Arbaminch Water Technology Institute
Faculty of Meteorology and Hydrology

Climate Change: Impact, Adaptation &Mitigation

Course code: MHF1303.

Course credit: 6

Target group: UG3_MHS

Instructor: *Gizachew K*

Physics of climate and climate change

Lecture Note1:

- Introduction to climate change
- Earth’s energy budget
- Radiative forcing
- Global warming potential
- Global temperature potential
- CO_2 equivalent
- Climate sensitivity and feedbacks
- Attribute of climate change

Introduction

Some Definitions:

- **Weather** : The fluctuating state of the atmosphere around us, characterized by the temperature, wind, precipitation, clouds and other weather elements
- **Climate** : The average weather in terms of the mean and its variability over a certain time-span and a certain area
- *"Climate is what we expect, weather is what we get." Mark Twain*

Cont.

- **Climate change** :Statistically significant variations of the mean state of the climate or of its variability, typically persisting for decades or longer
- Climate change : may be due to natural internal processes or external forcing’s such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use.
- Climate change could be due to natural climate variability or anthropogenic forcings (e.g., greenhouse gases), or a combination of the two .

Cont.

- **Climate variability** refers to fluctuations above and below the average conditions over time, on monthly, annual, and longer timescales.

- These fluctuations are called anomalies or departures
- Climate variability occurs naturally due to the complex interactions of the atmosphere, oceans, land surface, and land and sea ice
- Such as El Niño-Southern Oscillation (ENSO), Variations in the output of the sun and periodic large volcanic eruptions that cause brief cooling, also add to the natural variability.

The Composition of the Atmosphere

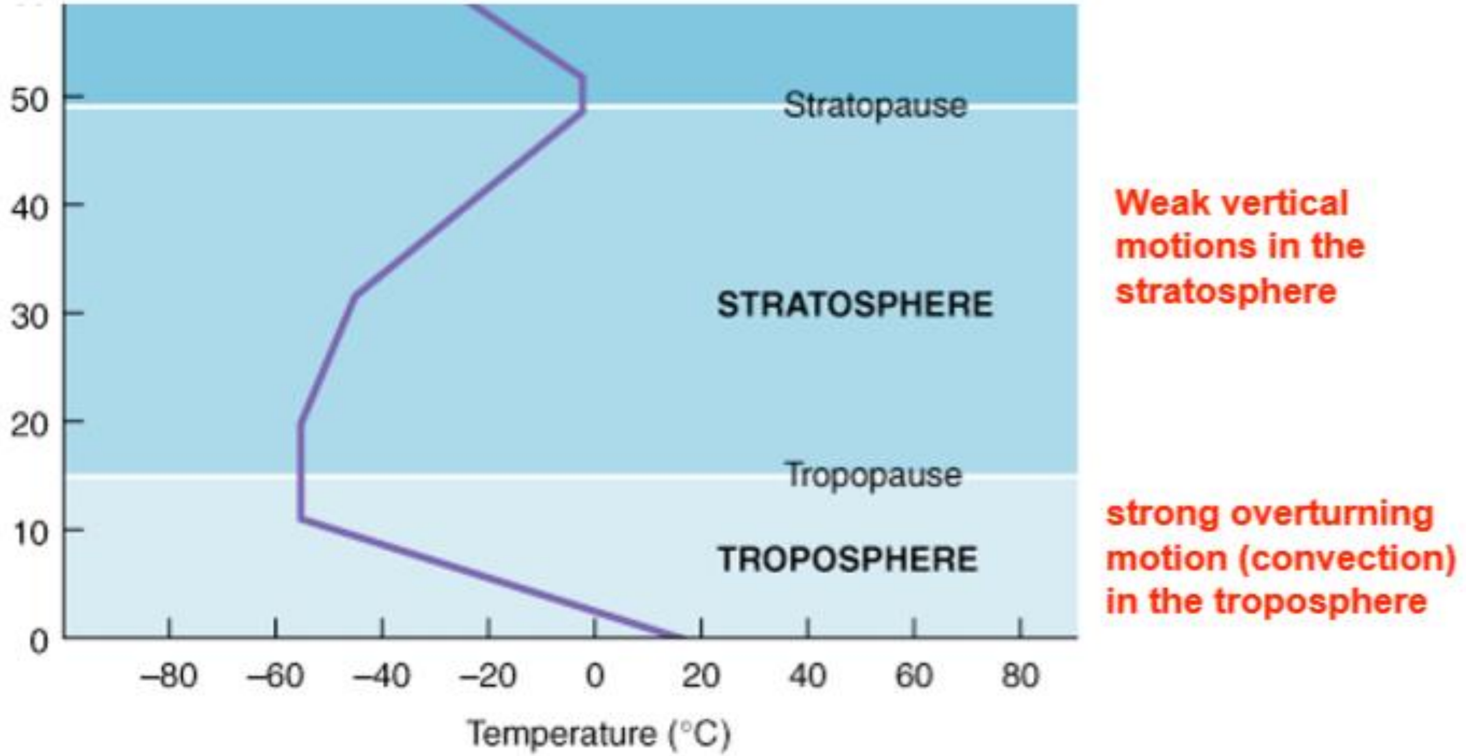
For Dry Air

Gas	Abundance (%)
Nitrogen (N_2)	78
Oxygen (O_2)	21
Argon (Ar)	0.93
Carbon Dioxide (CO_2)	0.038
Neon (Ne)	0.00182
Ozone (O_3)	< 0.001
Helium (He)	0.00052
Methane (CH_4)	0.00017

99.93% of the atmosphere

The abundance of most gases in the atmosphere is quite low and so they are called *trace gases*

The Vertical Structure of the Atmosphere



The layers of the atmosphere are defined by the variation of temperature with altitude:

Troposphere: temperature decreases with altitude

Stratosphere: temperature increases with altitude

Ways by which the atmosphere influences climate:

- Strong effects on radiative transfer, including filtering of ultraviolet radiation
- Large advective and convective heat transfer
- Main driver of ocean circulation
- Important role in biogeochemical cycles

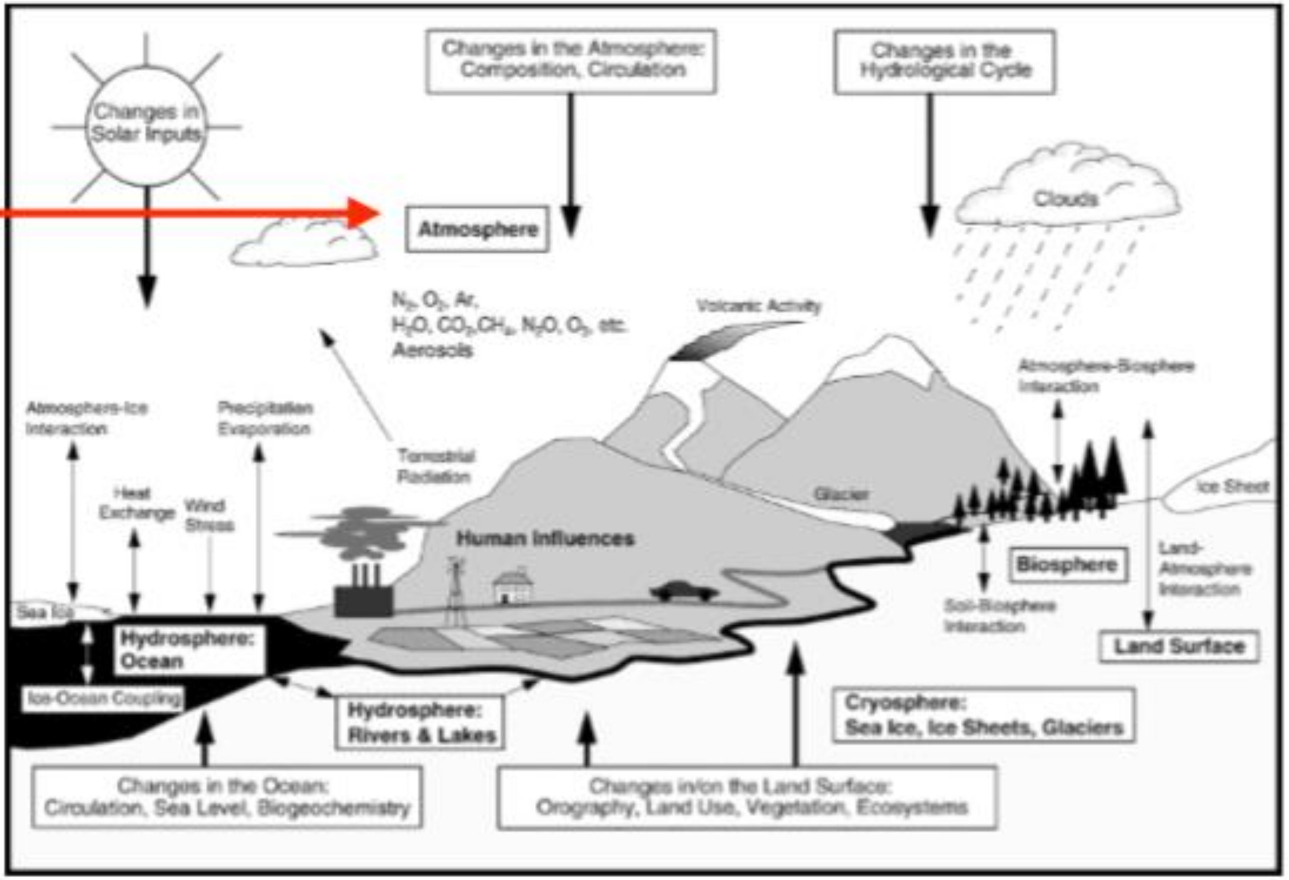
The Climate System

- The climate system is an interactive system forced or influenced by various external forcing mechanisms, the most important of which is the Sun.
- The atmosphere is the most unstable and rapidly changing part of the system.
- The climate of the Earth as a whole depends on factors that influence the radiative balance, such as, the atmospheric composition, solar radiation or volcanic eruptions.

Cont.

Climate system:

- Atmosphere
- Hydrosphere
- Cryosphere
- Land surface
- Biosphere



Schematic view of the components of the global climate system (bold), their processes and interactions (thin arrows) and some aspects that may change (bold arrows). http://www.grida.no/climate/ipcc_tar/wg1/index.htm

The Greenhouse effect

- The greenhouse effect is due to absorption and re-emission of the longwave radiative energy by greenhouse gases.
- These trace gases allow solar radiation pass through the atmosphere, but opaque for longwave radiation emitted by the earth's surface.

✓ How does greenhouse effect increase the surface temperature?

- Conceptually, the earth's atmosphere can approximately treat as multiple isothermal layers that let sun light penetrate through but trap all infrared radiation.

Cont.

- The more layers we have, the stronger the greenhouse effect is on the surface temperature.

✓ How does increase of GHGs increase the surface temperature?

- It increases temperature in the upper troposphere, which in turn, increases down welling longwave radiation ($F \sim T_e^4$), and warm the surface temperature.

