Arba Minch University

Water Technology Institute

Faculty Of Meteorology & Hydrology

Tropical Meteorology

Chapter One

Introduction

Definition of tropics

- **Tropics** Defined as the region of surplus radiation with net upward motion, easterly boundary layer flow and lower surface pressures associated with a meridional over turning upper level circulation
- In geographical terminology "the Tropics" refers to the region of the earth bounded by the Tropic of Cancer (lat. 23.5oN) and the Tropic of Capricorn (lat. 23.5oS)

Cont..

- The tropics include the Equator and parts of North America, South America, Africa, Asia, and Australia.
- The tropics account for 36 percent of the Earth's landmass and are home to about a third of the world's people.
- The tropics are warm all year, averaging 25 to 28 degrees Celsius (77 to 82 degrees Fahrenheit).

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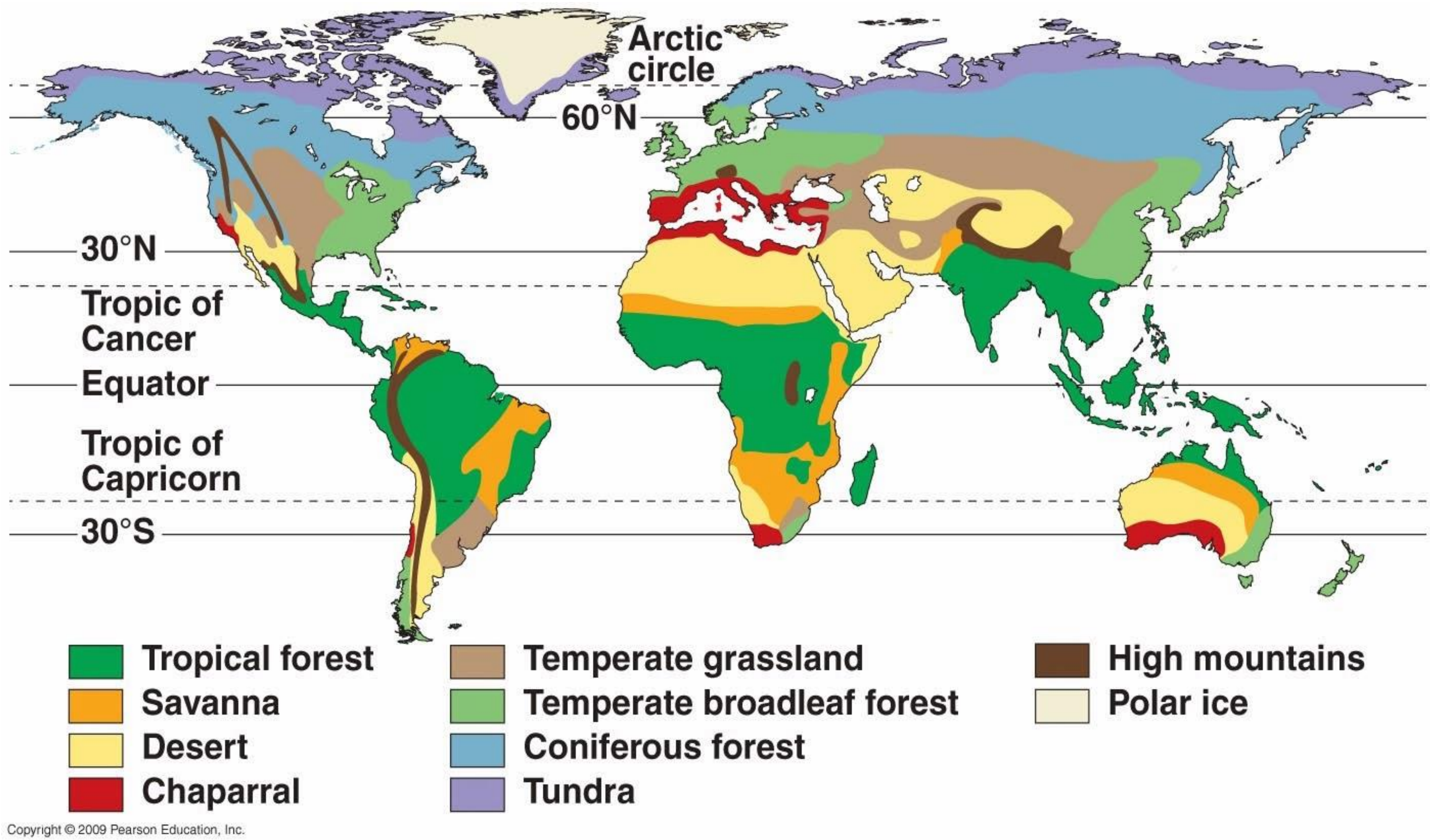
Arctic circle
60°N
30°N
Tropic of Cancer
Equator
Tropic of Capricorn
30°S
Tropical forest
Savanna
Desert
Chaparral
Temperate grassland
Temperate broadleaf forest
Coniferous forest
Tundra
High mountains
Polar ice
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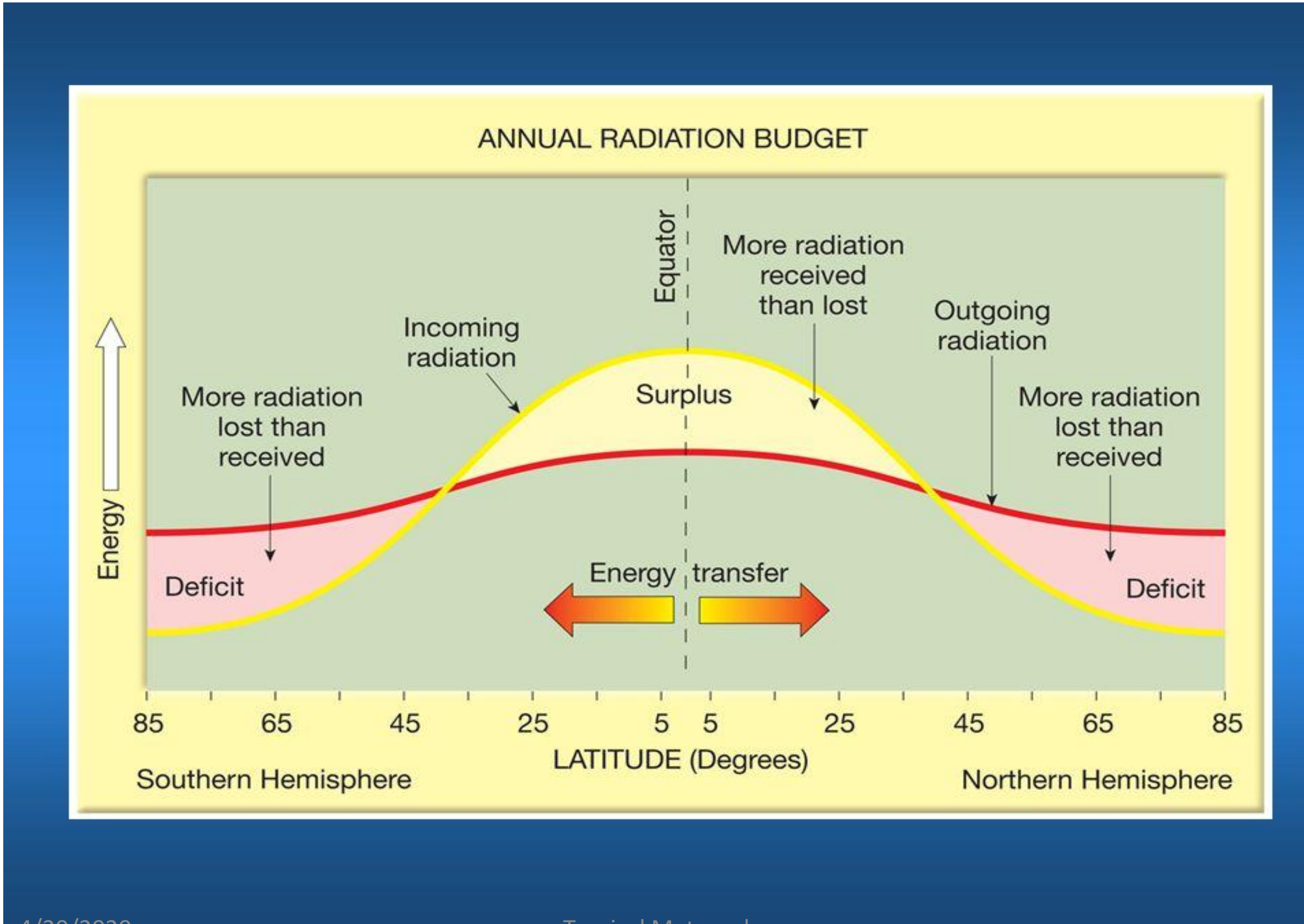
Annual radiation balance



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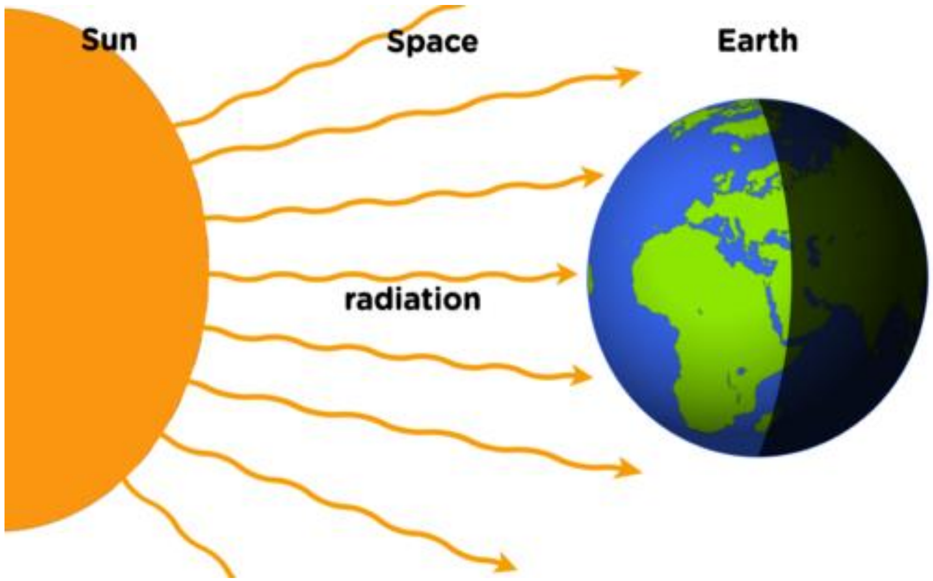
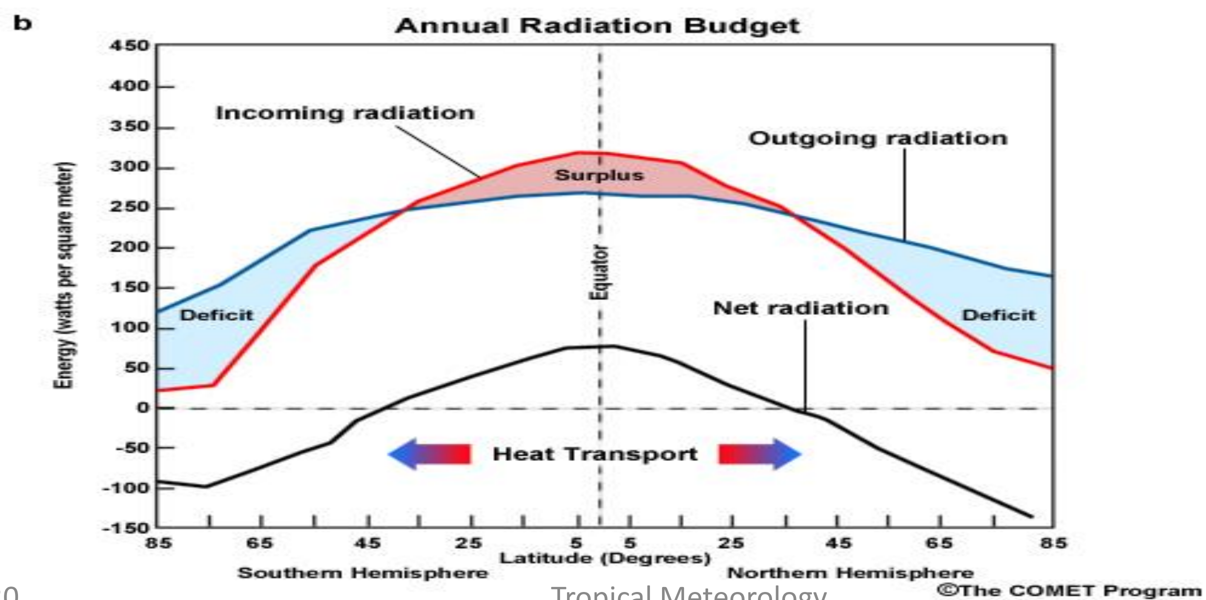


Sun
Space
Earth
radiation



b
Annual Radiation Budget
Incoming radiation
Outgoing radiation
Surplus
Deficit
Deficit
Net radiation
Heat Transport
Equator
Energy (watts per square meter)
450
400
350
300
250
200
150
100
50
0
-50
-100
-150
85
65
45
25
5
5
25
45
65
85
Latitude (Degrees)
Southern Hemisphere
Northern Hemisphere
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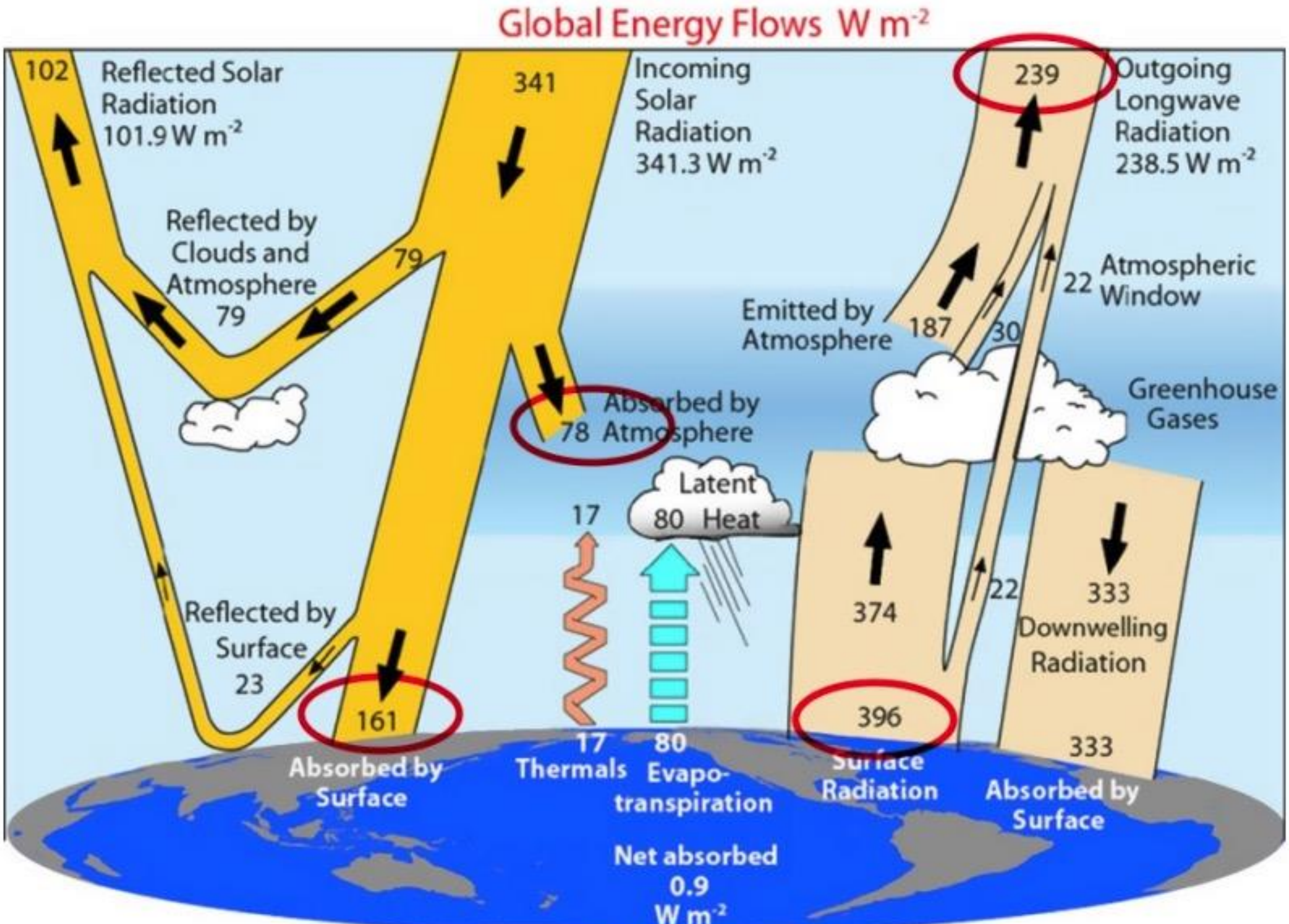
Cont..

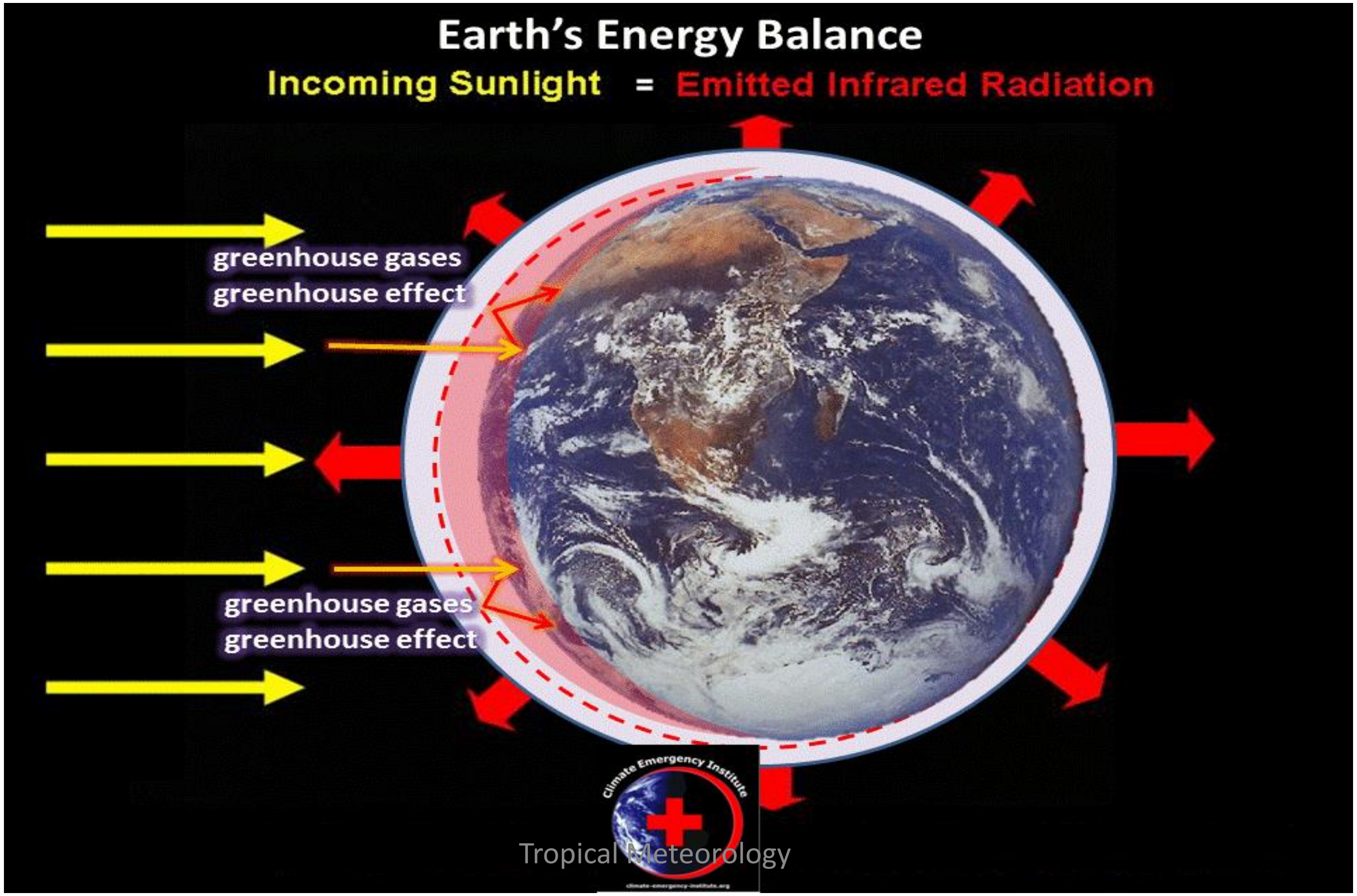

Global Energy Flows W m-2
102
Reflected Solar Radiation 101.9 W m-2
341
Incoming Solar Radiation 341.3 W m-2
239
Outgoing Longwave Radiation 238.5 W m-2
Reflected by Clouds and Atmosphere 79
79
Atmospheric Window
22
Emitted by Atmosphere
187
30
Greenhouse Gases
78 Absorbed by Atmosphere
17
Latent 80 Heat
374
22
333 Downwelling Radiation
Reflected by Surface 23
161
396
333
17 Thermals
80 Evapo-transpiration
Absorbed by Surface
Surface Radiation
Absorbed by Surface
Net absorbed 0.9 W m-2

Tropical meteorology and climatology

- **Tropical meteorology:**
- The study of the tropical atmosphere.
- The dividing lines, in each hemisphere, between the tropical easterlies and the midlatitude westerlies in the middle troposphere roughly define the poleward boundaries of this region.
- **Tropical climatology:**
- A tropical climate in the Köppen climate classification is a non-arid climate in which all twelve months have mean temperatures of warmer than 18 °C (64 °F).
- In tropical climates there are often only two seasons: a wet season and a dry season.
- Tropical climates are frost-free, and changes in the solar angle are small.

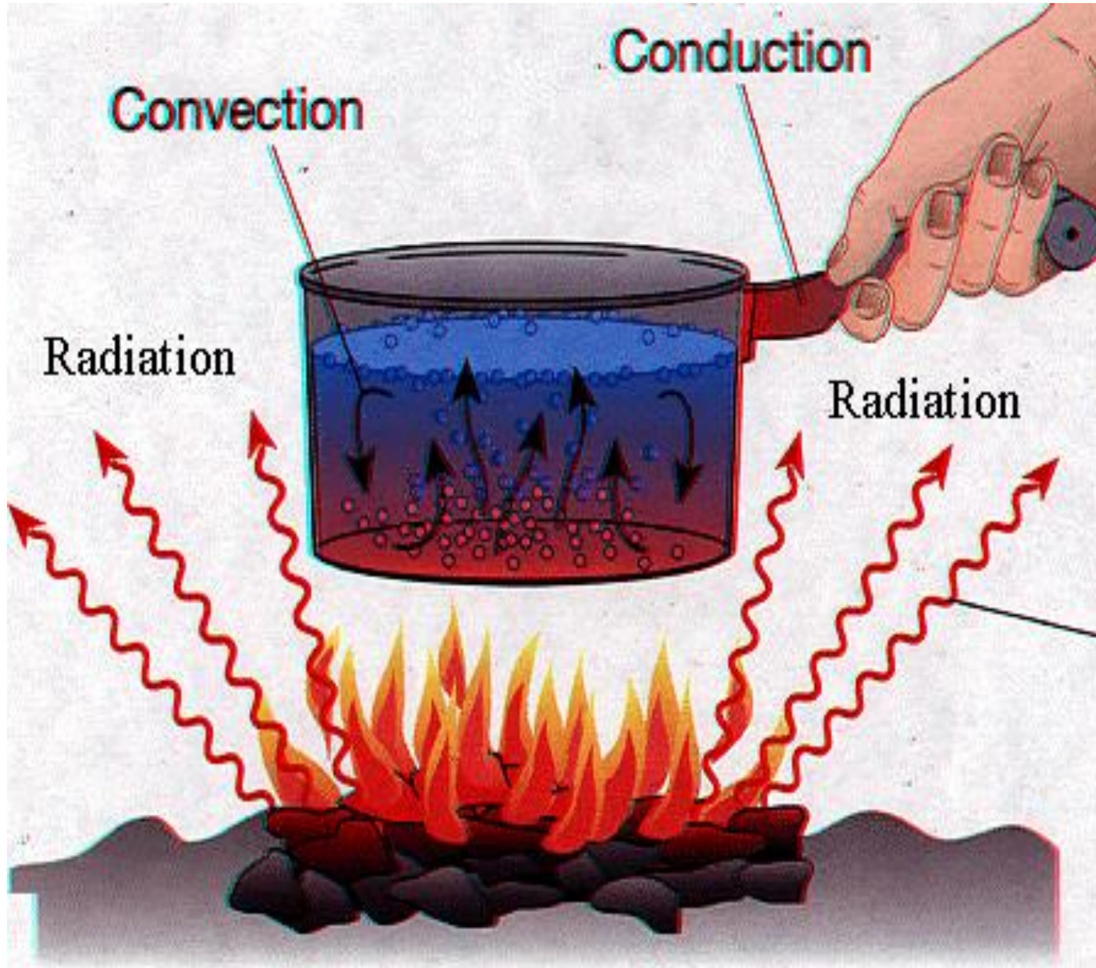
Cont..

- Energy and global climate:
- The sun is the primary source of energy for the earth system(atmosphere, hydrosphere, Biosphere, cryosphere and lithosphere)



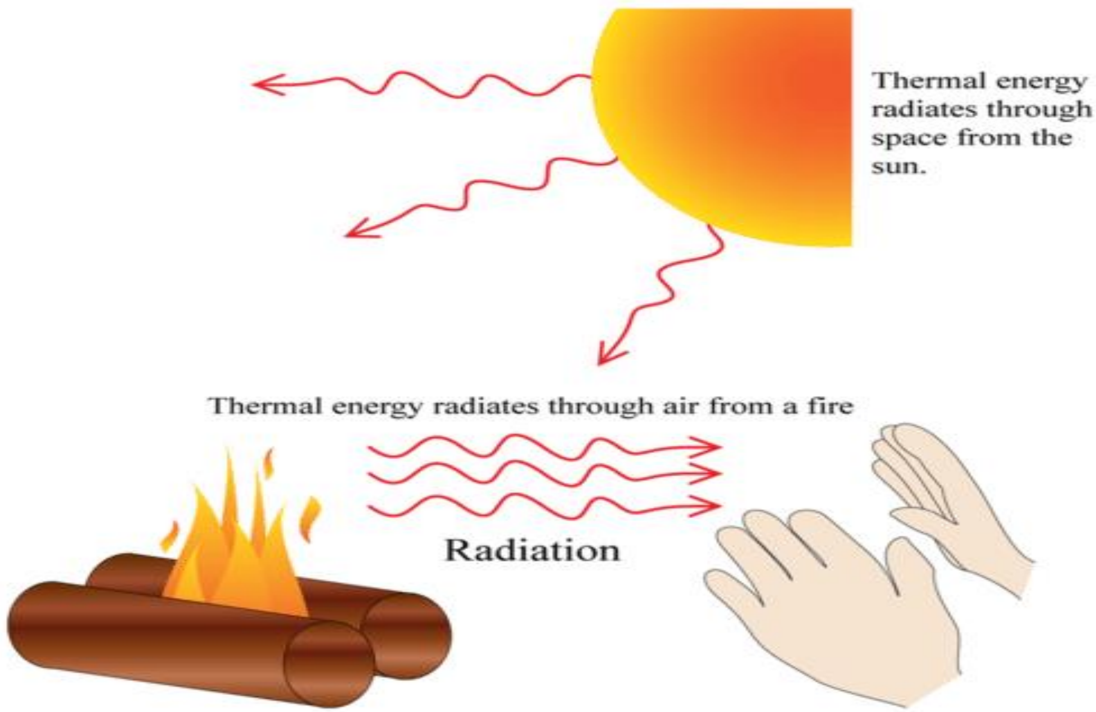
Energy transferred by:

- Radiation
- Conduction
- Convection
- Advection
- Global energy flow



Cont..

