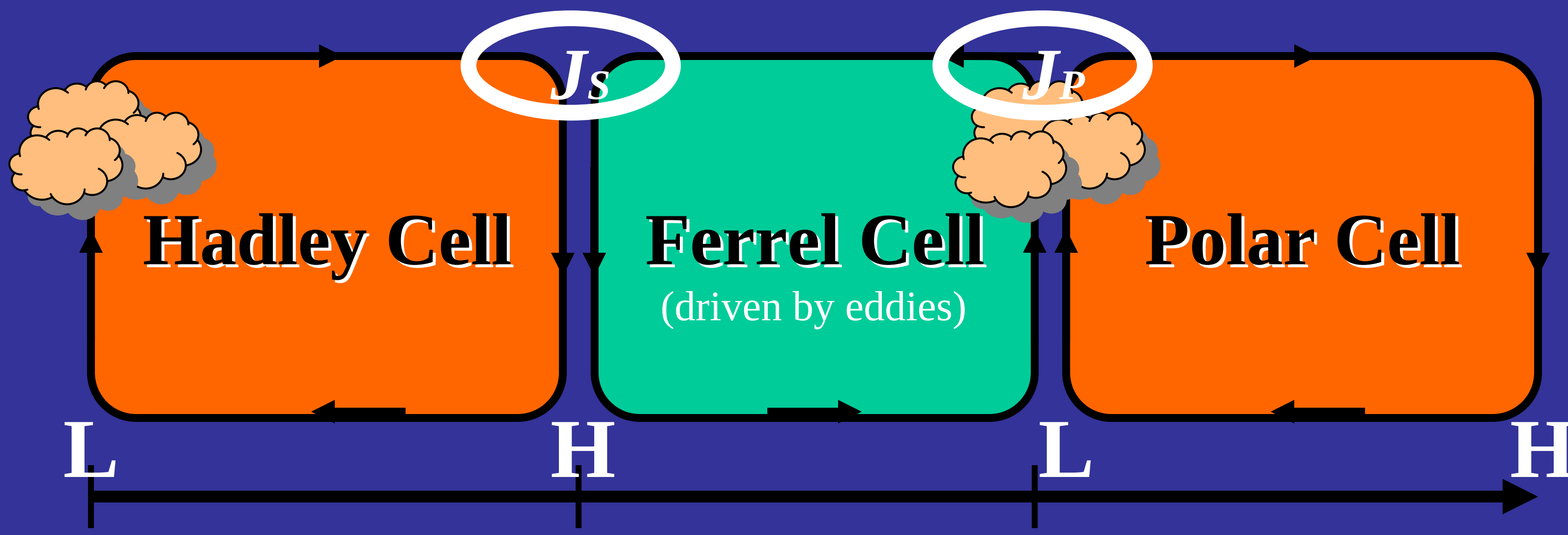
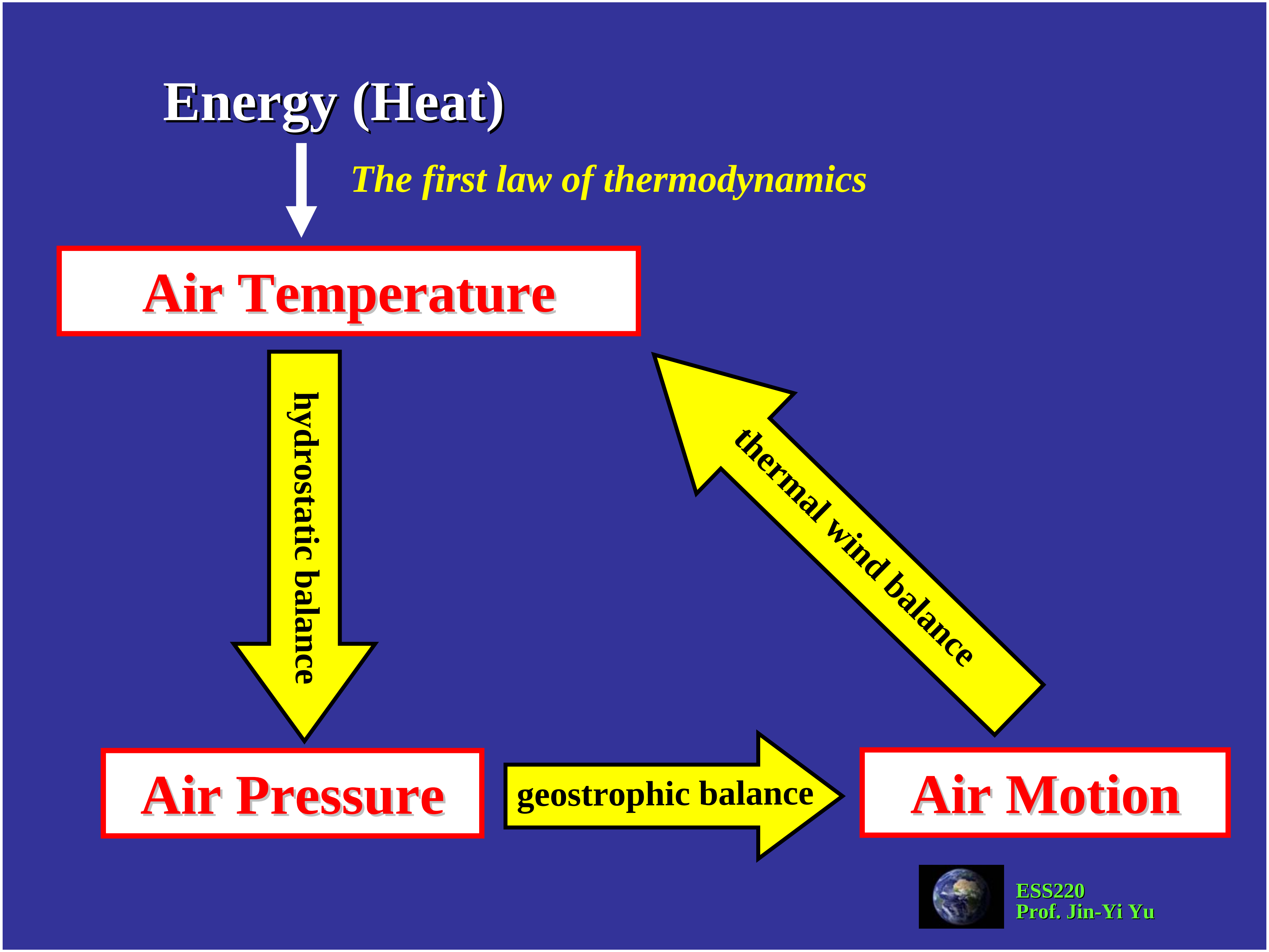
Lecture 3: ATMOSPHERE (Outline)



- Basic Structures and Dynamics
- General Circulation in the Troposphere
- General Circulation in the Stratosphere
- Jetstreams