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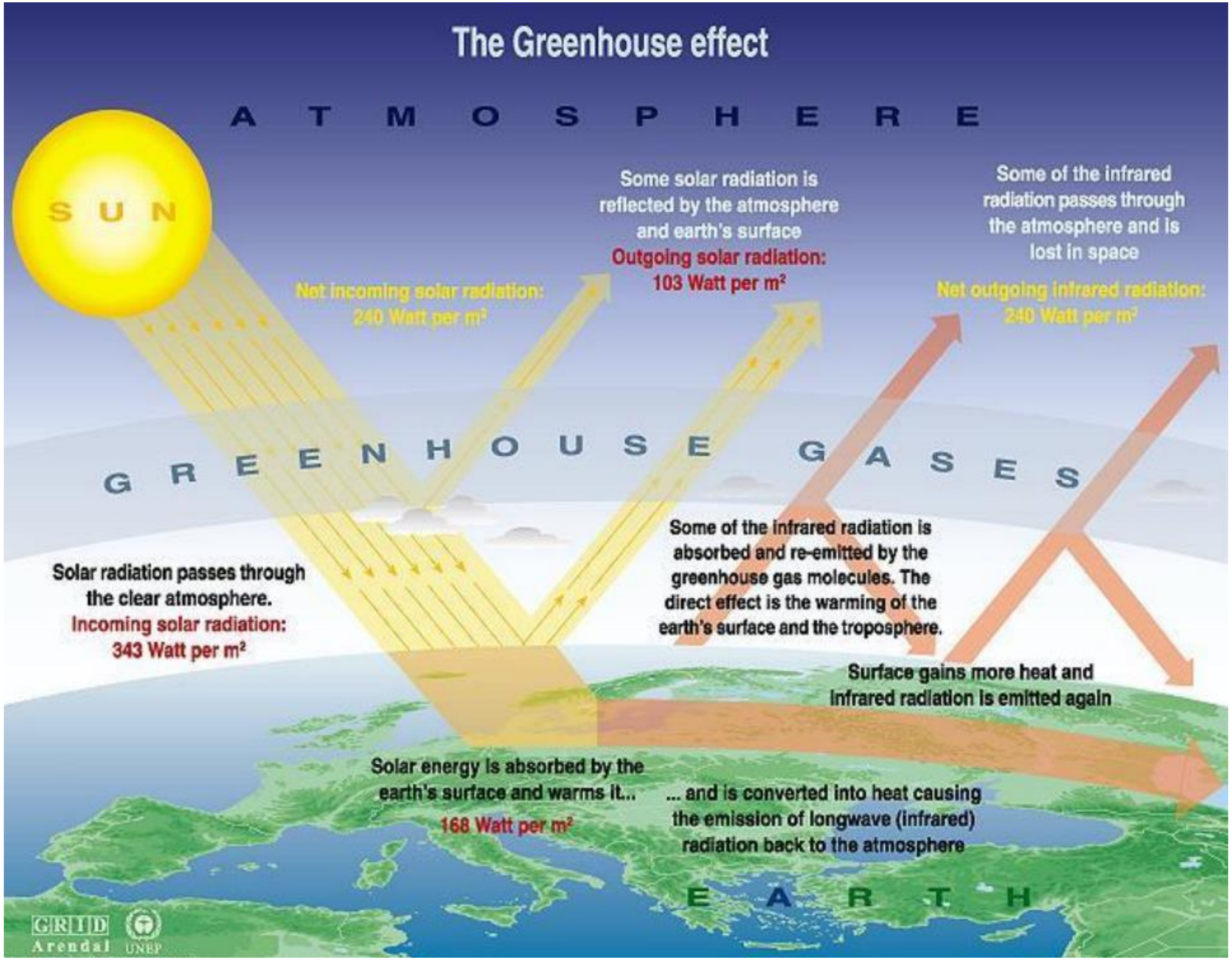


The Greenhouse effect
A T M O S P H E R E
S U N
Some solar radiation is reflected by the atmosphere and earth's surface
Outgoing solar radiation: 103 Watt per m²
Some of the infrared radiation passes through the atmosphere and is lost in space
Net incoming solar radiation: 240 Watt per m²
Net outgoing infrared radiation: 240 Watt per m²
G R E E N H O U S E G A S E S
Some of the infrared radiation is absorbed and re-emitted by the greenhouse gas molecules. The direct effect is the warming of the earth's surface and the troposphere.
Solar radiation passes through the clear atmosphere.
Incoming solar radiation: 343 Watt per m²
Surface gains more heat and infrared radiation is emitted again
Solar energy is absorbed by the earth's surface and warms it...
168 Watt per m²
... and is converted into heat causing the emission of longwave (infrared) radiation back to the atmosphere
E A R T H
GRID Arendal
UNEP

Earth's Energy Budget

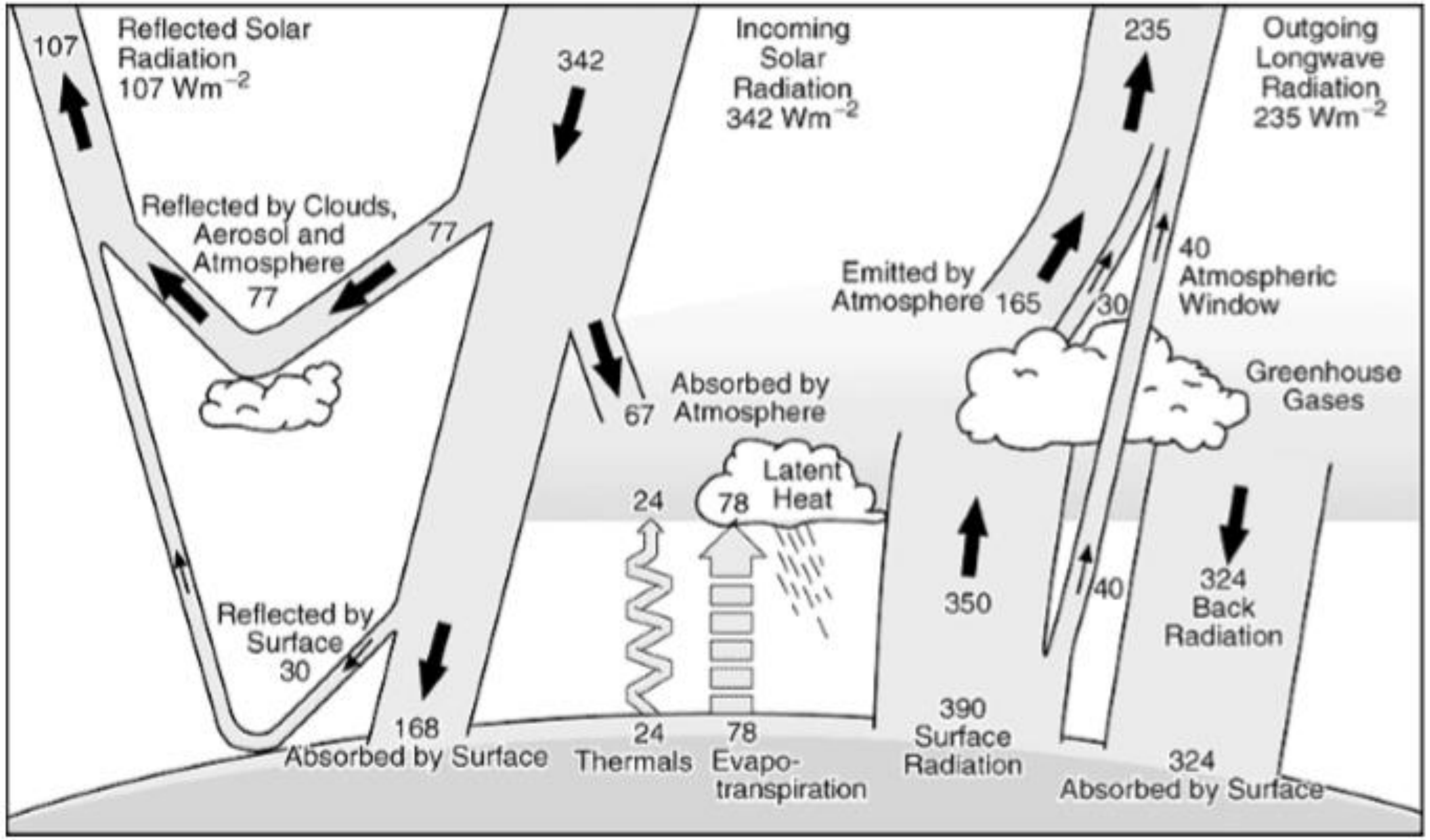


Figure 4: Earth's Annual Global Mean Energy Budget Source: Kiehl and Trenberth:

Radiative Forcing

- Radiative forcing is a first-order measure of the relative climatic importance of different agents.
- It has been employed to denote an externally imposed perturbation in the **radiative energy** budget of the Earth's climate system.
- Such a perturbation can be brought about by:

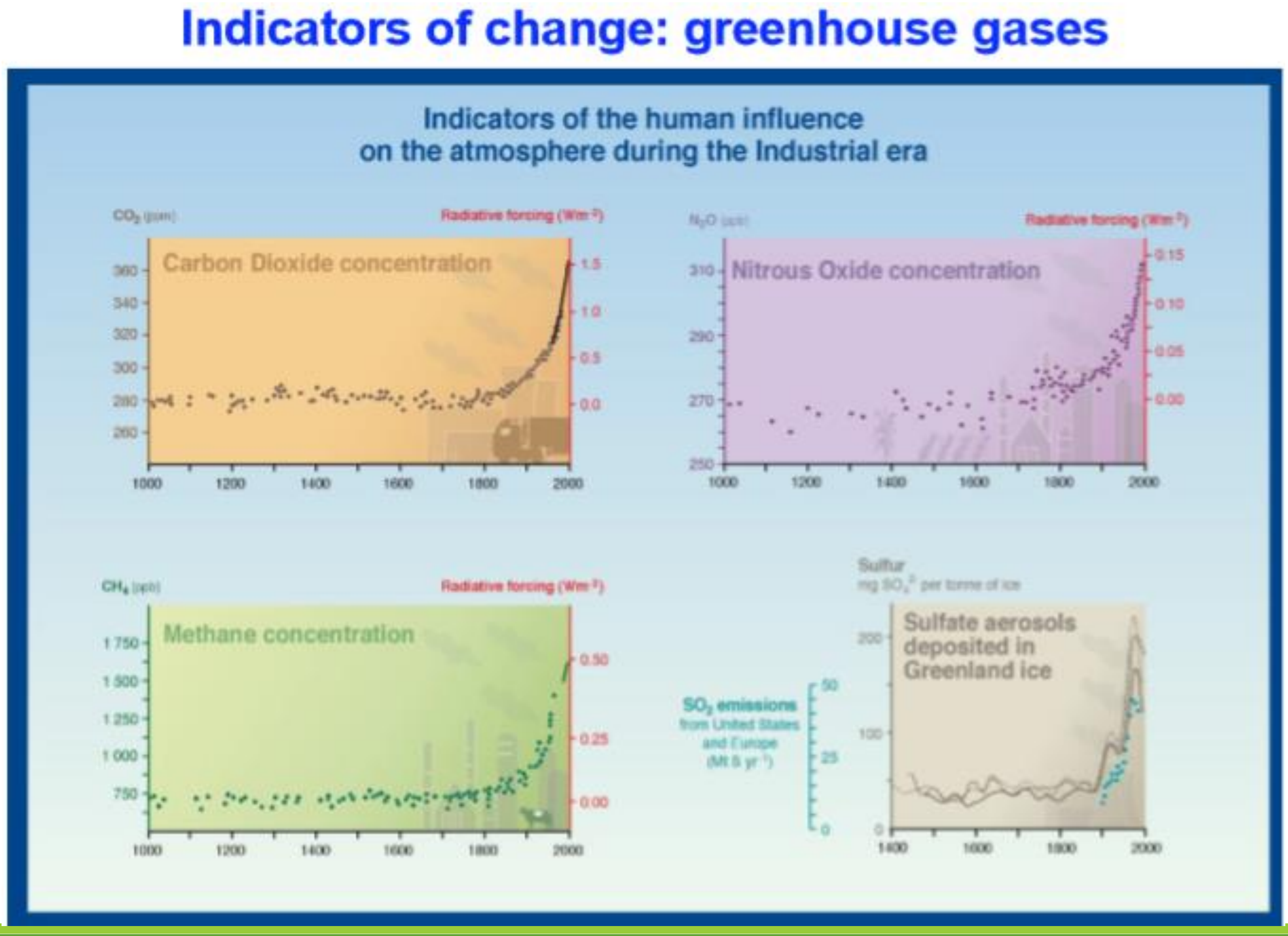
→ changes in the concentrations of radiatively active species (e.g., CO2, aerosols), → changes in the solar irradiance incident upon the planet, or

→ other changes that affect the radiative energy absorbed by the surface (e.g., changes in surface reflection properties).

Cont.

- This imbalance in the radiation budget has the potential to lead to changes in climate parameters and thus result in a new equilibrium state of the climate system. Radiation balance as driver for climate.
- More precisely, it can be defined as the difference in the balance of energy that enters the atmosphere and the amount that is returned to space compared to the pre-industrial situation. Therefore,
- Radiative forcing, the key driver for climate change, over a prescribed time period following pulse emissions of different greenhouse gases.

Cont.


Indicators of change: greenhouse gases
Indicators of the human influence
on the atmosphere during the Industrial era
Radiative forcing (Wm⁻²)
Carbon Dioxide concentration
Nitrous Oxide concentration
Methane concentration
Sulfur
Sulfate aerosols
deposited in
Greenland ice
SO₂ emissions
from United States
and Europe
(Mt S yr⁻¹)

Radiative Equilibrium of the Earth

- The driving force for the atmosphere is the absorption of solar energy at the Earth's surface.
- Over time scales long compared with those involved in the redistribution of energy, the Earth-atmosphere system is in thermal equilibrium.
- The net energy gained must then vanish.
  - Solar radiation is concentrated at visible wavelengths, termed shortwave (SW) radiation.
  - Terrestrial radiation that emitted by the Earth's surface and atmosphere, is concentrated at IR wavelengths, termed longwave (LW) radiation.