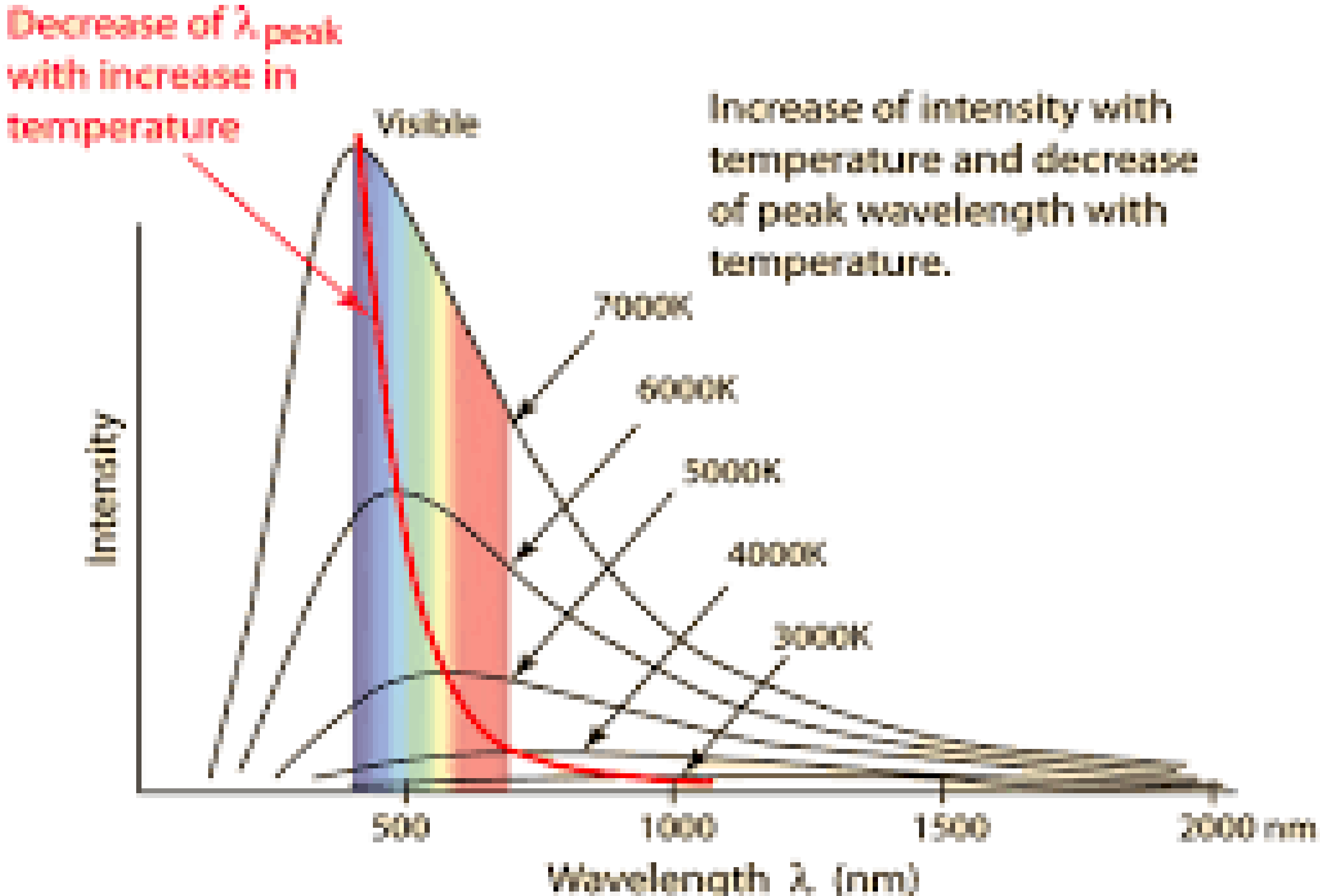
- Conduction and convection requires a medium to transfer energy however radiation does not require any medium. It can take place in vacuum.



Cont..

- **Stefan-Boltzmann law**, statement that the total radiant heat energy emitted from a surface is proportional to the fourth power of its absolute temperature.
- The law applies only to blackbodies, theoretical surfaces that absorb all incident heat radiation
- **Wien's displacement law** states that the black-body radiation curve for different temperatures will peak at different wavelengths that are inversely proportional to the temperature.

Cont….


Decrease of λ peak
with increase in
temperature
Visible
Increase of intensity with
temperature and decrease
of peak wavelength with
temperature.
7000K
6000K
5000K
4000K
3000K
Intensity
500
1000
1500
2000 nm
Wavelength λ (nm)

Cont….

- **Principles of atmospheric motion**
  - **Newton's law of motion**

Newton's Laws

1. A body will remain at rest, or moving at a constant velocity, unless it is acted on by an unbalanced force.
2. The force experienced by an object is proportional to its mass times the acceleration it experiences:

$$\vec{F} = m\vec{a}$$

3. If two bodies exert a force on one another, the forces are equal in magnitude, but opposite in direction:

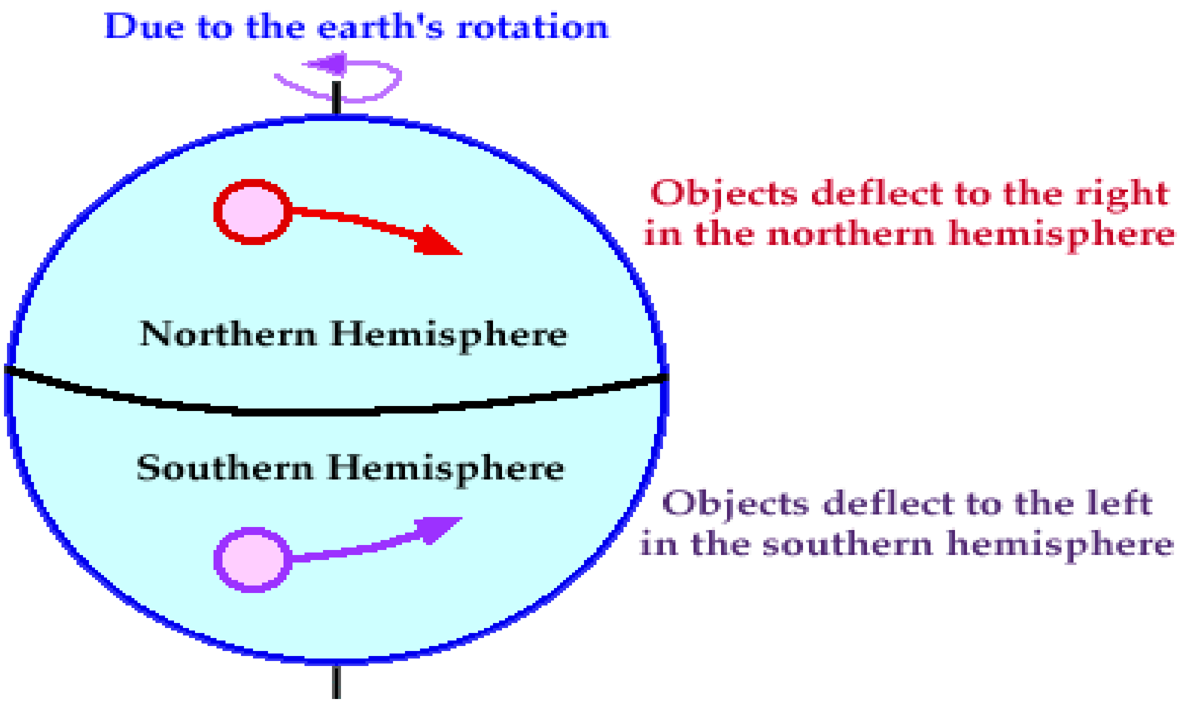
$$\vec{F}_{12} = -\vec{F}_{21}$$

Main atmospheric forces

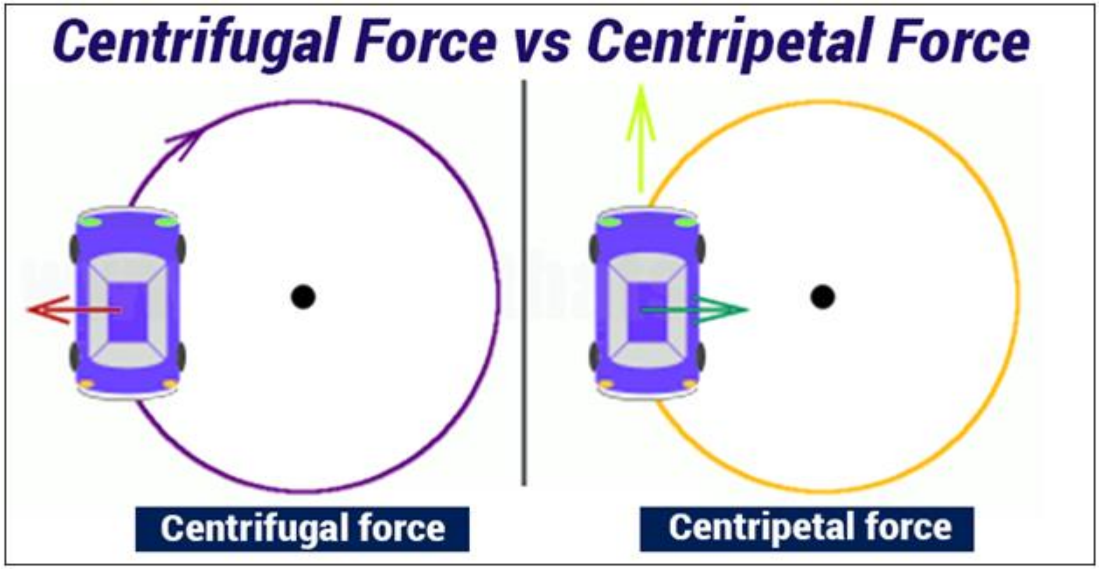
- PGF
- Coriolis force
- Centrifugal force
- Centripetal forces
- Friction force
- Gravitational forces
- Buoyancy force

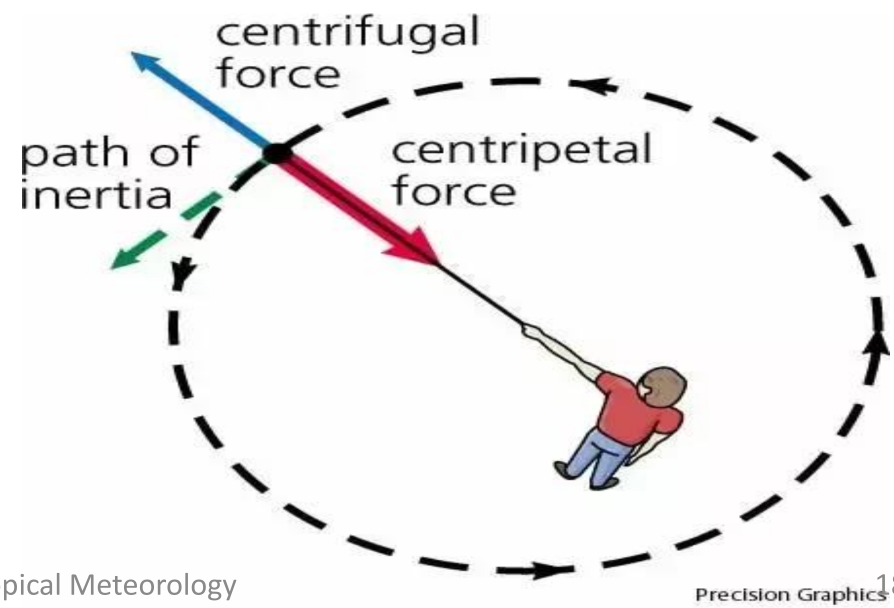
Coriolis force

- an apparent force that as a result of the earth's rotation deflects moving objects (such as projectiles or air currents) to the right in the northern hemisphere and to the left in the southern hemisphere



Center fugal and centripetal force





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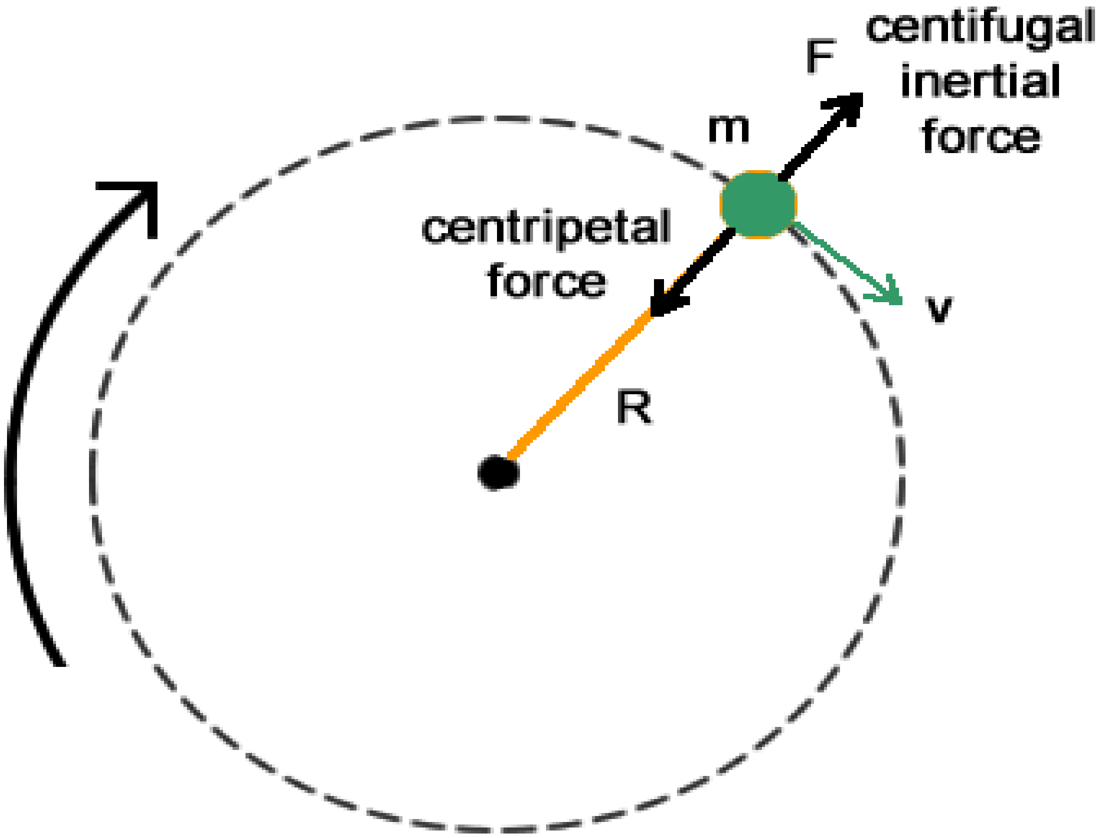
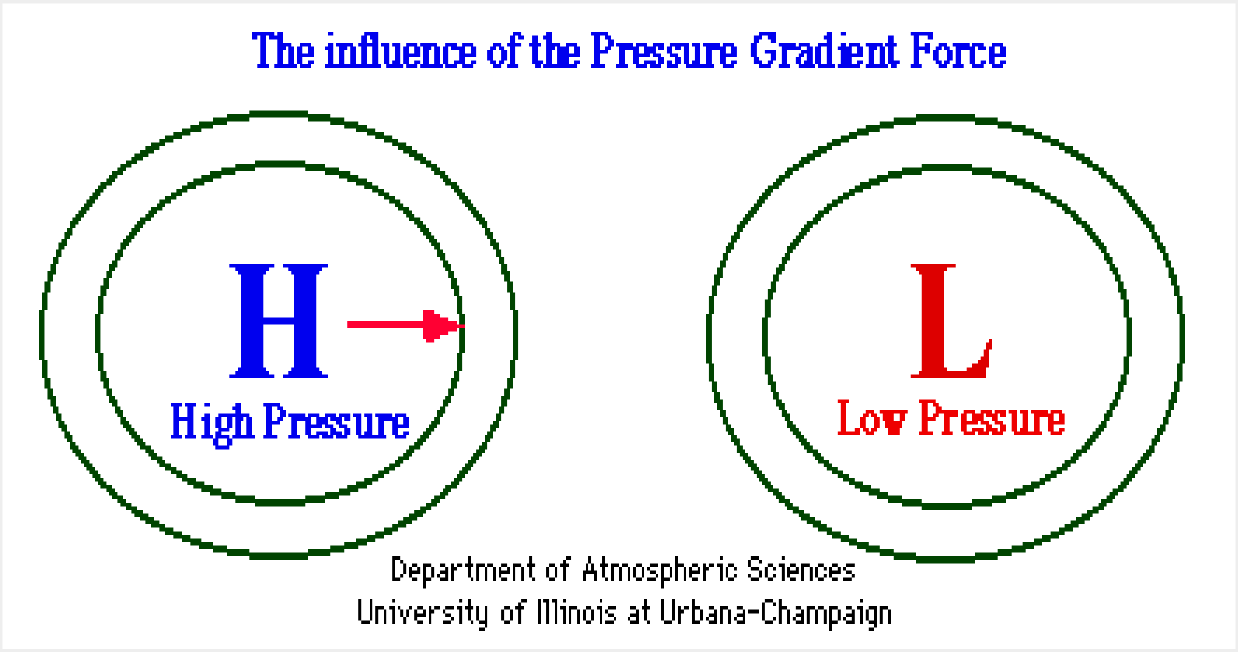
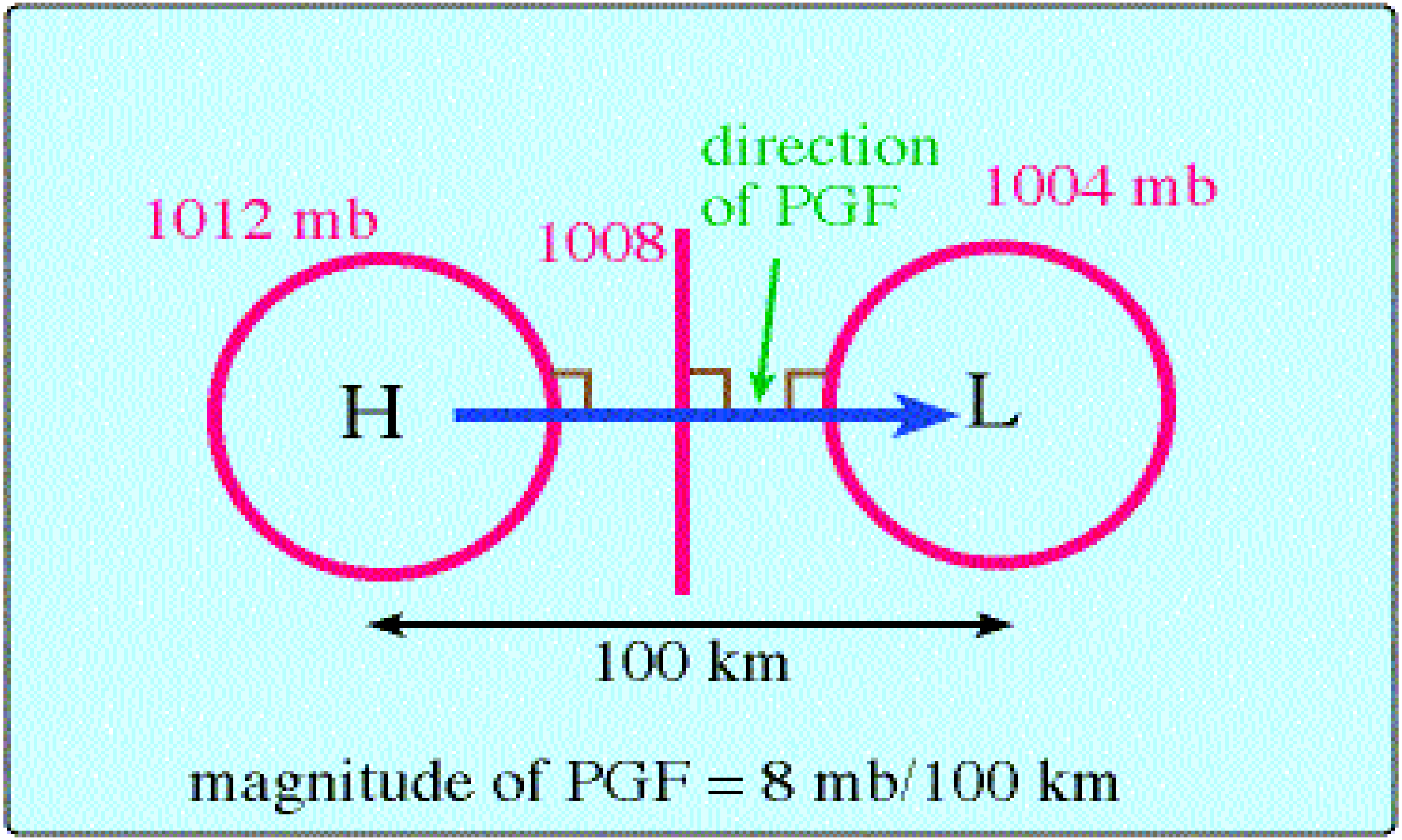


PGF

- The pressure-gradient force is the force that results when there is a difference in pressure across a surface. In general, a pressure is a force per unit area, across a surface.



PGF



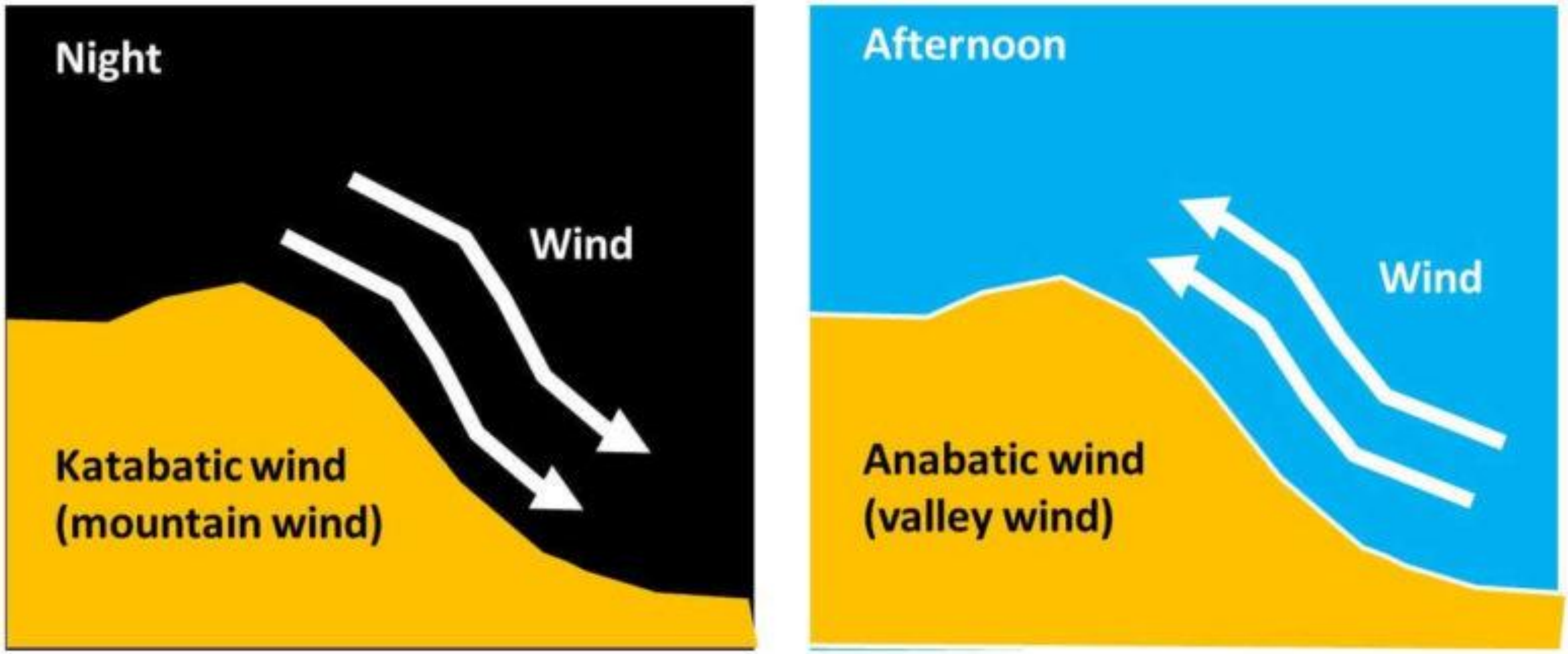
direction
of PGF
1012 mb
1008
1004 mb
H
L
100 km
magnitude of PGF = 8 mb/100 km

Scales of atmospheric motion

- **Planetary scale:-**
  - ✓circulations last for week or months
  - ✓Sixe from 5000 to 40,000 km
- **Synoptic scale**
  - ✓circulations last for day to weeks
  - ✓Size from 100km to 5000km
- **Meso scale**
  - ✓Circulation las from minute to hours
  - ✓Size from 1 to 100 km
- **Microscale**
  - ✓Lasting under a few minutes
  - ✓Size less than 1 km

Cont..

