of sunspots across the solar disk. The solar cycle variation of TSI is of the order of 0.1% (AMS 2000). See also Insolation.

Tree rings Concentric rings of secondary wood evident in a cross-section of the stem of a woody plant. The difference between the dense, small-celled late wood of one season and the wide-celled early wood of the following spring enables the age of a tree to be estimated, and the ring widths or density can be related to climate parameters such as temperature and precipitation. See Proxy.

Trend The word trend designates a change, generally monotonic in time, in the value of a variable.

Tropopause The boundary between the troposphere and the stratosphere.

Troposphere The lowest part of the atmosphere, from the surface to about 10 km in altitude at mid-latitudes (ranging from 9 km at high latitudes to 16 km in the tropics on average), where clouds and weather phenomena occur. In the troposphere, temperatures generally decrease with height.

U

Uncertainty An expression of the degree to which a value (e.g., the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgment of a team of experts (see Moss and Schneider 2000; Manning et al. 2004). See also Confidence.

United Nations Framework Convention on Climate Change (UNFCCC) The Convention was adopted on 9 May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. It contains commitments for all Parties. Under the Convention, Parties included in Annex I (all OECD countries and countries with economies in transition) aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The convention entered in force in March 1994. See Kyoto Protocol.

Uptake The addition of a substance of concern to a reservoir. The uptake of carbon containing substances, in particular carbon dioxide, is often called (carbon) sequestration.

Urban heat island (UHI) The relative warmth of a city compared with surrounding rural areas, associated with changes in runoff, the concrete jungle effects on heat retention, changes in surface albedo, changes in pollution and aerosols, and so on.

V

Ventilation The exchange of ocean properties with the atmospheric surface layer such that property concentrations are brought closer to equilibrium values with the atmosphere (AMS 2000).

W

Walker Circulation Direct thermally driven zonal overturning circulation in the atmosphere over the tropical Pacific Ocean, with rising air in the western and sinking air in the eastern Pacific.

Water mass A volume of ocean water with identifiable properties (temperature, salinity, density, chemical tracers) resulting from its unique formation process. Water masses are often identified through a vertical or horizontal extreme of a property such as salinity.

Weather The state of the atmosphere at a place and time as regards heat, cloudiness, dryness, sunshine, wind, rain, etc.

Y

Younger Dryas A period 12.9–11.6 kyear, during the deglaciation, characterized by a temporary return to colder conditions in many locations, especially around the North Atlantic.

Index

G.T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis: Volume 1 - The Physical Climate*, DOI 10.1007/978-94-007-5757-8,

J

K

O

P