- For thermal equilibrium, the absorption of SW radiation must be balanced by emission to space of LW radiation.
- This basic principle leads to a simple estimate of the mean temperature of the Earth.
- The Earth intercepts a beam of SW radiation of cross-sectional area πa^2 and flux Fs (energy/area time) (figure 4).
- A fraction of the intercepted radiation, the albedo A, is reflected back to space by the Earth’s surface and components of the atmosphere.

Cont.

- The remainder of the incident SW flux :
- (1−A) Fs, is then absorbed by the Earth-atmosphere system.
- It is distributed across the globe as it spins in the line of the SW beam.
- To maintain thermal equilibrium, the Earth and atmosphere must re-emit to space LW radiation at exactly the same rate.
- Also referred to as Outgoing Longwave Radiation (OLR),
- ✓ The emission to space of terrestrial radiation is described by the *Stefan Boltzmann law*.

Cont.

- $F_{emit} = \sigma T^4$ (i)
- Where F_{emit} represent the energy flux integrated over wavelength that is emitted by a blackbody at temperature T and σ is the Stefan-Boltzmann constant. $\sigma = 5.67 \times 10^{-8}\ wm^{-2}k^{-4}$
- Integrating the emitted LW flux over the Earth and equating the result to the SW energy absorbed obtains the simple energy balances:

$$(1-A)F_s\pi a^2 = 4\pi a^2\sigma T_e^4 \qquad \text{(ii)}$$

Where Te is the equivalent blackbody temperature of the Earth.

Cont.

$$T_e = \left[\frac{(1-A)F_s}{4\sigma}\right]^{\frac{1}{4}} \qquad \text{(iii)}$$

- Then equation (iii) provides a simple estimate of the Earth's temperature.
- An incident SW flux of Fs =1372 W m^{-2} and an albedo of A=0.30 lead to an equivalent blackbody temperature for Earth of Te=255 K.

This value is some 30 K colder than the global-mean surface temperature, Ts =288 K.

- The equivalent blackbody temperature of the Earth provides some insight into where LW radiation is ultimately emitted to space.

Cont.

- The value Te=255 K corresponds to the middle troposphere, above most of the water vapor and cloud.
- Most of the energy received by the atmosphere is supplied from the Earth’s surface, where SW radiation is absorbed.
- Transfers of energy from the surface constitute a heat source for the atmosphere. Conversely, LW emission to space by the middle troposphere constitutes a heat sink for the atmosphere.
- Representing heating and cooling, these energy transfers drive the atmosphere into motion.

Problems

- The effective temperature of the Venus atmosphere is 225k.

- a) What is the radiative energy emitted by the Venus atmosphere?

- b)The solar irradiance at the top of the Venus atmosphere is 2639 wm-2. How much solar radiation has to be reflected in order to balance the radiative energy emitted by the Venus atmosphere?

- **Solution**:

- (a) Based on the Stefan-Boltzmann law;

$F_{emit} = \sigma T^4 \quad = 5.67x10\text{-}8wm^{-2}(2.25x10^2\ k)^4 \ = 145\ wm^{-2}$

Venus atmosphere emits 145 wm^{-2} long wave radiative energy.

- (b)The solar radiation absorbed by the Venus atmosphere has to be balanced by long wave emission. Thus

$Fs(1\text{-}\alpha).\pi a^2 = \ 4\pi a^2\ F_{emit}$

$$\alpha = 1 - \frac{4F_{emit}}{F_S} \quad = 1\text{-}\ \frac{4x145\ wm-2}{2639\ wm-2}\ = 0.78$$

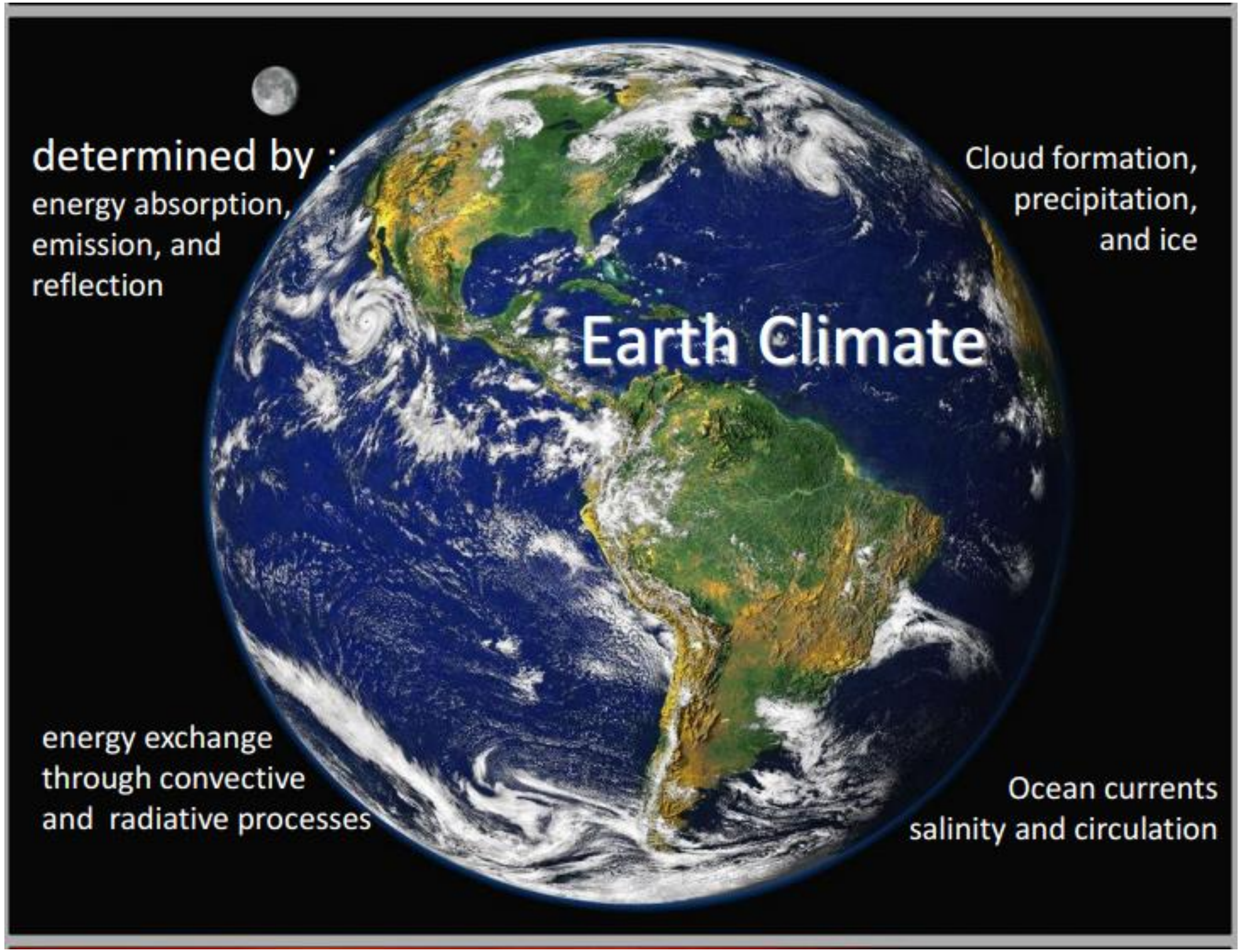
Climate change indicators

- ❖ Increase in greenhouse gas emission
- ❖ Increase in CO_2 concentration
- ❖ Global temperature increase
- ❖ Increase in heat waves and drought
- ❖ Change of precipitation rate
- ❖ Decline of arctic sea ice area
- ❖ Decline of high altitude glaciers

Earth's Climate determined by:

- Energy absorption, Emission, and reflection
- Energy exchange through convective and radiative processes ,Cloud formation,
- precipitation, and ice
- Ocean currents , salinity and circulation

Cont.


determined by :
energy absorption, emission, and reflection
Cloud formation, precipitation, and ice
Earth Climate
energy exchange through convective and radiative processes
Ocean currents salinity and circulation

Cont.

- Earth's climate state and variability are fundamentally controlled by the energy balance of its climate system, which is largely determined by:

- The physical properties and chemical composition of the Earth's climate system.
- These physical processes, through their control on energy and water, drive winds and ocean currents, and actively interact with the dynamic, chemical, biological and geological processes of the climate system.

Cont.

- Generally Climate physics determines the radiative and latent energy that drive the atmospheric circulation from weather to climate scales;
- It determines the climate conditions that are most critical to life (T, q, P etc).

Global warming potential (GWP)

- Certain greenhouse gases are more effective at warming the Earth than others.

- The two most important characteristics of a GHG in terms of climate impact are:
  - How well the gas absorbs energy (preventing it from escaping to space), and
  - How long the gas stays (life time) in the atmosphere
  - The global warming potential (GWP) for a gas is a measure of the total energy that a gas absorbs over a particular period of time (usually 100 years), compared to reference gas (carbon dioxide).

Cont.

- The GWP provides a simple measure of the radiative effect of emissions of various greenhouse gases, integrated over a specific time horizon, relative to an equal mass of CO_2 emissions.
- The larger the GWP, the more warming the gas causes. For example, methane's 100 year GWP is 21, which means that methane will cause 21 times as much warming as an equivalent mass of carbon dioxide over a 100–year time period.
- For example, the GWP of some of the important GHGs is as follows.

✓Carbon dioxide (CO_2) has a GWP of 1 and serves as a baseline for other GWP values.

Cont.…

- CO_2 remains in the atmosphere for a very long time– changes in atmospheric CO_2 concentration persist for thousands of years.

✓Methane (CH4) has a GWP more than 20 times higher than CO_2 for a 100-year time scale. CH_4 emitted today lasts for only about a decade in the atmosphere, on average.

- However, on a pound-for-pound basis, CH4 absorbs more energy than CO_2, making its GWP higher

✓Nitrous Oxide (N_2O) has a GWP 300 times that of CO_2 for a 100-year time scale.

Cont.…

- ✓N_2O emitted today remains in the atmosphere for more than 100 years average.
- ✓Chlorofluorocarbons (CFCs),
- ✓ hydrofluorocarbons (HFCs),
- ✓ hydro chlorofluorocarbons (HCFCs) ,
- ✓perfluorocarbons (PFCs), and
- ✓sulfur hexafluoride (SF6) are sometimes called high-GWP gases because, for a given amount of mass, they trap substantially more heat than CO_2.

Table. GHG Concentrations ,residence time and GWP

Gas	Pre-1750 Tropospheric Concentration	Recent tropospheric concentration	GWP (100-yr) time horizon	Atmospheric life time* (years)
Carbo dioxide	280 ppm	392.6 ppm	1	100
Methane (CH4)	700 ppb	1874 ppb (1758 ppb)	25	12
Nitrous Oxide (N_2O)	270 ppb	324 ppb (323 ppb)	298	114
Tropospheric Ozone (O_3)	25 ppb	34 ppb	NA	Hours- days
CFC-11 (trichlorofluoro- Methane, CCl_3F)	Zero	238 ppt (236 ppt)	4,750	45
HEC-134a (CH_2FCF_3)	Zero	68 ppt (58 ppt)	1,430	14
Sulfur Hexa-fluoride (SF_6)	Zero	7.47 ppt (7.09 ppt)	22,800	3,200

Present days concentrations and RF for measured LLGHGs. The changes since 1998 (the time TAR estimates) are also shown.