Energy (Heat)
The first law of thermodynamics
Air Temperature
hydrostatic balance
Air Pressure
geostrophic balance
Air Motion
thermal wind balance
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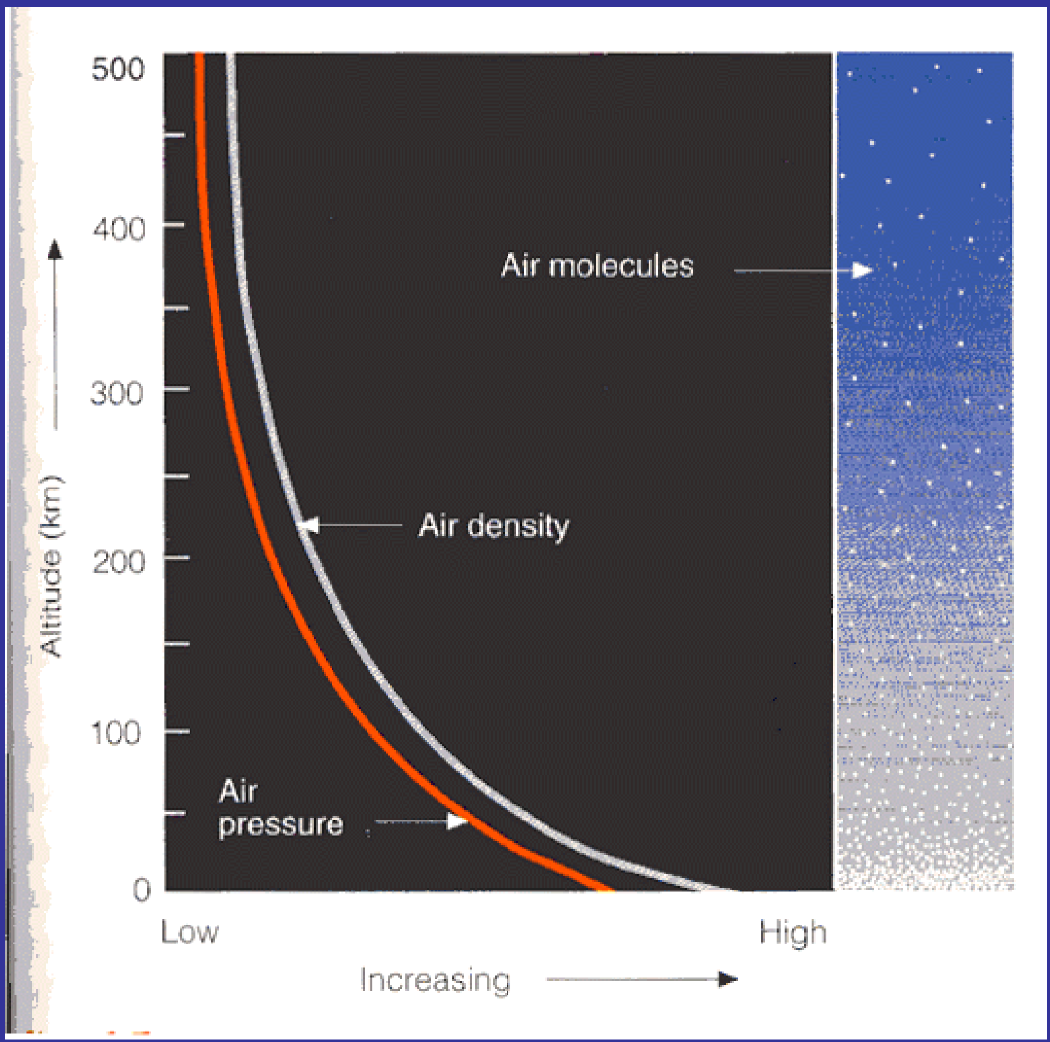
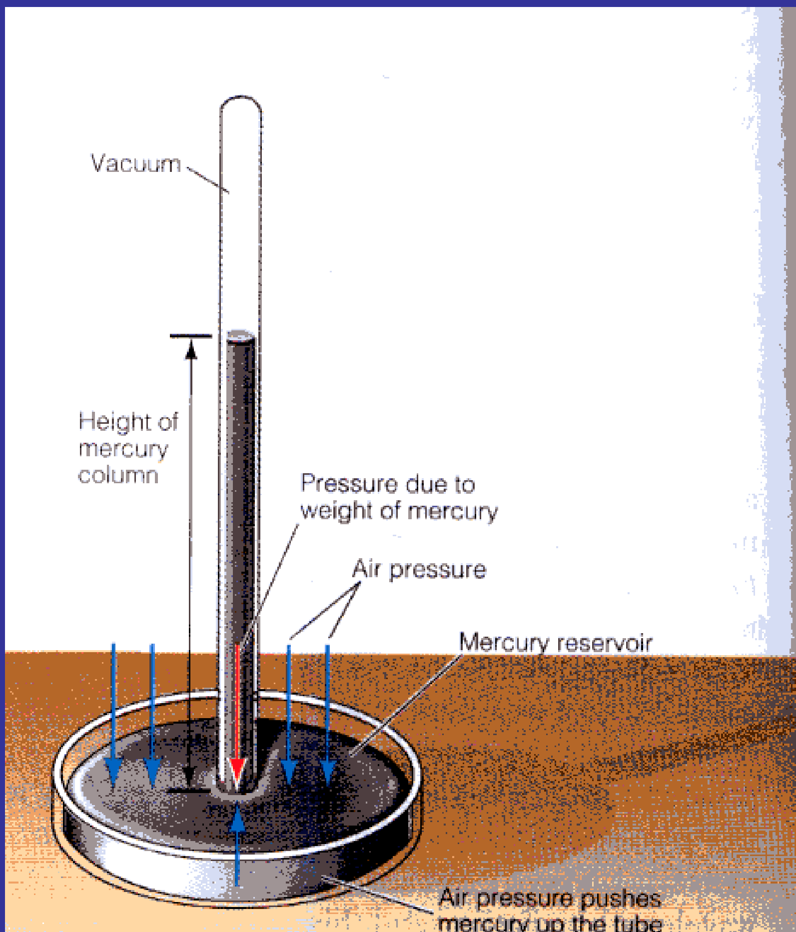
Air Pressure and Air Density



(from *Meteorology Today*)

- Weight = mass x gravity
- Density = mass / volume
- Pressure = force / area
  = weight / area

One Atmospheric Pressure



(from *The Blue Planet*)

- The average air pressure at sea level is equivalent to the pressure produced by a column of water about 10 meters (or about 76 cm of mercury column).
- This standard atmosphere pressure is often expressed as 1013 mb (millibars), which means a pressure of about 1 kilogram per square centimeter.

Units of Atmospheric Pressure

- **Pascal (Pa):** a SI (Systeme Internationale) unit for air pressure.

  1 Pa = a force of 1 newton acting on a surface of one square meter

  1 hectopascal (hPa) = 1 millibar (mb) [hecto = one hundred =100]

- **Bar:** a more popular unit for air pressure.

  1 bar = a force of 100,000 newtons acting on a surface of one square meter

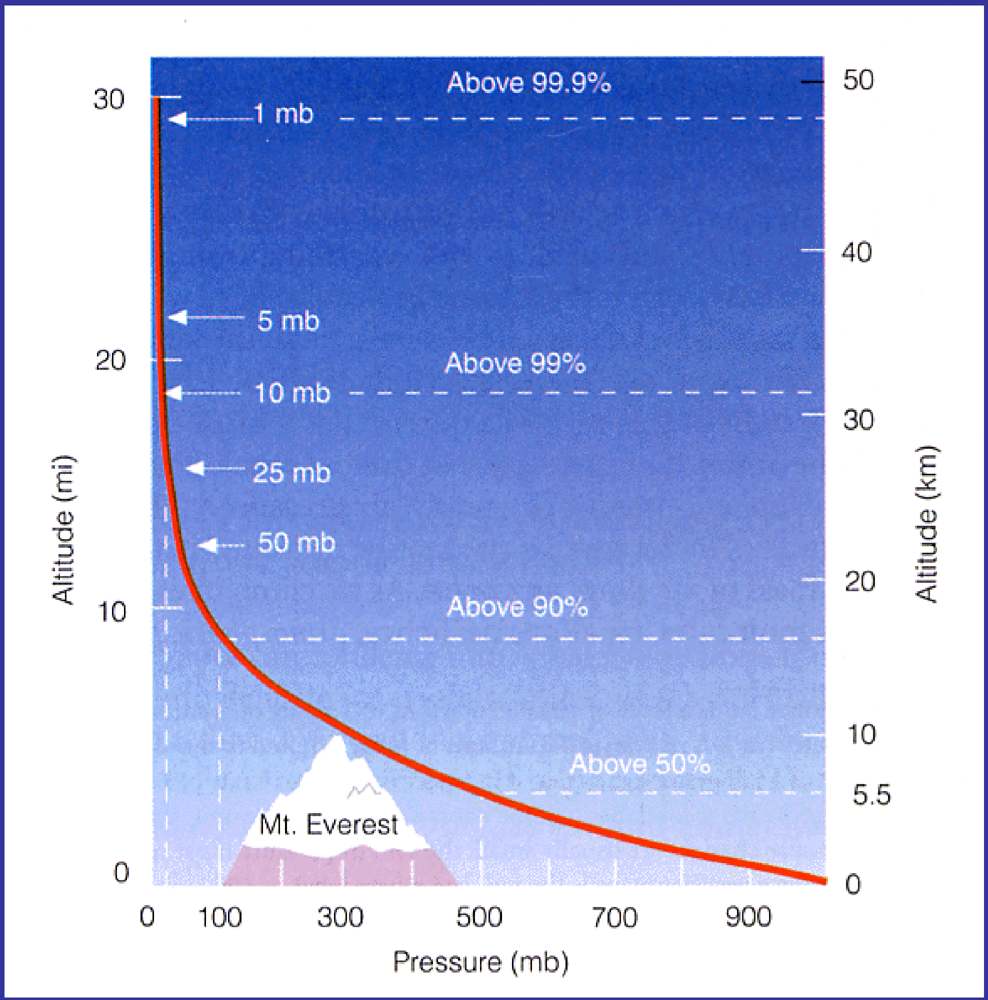
  = 100,000 Pa

  = 1,000 hPa

  = 1,000 mb

- **One atmospheric pressure** = standard value of atmospheric pressure at lea level = 1013.25 mb = 1013.25 hPa.