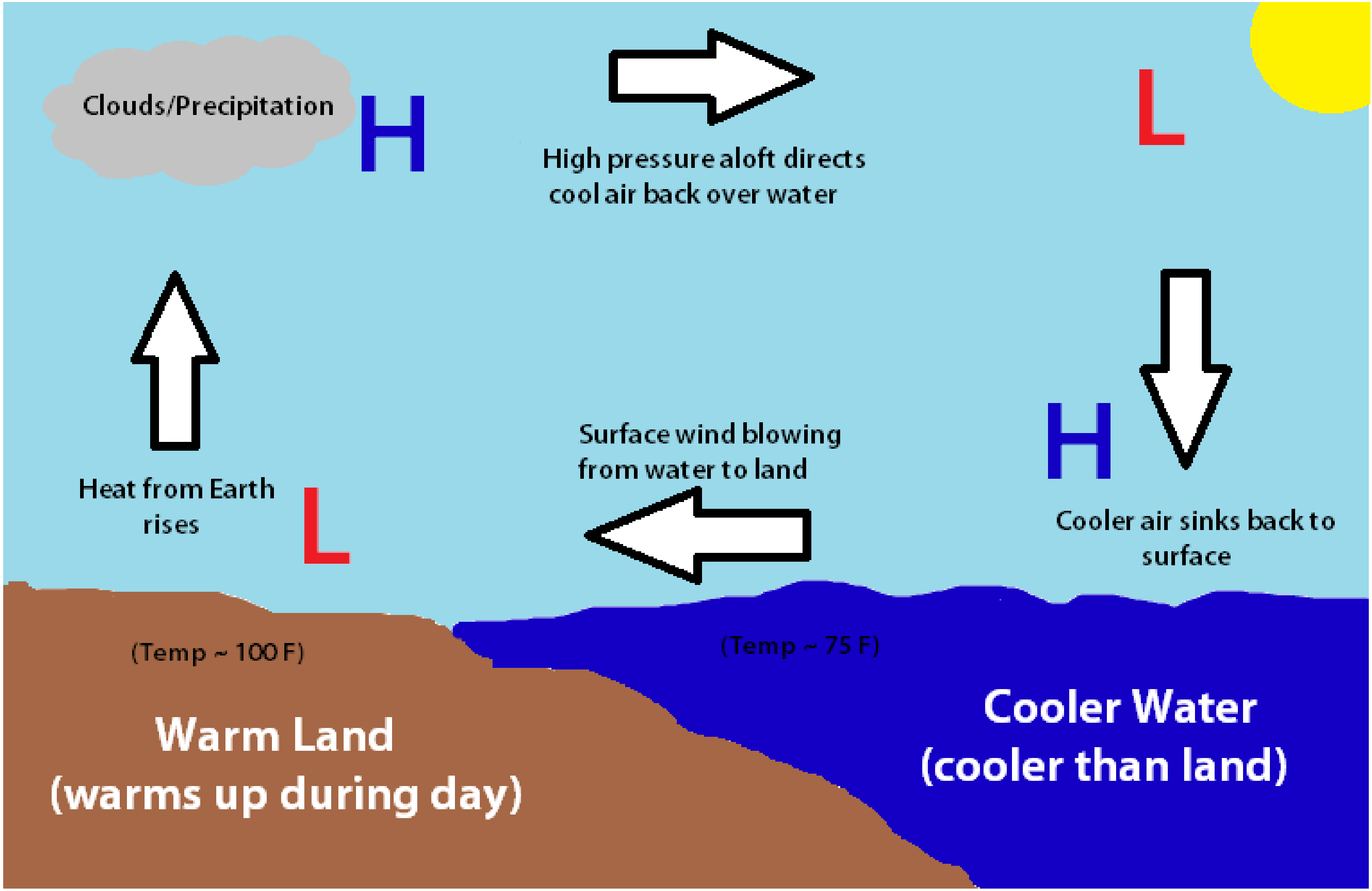
- Thermal circulation
- Sea and land breezes
- Katabatic and Anabatic winds



The mountain cools down, the air becomes heavier so it descends.

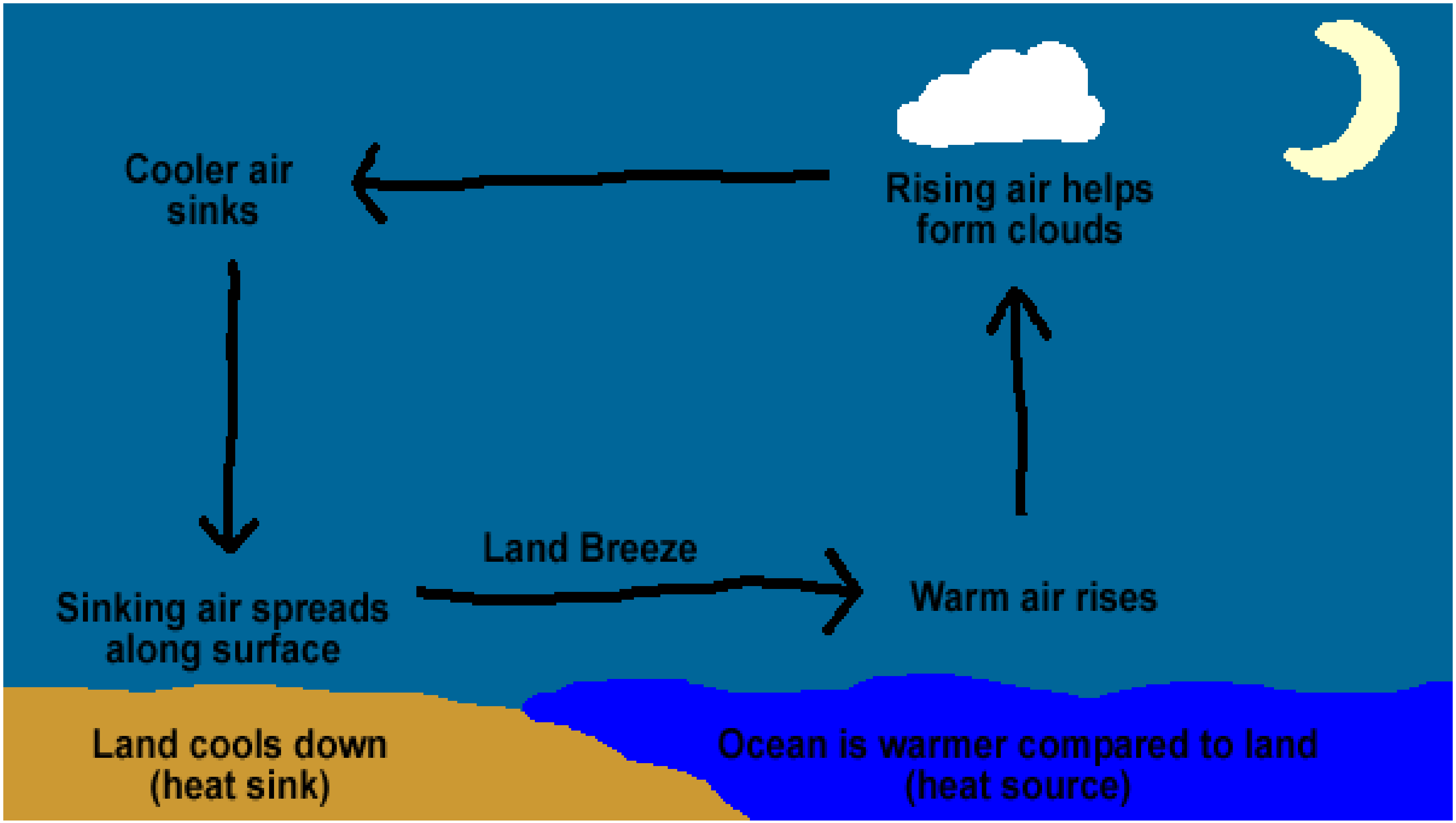
The sun warms the mountain, the aire is lighter and ascends

Seabreaze



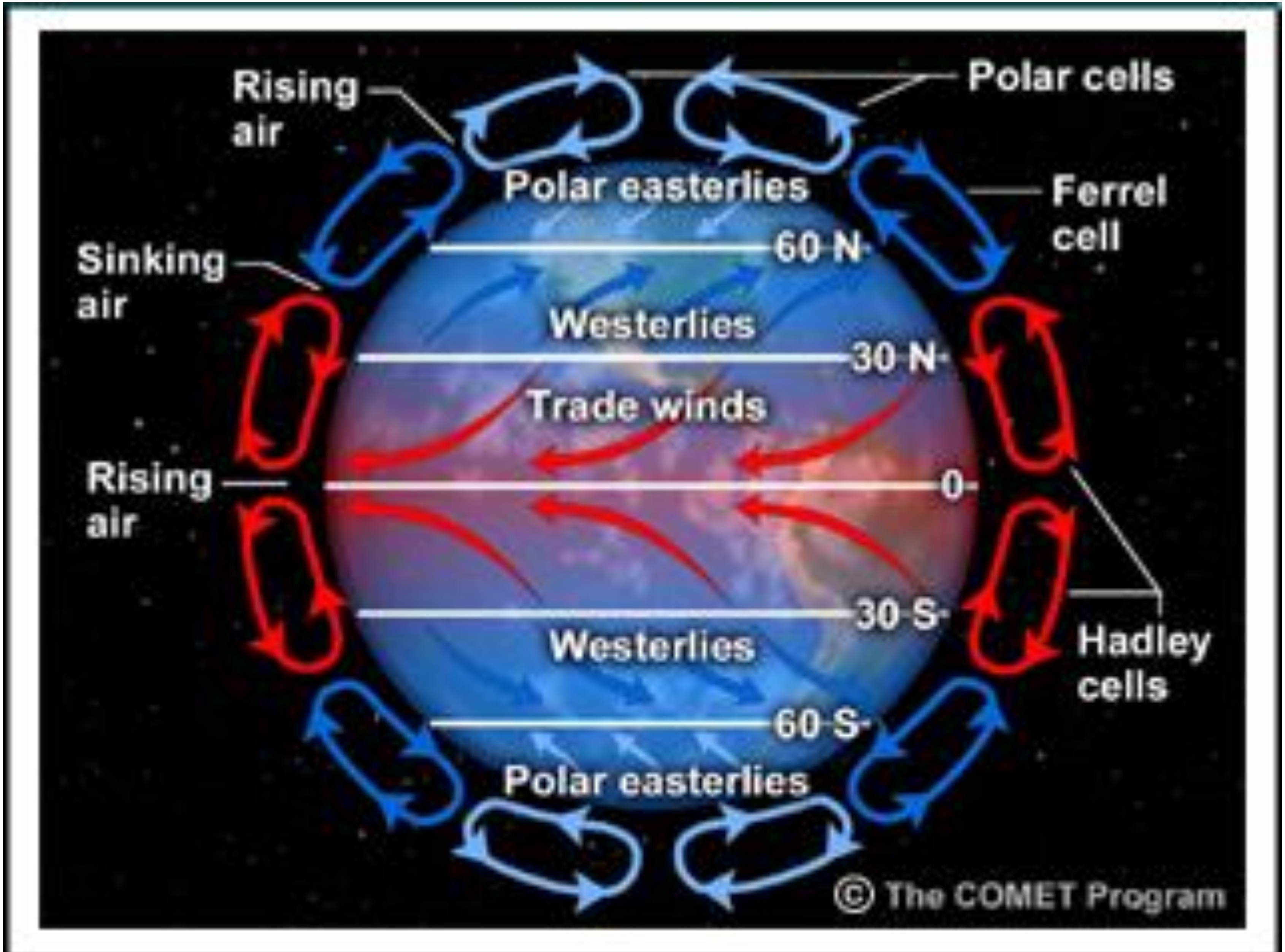
Clouds/Precipitation
H
High pressure aloft directs cool air back over water
L
Heat from Earth rises
L
Surface wind blowing from water to land
H
Cooler air sinks back to surface
(Temp ~ 100 F)
(Temp ~ 75 F)
Warm Land (warms up during day)
Cooler Water (cooler than land)

Land breeze


Cooler air sinks
Rising air helps form clouds
Land Breeze
Sinking air spreads along surface
Warm air rises
Land cools down (heat sink)
Ocean is warmer compared to land (heat source)

Chapter Two

Global Circulation


Rising air
Polar cells
Polar easterlies
Ferrel cell
Sinking air
60 N
Westerlies
30 N
Trade winds
Rising air
0
30 S
Westerlies
Hadley cells
60 S
Polar easterlies
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Introduction

- The chapter begins with a review of the general principles of atmospheric motion including scale analysis of tropical motions.
- An overview of the general circulation of the atmosphere and ocean is presented including stratospheric general circulation.

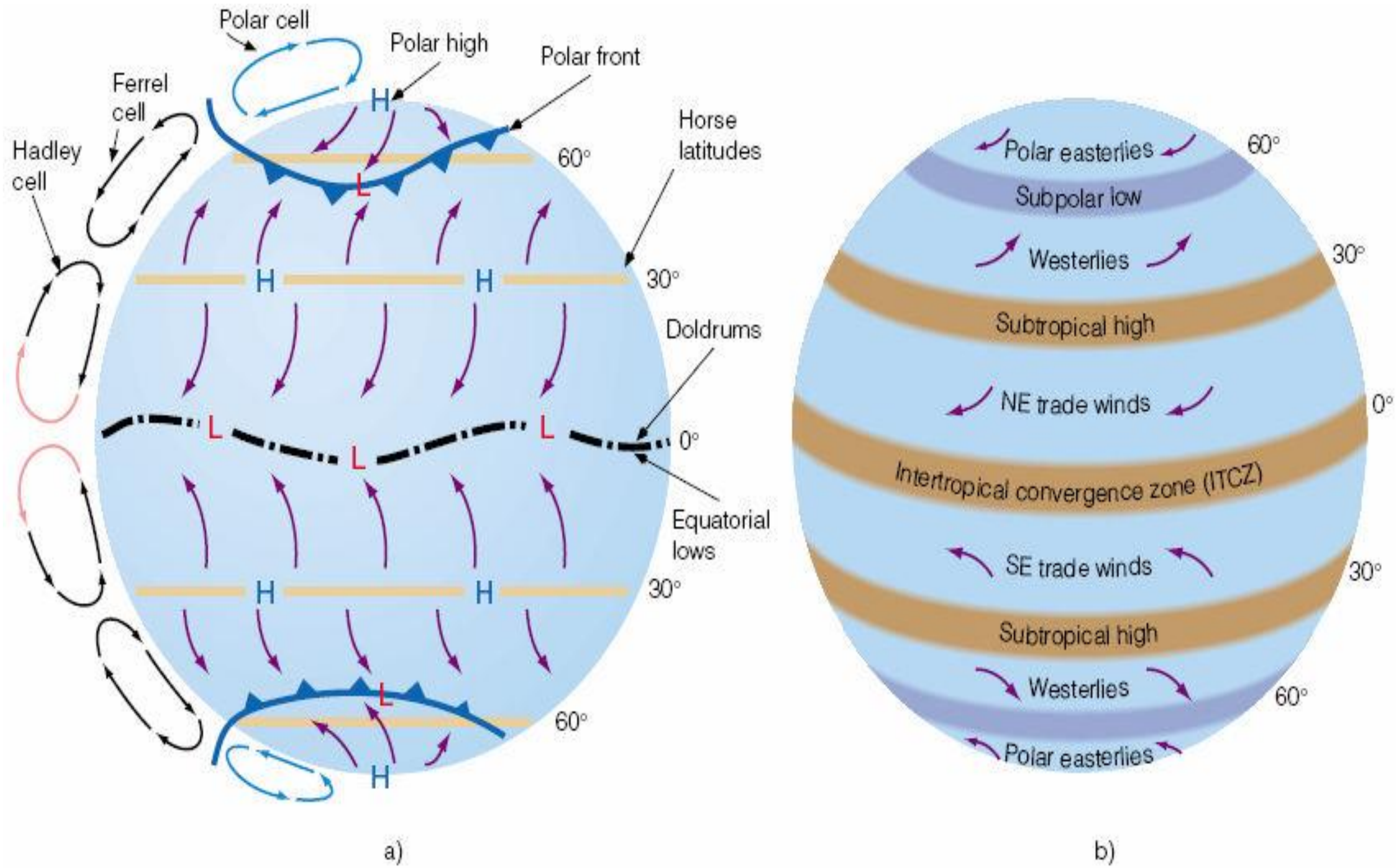
Cont..

- Tropical circulations are examined in a theoretical framework as responses to heating at the equator.
- Special emphasis is given to the Hadley circulation including its maintenance, seasonal migration, northern and southern hemispheric differences, and the contrast between tropical and midlatitude wind systems.

General circulation of atmosphere

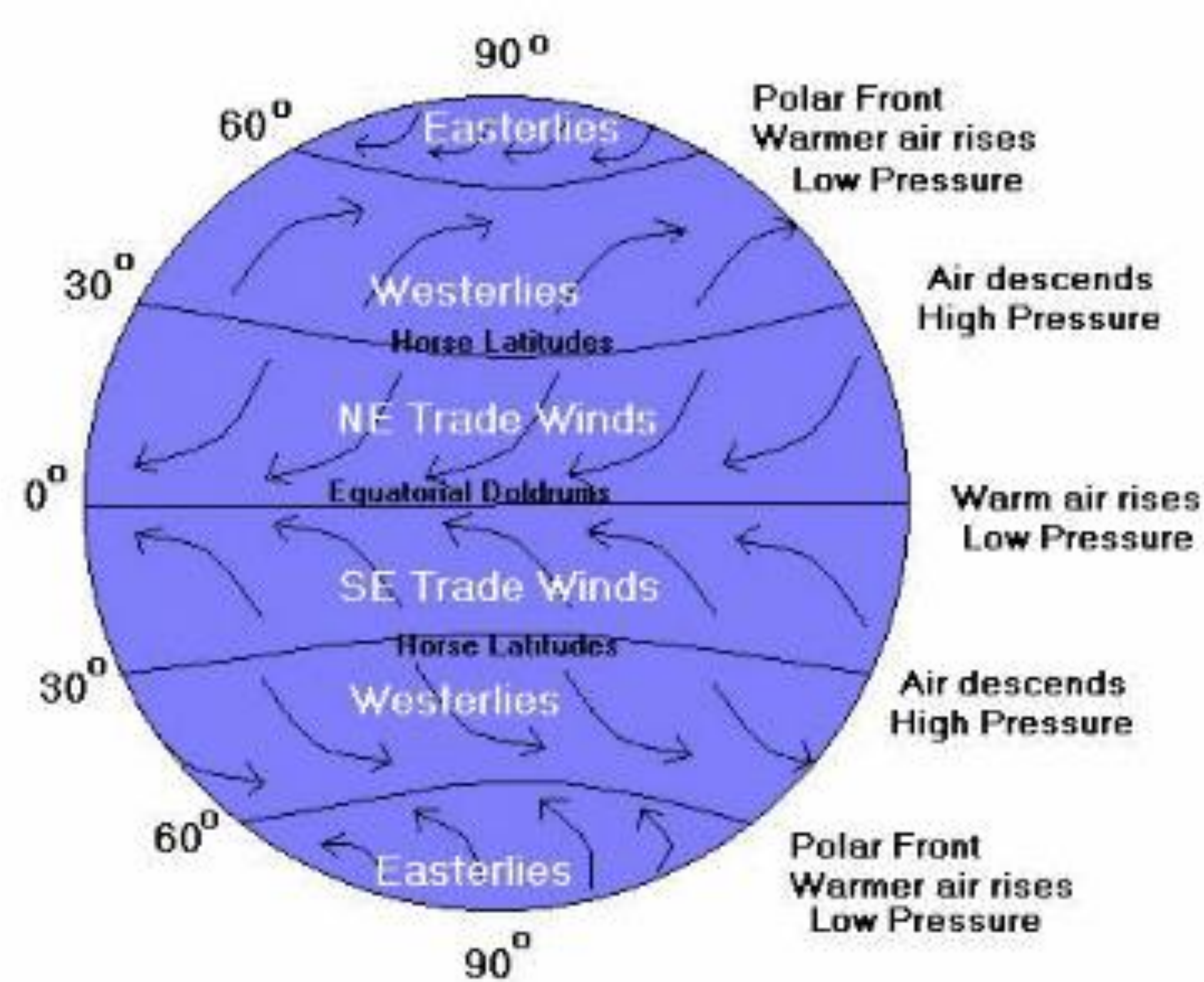
- Single cell model
- Three cell model
  - Hadley cell
  - Ferrell cell
  - Polar cell

Cont…



Polar cell
Polar high
Polar front
Ferrel cell
Hadley cell
Horse latitudes
60°
30°
Doldrums
0°
Equatorial lows
30°
60°
H
L
a)
Polar easterlies
Subpolar low
Westerlies
Subtropical high
NE trade winds
Intertropical convergence zone (ITCZ)
SE trade winds
Subtropical high
Westerlies
Polar easterlies
60°
30°
0°
30°
60°
b)

Trade winds



90°
60°
Easterlies
Polar Front
Warmer air rises
Low Pressure
30°
Westerlies
Air descends
High Pressure
Horse Latitudes
NE Trade Winds
0°
Equatorial Doldrums
Warm air rises
Low Pressure
SE Trade Winds
Horse Latitudes
30°
Westerlies
Air descends
High Pressure
60°
Easterlies
Polar Front
Warmer air rises
Low Pressure
90°

Hadley Cells

- The circulation cell closest to the equator is called the Hadley cell.
- The largest cells extend from the equator to between 30 and 40 degrees north and south, and are named Hadley cells, after English meteorologist George Hadley.
- Winds are light at the equator because of the weak horizontal pressure gradients located there.
- The warm surface conditions result in locally low pressure.
- The warm air rises at the equator producing clouds and causing instability in the atmosphere.

Cont.

- This instability causes thunderstorms to develop and release large amounts of latent heat.
- Latent heat is just energy released by the storms due to changes from water vapor to liquid water droplets as the vapor condenses in the clouds, causing the surrounding air to become more warm and moist, which essentially provides the energy to drive the Hadley cell.
- The Hadley Cell encompasses latitudes from the equator to about 30°.
- At this latitude surface high pressure causes the air near the ground to diverge.

Cont..

- This forces air to come down from aloft to "fill in" for the air that is diverging away from the surface high pressure.
- The air flowing northward from the equator high up in the atmosphere is warm and moist compared to the air nearer the poles.
- This causes a strong temperature gradient between the two different air masses and a jet stream results.

Cont..

- At the 30° latitudes, this jet is known as the subtropical jet stream which flows from west to east in both the Northern and Southern Hemispheres.
- Clear skies generally prevail throughout the surface high pressure, which is where many of the deserts are located in the world.

Cont..

- From the tops of these storms, the air flows towards higher latitudes, where it sinks to produce high-pressure regions over the subtropical oceans and the world's hot deserts, such as the Sahara dessert in North Africa.
- Within the Hadley cells, the trade winds blow towards the equator, then ascend near the equator as a broken line of thunderstorms, which forms the Inter-Tropical-Convergence Zone (ITCZ).

Ferrel Cells

- In the middle cells, which are known as the Ferrel cells, air converges at low altitudes to ascend along the boundaries between cool polar air and the warm subtropical air that generally occurs between 60 and 70 degrees north and south.
- This often occurs around the latitude of the UK which gives us an unsettled weather.
- From 30° latitude to 60° latitude, the Ferrel Cell takes control.

Cont..

- This cell produces prevailing westerly winds at the surface within these latitudes.
- This is because some of the air sinking at 30° latitude continues travelling northward toward the poles and the Coriolis force bends it to the right in the Northern Hemisphere.

Cont..

- This air is still warm and at roughly 60° latitude approaches cold air moving down from the poles.
- With the converging air masses at the surface, the low surface pressure at 60° latitude causes air to rise and form clouds.
- Some of the rising warm air returns to 30° latitude to complete the Ferrel Cell.

Cont....

- The circulation within the Ferrel cell is complicated by a return flow of air at high altitudes towards the tropics, where it joins sinking air from the Hadley cell.
- The Ferrel cell moves in the opposite direction to the two other cells Hadley cell and Polar cell and acts rather like a gear.
- In this cell the surface wind would flow from a southerly direction in the northern hemisphere.

Cont….

- However, the spin of the Earth induces an apparent motion to the right in the northern hemisphere and left in the southern hemisphere.
- This deflection is caused by the Coriolis effect and leads to the prevailing westerly and south- westerly winds often experienced over the UK.

Polar Cells

- The smallest and weakest cells are the Polar cells, which extend from between 60 and 70 degrees north and south, to the poles.
- Air in these cells sinks over the highest latitudes and flows out towards the lower latitudes at the surface.
- The two air masses at 60° latitude do not mix well and form the polar front which separates the warm air from the cold air.
- Thus the polar front is the boundary between warm tropical air masses and the colder polar air moving from the north.

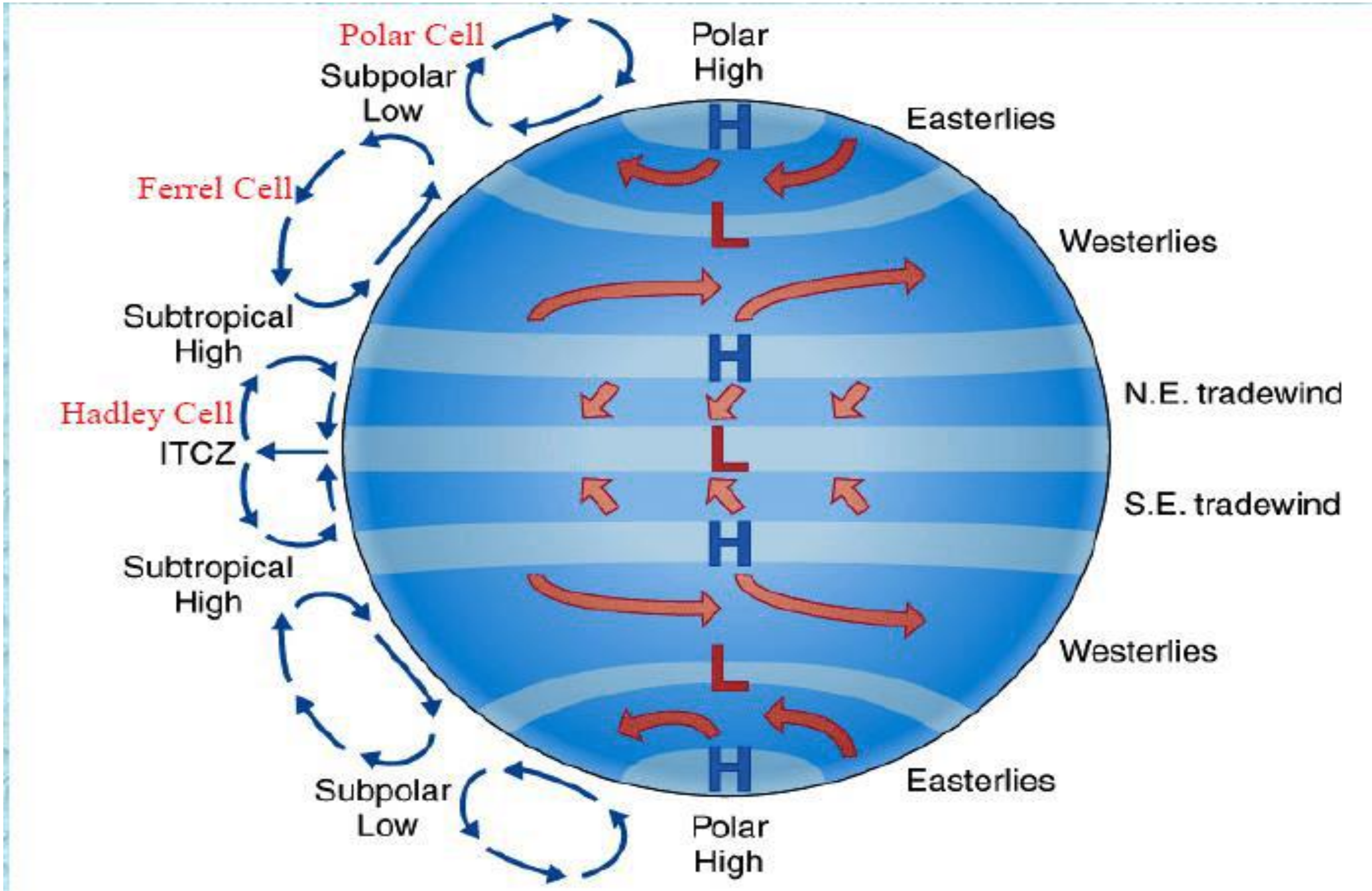
Cont..