	Concentrations[b] and their changes[c]		Radiative Forcing[d]	
Species[a]	2005	Change since 1998	2005 (W m^{-2})	Change since 1998 (%)
CO_2	**379 ± 0.65 ppm**	**+13 ppm**	**1.66**	**+13**
CH_4	**1,774 ± 1.8 ppb**	**+11 ppb**	**0.48**	**-**
N_2O	**319 ± 0.12 ppb**	**+5 ppb**	**0.16**	**+11**
	ppt	ppt		
CFC-11	251 ± 0.36	–13	0.063	–5
CFC-12	538 ± 0.18	+4	0.17	+1
CFC-113	79 ± 0.064	–4	0.024	–5
HCFC-22	169 ± 1.0	+38	0.033	+29
HCFC-141b	18 ± 0.068	+9	0.0025	+93
HCFC-142b	15 ± 0.13	+6	0.0031	+57
CH_3CCl_3	19 ± 0.47	–47	0.0011	–72
CCl_4	93 ± 0.17	–7	0.012	–7
HFC-125	3.7 ± 0.10[e]	+2.6[f]	0.0009	+234
HFC-134a	35 ± 0.73	+27	0.0055	+349
HFC-152a	3.9 ± 0.11[e]	+2.4[f]	0.0004	+151
HFC-23	18 ± 0.12[g,h]	+4	0.0033	+29
SF_6	5.6 ± 0.038[i]	+1.5	0.0029	+36
CF_4 (PFC-14)	74 ± 1.6[j]	-	0.0034	-
C_2F_6 (PFC-116)	2.9 ± 0.025[g,h]	+0.5	0.0008	+22
CFCs Total[k]			**0.268**	**–1**
HCFCs Total			**0.039**	**+33**
Montreal Gases			**0.320**	**–1**
Other Kyoto Gases ($HFCs + PFCs + SF_6$)			**0.017**	**+69**
Halocarbons			**0.337**	**+1**
Total LLGHGs			**2.63**	**+9**

Global Temperature Potential (GTP)

- Global-mean surface temperature change at a given future time horizon following an emission of a compound ‘x’ relative to a reference (say, CO2 gas)
- Advantage, directly related to surface temperature change; do not require simulations with AOGCMs; RF closer to end of horizon has more contribution; need to know response time of climate system
- The absolute GTP (AGTP) of a gas is the temperature increase, after a given amount of time, resulting from a pulse emission of this gas.

- Given that both GWP and GTP are orientated towards providing information for policies, there seems little to be gained and much to be lost by changing from the relatively familiar concept of GWP, which is a specific property of an individual gas and can be used both to rank emissions of individual gases (relative to one another) and to calculate the total climate change impact from all greenhouse gas emissions.
- The physics underlying the calculation of GWP are well understood for most greenhouse gases, the exception being carbon dioxide, where the range of atmospheric removal processes adds complication and uncertainty.

CO_2 Equivalent (CO_2-e)

- GWPs are used to convert emission of non-CO_2 gases in to their CO_2 warming equivalents (CO_2-e). the CO_2-e of a non-CO_2 gas is calculated by its GWP.
- **A carbon dioxide equivalent or CO_2 equivalent**, CO_2-e is a metric measure used to compare the emission from various GHGs on the basis of their GWP, by converting amounts of other gases to the equivalent amount of carbon dioxide with the same GWP. Carbon dioxide equivalents are commonly expressed as **million metric tones of carbon dioxide equivalents, MMTCDE.**

Cont.…

- The carbon dioxide equivalent for a gas s derived by multiplying the tones of the gas by the associated GWP.

➢ **MMTCDE = (million metric tones of a gas)*(GWP of the gas)**

- For example, the GWP for methane is 21 and for nitrous oxide 310.
- This means that emission of 1 million metric tones of methane and nitrous oxide respectively is equivalent to emission of 21 and 310 million metric tones of carbon dioxide.
- 1 Gigaton (Gt) = 1 Pentagram (Pg) =1 million Gig grams (Gg) =10^{15}grams = 1 billion (10^9) metric tons.

- 1 Tera gram(Tg) = 10^{12}grams = 1 million (10^6) metric tons
- 1 unit CO2 = 0.2727 or 12/44 units C
- 1 unit carbon(C) = 3.6667 or 44/12 units of carbon dioxide (CO2)
- 1 Gigaton C = 3.66 Gt of CO_2
- For converting values with Global Warming potential (GWP) - weighted emission, (sometimes reported in Tg of gas) to Tg of CO_2 equivalent, the following equation can be used.

▪ **Tg CO_2 equivalent = Tg of gas*** $\boldsymbol{\frac{1\ gigaton}{1000\ teragrams} * GWP}$

- Tg carbon equivalent = Tg CO2equivalent *$\frac{12g\ C}{44g\ CO2}$

- Tg CO_2 Eq. = Tera grams of Carbon Dioxide Equivalents
- Gg = Gig grams (equivalent to a thousand metric tons), GWP = Global Warming Potential, Tg = Tera grams.

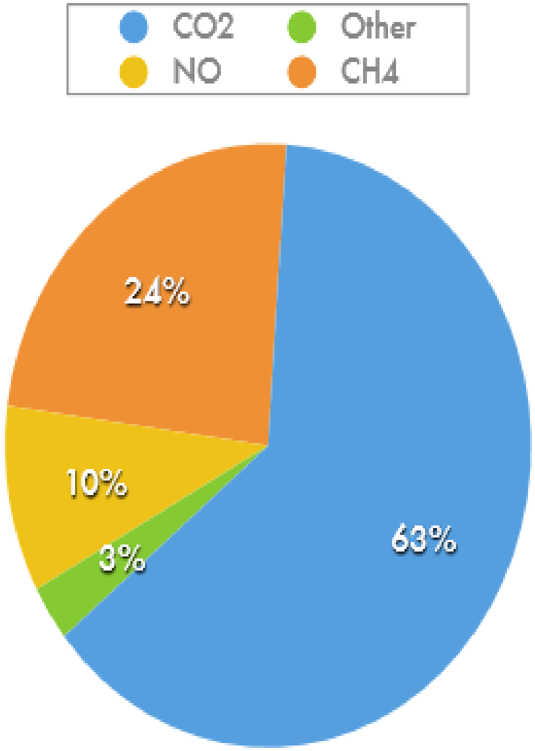
- **GWP values** allow policy makers to compare the impacts of emissions and reductions of different gases.
- **Greenhouse** gases with relatively **long atmospheric lifetimes** (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, and SF6) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined.

Cont.

- The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, other ambient air pollutants (e.g., NOx, and NMVOCs), and tropospheric aerosols; however, vary spatially, and consequently it is difficult to quantify their global radiative forcing impacts.
- GWP values are generally not attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere.
- **Atmospheric Life time-** The atmospheric lifetime is used to characterize the decay of an instantaneous pulse input to the atmosphere, and can be likened to the time it takes that pulse input to decay to 0.368 (1/e) of its original value.

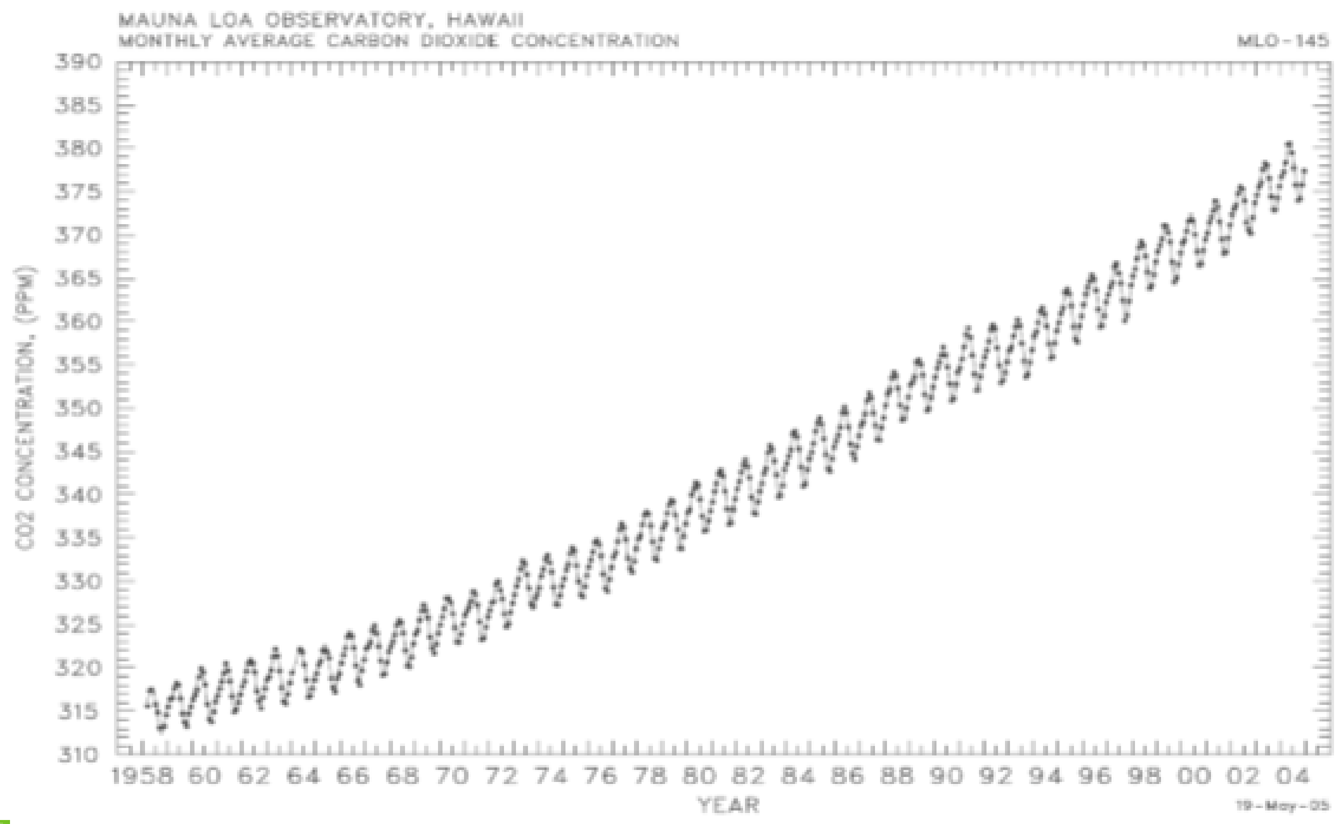
CO_2 is not the *only* greenhouse gas

- Taking into account the affectivity, residence, and concentration of the different gases:



The relative warming of different greenhouse gases based on current emissions, effect quantified over the next 100 years

CO_2 Concentrations in the Atmosphere
(measured at Mauna Loa, Hawaii)



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Climate sensitivity and feedbacks

➢Climate is very complex because of the large number of processes operating, and the set of non-linear interactions coupling them.

➢The identification of which set of processes and interactions are most important for a given climate problem can be aided by the following strategies:

▪Identify a "forcing mechanism", at least conceptually

▪Try to determine the direct response to that forcing mechanism

▪Then try to determine the indirect responses induced by the couplings

Cont.

▪Note that what we consider a forcing mechanism and a response depends very much on the problem at hand.

- **Climate Sensitivity** = relationship between forcing and the direct and indirect responses
- **Feedback Mechanism** = A process that changes the sensitivity.
- The feedback mechanisms are responsible for the difference between direct and total (direct + indirect) responses
- **Positive Feedback** increases climate sensitivity
- **Negative Feedback** decreases climate sensitivity

Cont.

- Example: Consider Ts = globally averaged surface temperature as the measure of climate, and the measure of climate forcing the solar constant SO; Ts = Ts (SO, y_1, y_2, …, y_n) where the y_i are n other variables which Ts may depend on.

- If these additional variables also depend on SO, which is usually the case, then we have $$\frac{dT_s}{dS_0} = \frac{\partial T_s}{\partial S_0} + \sum_{j=1}^{n} \frac{\partial T}{\partial y_j}\frac{dy_j}{dS_0}$$

- The first term measures the sensitivity of Ts to the SO, and the remaining terms show the feedback effects of the other variables.

Cont.

Basic Radiative Sensitivity

- Consider the forcing to be the global mean radiative input at the top of the atmosphere Q. It satisfies the balance:
- $Q = S_O/4\ (1 - \alpha) = F(T_s) = \sigma T_s^4$ where α is the planetary albedo**,** F is the outgoing long-wave radiation (global mean) at the top of the atmosphere,
- written as a function of surface temperature.

Cont.

- The relationship between a change dTs in the surface temperature and a change dQ in the forcing is simply given by:

$$dQ = -\frac{S_O}{4}\frac{\partial\alpha}{\partial T_s}dT_s = \frac{\partial F}{\partial T_s}dT_s$$

$$\frac{dQ}{dT_s} = -\frac{S_O}{4}\frac{\partial\alpha}{\partial T_s} = \frac{\partial F}{\partial T_s}$$

$$\frac{dT_s}{dQ} = \left(\frac{dQ}{dT_s}\right)^{-1} = \left(\frac{\partial F}{\partial T_s}\right)^{-1} = (4\sigma T_s^3)^{-1}$$

- where we have used the Stefan-Boltzmann law to relate the OLR to the surface temperature.

Cont.

- we obtain 0.18 K (Wm-2)-1, so that a 5.4 (Wm-2) change in forcing is necessary to increase Ts by 1 degree.
- This requires a 31 (Wm-2) change in S_O (if we assume an albedo of 0.3), or about a 2.2 percent change.
- This sensitivity alone is probably not enough to explain the large climate fluctuations.