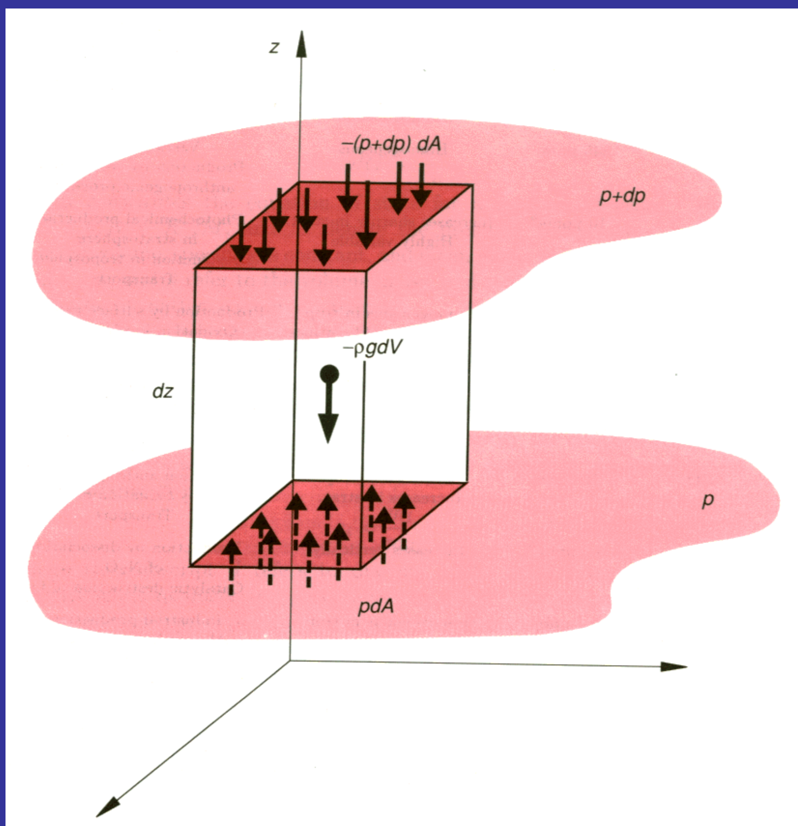
Air Mass and Pressure



(from *Meteorology Today*)

- ❑ Atmospheric pressure tells you how much atmospheric mass is above a particular altitude.
- ❑ Atmospheric pressure decreases by about 10mb for every 100 meters increase in elevation.

Hydrostatic Balance in the Vertical



(from *Climate System Modeling*)

- vertical pressure force = gravitational force

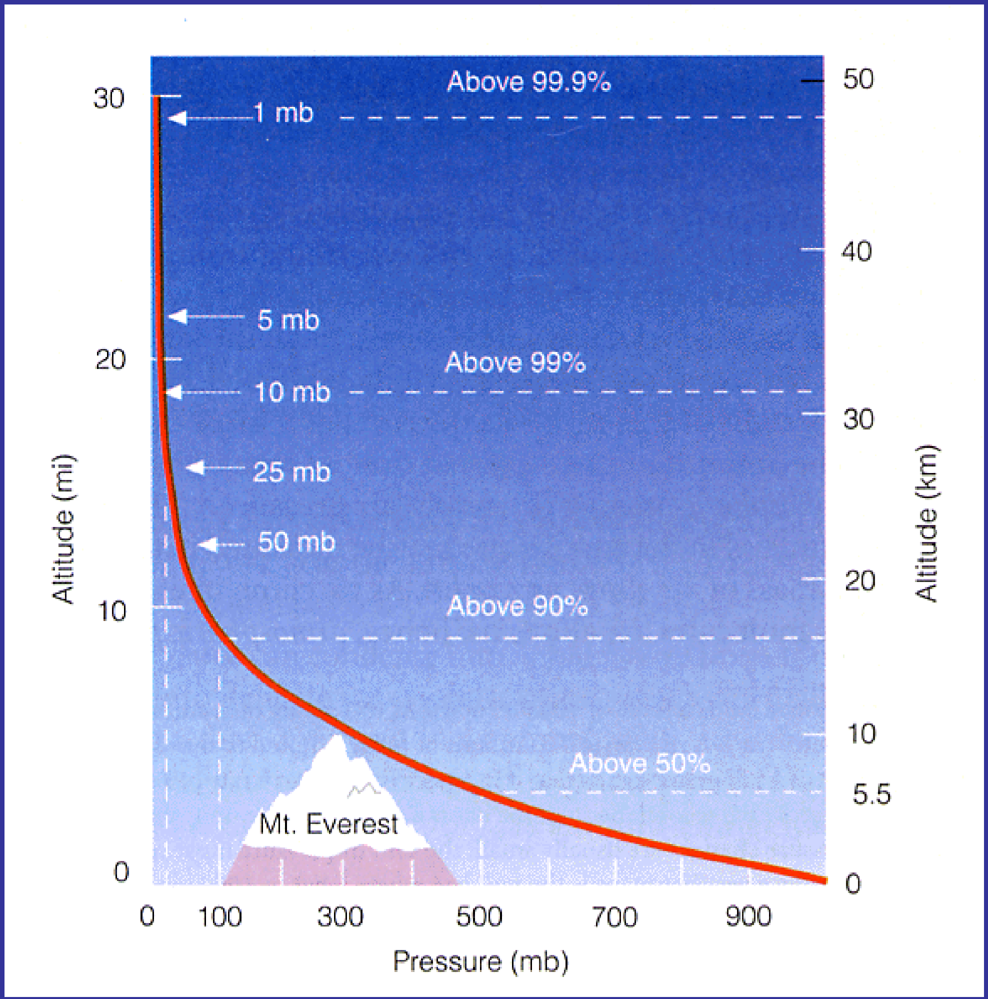
$$-(dP) \times (dA) = \rho \times (dz) \times (dA) \times g$$

$$dP = -\rho g dz$$

$$dP/dz = -\rho g$$

The hydrostatic balance !!

Hydrostatic Balance and Atmospheric Vertical Structure



(from *Meteorology Today*)

- Since P= ρRT (the ideal gas law), the hydrostatic equation becomes:

  dP = -P/RT x gdz

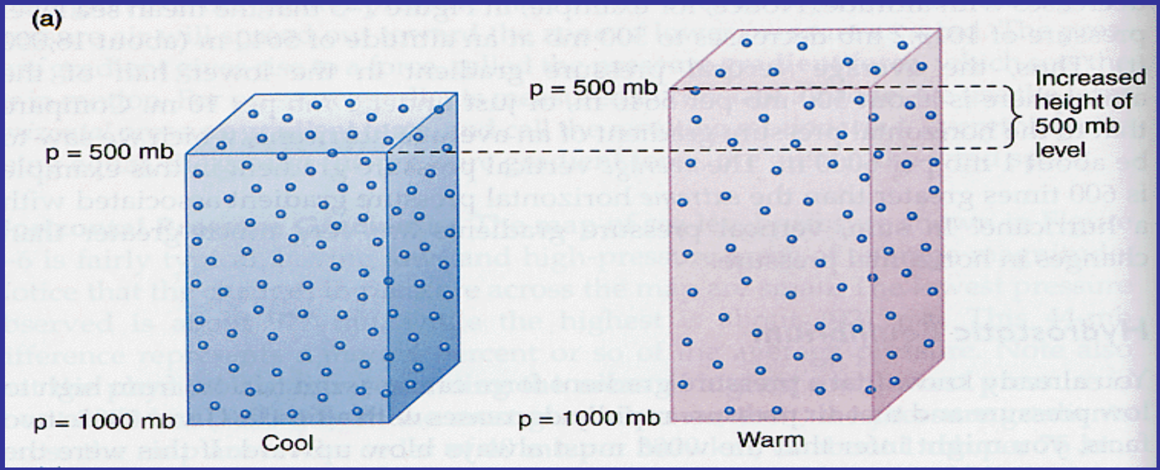
➔ dP/P = -g/RT x dz

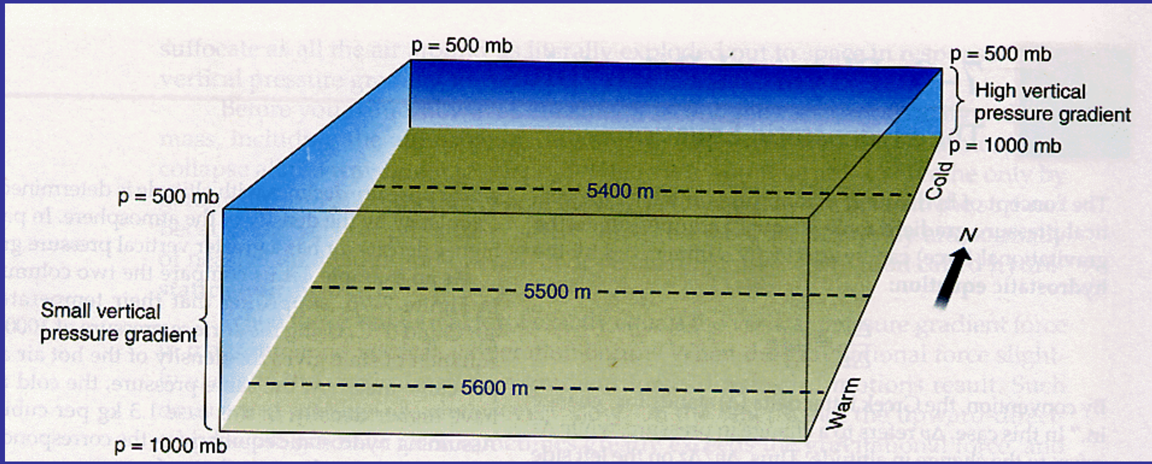
➔ **$P = P_s \exp(-gz/RT)$**

➔ $P = P_s \exp(-z/H)$

- The atmospheric pressure decreases exponentially with height

Temperature and Pressure

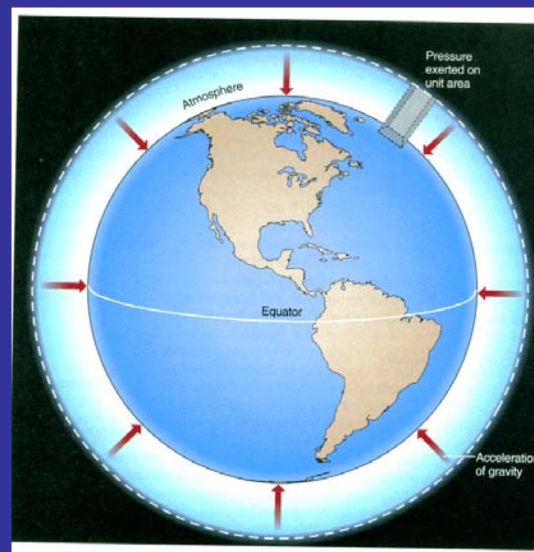


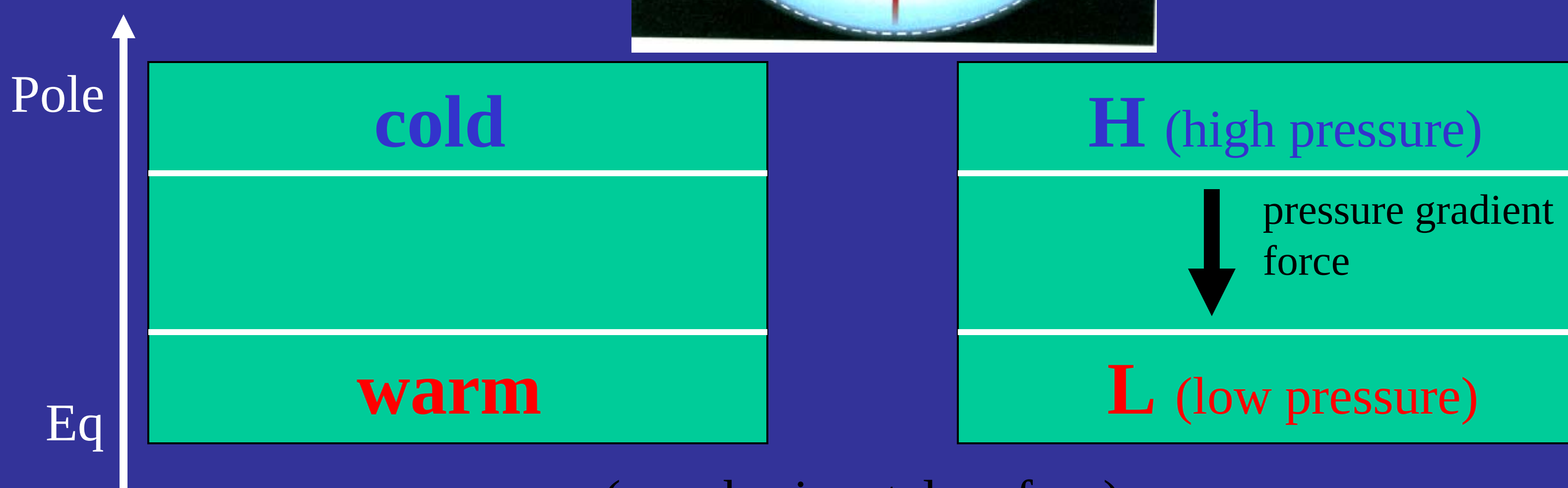


(from *Weather & Climate*)

- Hydrostatic balance tells us that the pressure decrease with height is determined by the temperature inside the vertical column.
- Pressure decreases faster in the cold-air column and slower in the warm-air column.
- Pressure drops more rapidly with height at high latitudes and lowers the height of the pressure surface.

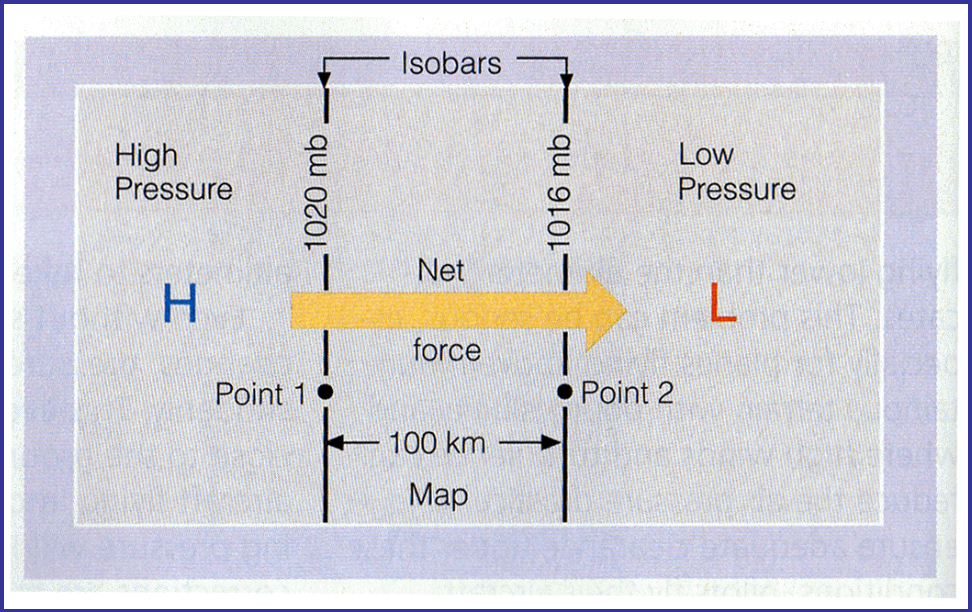
Thermal Energy to Kinetic Energy

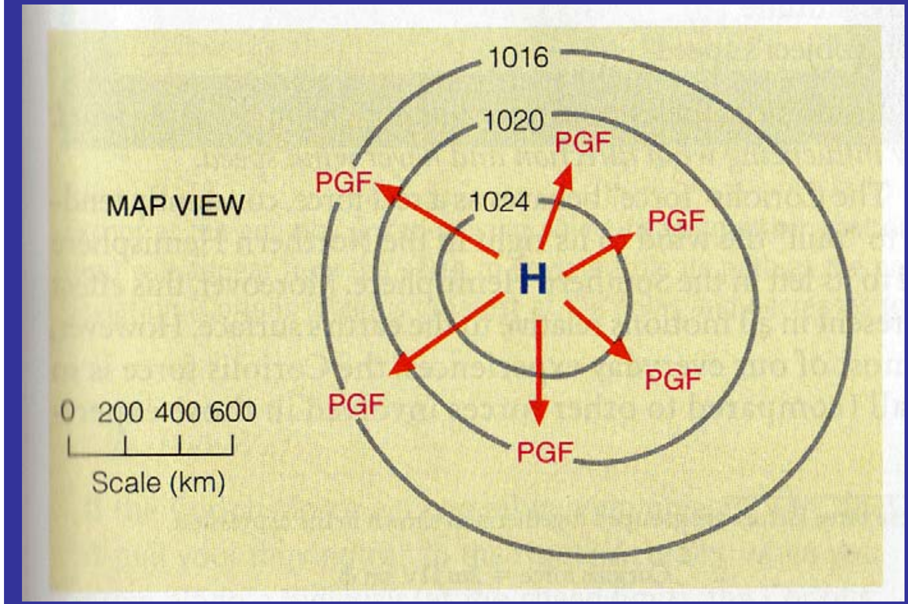




(on a horizontal surface)

Pressure Gradient Force



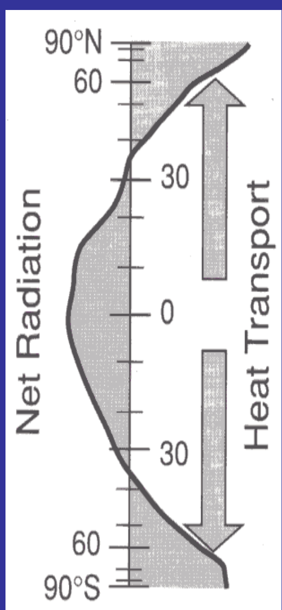


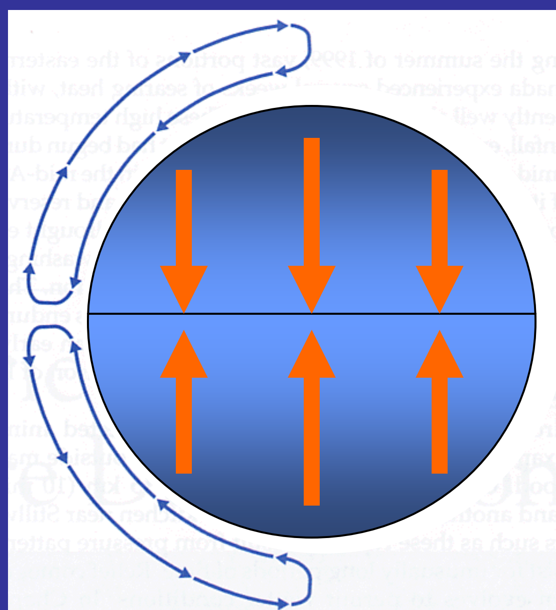
(from Meteorology Today)

- PG = (pressure difference) / distance
- Pressure gradient force goes from high pressure to low pressure.
- Closely spaced isobars on a weather map indicate steep pressure gradient.