- The polar jet stream aloft is located above the polar front and flows generally from west to east.
- The polar jet is strongest in the winter because of the greater temperature contrasts than during the summer.
- Waves along this front can pull the boundary north or south, resulting in local warm and cold fronts which affect the weather at particular locations.

Cont….

- Above 60° latitude, the polar cell circulates cold, polar air equatorward.
- The air from the poles rises at 60° latitude where the polar cell and Ferrel cell meet, and some of this air returns to the poles completing the polar cell.
- Because the wind flows from high to low pressure and taking into account the effects of the Coriolis force, the winds above 60° latitude are prevailing easterlies.

Cont..


Polar Cell
Polar High
Subpolar Low
Easterlies
Ferrel Cell
Westerlies
Subtropical High
Hadley Cell
N.E. tradewind
ITCZ
S.E. tradewind
Subtropical High
Westerlies
Subpolar Low
Easterlies
Polar High
H
L
H
L
H
L
H

General Principles of Atmospheric Motion

- Motion in the atmosphere and the ocean can be considered in terms of Newtonian principles,
- i.e., force = mass × acceleration.
- Meteorologists are interested in the acceleration of a parcel of air or rate of change of velocity per unit mass = force.
- This formulation, in terms of time rate of change, produces the Navier-Stokes equations or equations of motion, which apply to both air and water.

Cont..

- The pressure gradient force moves fluid from high to low pressure.
- When rotation, friction, and gravity are added, the acceleration of motion following a fluid on a rotating planet can be written as:
- Acceleration = pressure gradient + Coriolis + effective gravity + frictional forces.

Cont..

- $$\frac{D\vec{U}}{Dt} = -\frac{1}{\rho}\nabla \mathrm{p} - f\vec{\mathbf{k}} \times \vec{U} - \mathrm{g}\vec{\mathbf{k}} + \mathbf{Fr}$$
- where vector U (u,v, w) is the velocity vector (ms-1); p is pressure (Pa); ρ is density (kg m-3); f is the Coriolis parameter,
- defined as f = 2ΩsinΦ = the vertical component of Ω, the Earth's rotation rate (rad S-1), and with Φ as the latitude;
- and g is effective gravity (m s-2), a combination of the Earth's gravitational and the centrifugal forces.

Cont..

- The acceleration due to the Coriolis Effect, f k x vector U, is at right angles to the velocity (to the right in the Northern Hemisphere and left in the Southern Hemisphere) and frictional forces, Fr, oppose the motion.

- D/Dt is the sum of the local rate of change plus advection terms,

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \vec{U}.\nabla = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$$

Cont..

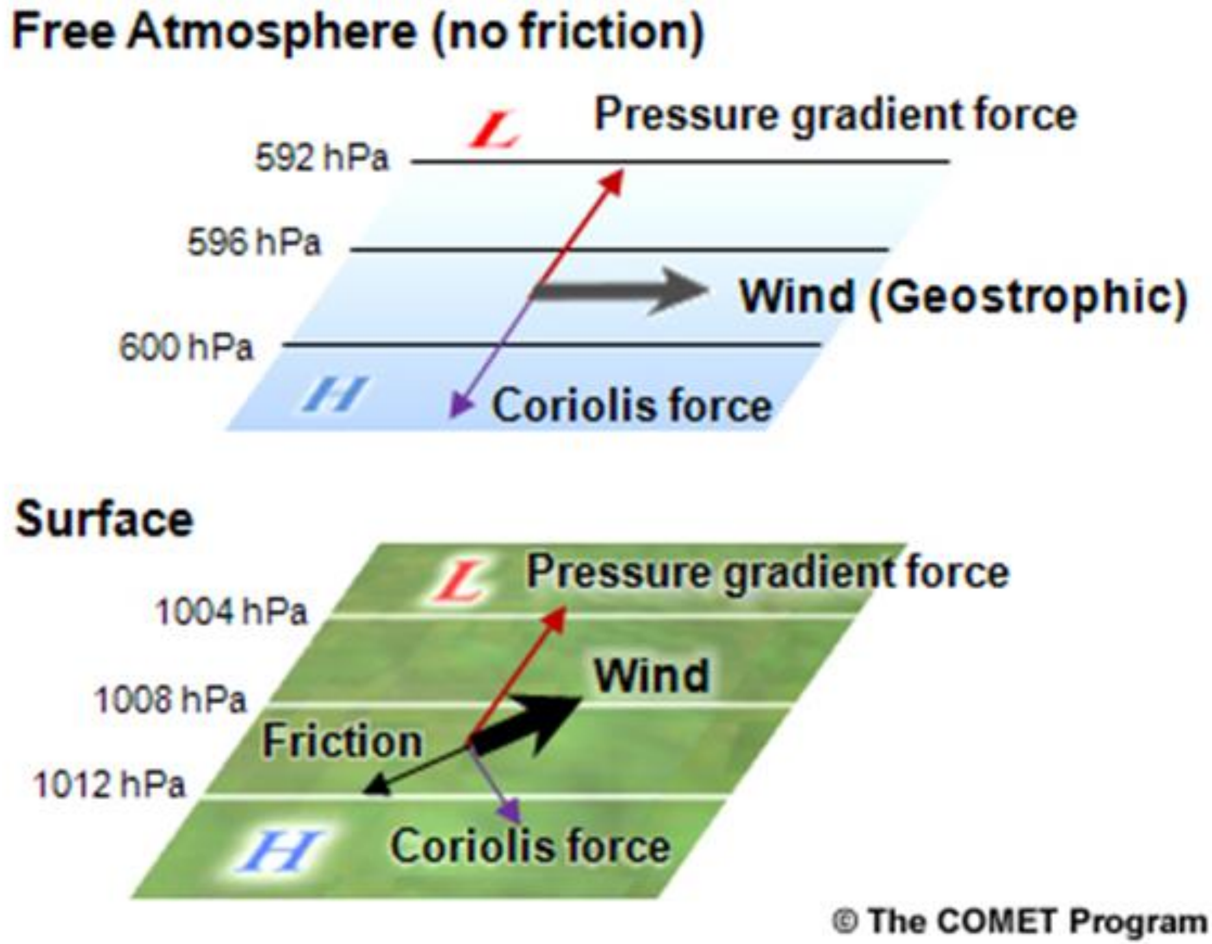


Fig.3.1. Schematic of horizontal forces acting on air parcels near the surface and above the friction layer.

Cont..

- Above the friction layer, balance is between the pressure gradient and the Coriolis force (Fig. 3.1, upper).
- The actual wind here can be well approximated by the geostrophic wind, $V_g = \vec{k} \times \frac{1}{\rho f} \nabla p$
- the wind calculated from this force balance.

Cont..

- The wind in geostrophic balance blows parallel to the isobars, which means that these winds are parallel to the other mass fields (density, temperature).
- This geostrophic approximation holds for large-scale motion away from the equator.
- Moving downwards to the surface, frictional forces increase and the surface winds are no longer parallel to the pressure field but angled toward lower pressure (Fig. 3.1, lower).

Cont..

- Flow that is parallel to the isobars around high and low pressure areas results from balance between pressure gradient, Coriolis, and centripetal (negative centrifugal) forces.

- In these regions near circulation centers the geostrophic wind is not a good enough balance to the observed wind because of the curved flow.

Cont..

- The wind calculated from this three force balance is referred to as the gradient wind.
- While gradient balance exists only near circulation centers, a gradient wind can be defined for the level at which friction is considered negligible; about 2000 ft above the surface.

Cont..

- Vertical motion is expressed as acceleration = pressure gradient + gravity.
- Where w is the vertical velocity and g is the acceleration due to gravity (a positive constant, 9.8 m s-2).
- Since pressure decreases with height, the first term on the right is positive and -g is negative, so the resulting vertical acceleration is determined by their relative magnitudes.

Cont..

- The flow of air follows the basic principles described previously.
- At the large scale (1000–10,000 km), air flows around low and high pressure areas, creating wave-like patterns.
- Troughs and ridges in the pressure field are analogous to valleys and mountains in terrain.

Cont..

- Air converges into low pressure areas and diverges away from high pressure areas with corresponding vertical motion for mass continuity.
- Figure 3.3 and the animation linked below illustrate air in motion for low and high pressure areas in the Northern Hemisphere.
- The direction is opposite in the Southern Hemisphere where the Coriolis force deflection is to the left.

Cont..

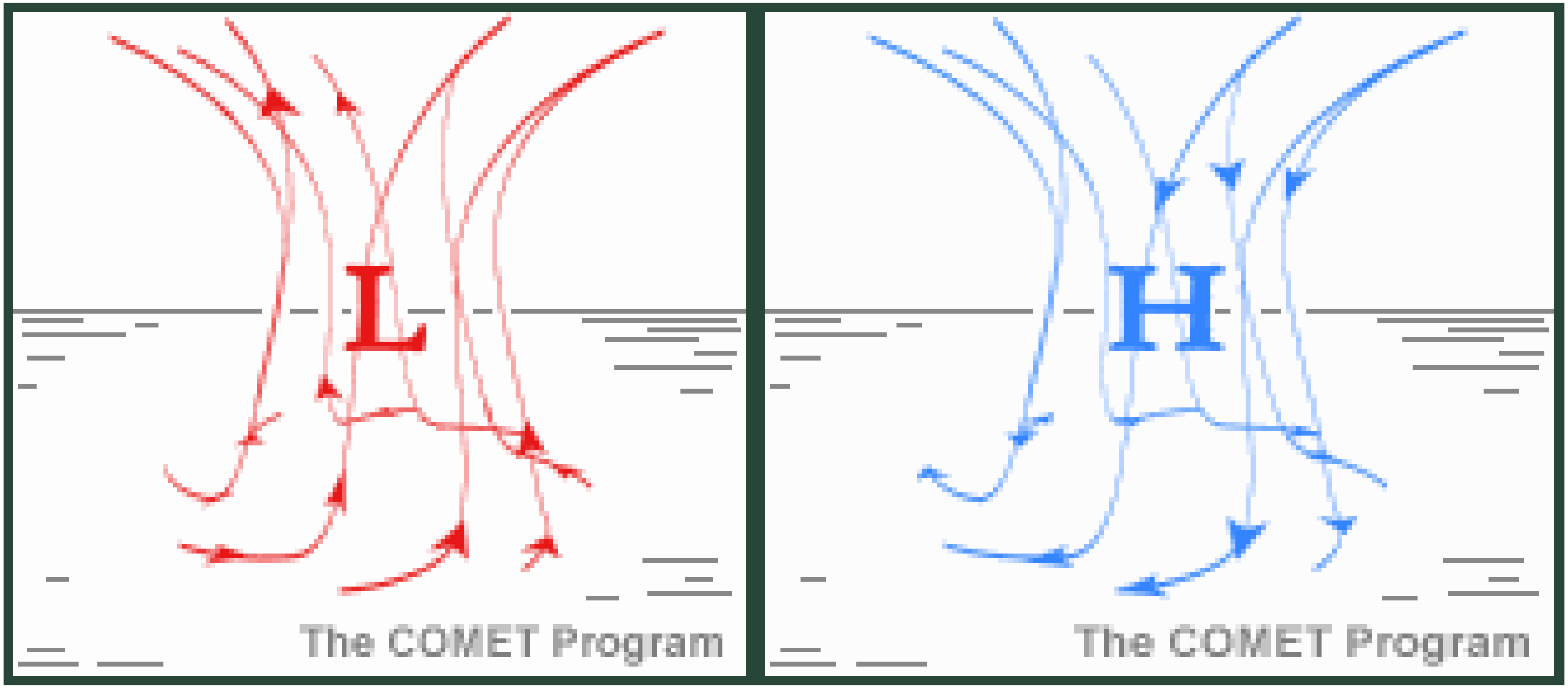


Fig 3.2 Schematic of 3-D flow in low and high pressure systems in the Northern Hemisphere.

Cont..

- Vertical motion leads to adiabatic temperature change, thus the location of high and low pressures give us information about expected cloudiness and precipitation.
- Rising motion in low pressure leads to expansion, adiabatic cooling, and condensation while sinking in high pressures leads to adiabatic compression, warming, and dry conditions.

General Circulation of the Atmosphere

- The general circulation of the atmosphere refers to the mean global flow over a long enough period to remove variations caused by weather systems but short enough to capture seasonal and monthly variability.
- The major influences on the general circulation of the atmosphere are:
  - Differential heating
  - Rotation of the planet
  - Topography
  - Atmospheric and oceanic fluid dynamics

Tropical Circulation and Precipitation Distribution

- The large-scale circulation features in the tropics affects the distribution of precipitation over tropical ocean basins and nearby continental regions.
- In general, the subtropical eastern ocean and nearby continent are dry.

Cont..

- Moving westward, the subtropical ridge and trade wind inversion weaken, clouds grow taller, and precipitation intensity and amount increase as depicted schematically in Fig. 3.62.
- The major exception to this rule is the Indian Ocean where monsoon westerlies dominate.

Cont..

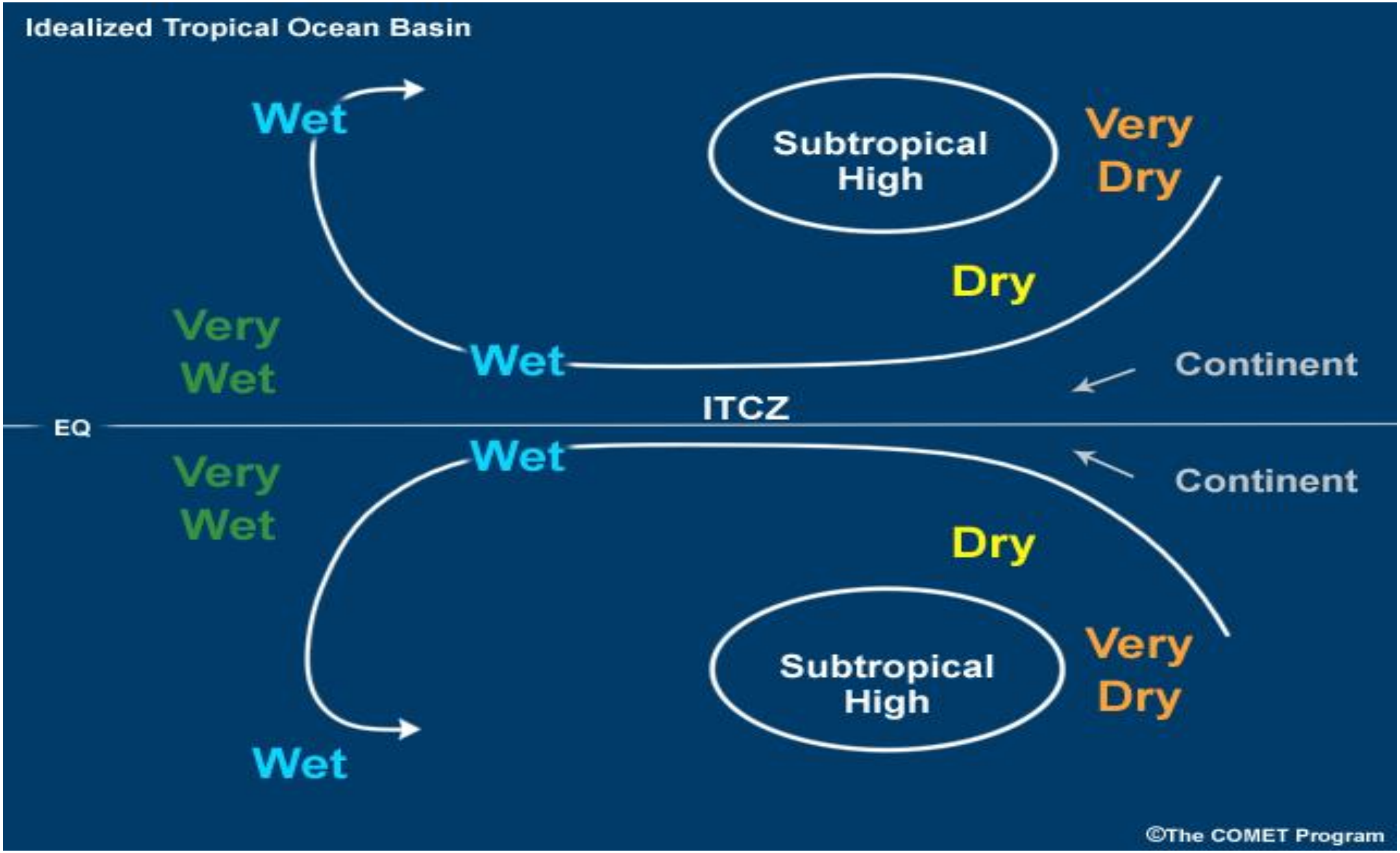


Fig. 3.62. Idealized distribution of precipitation influenced by the subtropical highs, ITCZ and trade wind inversion.

Cont..

- The wettest regions are found over the western tropical ocean basin, the result of pooling of warm surface waters driven by the trade winds.
- The warmest ocean is the tropical western Pacific, a region known as the Tropical Warm Pool.
- Heavy precipitation over nearby land results from evaporation from the warm ocean and water vapor being advected downstream.

Cont..

- Moderately wet regions are found to the north and east of the very wet areas.
- Figure 3.63 confirms the conceptual pattern of precipitation and prevailing flow for the tropical Atlantic and Pacific during July and as well as the southeast Indian Ocean during January.

Cont..

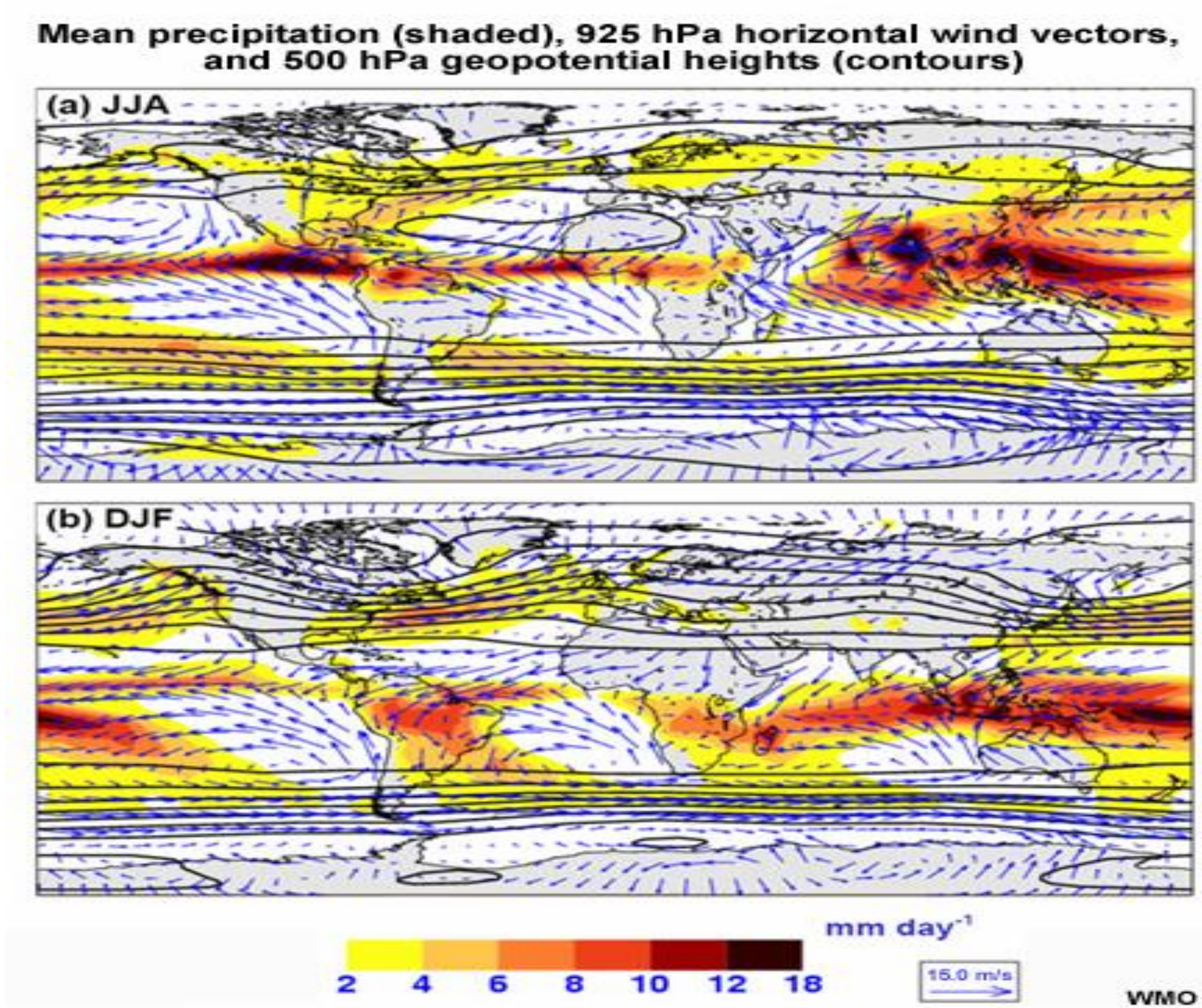


Fig. 3.63. Seasonal mean precipitation (shaded, 925 hPa horizontal wind vectors, and 500 hPa geopotential heights

The Role of the Tropics in the General Circulation

- The role of the tropics in the general circulation can be summarized by Fig. 3.64.
- The tropics serve as a source of surplus heating that drives the global circulation.
- The transport of heat and momentum by the Hadley Cells is vital to the maintenance of the global heat balance and angular momentum balance.

Cont..

- Recent studies have found that the strength of the Hadley and Walker circulations can fluctuate and they actually strengthened during the 1990s.
- Scientists related changes in cloud cover and radiation in the regions of subsidence (sinking) and convection (rising) in the circulation cells to changes in the vertical velocity of air.

Cont..

- This acceleration of the Hadley and Walker circulations was associated with more thermal, long-wave radiation escaping the tropical atmosphere and a decrease in the reflected sunlight (by about 4 watts per square meter).

Cont..

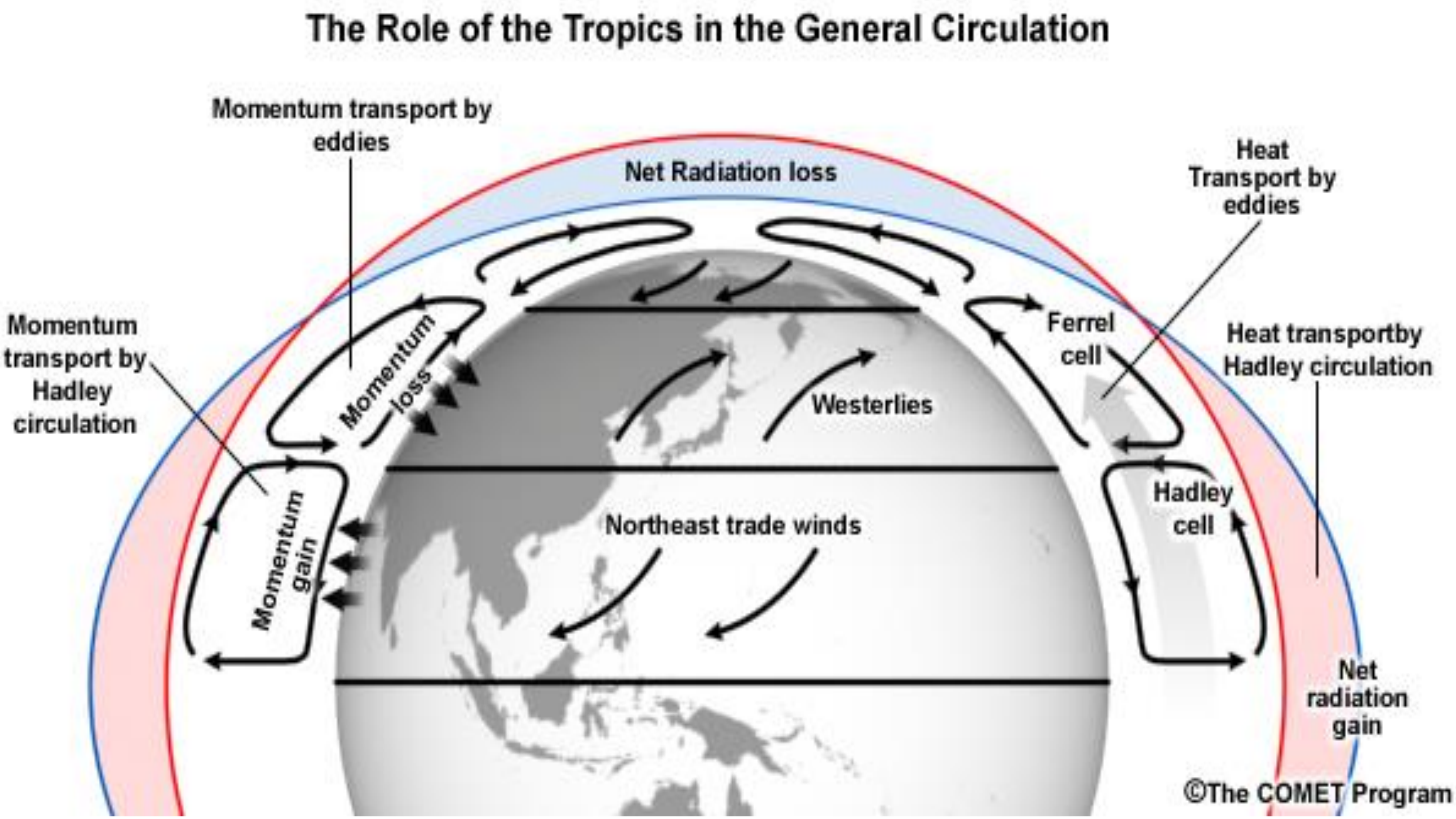


Fig. 3.64. Schematic of the role of the tropics in the transport of heat and momentum in the general circulation.

Chapter Three

Tropical Variability

Outline

- **Intra-seasonal variability**
  - **The madden-Julian oscillation (MJO)**
  - **Tropical waves**
- **Inter-annual variability**
  - **Indian ocean Dipole (IOD)**
  - **El Nino southern oscillation (ENSO)**
  - **Quasi-Biennal oscillation (QBO)**

Introduction

- How can you tell the difference between the tropics and the midlatitude?
- For example, the midlatitude atmosphere is often unstable because of air masses with contrasting temperature and density
- In the areas where air masses interact, energy is concentrated into extratropical cyclones.

Cont..

- In comparison, the tropical atmosphere is relatively homogeneous, so that, except for tropical cyclones, local and mesoscale effects are more dominant than synoptic influences.
- Many scales of motion interact to transport energy, moisture, and momentum within the tropics and between the tropics and the midlatitude.

Cont....

- Here, we explore sources of variability in the tropics on timescales ranging from **intraseasonal,** to a **few years**, and **decades**.
- First, we examine major sources of tropical variability on timescales less than a season, the **Madden Julian Oscillation (MJO) and tropical waves**
- then increasing in timescale to the **El Niño-Southern Oscillation (ENSO)** and the **Quasi-Biennial Oscillation (QBO)** of the stratospheric winds,

Cont..