Examples of Feedbacks:

- Water vapor
- Ice-albedo
- Clouds
- Surface evaporation
- Biogeochemical feedbacks

Water Vapor Feedback

- This powerful feedback occurs because of the temperature dependence of the saturation vapor pressure of water.
- The amount of water vapor in saturated air increases sharply as the temperature increases.
- Since water vapor is the principal greenhouse gas, increasing water vapor content by increasing the temperature will increase the greenhouse effect and raise the surface temperature even further.

Cont.

- Thus the temperature dependence of the water vapor constitutes a positive feedback.
- The dependence of the saturation water vapor content on temperature can be derived from the Clausius-Clapeyron equation:

$$\frac{dq^*}{q^*} = \frac{L}{R_v T}\frac{dT}{T}$$

- Where q* is the saturation specific humidity, L the latent heat of condensation, Rv the gas constant of moist air, and T temperature

Cont.

- Approximating the quantity L/(RvT) as a constant C ~ 20, we obtain

$$d\log(q^*) = Cd\log(T) = d\left(\log(T)^C\right)$$
$$\log(q^*) = \log(T)^C + const$$
$$q^* = const\, T^C$$

- To evaluate this feedback in a realistic setting, we can assume that the relative humidity stays constant as the surface temperature increases, and
- use a (one dimensional) radiative-convective equilibrium model to compute the resulting change in OLR at the top of the atmosphere.

Examples of feedback magnitudes:

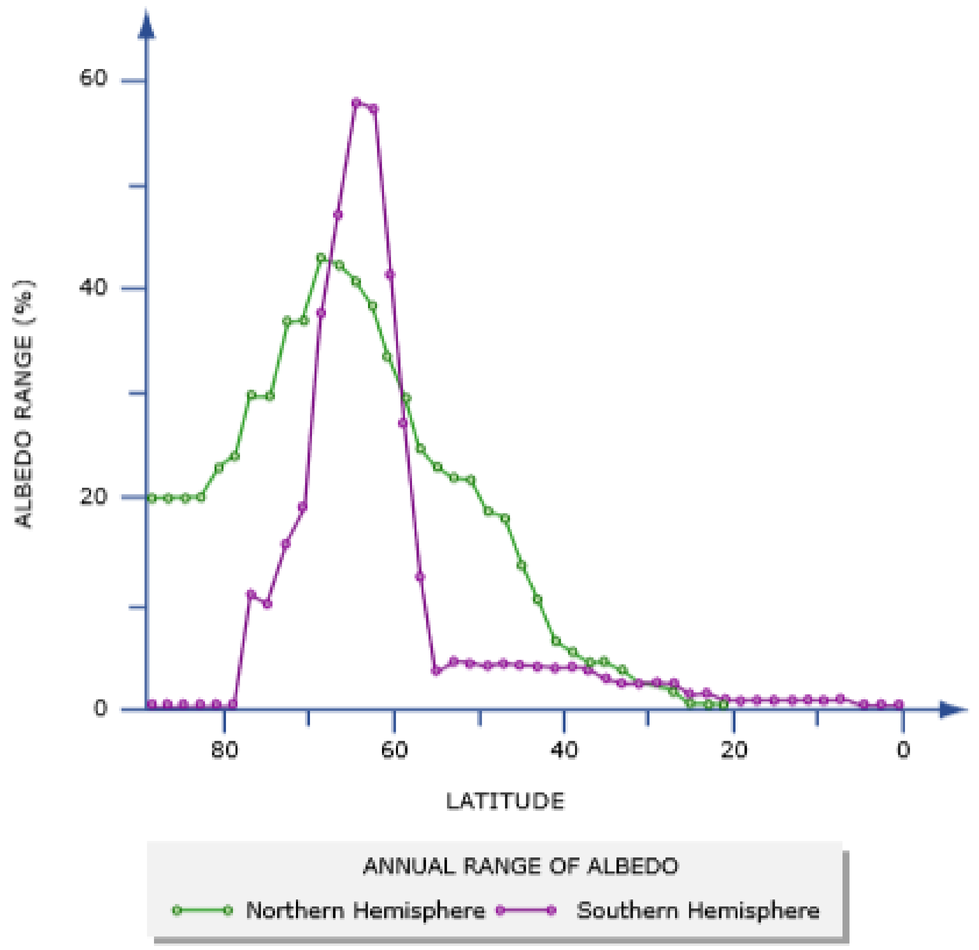
- Experiments with one-dimensional radiative convective models suggest that holding the relative humidity fixed,

$$\left(\frac{\partial F_{TOA}}{\partial q}\right)\left(\frac{\partial q}{\partial T_s}\right)_{RH} \cong 2\, Wm^{-2}K^{-1},$$

$$S\left(\frac{\partial F_{TOA}}{\partial q}\right)\left(\frac{\partial q}{\partial T_s}\right)_{RH} \cong 0.5$$

- This, by itself, doubles climate sensitivity; with other positive feedbacks, effect on sensitivity is even larger.

Ice-Albedo Feedback



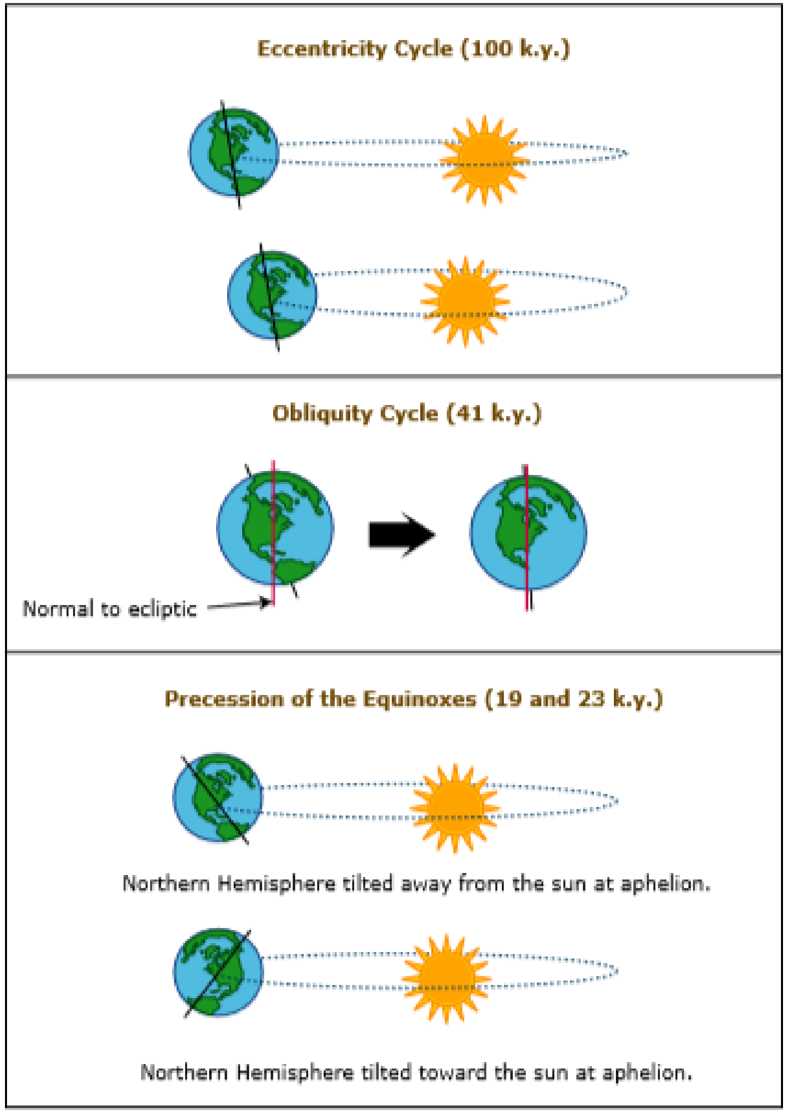
Annual range of zonal monthly surface albedo estimates by 2° latitudinal belts.

Cont.

Examples of Forcing:

- Changing solar constant
- Orbital forcing
- Changing concentrations of non-interactive greenhouse gases
- Volcanic aerosols
- Manmade aerosols
- Land use changes

Climate Forcing by Orbital Variations



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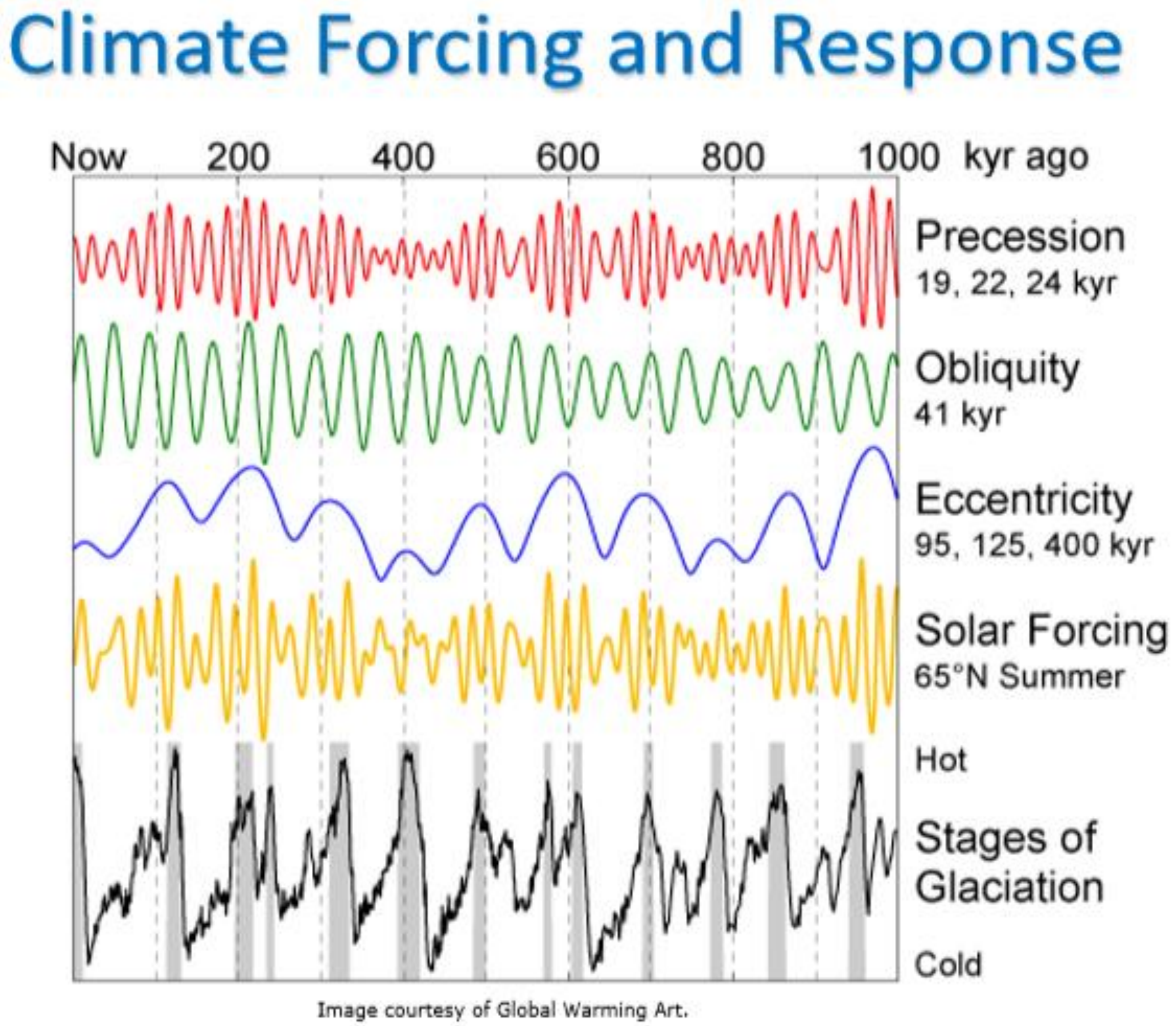
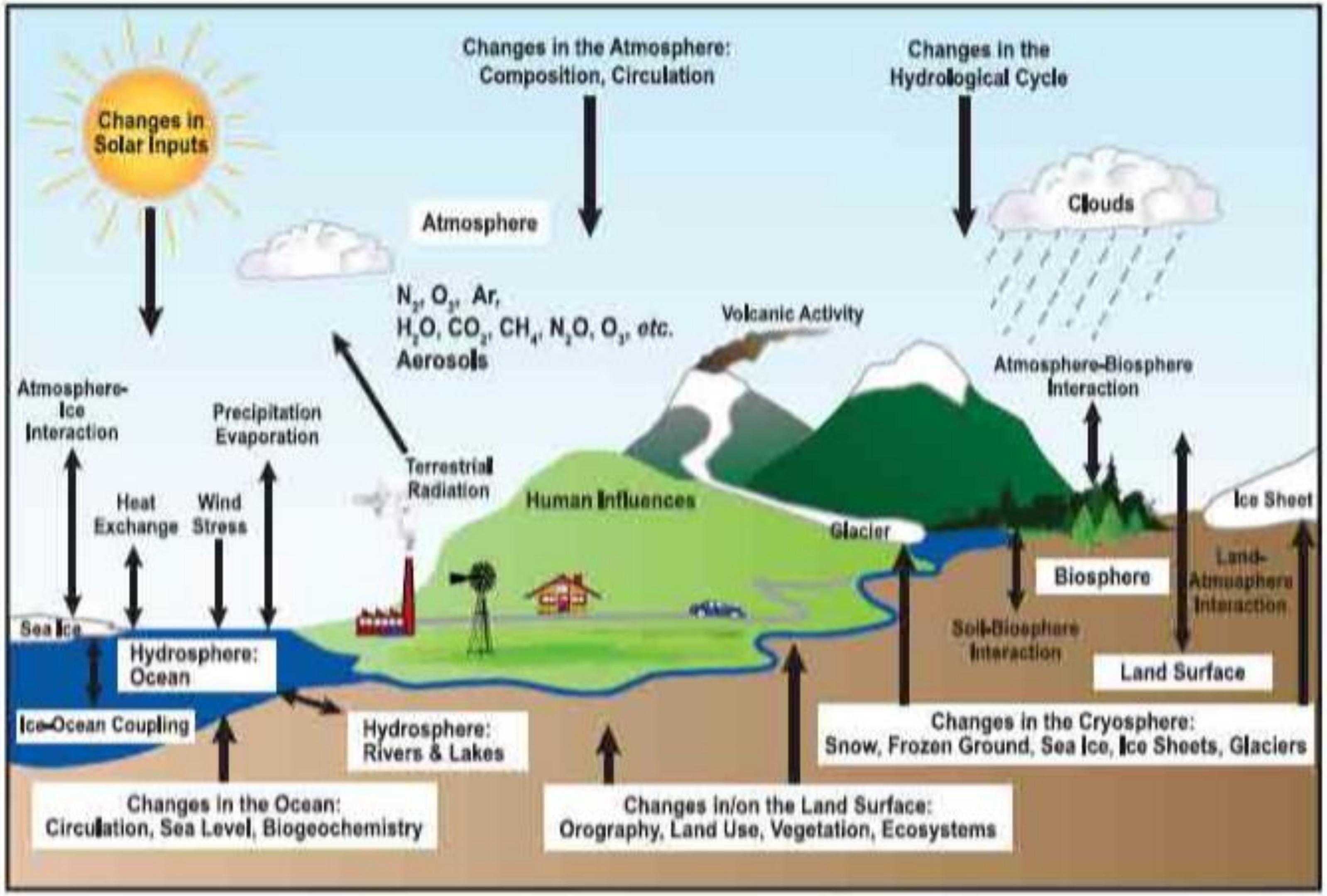