Single-Cell Model:
Explains Why There are Tropical Easterlies

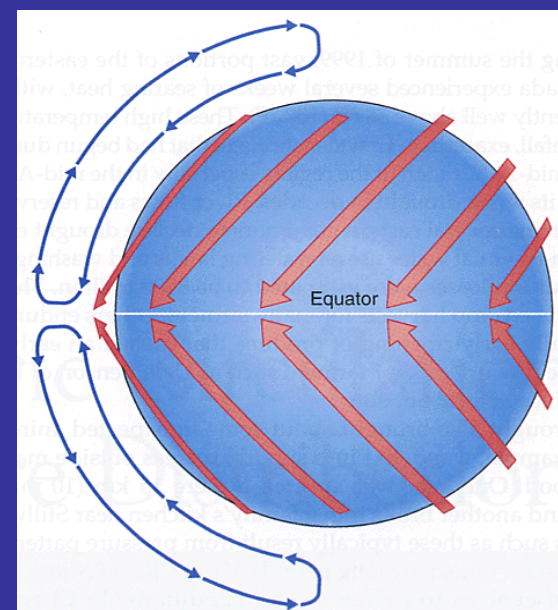
Without Earth Rotation





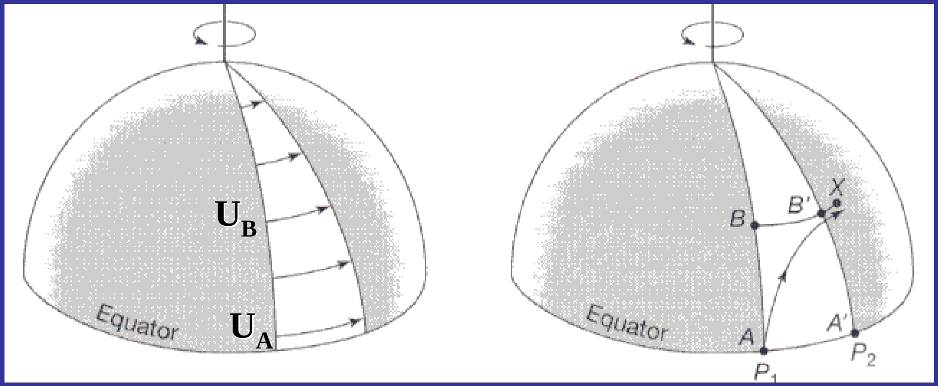
Coriolis Force

With Earth Rotation



(Figures from *Understanding Weather & Climate* and *The Earth System*)

Coriolis Force



(from *The Earth System*)

- First, Point A rotates faster than Point B ($U_A > U_B$)

➔ $U_A > U_B$

➔ A northward motion starting at A will arrive to the east of B

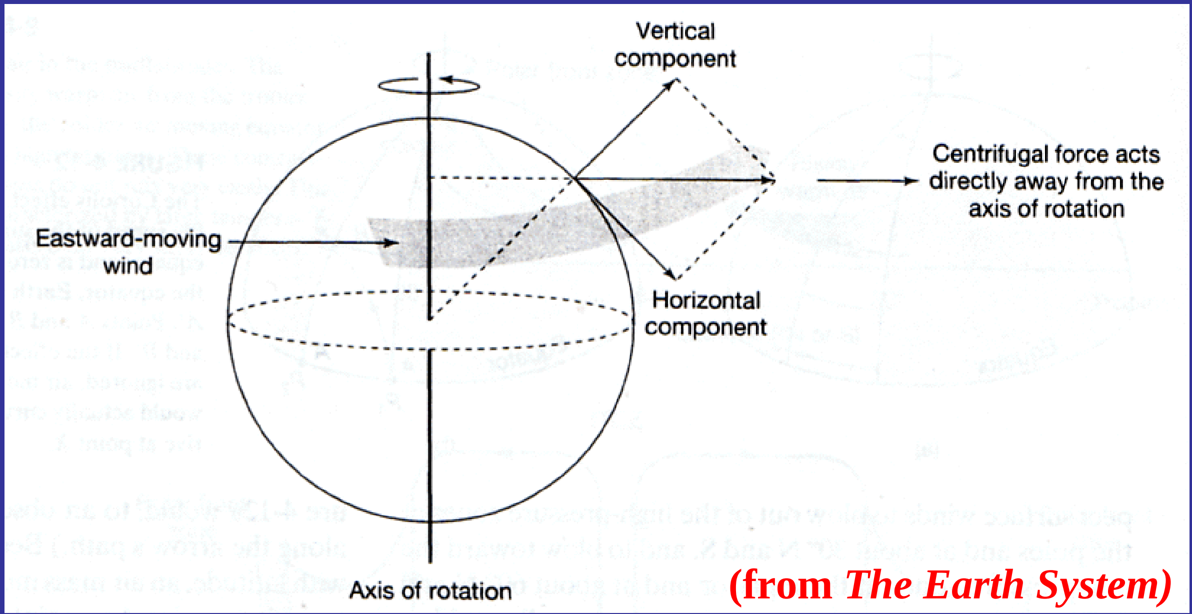
➔ It looks like there is a “force” pushing the northward motion toward right

➔ This apparent force is called “Coriolis force”:

Coriolis Force = f V

where $f = 2*\Omega*\mathrm{Sin(lat)}$ and $\Omega = 7.292 \times 10^{-5}$ rad s^{-1}

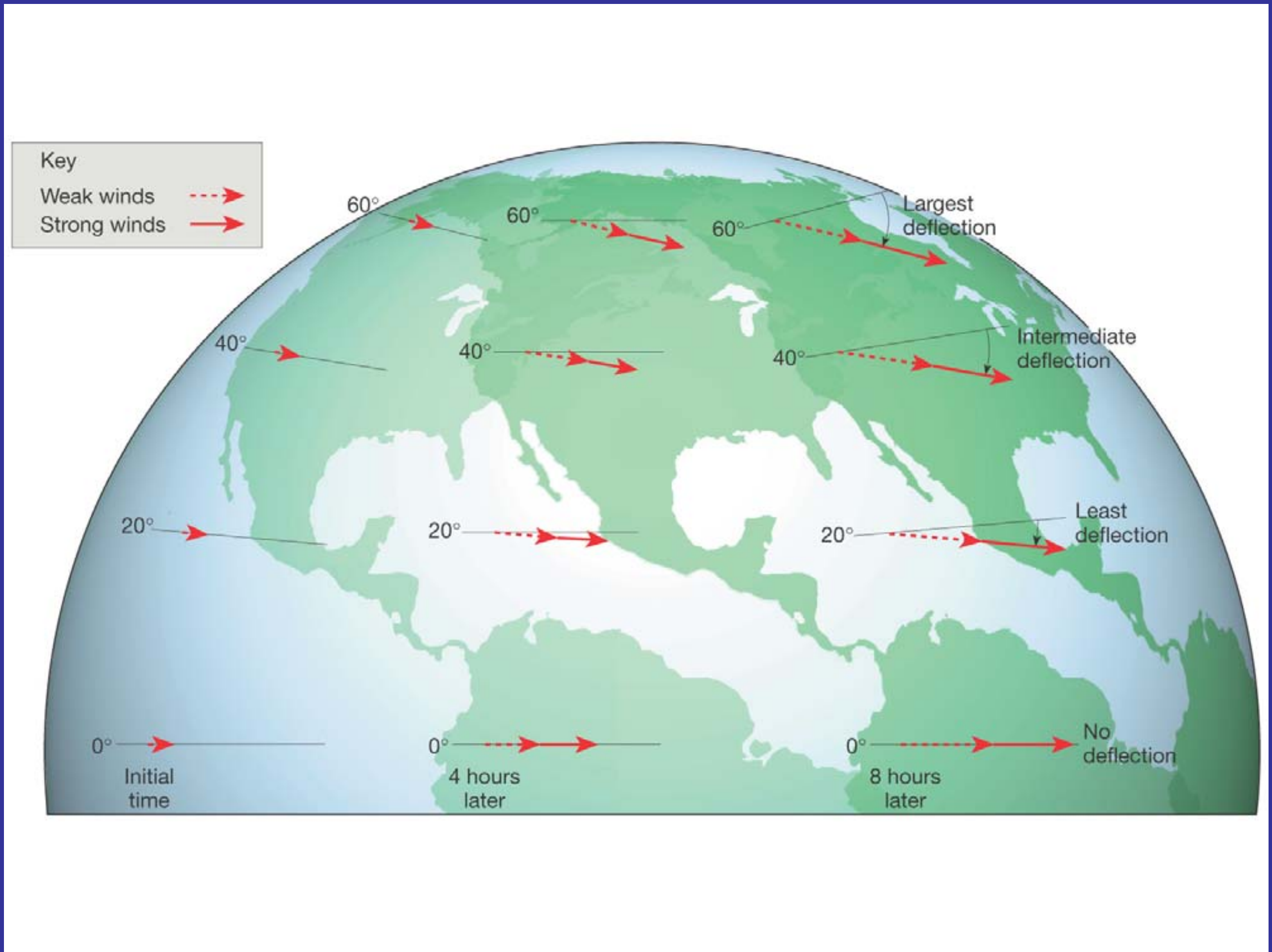
Another Kind of Coriolis Force



(from *The Earth System*)

- The Coriolis force also causes the east-west wind to deflect to the right of its intent path in the Northern Hemisphere and to the left in the Southern Hemisphere.
- The deflections are caused by the centrifugal force associated with the east-west motion, and , therefore, related to rotation of the Earth, and are also considered as a kind of Coriolis force.
- Although the description of the deflection effect for north-south and east-west motions are very different, their mathematical expressions are the same.