- For the most part, atmospheric transport of heat and moisture across latitudes is accomplished through meridional transport in the Hadley cells;
- warm air **rises** in thunderstorm systems in the **tropics**, cools, and **sinks** in the **subtropics**
- Regions of heating and strong convection are observed over the tropical continents and warm ocean basins. Zonal circulations also arise from this convection.

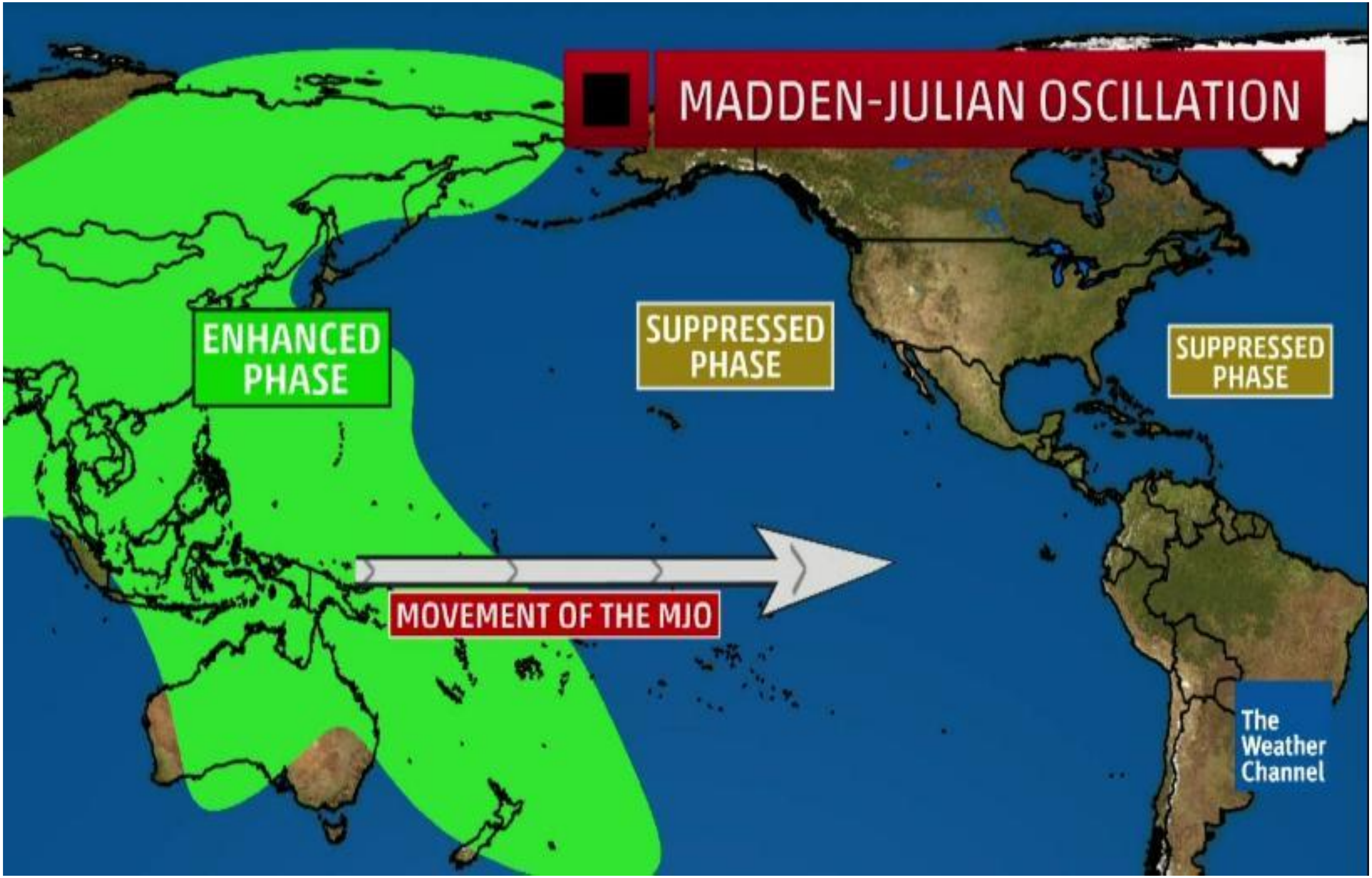
The Madden-Julian Oscillation

- The Madden-Julian Oscillation (MJO) was a first identified in 1971 and documented shortly thereafter.
- The MJO has been demonstrated to influence tropical weather from small-scale tropical convection through to planetary-scale circulations.
- In this section we will describe the basic **structure** and **time scale of the MJO**, examine the mechanisms that form the MJO and seek to understand the role of the MJO in **atmospheric and oceanic variability.**

Cont..

- Subsequent research has tied these variations to alternation of broad active and inactive tropical rainfall in both the **Northern and Southern hemispheres**: a broad area of active cloud and rainfall propagates **eastwards** around the equator at intervals of between about **30 to 60 days.**
- Rainfall in the near-equatorial regions of the Indian and Pacific Oceans also show a strong association with the disturbance.

Cont..



MADDEN-JULIAN OSCILLATION
ENHANCED PHASE
SUPPRESSED PHASE
SUPPRESSED PHASE
MOVEMENT OF THE MJO
The Weather Channel

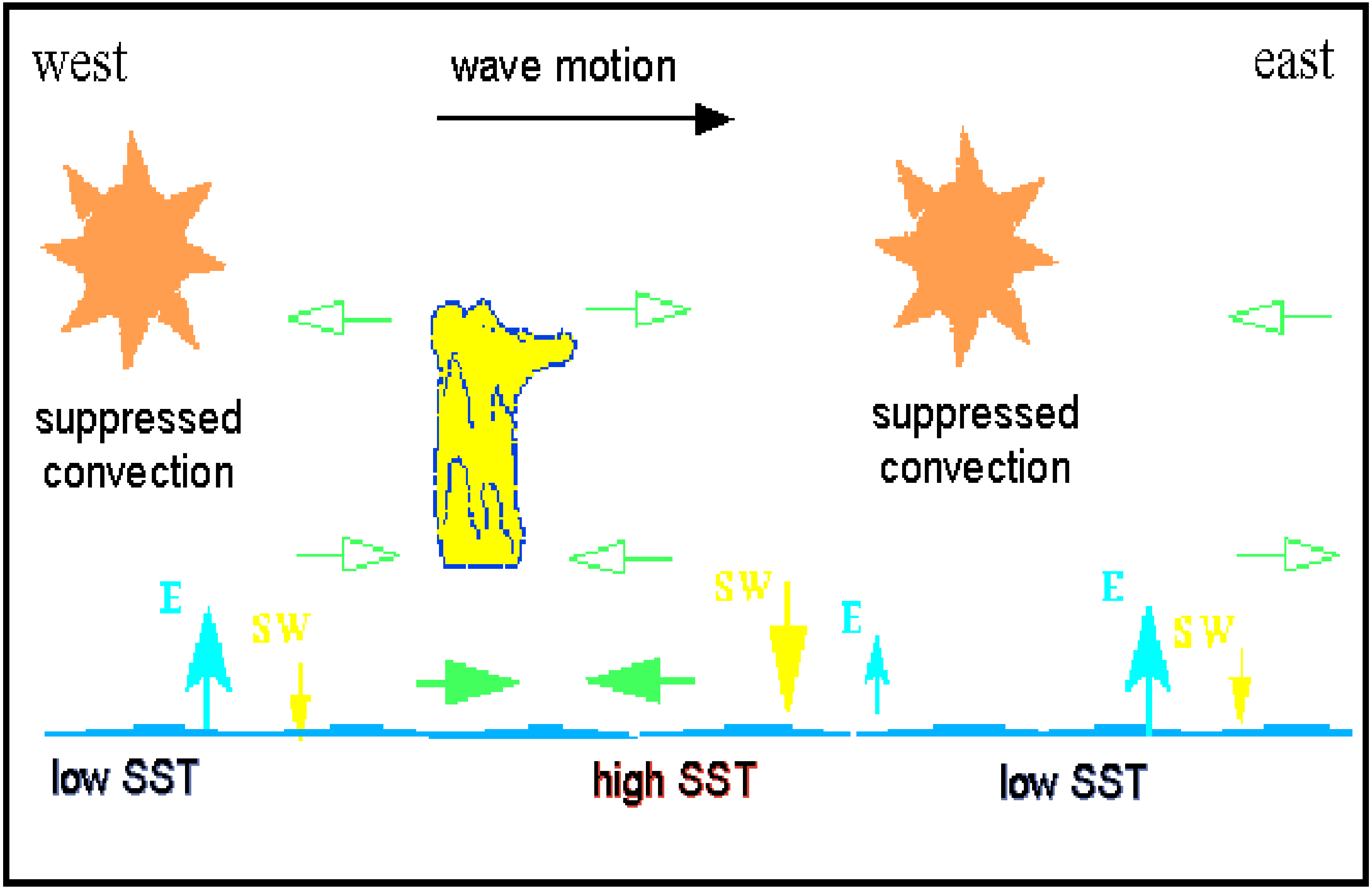
Cont….

- The MJO is a coupled **ocean-atmosphere** system.
- The atmospheric component is characterized as an oscillation propagating eastwards from the **Maritime Continent** around the equator at about **5 m/s**;
- This gives the atmospheric MJO a period of roughly 30-60 days.
- The **spatial scale** of the atmospheric MJO can be described in terms of a local wavelength of roughly **12,000-20,000 km**.

Cont..

- The MJO is generally best developed in the region from the southern Indian Ocean eastward across Australia to the western Pacific Ocean in austral summer.
- The oceanic component of the MJO has an oscillation with a somewhat longer period of **60-75** days.
- The oceanic signature of the MJO is evident in the sea surface temperature (SST), mixed layer depth, surface latent heat flux and surface wind stress fields.

Cont….



west
wave motion
east
suppressed convection
suppressed convection
E
SW
SW
E
E
SW
low SST
high SST
low SST

Tropical waves

- Perturbations/disturbances in the tropical easterlies that typically move from east to west.
- Often seen as inverted troughs of low pressure (inverted-V pattern in satellite imagery).
- Significant rain producers.
- Convection typically on the east side.
- Subsidence/clearing on the west side.
- Develop into tropical cyclones.
- Around 60 tracked per year (little annual variability)

Cont….

- Tropical waves/African easterly waves move westward with in the
- trade wind flow south of the Bermuda-Azores high
- wavelength of about 2000 km
- period of 3 to 4 days.
- Typically move westward at 10 to 15 kt
- Maximum amplitude is around 700 mb

How/where they form

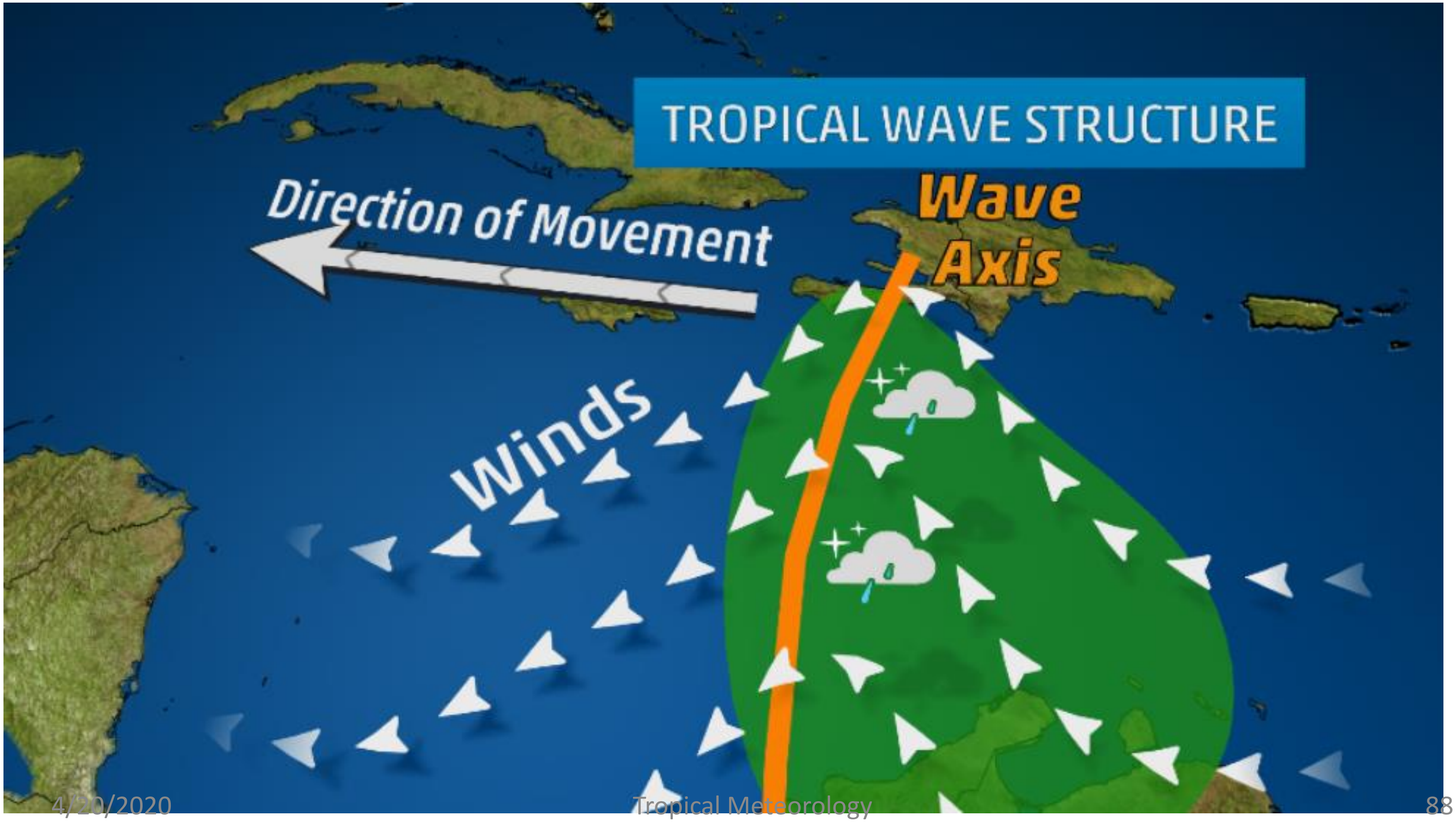
- Generated by an instability (Baroclinic-barotropic)of the **African easterly jet**.
- Jet arises as a result of reversed lower tropospheric temperature gradient over west-central north Africa due to extremely warm temperatures over the Sahara Desert and substantially cooler temperatures along the coast of Guinea.

Cont..

African Easterly Jet
H
tropical storm
tropical disturbance
L
Atlantic
Ocean

Cont..

- Approximately 60 % of Atlantic tropical cyclones and 85 % of major hurricanes originate from tropical waves

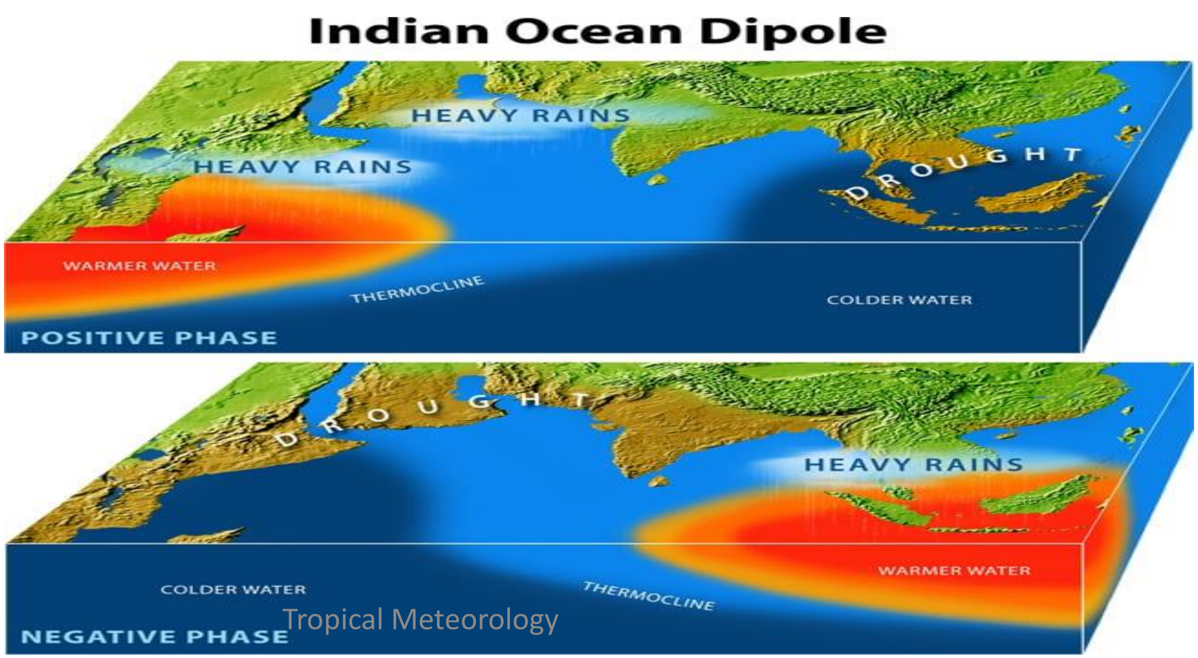


Cont..

Inter-annual variability

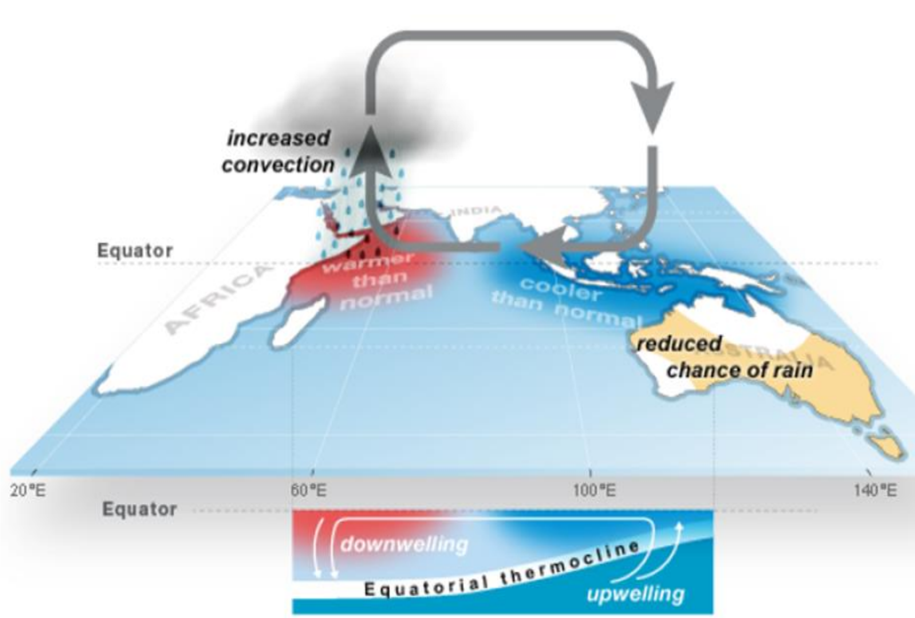
Indian ocean Dipole

- The Indian Ocean Dipole (IOD), also known as the Indian Niño, is an irregular oscillation of sea-surface temperatures in which the western Indian Ocean becomes alternately warmer and then colder than the eastern part of the ocean

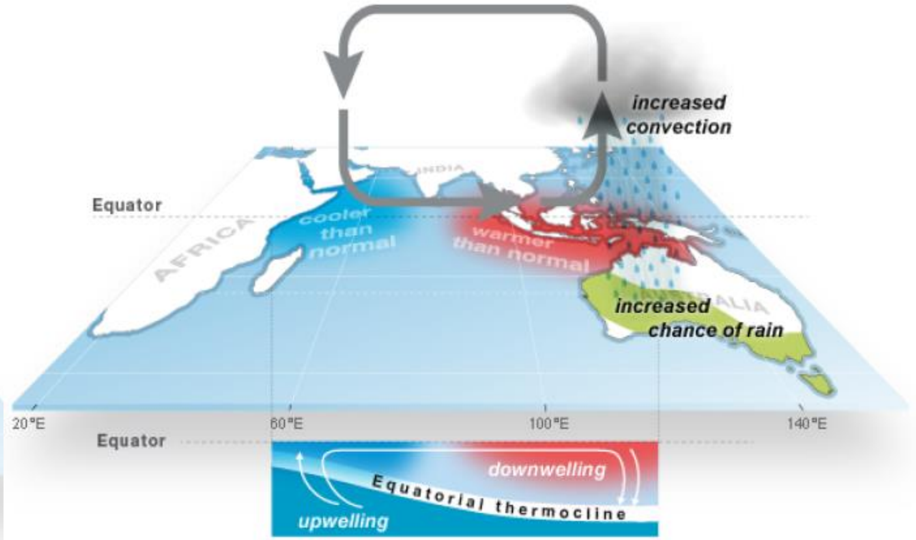


IOD

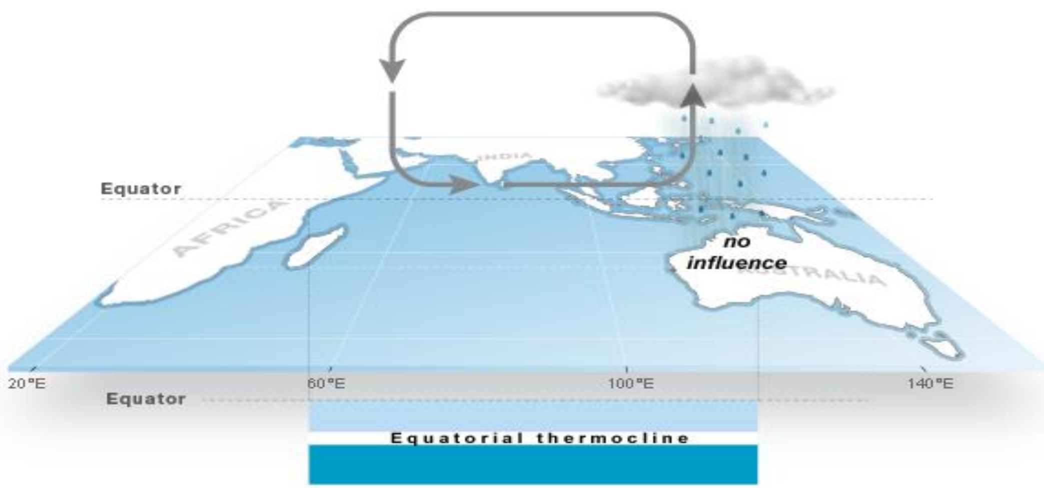
- The Indian Ocean Dipole (IOD) is the Indian Ocean counterpart of the Pacific El Niño and La Niña.
- The term dipole means two “poles” or two areas of differences.
- The IOD measures differences in SSTs between the Arabian Sea (western pole) and the eastern Indian Ocean south of Indonesia (eastern pole).



Indian Ocean Dipole (IOD): **Positive phase**



Indian Ocean Dipole (IOD): **Negative phase**



Indian Ocean Dipole (IOD): **Neutral phase**

Cont..

- Both of these poles are situated within the equatorial belt of the Indian Ocean (i.e., between 10°N and 10°S) but they have a northwest-southeast diagonal orientation because of the physical configuration of the North Indian Ocean.
- Two types of IOD
- Positive and negative IOD

Cont….

- During a positive IOD warmer SSTs develop over western Indian Ocean (Arabian Sea, in particular).
- During a negative IOD, the opposite happens, that is, the western Indian Ocean becomes cooler with higher air pressures resulting in westerly winds blowing toward the Indian subcontinent (i.e., reversing the prevailing easterlies).
- Positive IODs are often associated with El Niño and negative IODs with La Niña.

ENSO

- El Niño–Southern Oscillation is an irregularly periodic variation in **winds** and **sea surface temperatures** over the tropical **eastern Pacific Ocean**, affecting the climate of much of the **tropics** and **Subtropics.**
- The **warming phase** of the sea temperature is known as **El Niño** and the **cooling phase as La Niña.**
- On periods ranging from about **three to seven years**, the surface waters across a large swath of the tropical Pacific Ocean warm or cool by anywhere from **1°C to 3°C**, compared to normal.

Cont..

- This oscillating warming and cooling pattern, referred to as the **ENSO cycle**, directly affects rainfall distribution in the **tropics** and can have a strong influence on weather across the United States and other parts of the world.
- El Niño and La Niña are the extreme phases of the ENSO cycle; between these two phases is a third phase called **ENSO-neutral.**

El Niño:

- A warming of the ocean surface, or above-average sea surface temperatures (SST), in the **central** and **eastern tropical Pacific Ocean.**
- Over I**ndonesia**, rainfall tends to become **reduced** while rainfall **increases** over the **central and eastern** tropical Pacific Ocean.

Cont..

- The low-level surface winds, which normally blow from east to west along the equator (“easterly winds”), instead weaken or, in some cases, start blowing the other direction (from west to east or “westerly winds”).
- In general, the warmer the ocean temperature anomalies, the stronger the **El Niño** (and vice-versa).

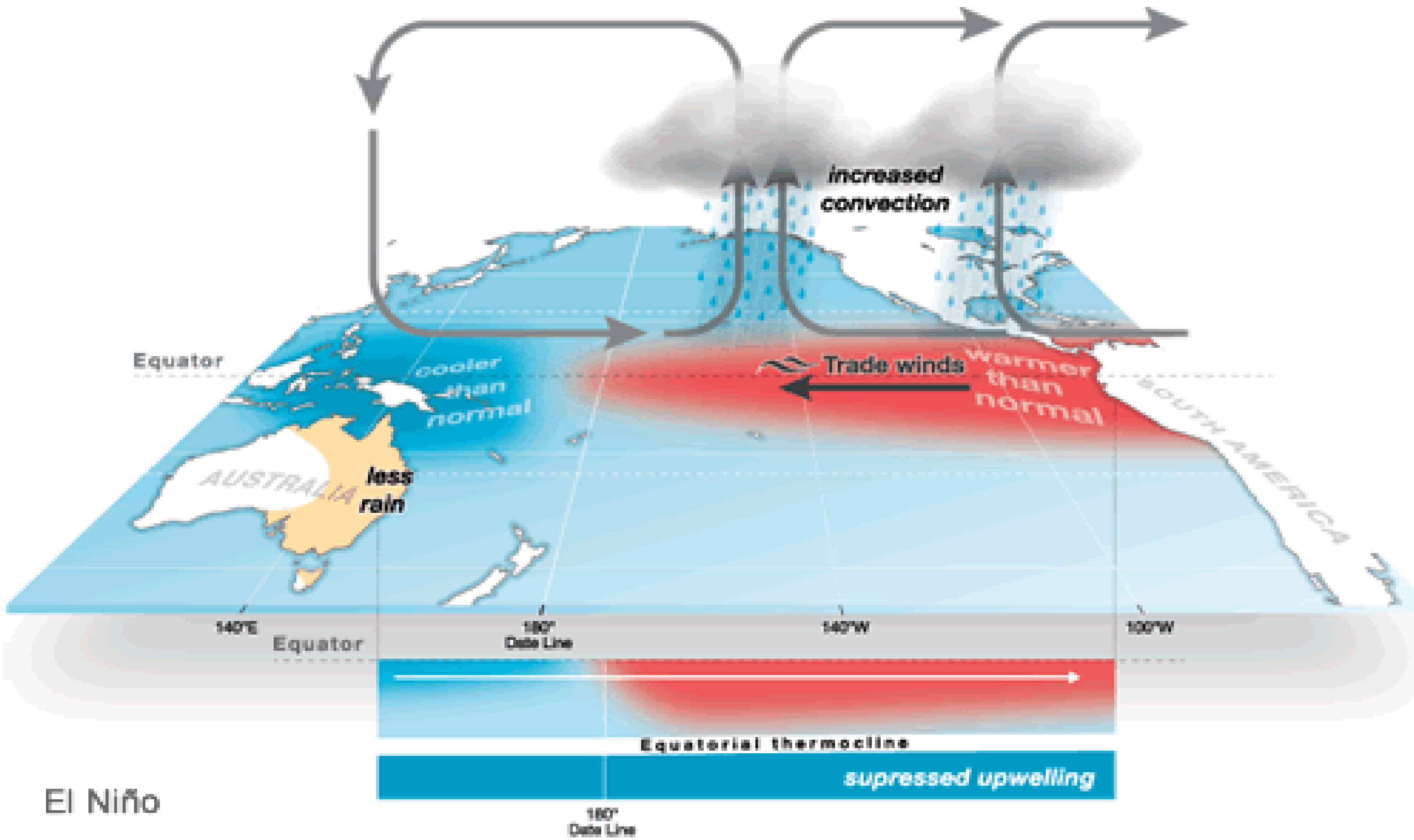
Cont..