Climate Forcing and Response
Now
200
400
600
800
1000
kyr ago
Precession
19, 22, 24 kyr
Obliquity
41 kyr
Eccentricity
95, 125, 400 kyr
Solar Forcing
65°N Summer
Hot
Stages of Glaciation
Cold
Image courtesy of Global Warming Art.

Cont.

Forcings and Feedbacks in the Climate System



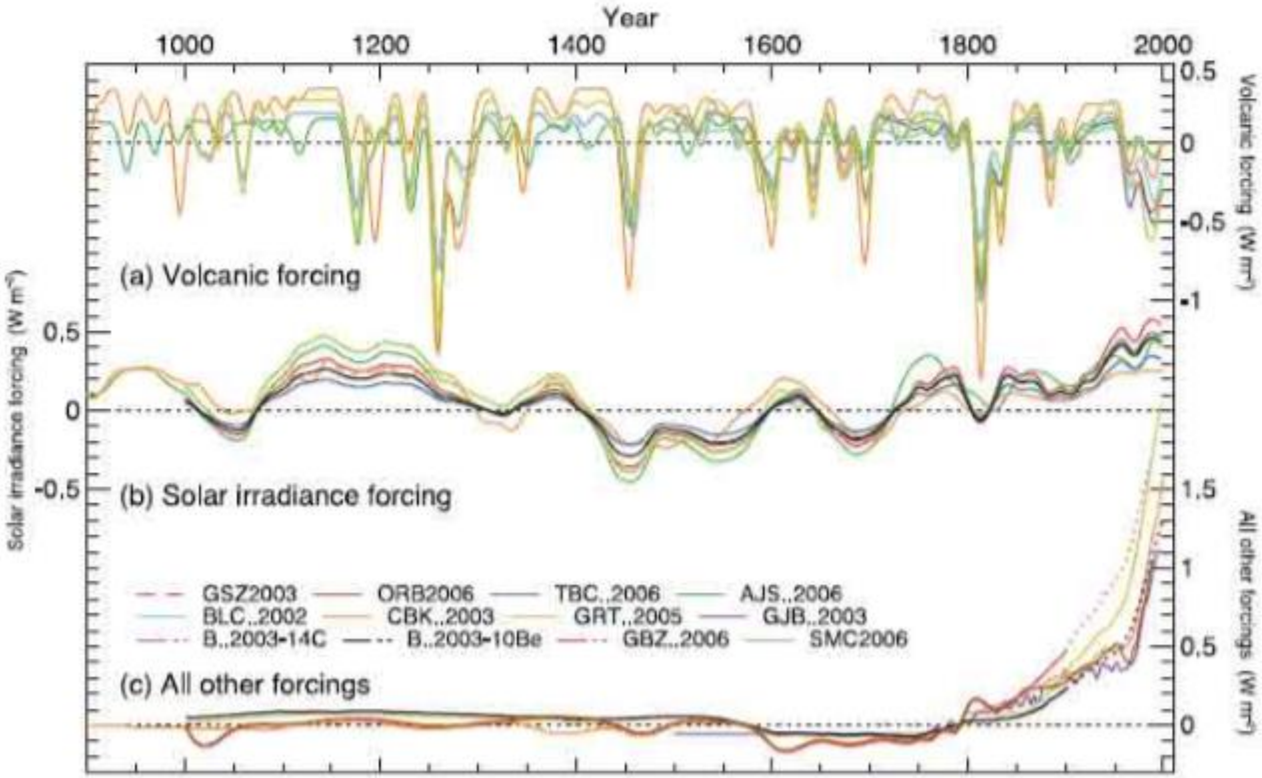
Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, FAQ 1.2, Figure 1. Cambridge University Press. Used with permission.

2

Examples of Forcing Magnitudes:

- A 1.6% change in the solar constant, equivalent to 4 Wm-2, would produce about 1oC change in surface temperature
- Doubling CO2, equivalent to 4 Wm-2, would produce about 1oC change in surface temperature.

Variation with Time of Natural Climate Forcings:



Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 6.13. Cambridge University Press. Used with permission.

Attribution of climate change

➢ The Meaning of Detection and Attribution

- The response to anthropogenic changes in climate forcing occurs against a backdrop of natural internal and externally-forced climate variability that can occur on similar temporal and spatial scales.
- **Internal climate variability**, by which we mean climate variability not forced by external agents, occurs on all timescales from weeks to centuries and millennia. Slow climate components, such as the ocean, have particularly important roles on decadal and century timescales because they integrate high frequency weather variability and interact with faster components.

Cont.

- Thus the climate is capable of producing long timescale internal variations of considerable magnitude without any external influences.
- **Externally-forced climate variations** may be due to changes in natural forcing factors, such as solar radiation or volcanic aerosols, or to changes in anthropogenic forcing factors, such as increasing concentrations of greenhouses gases or sulphate aerosols.
- The presence of this natural climate variability means that the detection and attribution of anthropogenic climate change is a statistical "signal-in-noise" problem.

Cont.

- **Detection** is the process of demonstrating that an observed change is significantly different (in a statistical sense) than can be explained by natural internal variability. However, the detection of a change in climate does not necessarily imply that its causes are understood.
- Unequivocal **attribution of climate change** to anthropogenic causes (i.e., the isolation of cause and effect) would require controlled experimentation with the climate system in which the hypothesised agents of change are systematically varied in order determine the climate's sensitivity to these agents. Such an approach to attribution is clearly not possible.

Cont.

- Thus from a practical perspective, **attribution of observed climate change** to a given combination of human activity and natural influences requires another approach.
- This involves statistical analysis and the careful assessment of multiple lines of evidence to demonstrate, within a pre-specified margin of error, that the observed changes are:
- unlikely to be due entirely to internal variability;
- consistent with the estimated responses to the given combination of anthropogenic and natural forcing; and

Cont.

- not consistent with alternative, physically-plausible explanations of recent climate change that exclude important elements of the given combination of forcings.

Cont.

➢ Internal Climate Variability

- Detection and attribution of climate change is a statistical "signal-in-noise" problem, it requires an accurate knowledge of the properties of the "noise".
- Ideally, internal climate variability would be estimated from instrumental observations, but a number of problems make this difficult.
- The instrumental record is short relative to the 30-50 year time scales that are of interest for detection and attribution of climate change, particularly for variables in the free atmosphere.
- The instrumental record also contains the influences of external anthropogenic and natural forcing.

➢ Climate Forcings and Responses

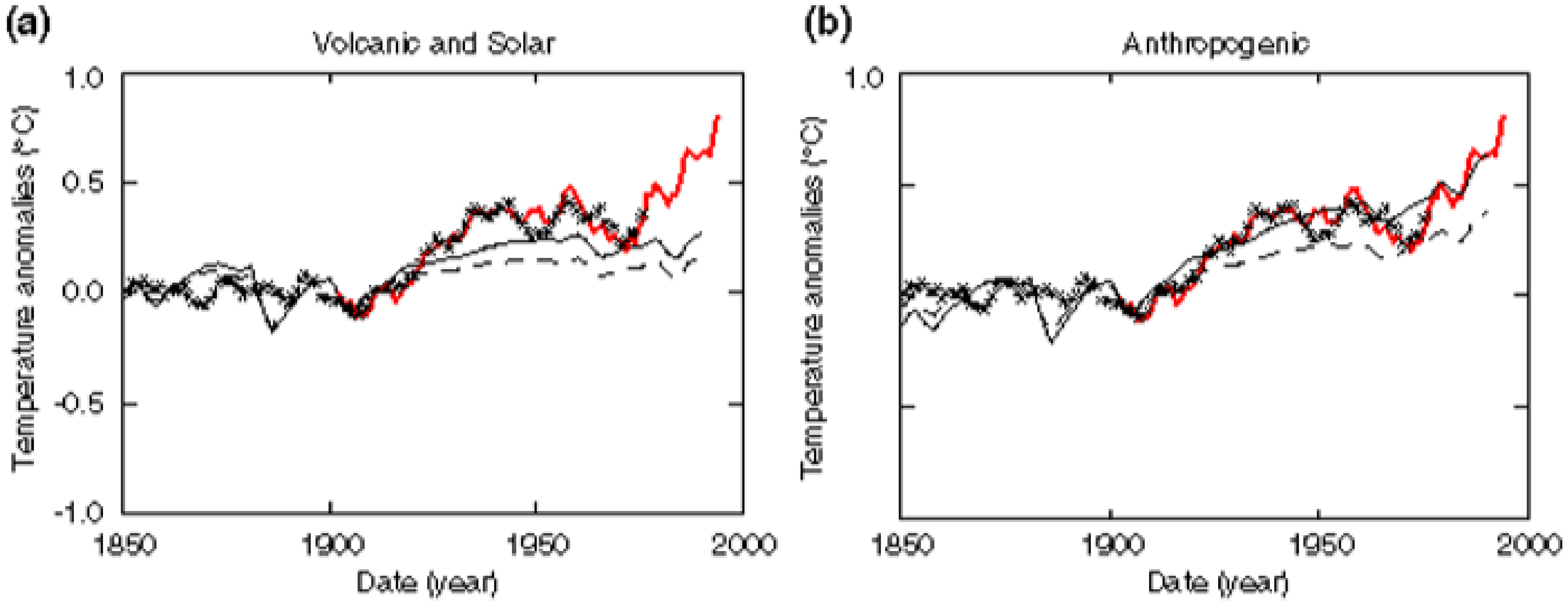
- There are several reasons why one should not expect a simple relationship between the patterns of **radiative forcing** and **temperature response**.