Coriolis Force Change with latitudes



(from *The Atmosphere*)

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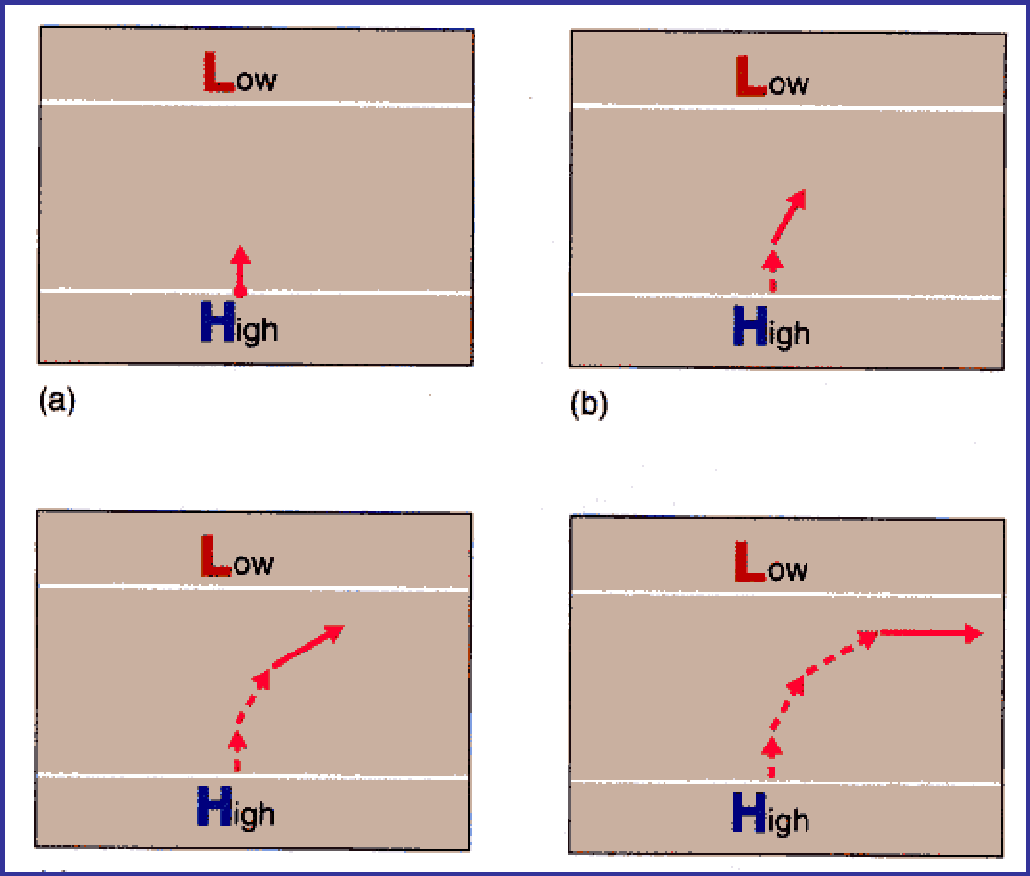
Coriolis Force

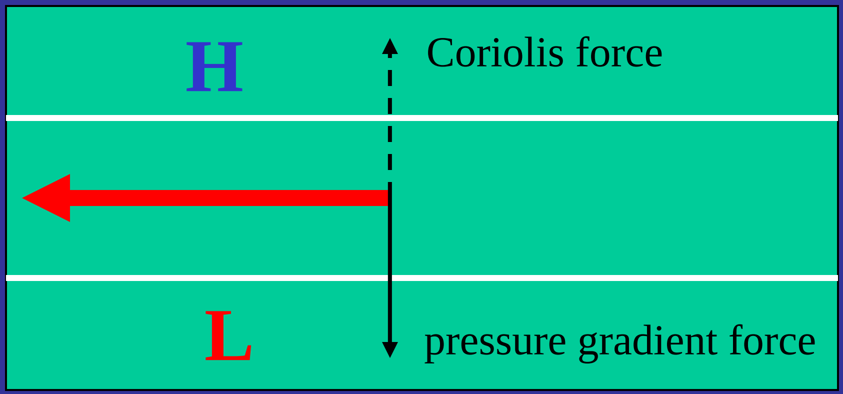
- Coriolis force causes the wind to deflect to the right of its intent path in the Northern Hemisphere and to the left in the Southern Hemisphere.
- The magnitude of Coriolis force depends on (1) the rotation of the Earth, (2) the speed of the moving object, and (3) its latitudinal location.
- The larger the speed (such as wind speed), the stronger the Coriolis force.
- The higher the latitude, the stronger the Coriolis force.
- The Corioils force is zero at the equator.
- Coriolis force is one major factor that determine weather pattern.

How Does Coriolis Force Affect Wind Motion?



(from *Weather & Climate*)

Geostrophic Balance



- ❑ By doing scale analysis, it has been shown that large-scale and synoptic-scale weather system are in geostropic balance.
- ❑ Geostrophic winds always follow the constant pressure lines (isobar). Therefore, we can figure out flow motion by looking at the pressure distribution.