- During an El Niño event, trade winds weaken or may even reverse, allowing the area of warmer than normal water to move into the central and eastern tropical Pacific Ocean
- These warmer than normal ocean temperatures are associated with a deepening of the thermocline in the central to eastern Pacific.
- A weaker upwelling of cooler ocean waters from below also contributes to warmer sea surface temperatures.

Cont..

- Sea surface temperatures around northern Australia are cooler than normal and the focus of convection migrates away from Australia eastward towards the central tropical Pacific Ocean.
- This results in increased rainfall for nations such as Kiribati and Peru, but less rainfall over Australia.
- The greatest impacts are usually felt over inland eastern Australia, while effects for regions such as southwest Western Australia and coastal New South Wales can vary from event to event, and in western Tasmania the effects are generally weak.

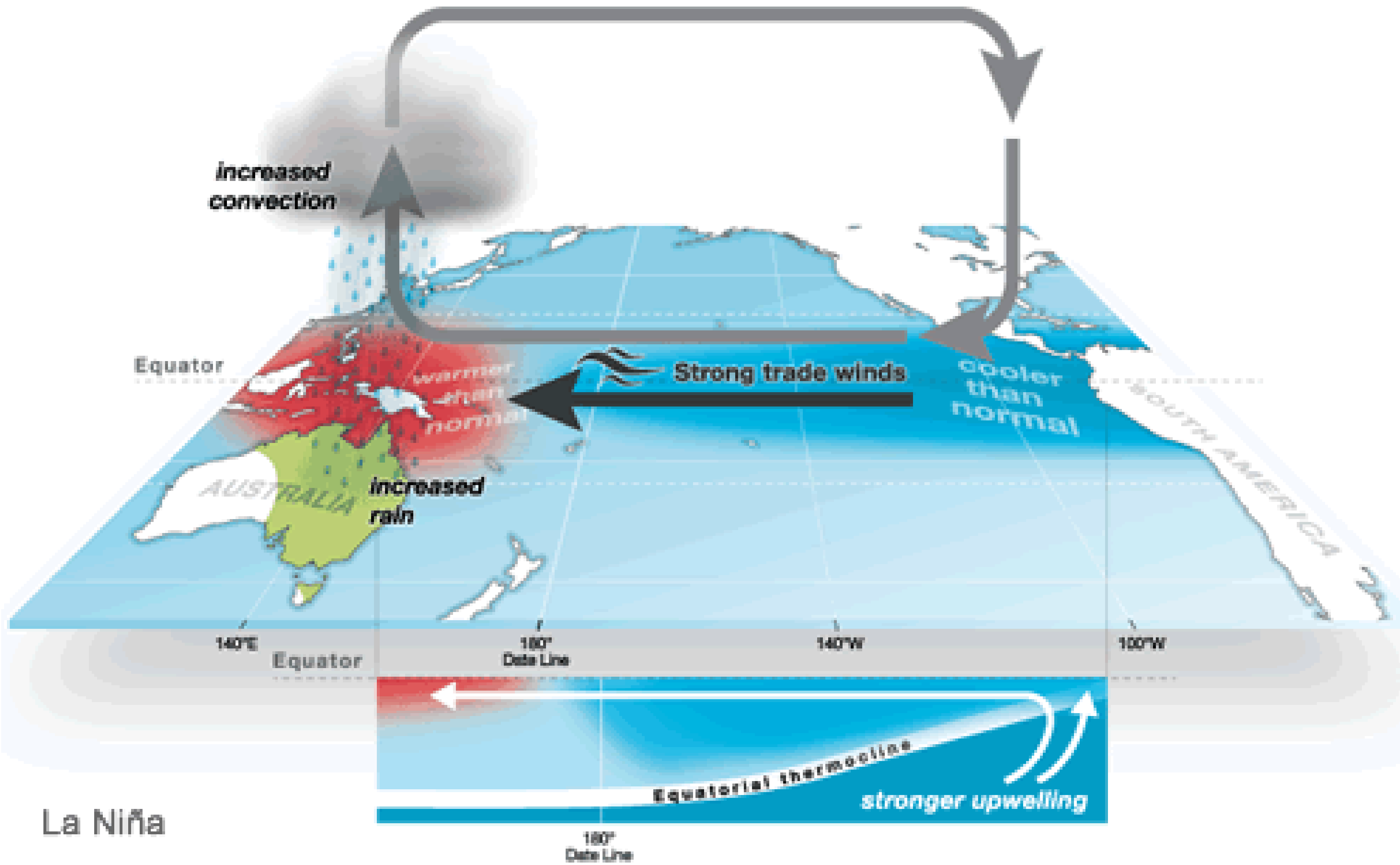
Cont..


increased convection
Equator
cooler than normal
Trade winds
warmer than normal
SOUTH AMERICA
AUSTRALIA
less rain
140°E
Equator
180° Date Line
140°W
100°W
Equatorial thermocline
supressed upwelling
El Niño
180° Date Line

La Niña:

- A cooling of the ocean surface, or below-average sea surface temperatures (SST), in the central and eastern tropical Pacific Ocean.
- Over Indonesia, rainfall tends to increase while rainfall decreases over the central and eastern tropical Pacific Ocean.
- The normal easterly winds along the equator become even stronger.
- In general, the cooler the ocean temperature anomalies, the stronger the La Niña (and vice-versa)

Cont….

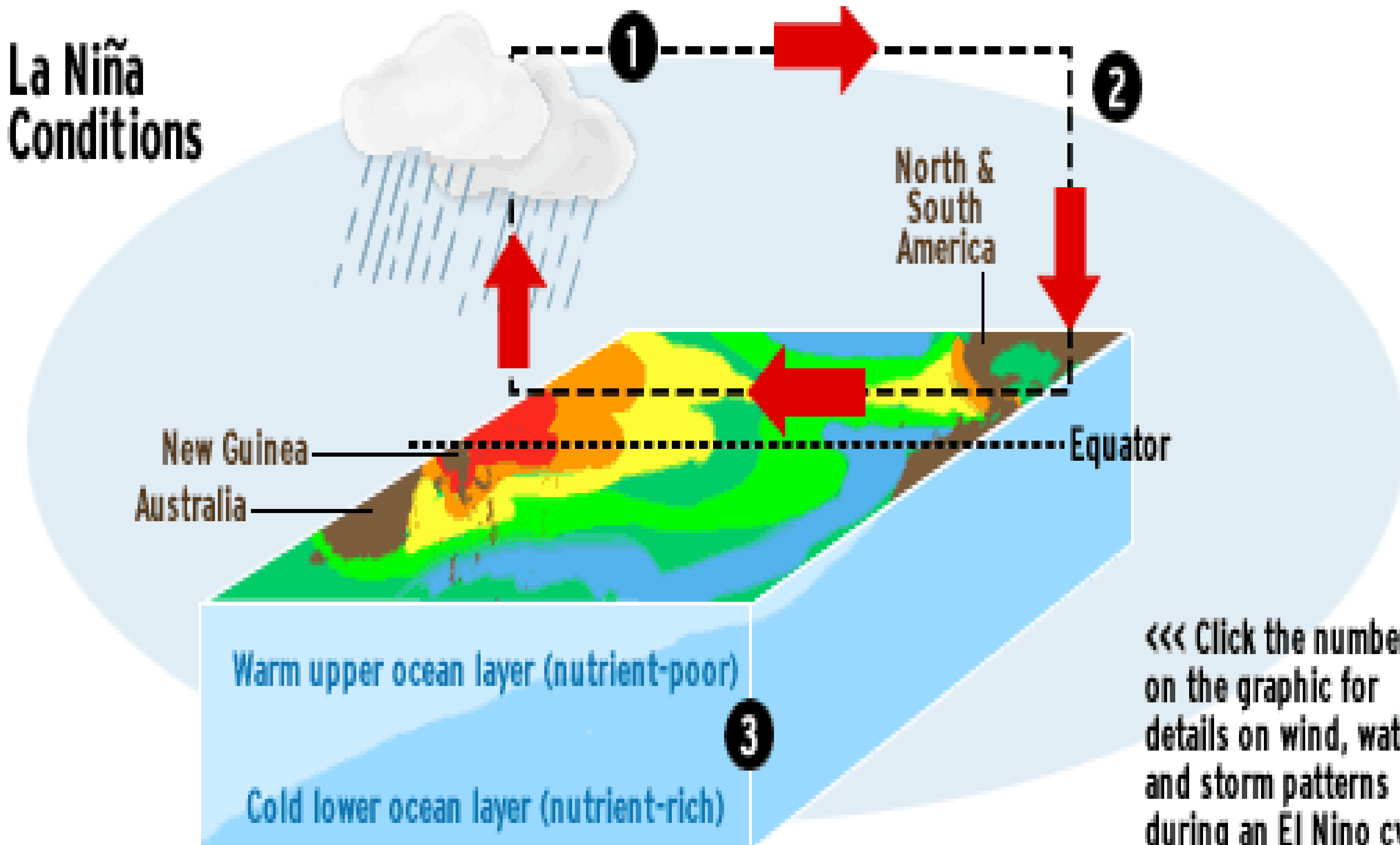


increased convection
Equator
warmer than normal
Strong trade winds
cooler than normal
SOUTH AMERICA
AUSTRALIA
increased rain
140°E
180° Date Line
140°W
100°W
Equator
Equatorial thermocline
stronger upwelling
180° Date Line
La Niña

Cont..

- La Niña events are associated with increased rainfall over much of northern and eastern Australia.
- Parts of northern and central Australia tend to feel the impacts of La Niña more than they feel the impacts of El Niño.

Cont..



<<< Click the numbers on the graphic for details on wind, water and storm patterns during an El Nino cycle.

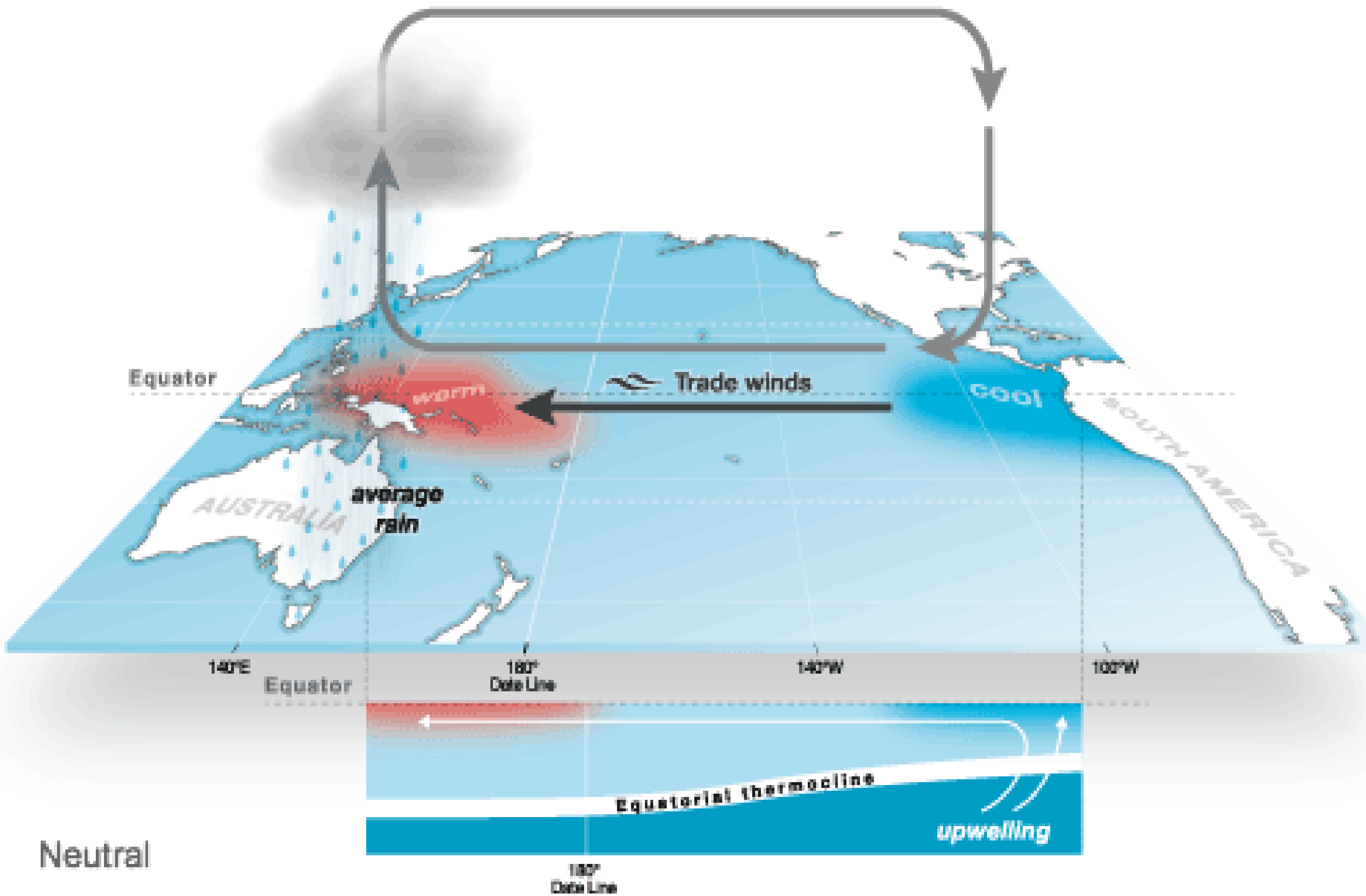
Neutral:

- In the neutral state (neither El Niño nor La Niña) trade winds blow east to west across the surface of the tropical Pacific Ocean, bringing warm moist air and warmer surface waters towards the western Pacific and keeping the central Pacific Ocean relatively cool.
- The thermocline is deeper in the west than the east

Cont..

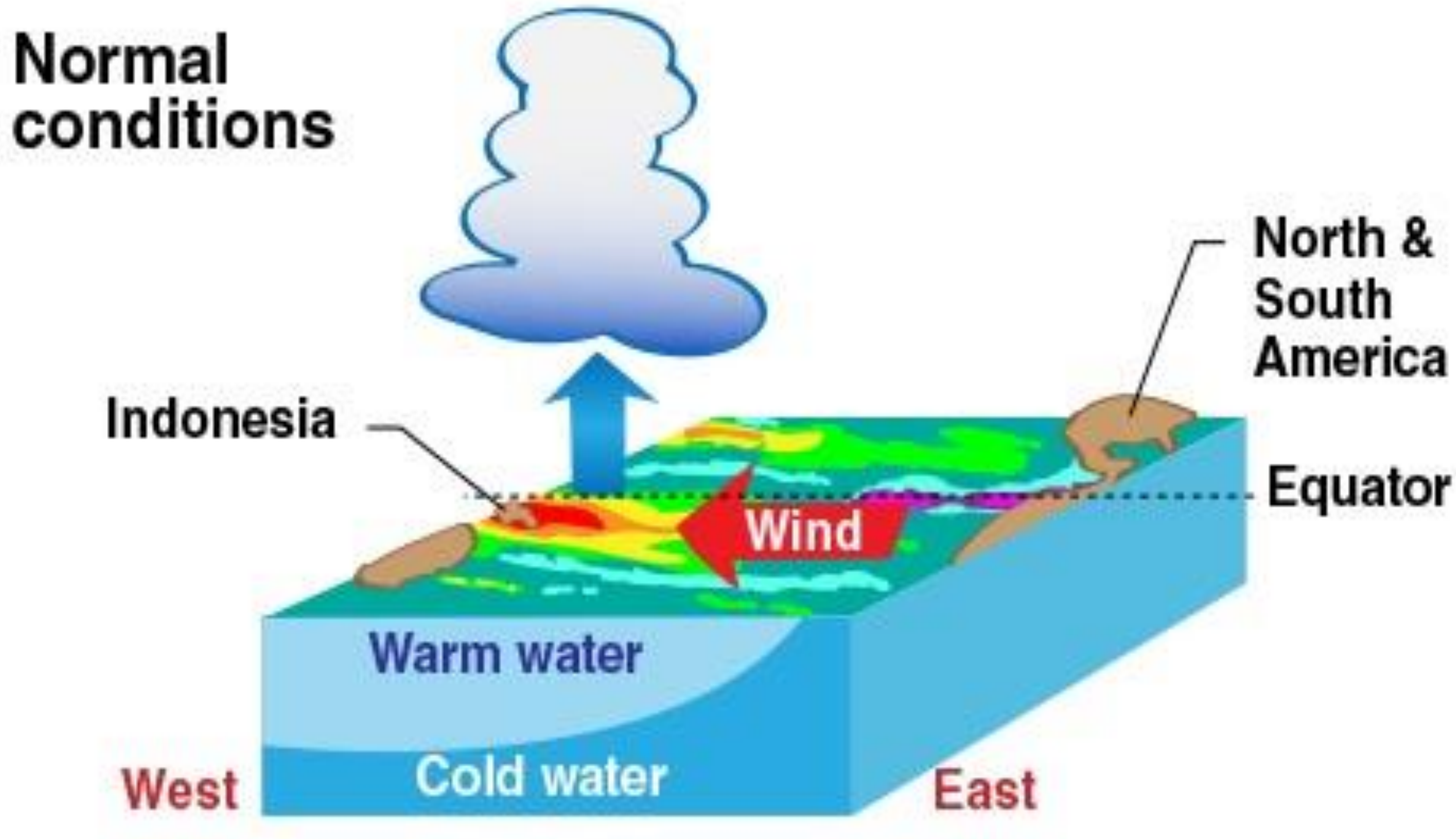
- Warm sea surface temperatures in the western Pacific pump heat and moisture into the atmosphere above.
- In a process known as atmospheric convection, this warm air rises high into the atmosphere and, if the air is moist enough, causes towering cumulonimbus clouds and rain.
- This now-drier air then travels east before descending over the cooler eastern tropical Pacific.
- The pattern of air rising in the west and falling in the east with westward moving air at the surface is referred to as the **Walker Circulation.**

Cont..



Equator
warm
Trade winds
cool
SOUTH AMERICA
AUSTRALIA
average rain
140°E
180°
Date Line
140°W
100°W
Equator
Equatorial thermocline
upwelling
Neutral
180°
Date Line

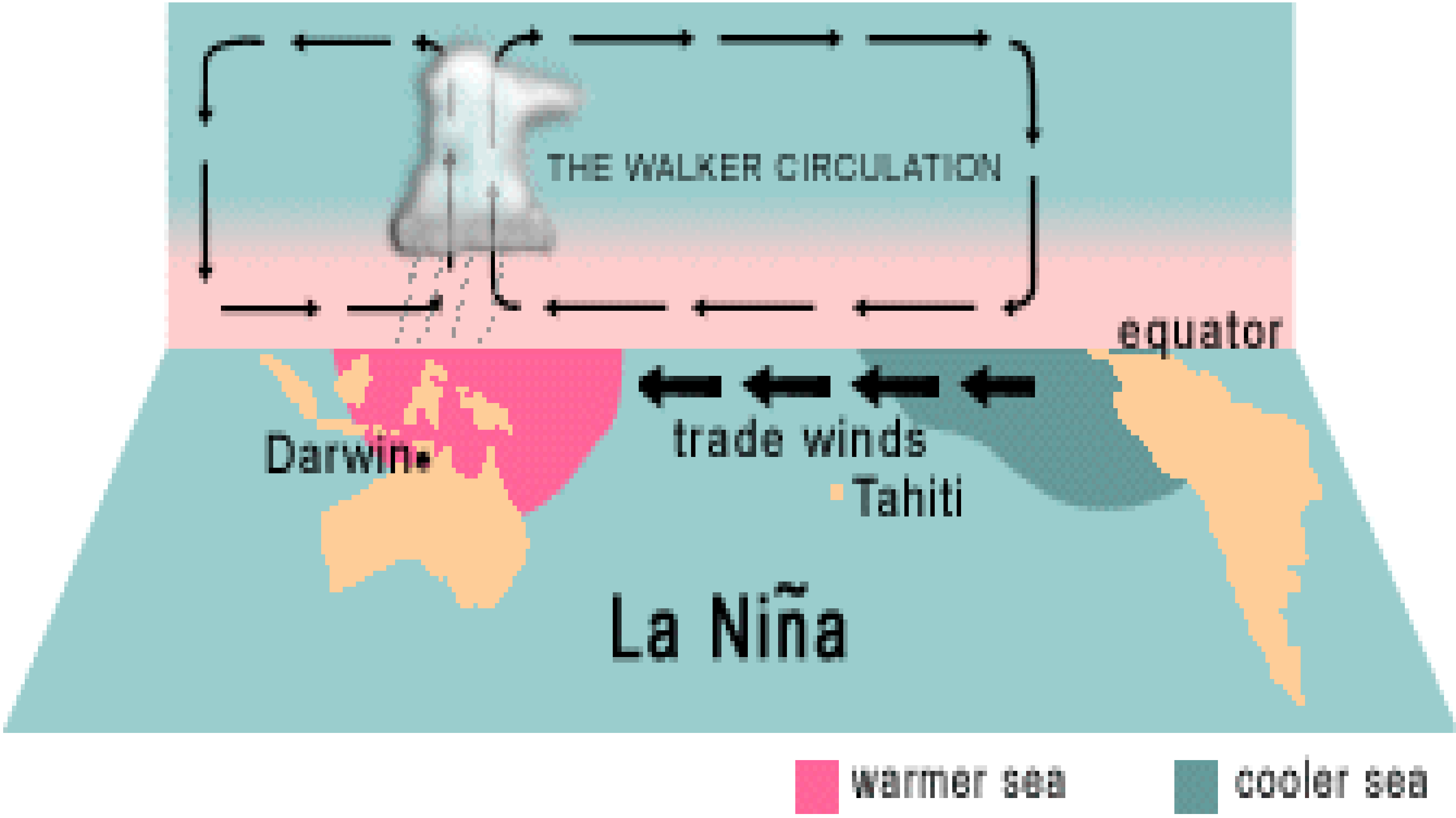
Cont..


Normal conditions
Indonesia
North & South America
Equator
Wind
Warm water
Cold water
West
East

Cont..

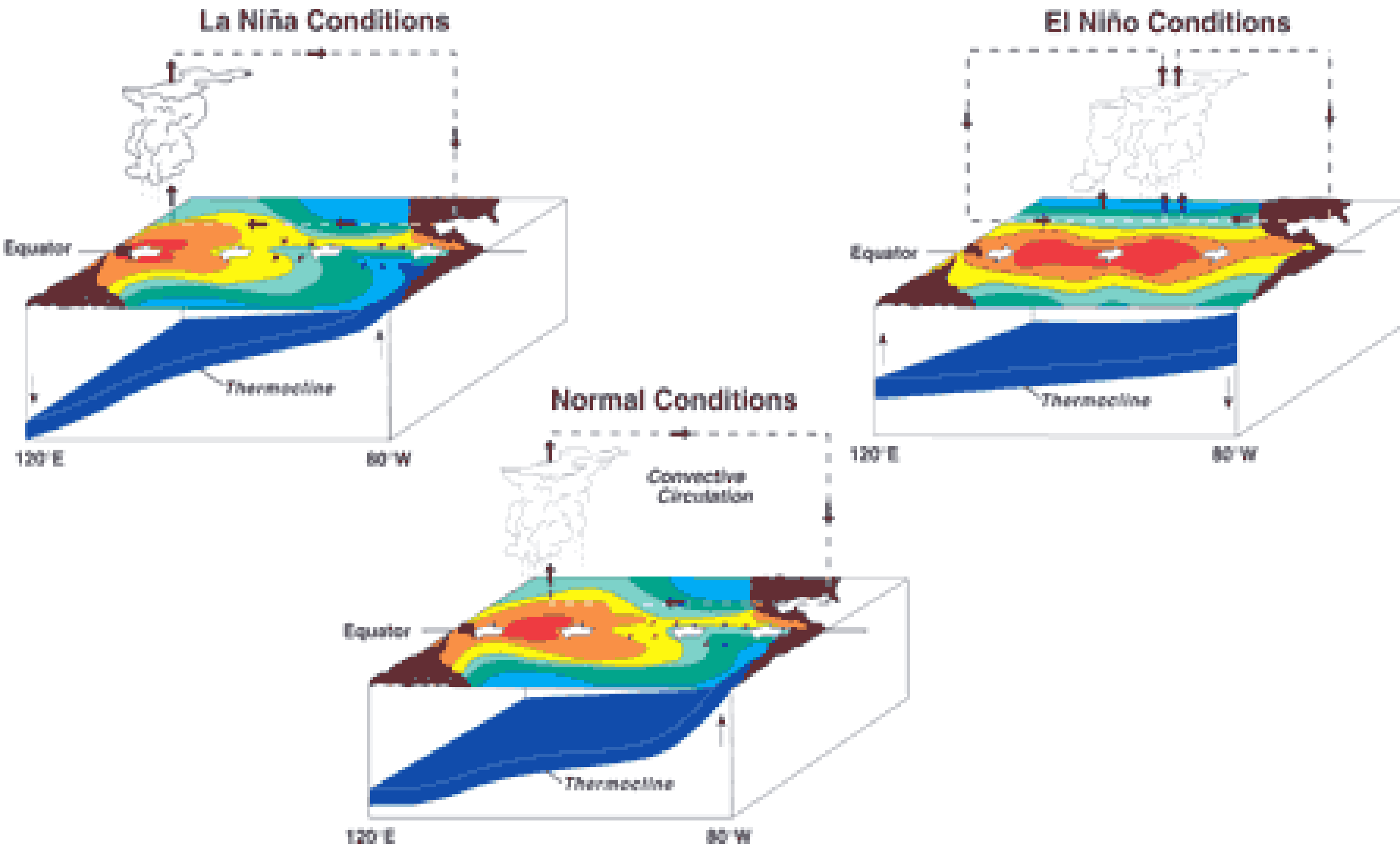
- ENSO is one of the most important climate phenomena on Earth due to its ability to change the global **atmospheric circulation**, which in turn, influences **temperature and precipitation** across the globe.
- We also focus on ENSO because we can often predict its arrival many seasons in advance of its strongest impacts on weather and climate

Cont..