- First, strong feedbacks such as those due to water vapour and sea-ice tend to reduce the difference in the temperature response due to different forcings.

- Second, atmospheric circulation tends to smooth out temperature gradients and reduce the differences in response patterns. Similarly, the thermal inertia of the climate system tends to reduce the amplitude of short-term fluctuations in forcing.

Cont.

- Third, changes in radiative forcing are more effective if they act near the surface, where cooling to space is restricted, than at upper levels, and in high latitudes, where there are stronger positive feedbacks than at low latitudes.



Attribution of climate change: the Specter of Liability

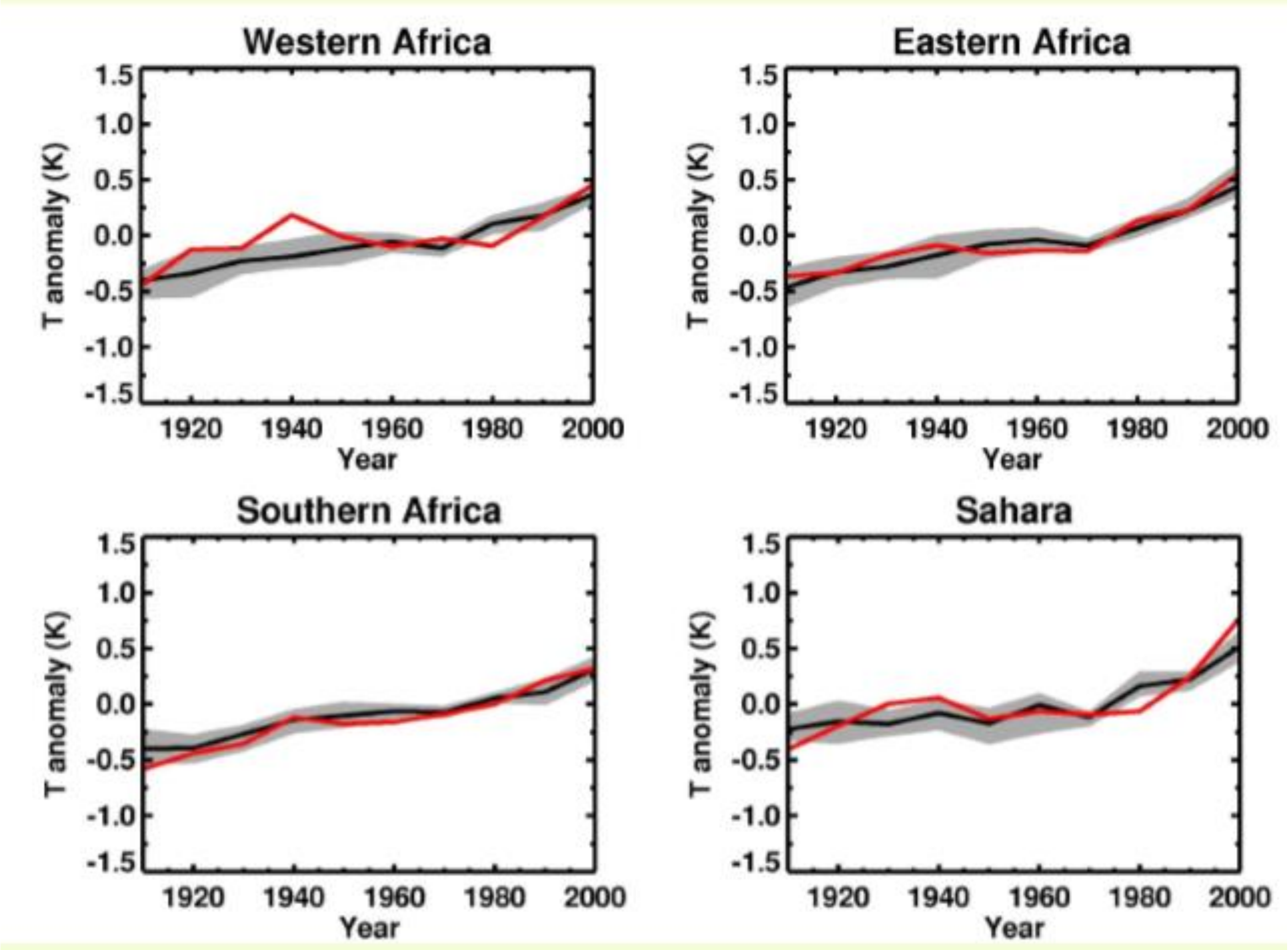
- **How can anyone be to blame for bad weather?**

- Increasingly strong evidence for human influence on global and regional temperatures.
- Some examples of weather trends and events that are likely be affected by human influence: →2003 Summer Heat-Wave in Europe
- →Recent warming trends in across all African regions
- Some examples of weather trends and events that may be affected by human influence: →Low-frequency changes in African rainfall

→2004/2005 Hurricane seasons in the Southern United States

Cont.

- **Simulated and Observed African temperature changes over the 20th century**



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Regional temperature trends

- Most of the warming observed over the past 50 years in many regions of the world can be attributed to the influence of greenhouse gas emissions.
- But what about actual weather events?

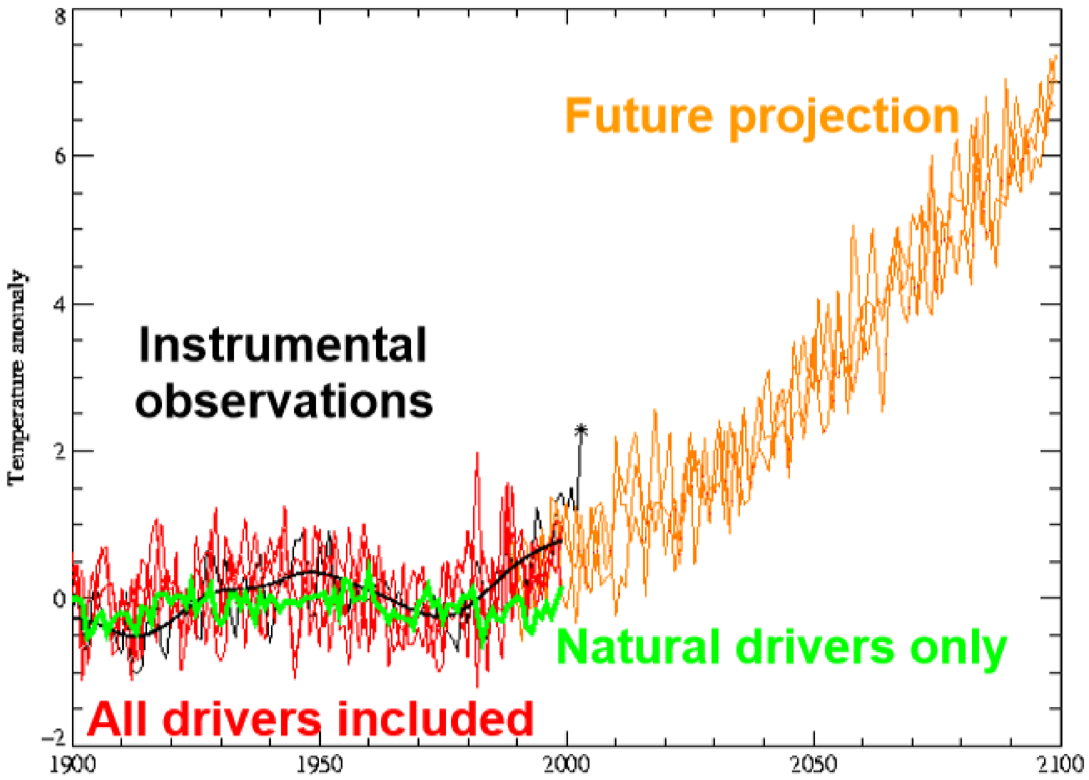
➢ Weather varies naturally: how can we pin down the role of climate change?

- "Climate is what you expect, weather is what you get" (Lorenz, 1982) and in the 21st century:
- "Climate is what you affect, weather is what gets you"
- Needed: a probabilistic, risk-based approach to attributing cause and effect.

Cont.

➢ How can we pin down the role of climate change?

- Heat-waves (and droughts, floods etc.) occur naturally, so we will almost never be able to say that “but for” human influence on climate, this event would definitely not have occurred.
- Instead, we ask how human influence on climate has affected the risk of such a weather event.



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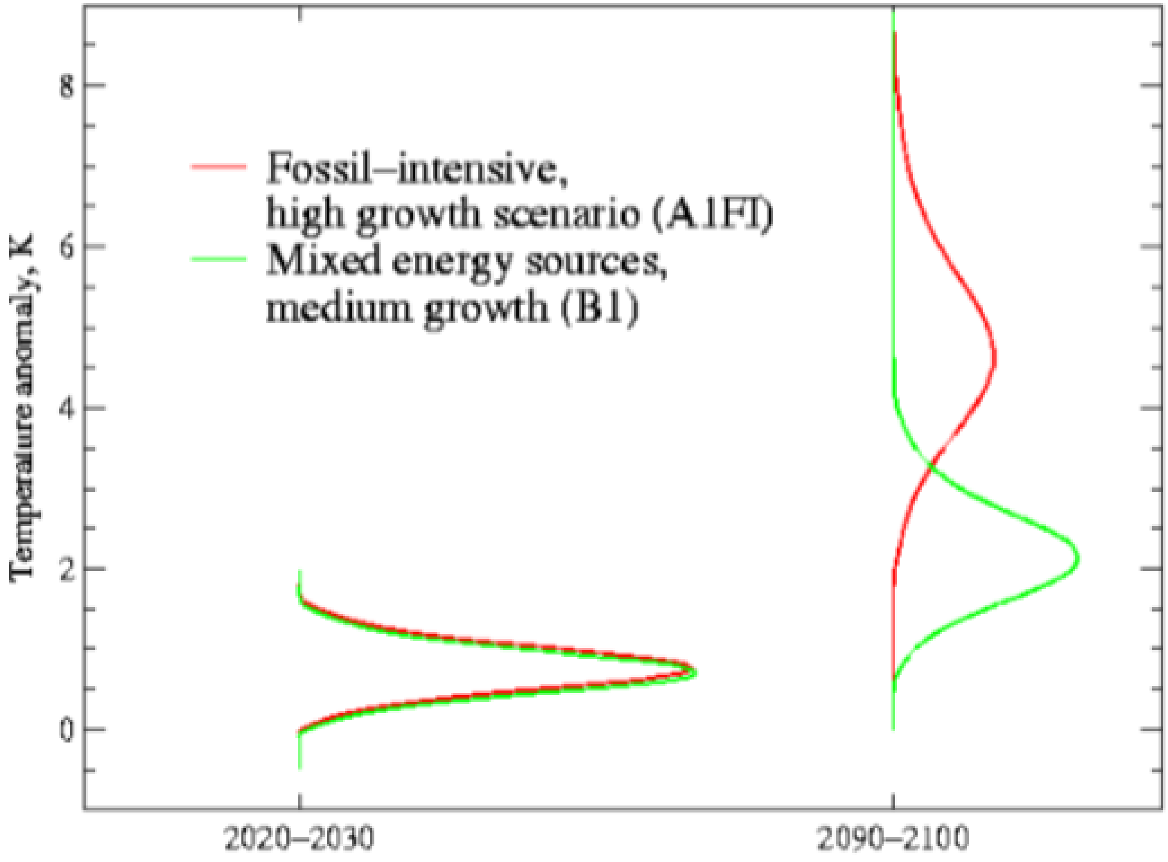
➢ Attribution of trends in African rainfall