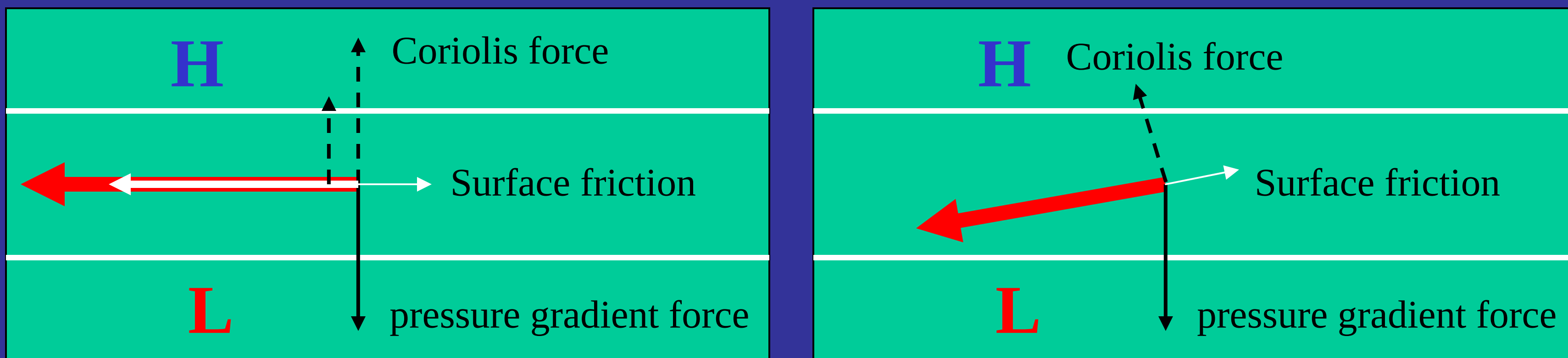
Surface Friction

- Friction Force = c * V

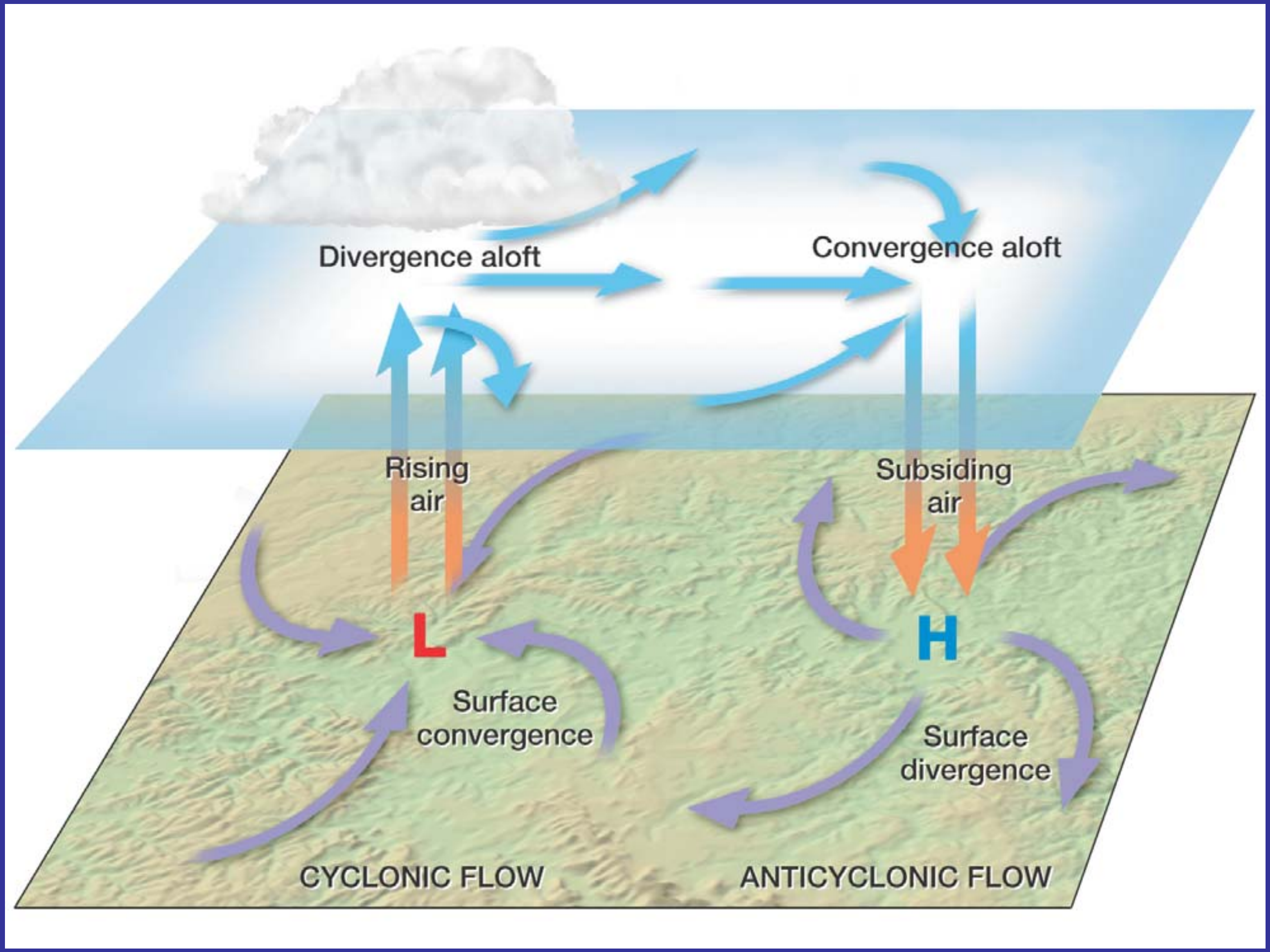
  c = friction coefficient

  V = wind speed

Frictional Effect on Surface Flow

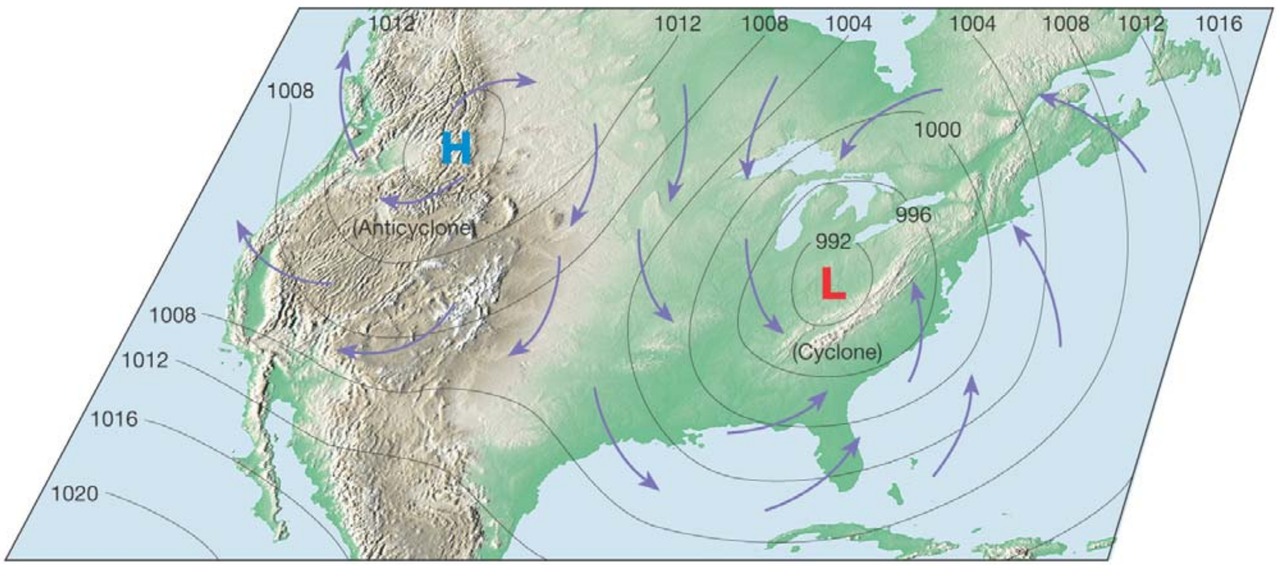


- Surface friction force slows down the geostrophic flow.
- The flow turns into (out of) the low (high) press sides.
- Convergence (divergence) is produced with the flow.



(from *The Atmosphere*)

Surface High and Low Pressure Systems



(from *The Atmosphere*)

Balance of Force in the Horizontal

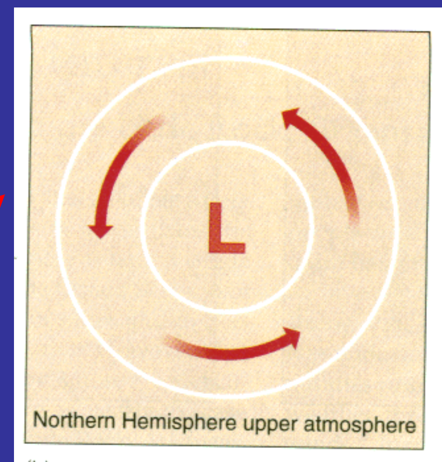
H (high pressure)

pressure gradient force

L (low pressure)

Can happen in the tropics where the Coriolis force is small.

geostrophic balance



Upper Troposphere (free atmosphere)

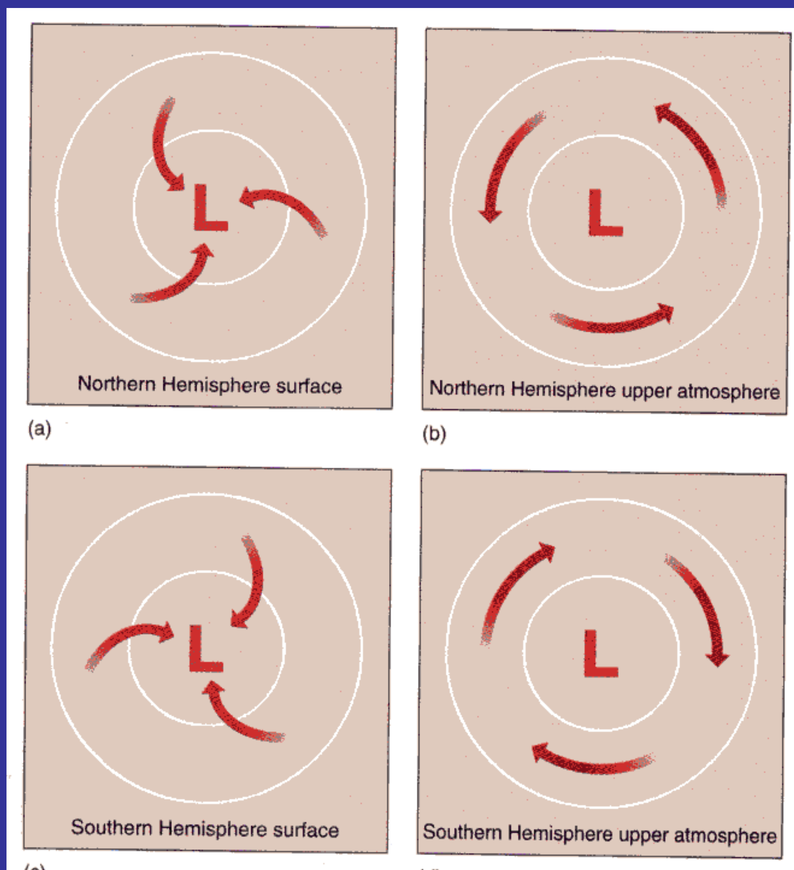
geostrophic balance plus frictional force