THE WALKER CIRCULATION
equator
Darwin
trade winds
Tahiti
La Niña
warmer sea
cooler sea

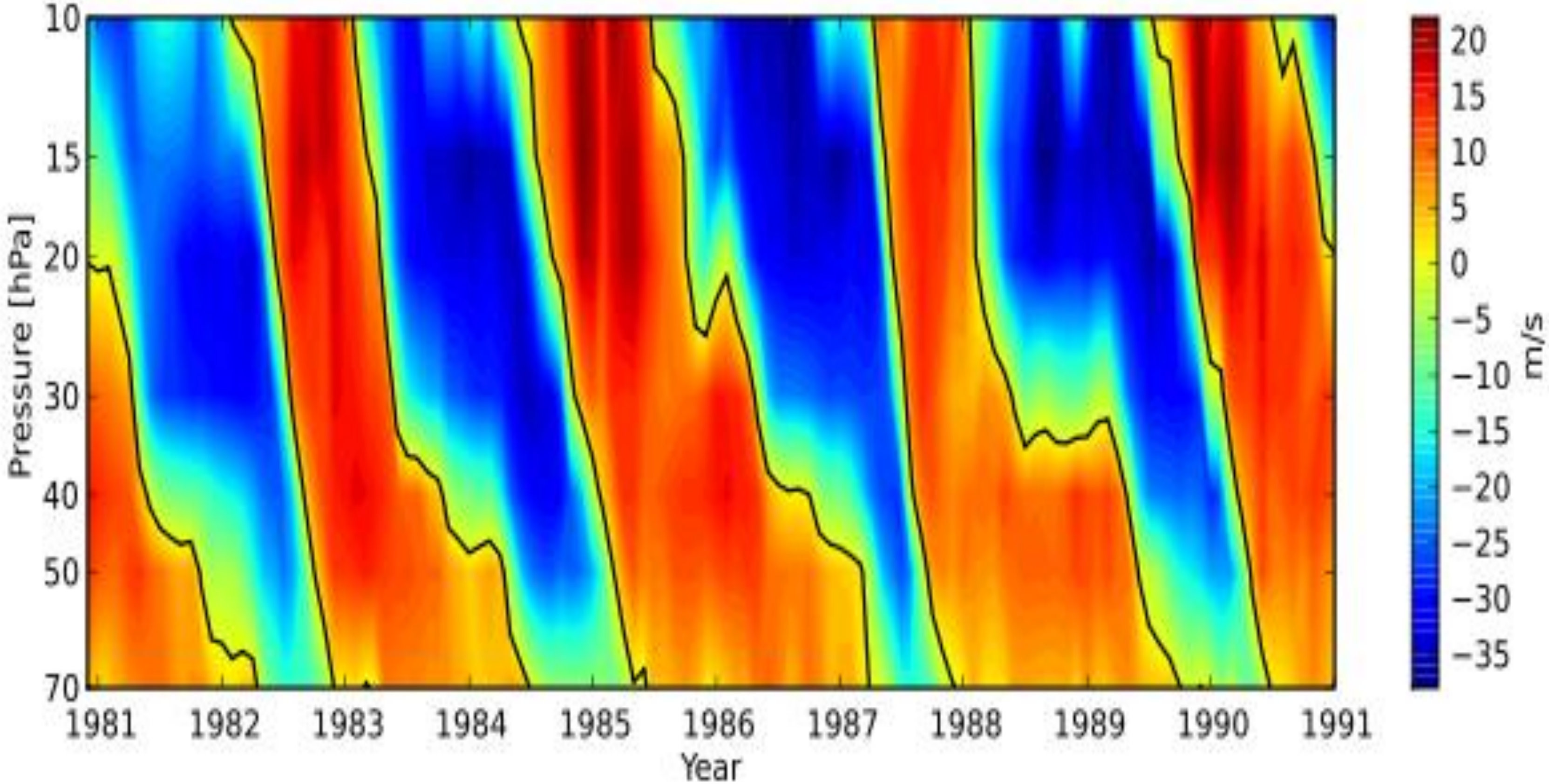
Cont..


La Niña Conditions
Equator
Thermocline
120°E
80°W
El Niño Conditions
Equator
Thermocline
120°E
80°W
Normal Conditions
Convective Circulation
Equator
Thermocline
120°E
80°W

Quasi-Biennial Oscillation

- The Quasi-Biennial Oscillation is a regular variation of the winds that blow high above the equator.
- Strong winds in the stratosphere travel in a belt around the planet, and every **14 months** or so, these winds completely change direction.
- This means a full cycle takes roughly **28 months**, making it the most regular slow variation in the atmosphere after the cycle of the seasons.

Cont..



10
15
20
30
40
50
70
Pressure [hPa]
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
Year
20
15
10
5
0
−5
−10
−15
−20
−25
−30
−35
m/s

Cont..

- The quasi-biennial oscillation (QBO) is a quasi-periodic oscillation of the equatorial zonal wind between **easterlies** and **westerlies** in the tropical stratosphere with a mean period of **28 to 29** months.
- The alternating wind regimes develop at the top of the lower stratosphere and propagate downwards at about 1 km (0.6 mi) per month until they are dissipated at the tropical tropopause.

Cont..

- Downward motion of the **easterlies** is usually more irregular than that of the **westerlies.**
- The amplitude of the **easterly phase** is about twice as strong as that of the westerly phase.
- At the **top of** the vertical QBO domain, **easterlies dominate,** while at the **bottom, westerlies** are more likely to be found.

Cont..

- The Quasi-Biennial Oscillation can affect the Atlantic jet stream.
- The speed of the winds in the jet stream weaken and strengthen with the direction of the QBO.
- The jet stream is an important atmospheric feature that brings us our weather here in the UK, and the risk of winter conditions in Northern Europe can differ depending on the phase of the QBO:

Cont..

- When the **QBO is easterly,** the chance of a weak jet stream, sudden stratospheric warming events and colder winters in Northern Europe is increased.
- When the QBO is westerly, the chance of a strong jet, a mild winter, winter storms and heavy rainfall increases.

Chapter Four

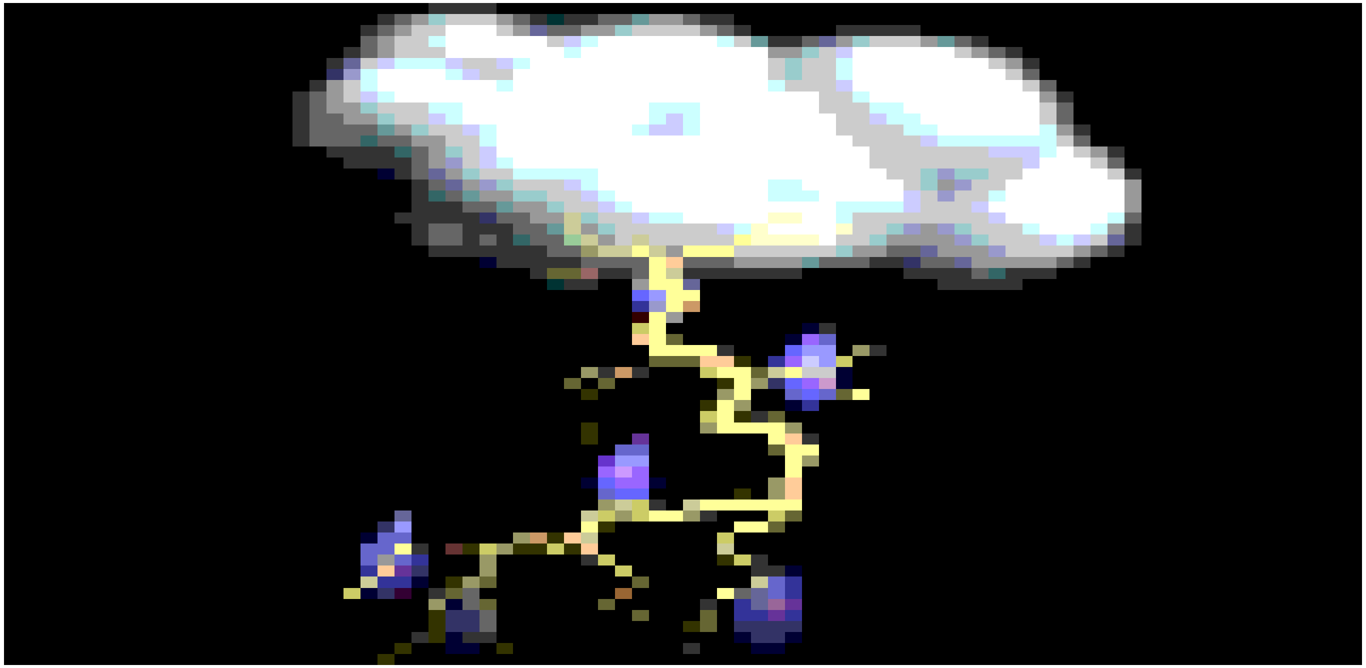
Tropical mesoscale system

outline

- **Thunder storm and lighting**
- **Easterly waves and jet streams**
- **Intertropical convergence zone**
- **Monsoon depression**

Thunderstorm and lighting

- A thunderstorm is a rain shower during which you hear thunder.
- Since thunder comes from lightning, all thunderstorms have lightning
- **Thunderstorms** occur in a type of cloud known as a **cumulonimbus.**
- Thunderstorms are most likely in the **spring** and **summer** months and during the **afternoon** and **evening** hours, but they can occur year-round and at all hours.
- Along the Gulf Coast and across the southeastern and western states, most thunderstorms occur during the afternoon.
- Thunderstorms frequently occur in the late afternoon and at night in the Plains states.



Cont..

- Three basic ingredients are required for a thunderstorm to form:
  - **moisture**, **rising unstable air** (air that keeps rising when given a nudge), and a **lifting mechanism to provide the "nudge."**
- The sun heats the surface of the earth, which warms the air above it.
- If this warm surface air is forced to rise hills or mountains, or areas where warm/cold or wet/dry air bump together can cause rising motion it will continue to rise as long as it weighs less and stays warmer than the air around it.

Cont..

- As the air rises, it transfers heat from the surface of the earth to the upper levels of the atmosphere (the process of convection).
- The water vapor it contains begins to cool, releases the heat, condenses and forms a cloud.
- The cloud eventually grows upward into areas where the temperature is below freezing.

Cont..

- As a storm rises into freezing air, different types of ice particles can be created from freezing liquid drops.
- The ice particles can grow by condensing vapor (like frost) and by collecting smaller liquid drops that haven't frozen yet (a state called "supercooled").
- When two ice particles collide, they usually bounce off each other, but one particle can rip off a little bit of ice from the other one and grab some electric charge.
- Lots of these collisions build up big regions of electric charges to cause a bolt of lightning, which creates the sound waves we hear as thunder

The Thunderstorm Life Cycle

- Thunderstorms have three stages in their life cycle:
  - ✓**The Developing Stage,**
  - ✓**The Mature Stage &**
  - ✓**The Dissipating Stage**.
- The developing stage of a thunderstorm is marked by a cumulus cloud that is being pushed upward by a rising column of air **(updraft).**
- The cumulus cloud soon looks like a tower (called towering cumulus) as the updraft continues to develop.

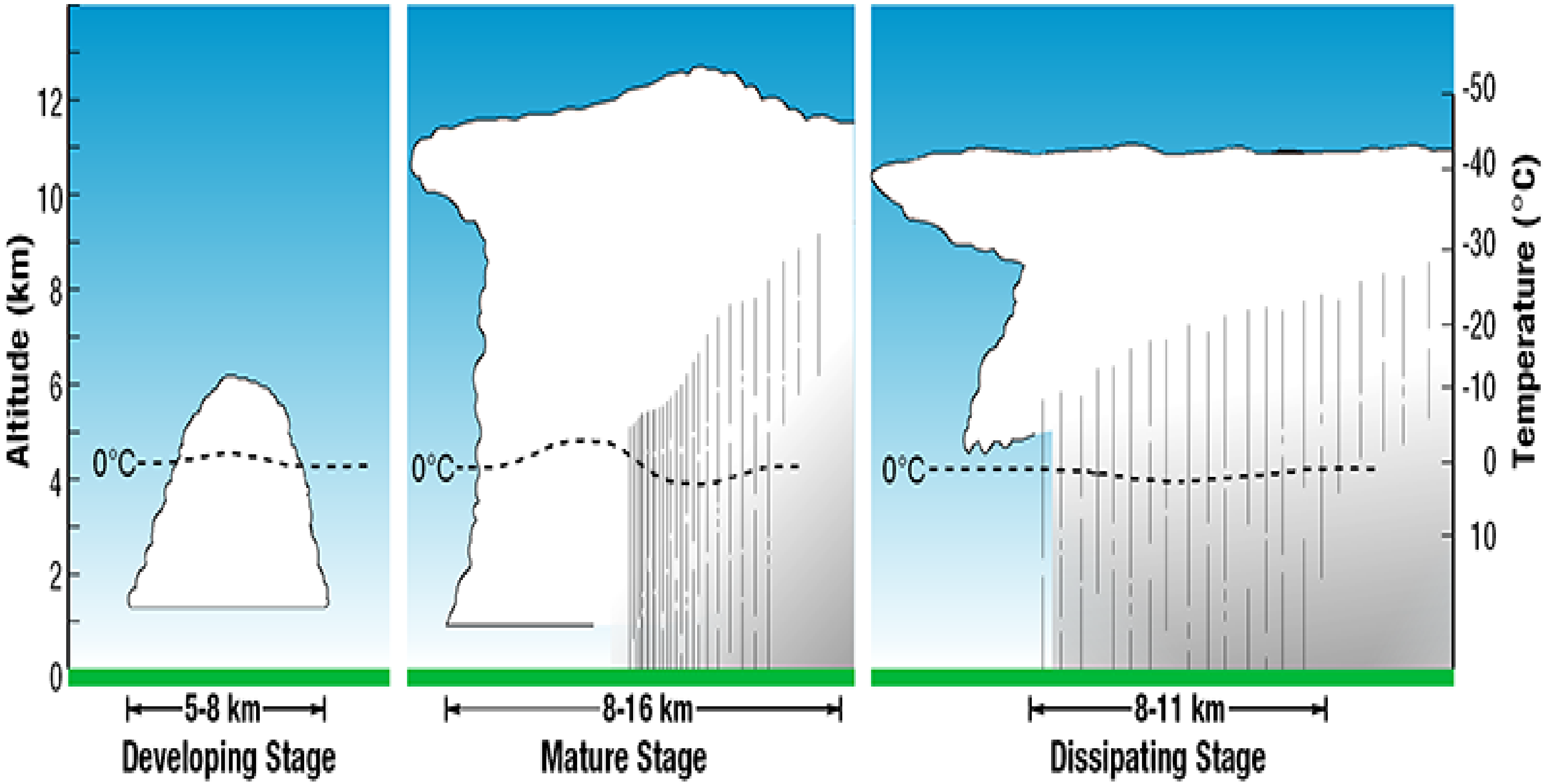
Cont..

- There is little to **no rain** during this stage but occasional **lightning**.
- The thunderstorm enters the mature stage when the updraft continues to feed the storm, but precipitation begins to **fall out of the storm, creating a downdraft (a column of air pushing downward).**
- When the downdraft and rain-cooled air spreads out along the ground it forms a **gust front**, or a **line of gusty winds.**

Cont..

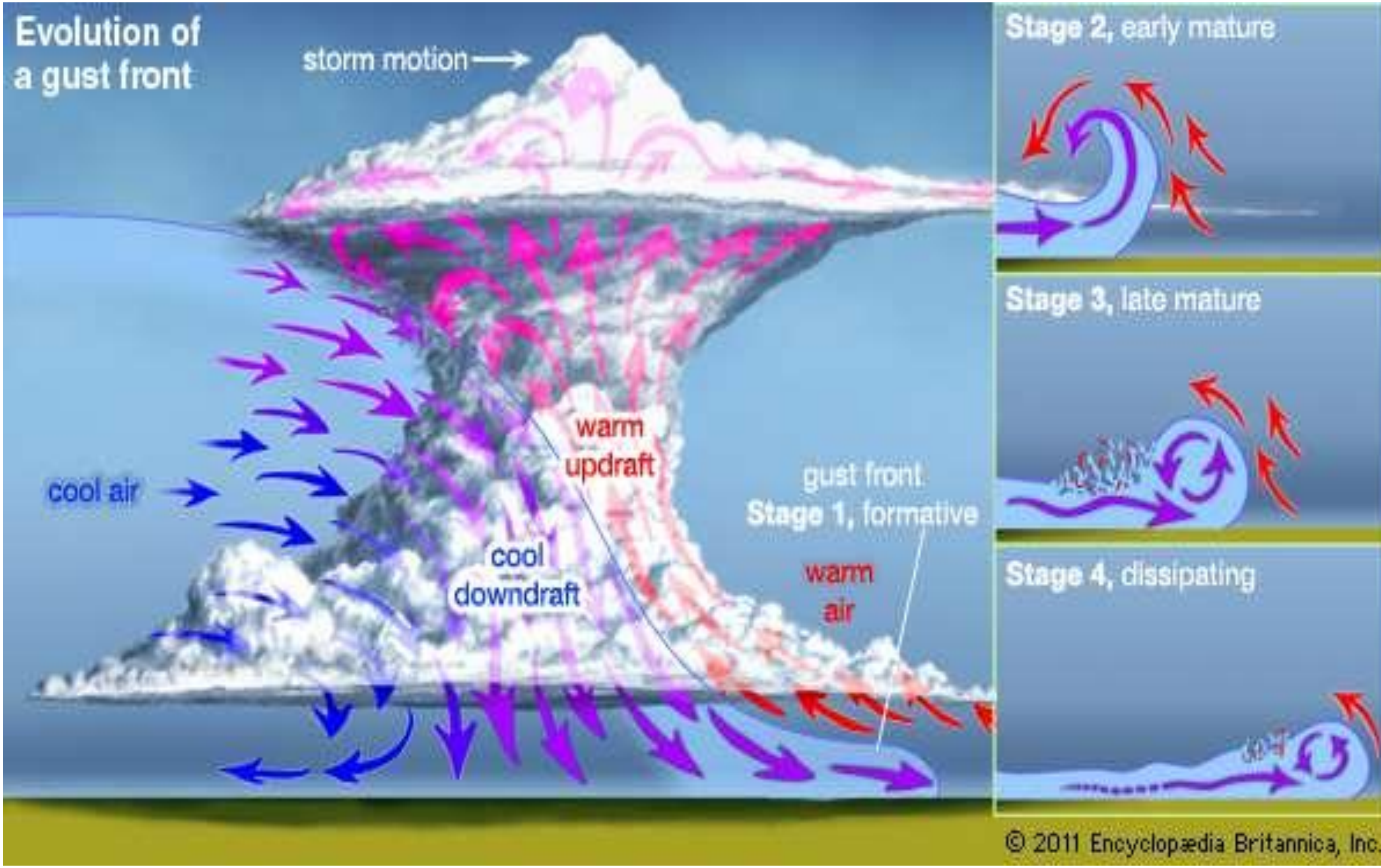
- **The mature stage** is the most likely time **for hail, heavy rain, frequent lightning, strong winds, and tornadoes**.
- Eventually, a large amount of precipitation is produced and the updraft is overcome by the downdraft beginning the dissipating stage.
- At the ground, the gust front moves out a long distance from the storm and cuts off the warm moist air that was feeding the thunderstorm.
- Rainfall decreases in intensity, but lightning remains a danger.

Cont..



Altitude (km)
12
10
8
6
4
2
0
0°C
5-8 km
Developing Stage
8-16 km
Mature Stage
8-11 km
Dissipating Stage
-50
-40
-30
-20
-10
0
10
Temperature (°C)

Cont..



Evolution of a gust front
storm motion
Stage 2, early mature
Stage 3, late mature
Stage 4, dissipating
warm updraft
cool air
cool downdraft
gust front
Stage 1, formative
warm air
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What kinds of damage can thunderstorms cause?

- Many hazardous weather events are associated with thunderstorms.
- Under the right conditions, rainfall from thunderstorms causes **flash flooding**, **killing more people each year than hurricanes, tornadoes or lightning.**
- Lightning is responsible for many fires around the world each year, and causes fatalities.

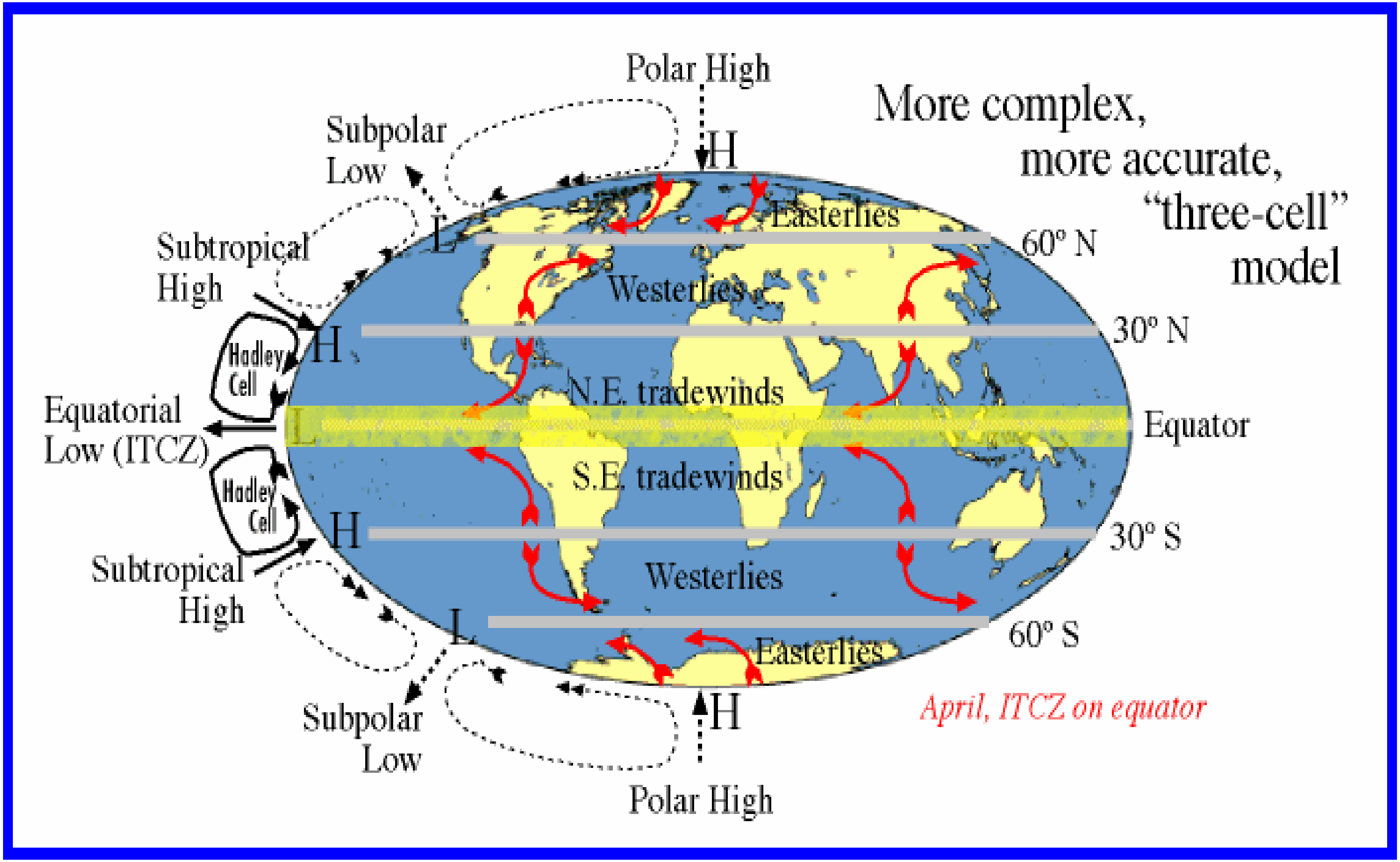
Intertropical convergence zone

- The Inter Tropical Convergence Zone, or ITCZ, is a belt of low pressure which circles the Earth generally near the equator where the trade winds of the Northern and Southern Hemispheres come together.
- It is characterized by convective activity which generates often vigorous thunderstorms over large areas.
- It is most active over continental land masses by day and relatively less active over the oceans.

Cont..

- ITCZ, also called equatorial convergence zone, belt of converging trade winds and rising air that encircles the Earth near the Equator.
- The rising air produces high cloudiness, frequent thunderstorms, and heavy rainfall; the doldrums, oceanic regions of calm surface air, occur within the zone.
- The ITCZ shifts north and south seasonally with the Sun.
- Over the Indian Ocean, it undergoes especially large seasonal shifts of 40°–45° of latitude.

ITC


Polar High
Subpolar Low
Subtropical High
Hadley Cell
Equatorial Low (ITCZ)
Hadley Cell
Subtropical High
Subpolar Low
Polar High
H
L
H
L
H
L
H
Easterlies
Westerlies
N.E. tradewinds
S.E. tradewinds
Westerlies
Easterlies
60° N
30° N
Equator
30° S
60° S
More complex, more accurate, "three-cell" model
April, ITCZ on equator

Cont..

- The position of the ITCZ varies with the seasons, and lags behind the sun's relative position above the Earth's surface by about 1 to 2 months, and correlates generally to the thermal equator.
- Since water has a higher heat capacity than land, the ITCZ propagates poleward more prominently over land than over water, and over the Northern Hemisphere than over the Southern Hemisphere.

Cont..

- In July and August, over the Atlantic and Pacific, the ITCZ is between 5 and 15 degrees north of the Equator, but further north over the land masses of Africa and Asia.
- In eastern Asia, the ITCZ may propagate up to 30 degrees north of the Equator.
- In January, over the Atlantic, the ITCZ generally sits no further south than the Equator, but extends much further south over South America, Southern Africa, and Australia.
- Over land, the ITCZ tends to follow the sun's zenith point.