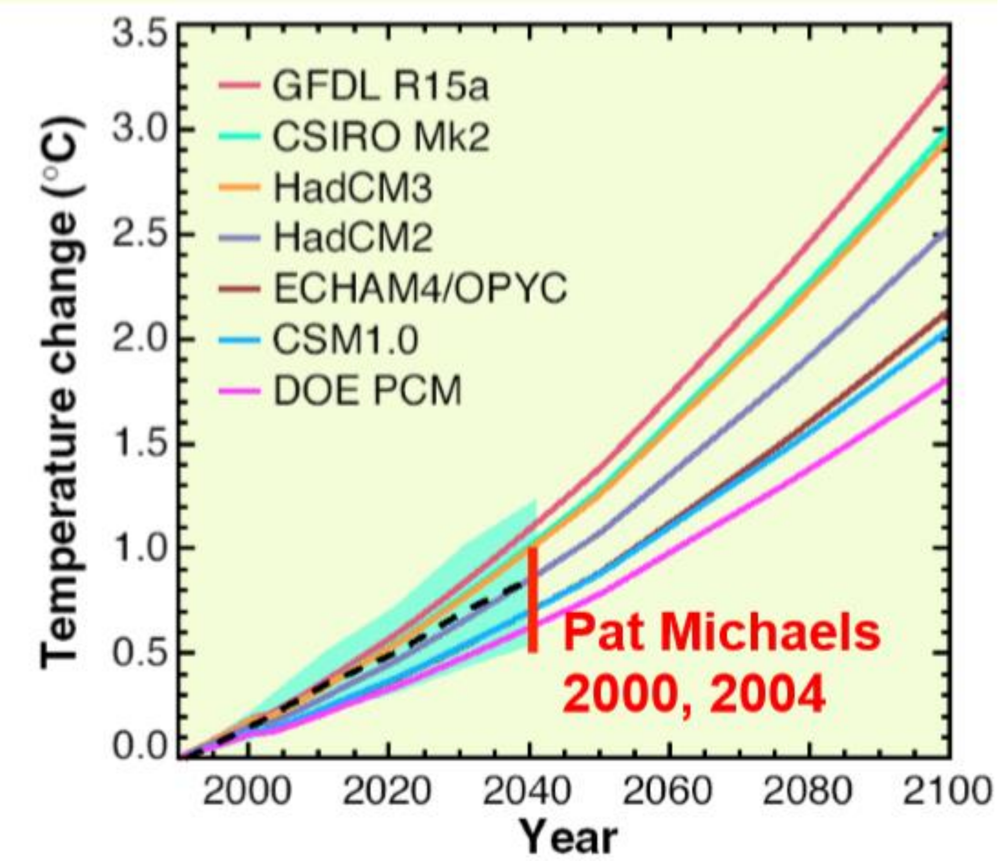
- Latest simulations (Hurrell and Hoerling, 2005) suggest a strong role for large-scale sea surface temperatures in both Sahel and Southern African rainfall trends.
- Sahel drought may reverse, possibly as a result of the changing balance between greenhouse warming and aerosol cooling.
- Southern African drought is more closely linked to warming temperatures in the Indian Ocean, which are attributable to human influence, and are likely to get worse.

Cont.

- Uncertainty in global warming under two scenarios of future emissions



- There is a very high level of consensus in the range of responses over the next few decades



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➢ The Specter of Liability

- Modest background warming substantially increases the risk of extreme high temperatures.
- It is likely (90% confidence) that past human influence on climate was responsible for at least half the risk of the 2003 European summer heat-wave.
- "Plaintiffs ... must show that, more probably than not, their individual injuries were caused by the risk factor in question, as opposed to any other cause. This has sometimes been translated to a requirement of a relative risk of at least two." (Grossman, 2003)

Cont.

➢ **Civil liability: a new paradigm for redistributing the costs of climate change?**

- The contribution of past greenhouse gas emissions to some current climate risks may already exceed 50%, the threshold for civil tort actions.
- Over the coming decade, both the cost and the inevitability of climate change will become clearer, fuelling demands for compensation for:
  - Flooding and droughts
  - Heat wave damages and deaths
  - Threats to water supplies, especially from glacial sources
  - Coastal erosion and (possibly) hurricanes

Cont.

➢Power to the people

- Politicians tend to talk about climate change as an environmental or ethical issue: care for polar bears or future generations.
- To be addressed by regulation, on their timetable.
- This diverts attention from the injustices that are happening now: all benefit from burning fossil fuels, but some are losing out much more than others from the impacts of climate change.
- The risk, even if remote, of a successful class-action damages suit would have far more impact than any conceivable follow-up to the Kyoto Protocol.

Cont.

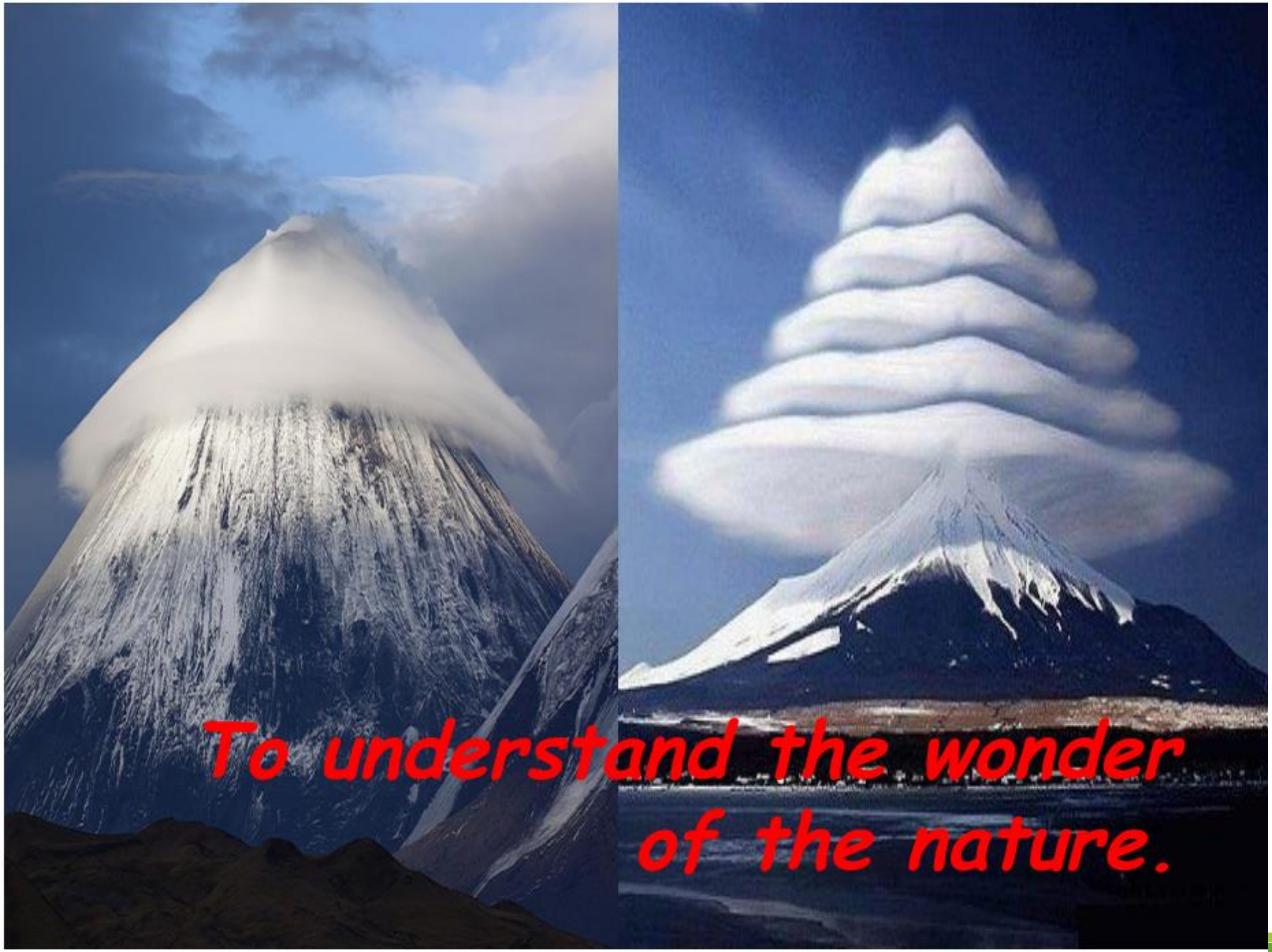
➢But what could be done?

- Fossil fuels are still remarkably cheap, since we pay for the cost of extraction (and profits), not the cost of their impact.
- The current profit to be made on many sources of fossil fuel may exceed industry estimates of the cost of sequestering (burying) the carbon they generate.
- If politicians were to apply the "Polluter Pays Principle" to producers of fossil fuels, this would change rapidly: it might well make more sense to bury carbon than to risk liability.
- Countries at high risk, but which have contributed very little so far, should be lobbying hard for this.

Cont.

- **Beware the Danae when they come bearing gifts**

- The European Commission is arguing for Kyoto-style emission regulations as the way forward to control climate change.
- In their Environmental Directive of 2004, they explicitly advised that civil liability "for large-scale environmental problems to which many actors contribute" should be pre-empted if a regulatory regime is in place.
- Are these connected?


To understand the wonder
of the nature.

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To address the most pressing challenge
that humanity face in the 21st century
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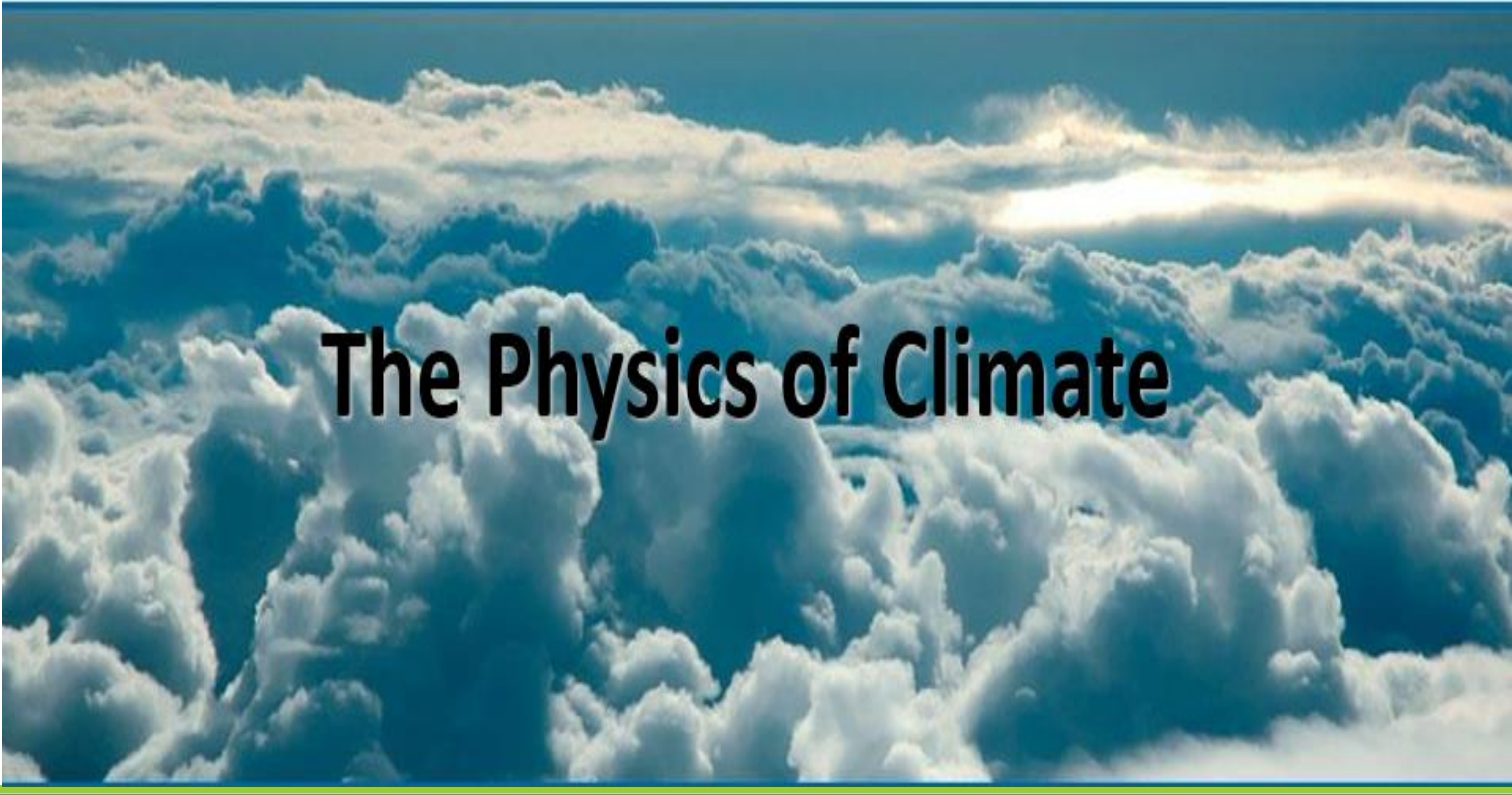
The Physics of Climate