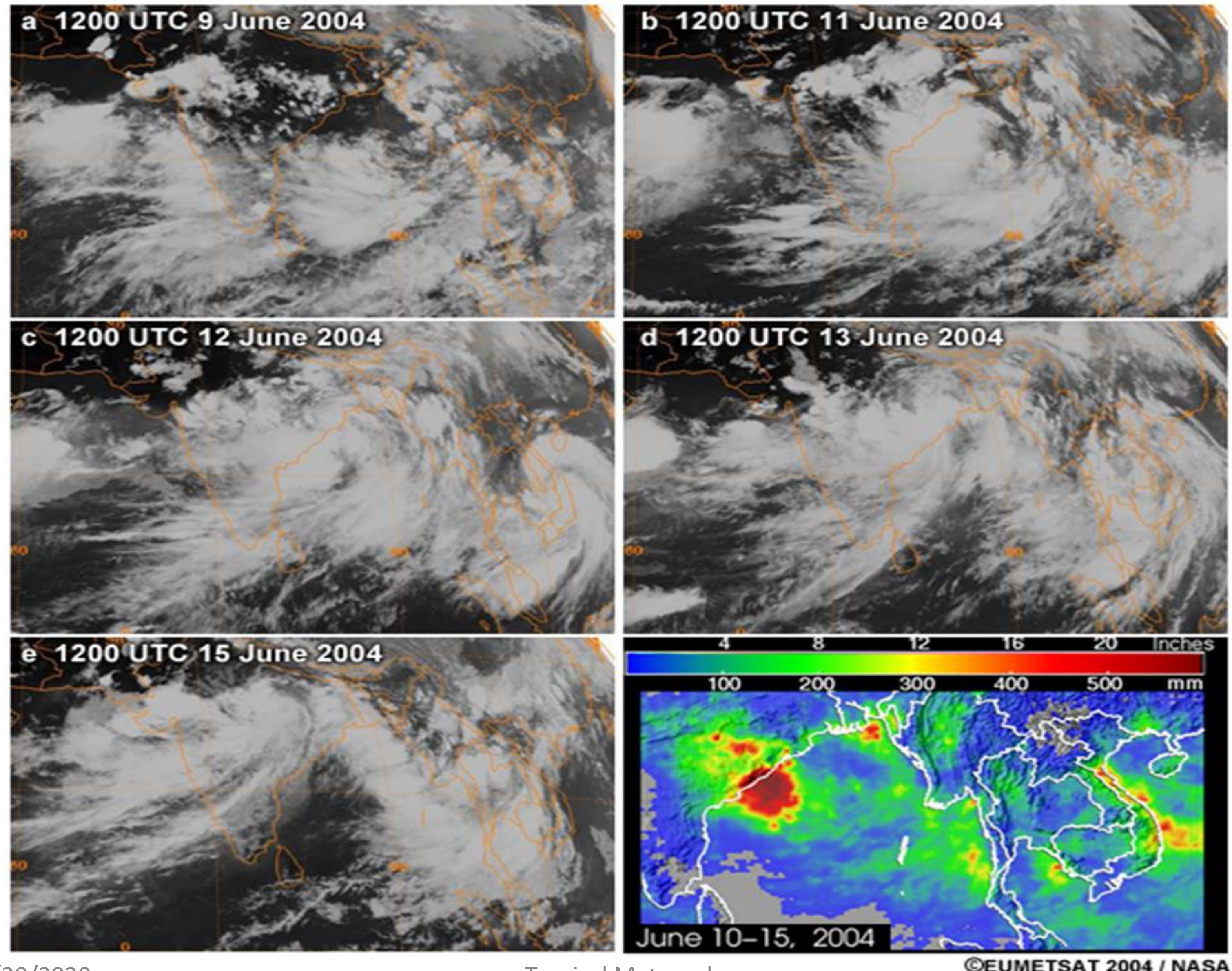
Cont..

- Where the trade winds are weak, the ITCZ is characterized by isolated Cumulus (Cu) and Cumulonimbus (Cb) (Cb) cells.
- However, where the trade winds are stronger, the ITCZ can spawn a solid line of active Cb cells embedded with other cloud types developing as a result of instability at higher levels

Monsoon depression

- The name “monsoon depression” usually refers to a weak, low-pressure circulation within the monsoon trough that forms in the Bay of Bengal and moves northwestward and westward across the Indian subcontinent during the summer monsoon (June–September).
- They are persistent rainfall producers, e.g., 400-600 mm of rainfall during 10-15 June 2004

Cont..


a 1200 UTC 9 June 2004
b 1200 UTC 11 June 2004
c 1200 UTC 12 June 2004
d 1200 UTC 13 June 2004
e 1200 UTC 15 June 2004
4 8 12 16 20 Inches
100 200 300 400 500 mm
June 10–15, 2004
©EUMETSAT 2004 / NASA

Monsoon depressions, generally:

- Have a large diameter, on the order of 1000 km (1500-3000 km)
- Are strongest below 700 hPa and weaken quickly above that level
- Extend to about 8 km above the surface (restricted in upward extent by the Tibetan High)
- Produce rainfall rate as high as 100-200 mm in 24 hours
- Move slowly, west or northwestward at 2-6 m s-1 (zonally at 2-5° per day); movement that is counter to strong low-level monsoon flow

Chapter Five

Tropical Cyclone

outline

- Global distribution
- Cyclogenesis and Cyclolysis
- Stages of a tropical cyclone
- Extratropical transition

Tropical cyclone

- Tropical cyclone, also called typhoon or hurricane, an intense circular storm that originates over warm tropical oceans and is characterized by low atmospheric pressure, high winds, and heavy rain.
- Drawing energy from the sea surface and maintaining its strength as long as it remains over warm water,
- a tropical cyclone generates winds that exceed 119 km (74 miles) per hour.
- In extreme cases winds may exceed 240 km (150 miles) per hour, and gusts may surpass 320 km (200 miles) per hour.

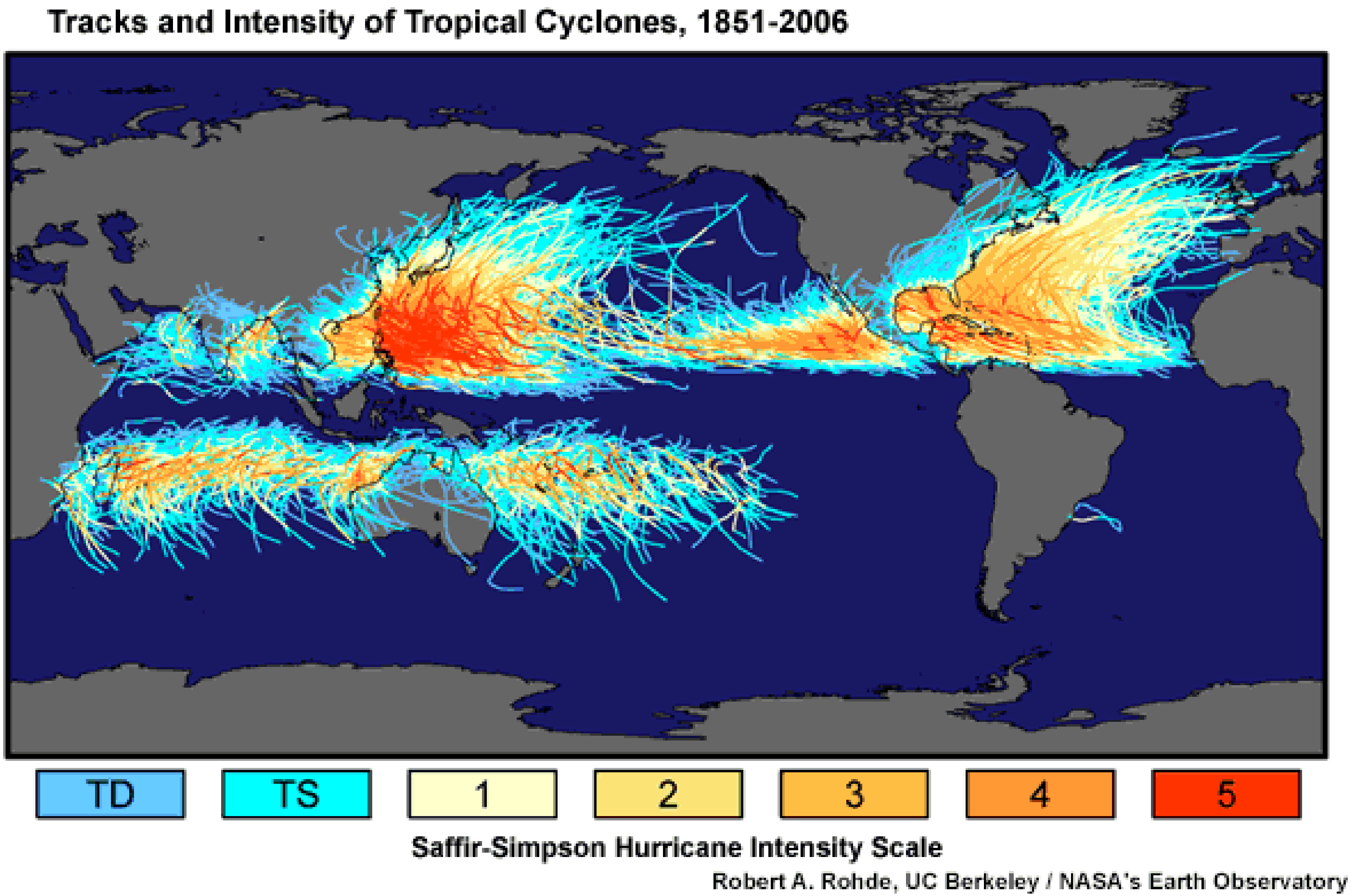
Cont....

- Tropical cyclones are known by various names in different parts of the world.
- In the western North Atlantic, central and eastern North Pacific, Caribbean Sea and Gulf of Mexico, such a weather phenomenon is called **"hurricanes".**
- In the western North Pacific, it is called **"typhoons“**
- In the Bay of Bengal and Arabian Sea, it is called **"cyclones"**

Cont….

- In western South Pacific and southeast India Ocean, it is called **“severe tropical cyclones”**
- In the southwest India Ocean, it is called **“tropical cyclones”**
- All these different names refer to the same type of storm.

Global distribution

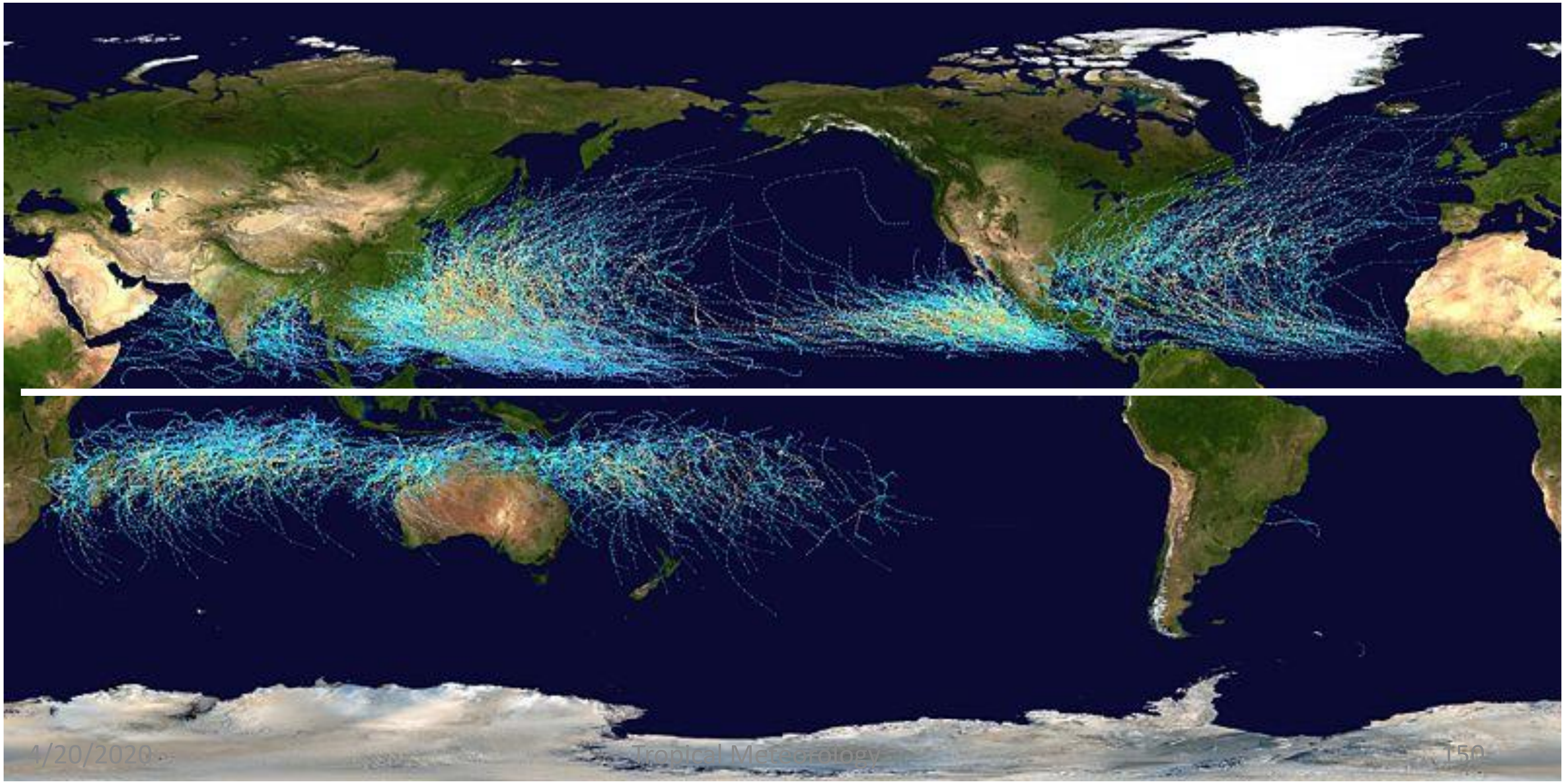


Cont..

- Tropical cyclones do not form very close to the equator and do not ever cross the equator;
- The western North Pacific is the most active tropical cyclone region.
- It is also the region with the largest number of intense tropical cyclones (orange through red tracks);
- Tropical cyclones in the western North Pacific and the North Atlantic can have tracks that extend to very high latitudes.

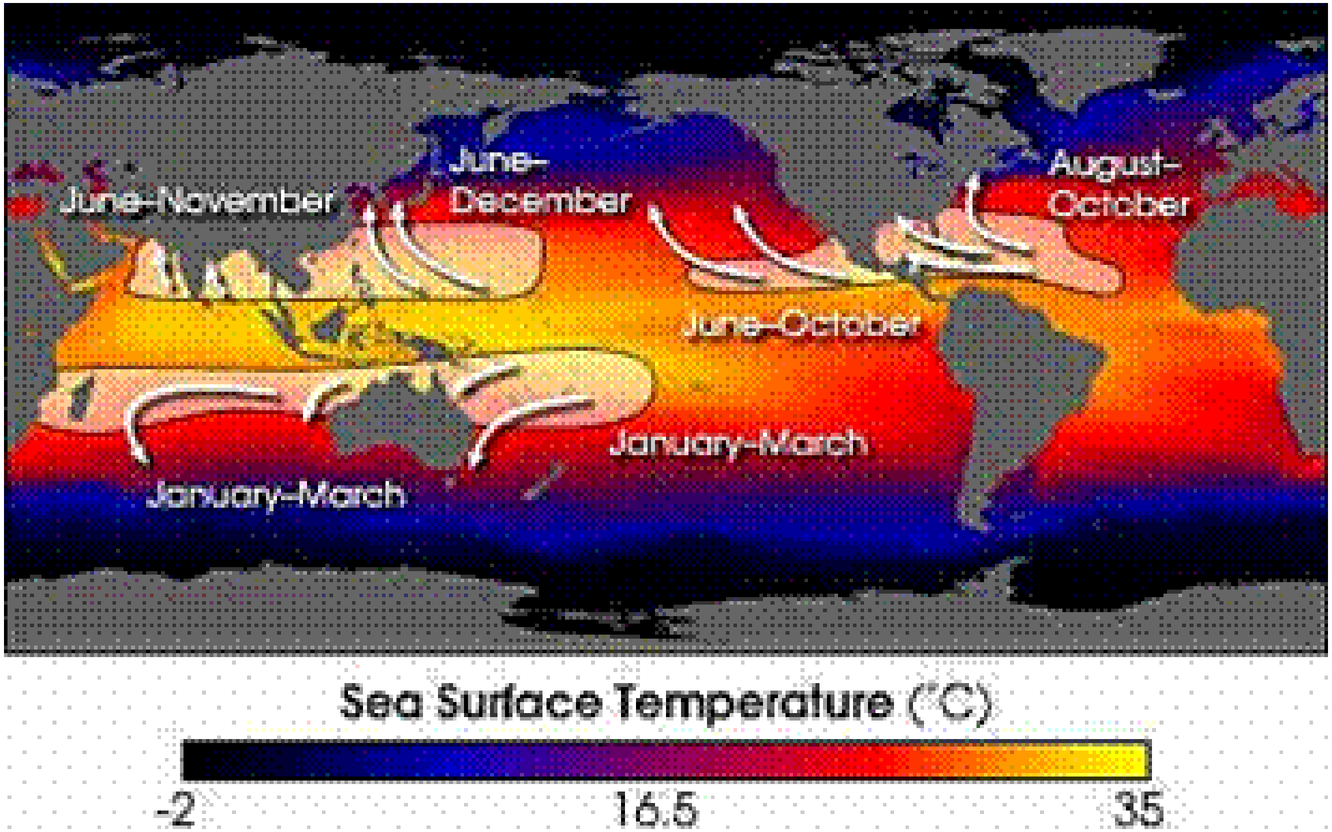
Where and When

- Note that tropical cyclones do not form near the equator due to the lack of the Coriolis effect.
- Also, storms tend to curve to the north and east as they interact with the westerlies.



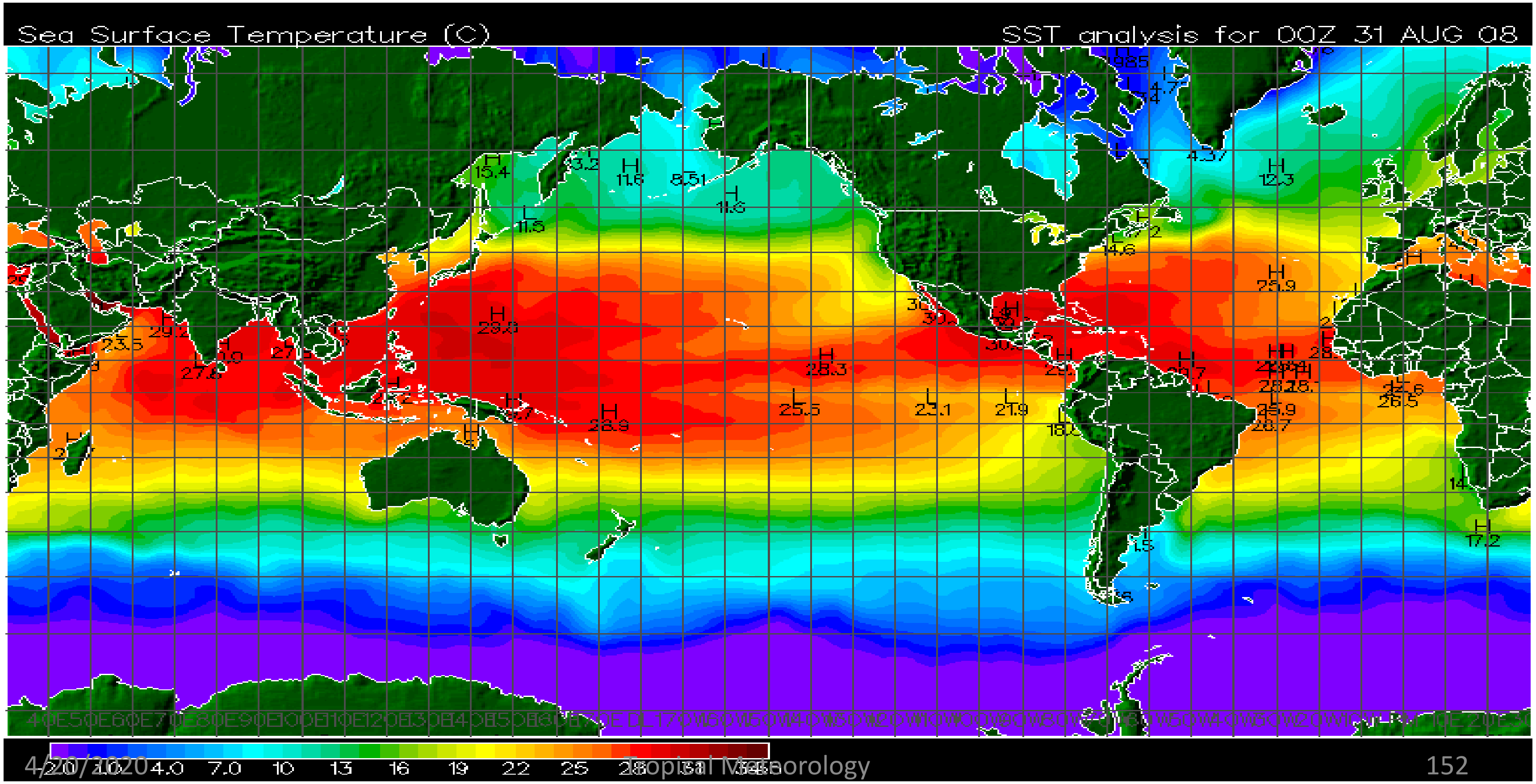
Where and When

- Worldwide, tropical cyclone activity peaks in late **summer** when water temperatures are warmest.



Where and When

- In general, sea surface temperatures are warmer along eastern coasts than western coasts and are warmest near Indonesia accounting for the strongest and most frequent activity.



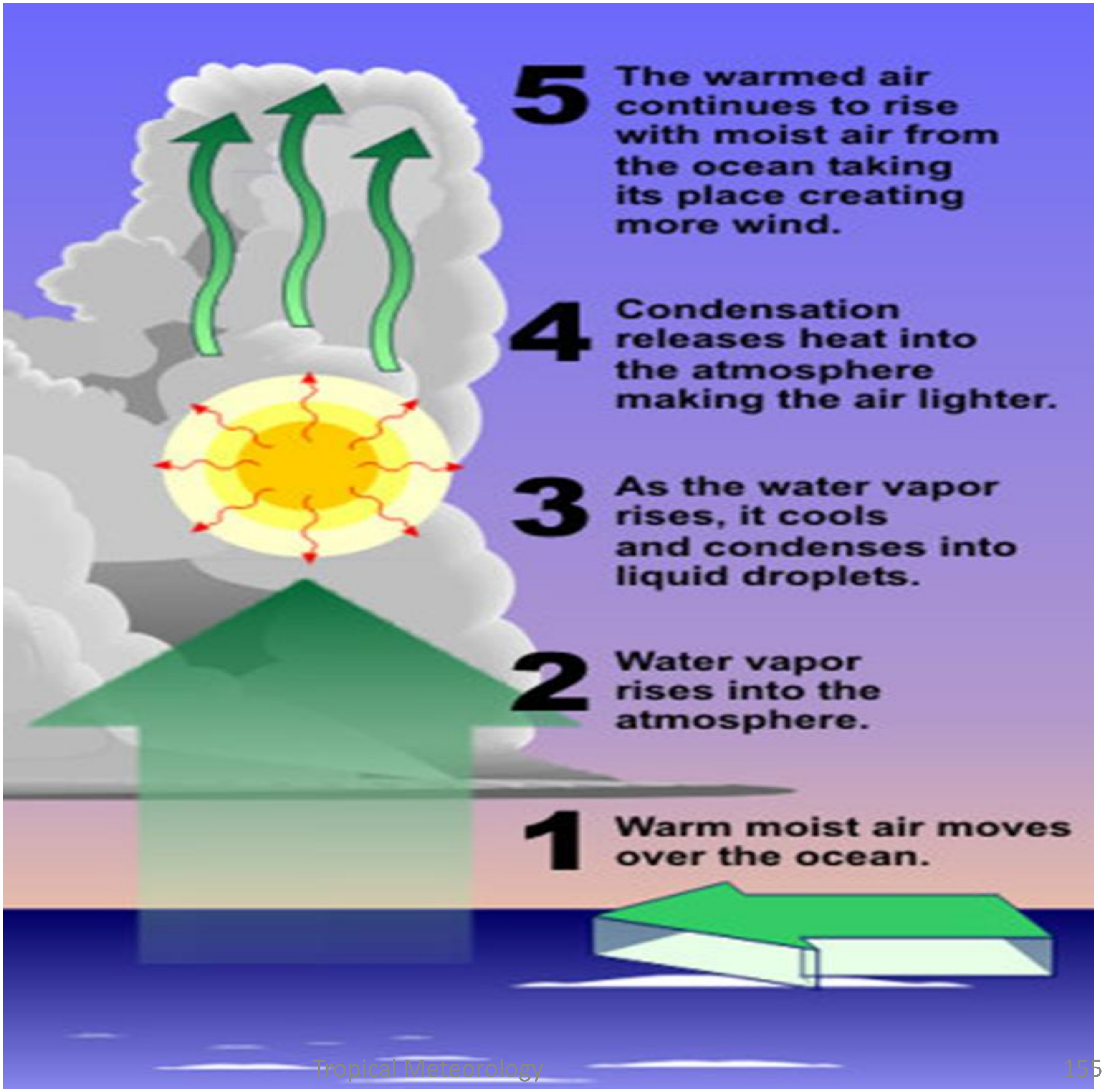
Cont..

- Storms following these long tracks generally undergo extratropical transition;
- The North Indian Ocean (Bay of Bengal and Arabian Sea) is bounded by land to the north and the eastern North Pacific is bounded by cold water to the north.
- These environmental features limit the lifetimes of storms in these regions.
- The Bay of Bengal has about five times as many tropical cyclones as the Arabian Sea.
- The high mountain ranges and low-lying coastal plains and river deltas of the Bay of Bengal combine to make this region extremely vulnerable to tropical cyclones.

Cont..

- Southern Hemisphere tropical cyclones are generally weaker than storms in the North Pacific and Atlantic basins;
- The extension of the subtropical jet into tropical latitudes in the Southern Hemisphere acts to constrain the tracks of tropical cyclones.
- Even so, a few Southern Hemisphere tropical cyclones undergo extratropical transition;
- Although rare, systems resembling tropical cyclones can occur in the South Atlantic Ocean and off the subtropical east coasts of Australia and southern Africa.

Cont..



5 The warmed air continues to rise with moist air from the ocean taking its place creating more wind.
4 Condensation releases heat into the atmosphere making the air lighter.
3 As the water vapor rises, it cools and condenses into liquid droplets.
2 Water vapor rises into the atmosphere.
1 Warm moist air moves over the ocean.

Cyclogenesis and Cyclolysis

- Cyclogenesis is the development or strengthening of cyclonic circulation in the atmosphere (a low-pressure area).
- Cyclogenesis is an umbrella term for at least three different processes, all of which result in the development of some sort of cyclone, and at any size from the microscale to the synoptic scale.
- cyclogenesis is (meteorology) the process which leads to the formation of tropical storms, cyclones and hurricanes; typically involves an interaction that leads to vertical wind shear.

Cont..

- Cyclolysis:- Any weakening of cyclonic circulation in the atmosphere; the opposite of cyclogenesis.
- Cyclolysis, which refers to the circulation, is to be distinguished from filling, an increase in atmospheric pressure, although the two processes commonly occur simultaneously

Thanks!

Use the following link for details about tropical meteorology

https://www.meted.ucar.edu/tropical/textbook_2nd_edition/navmenu.php?tab=1