Surface

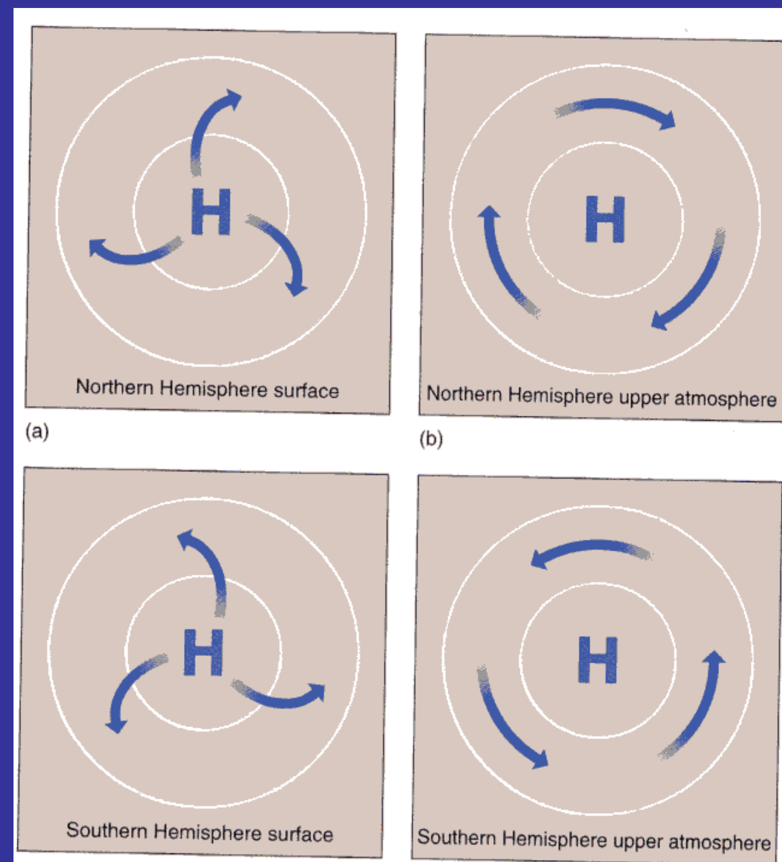
(from *Weather & Climate*)

Surface Geostrophic Flow

Cyclonic Flow

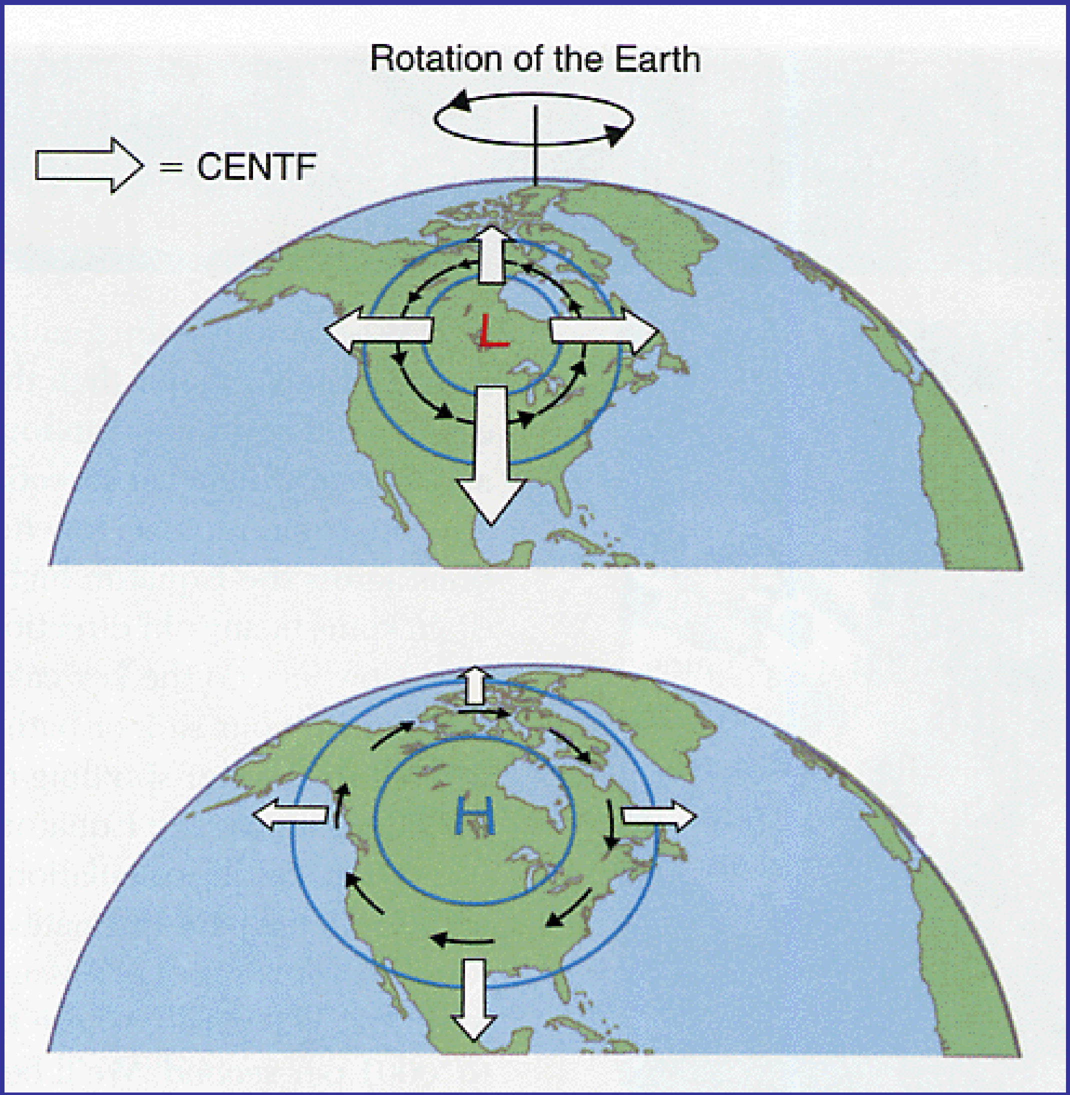


Anticyclonic Flow



(figures from *Weather & Climate*)

Centrifugal Force

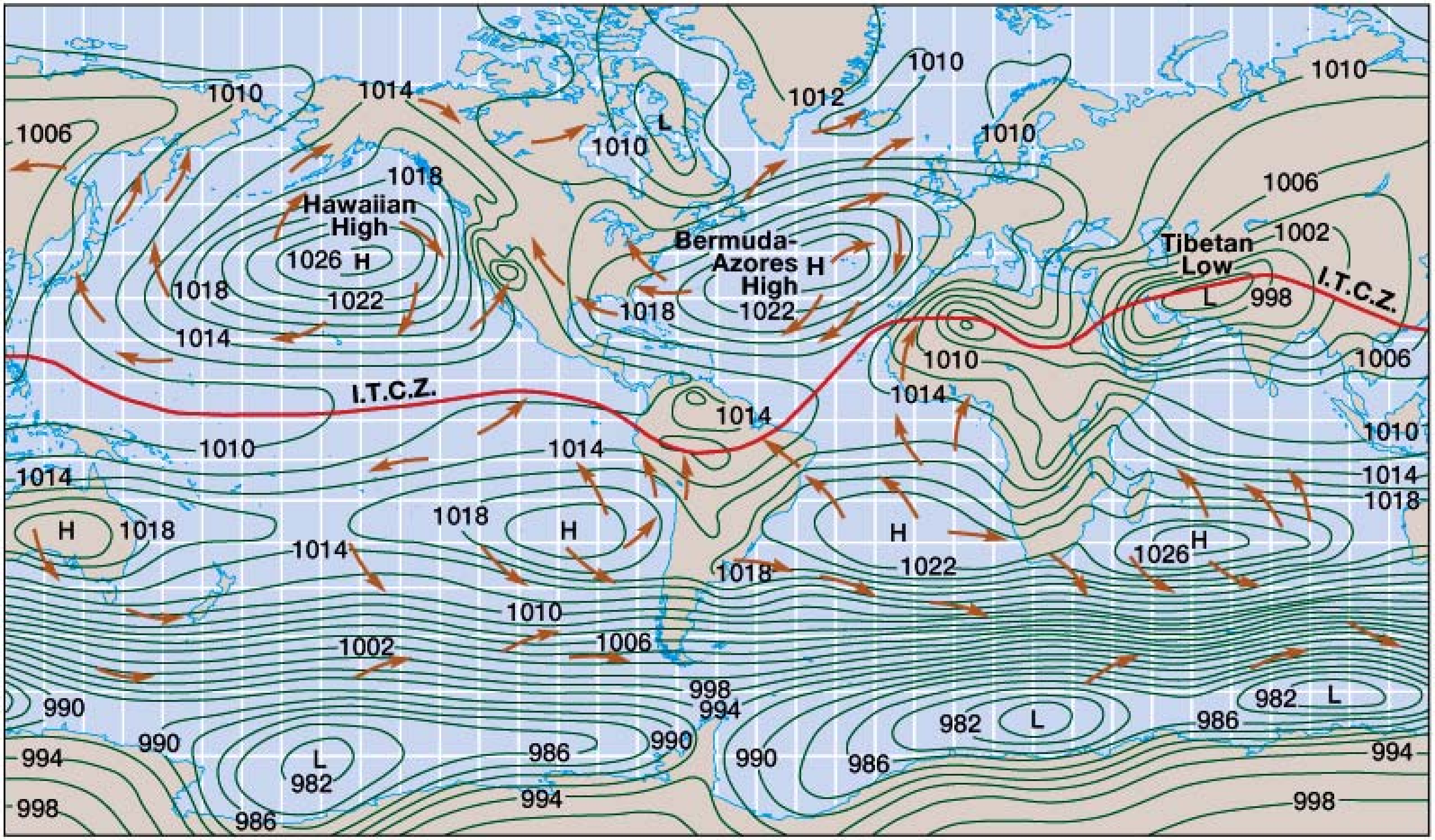


(from *The Atmosphere*)

- The force that change the direction (but not the speed) of motion is called the centrifugal force.

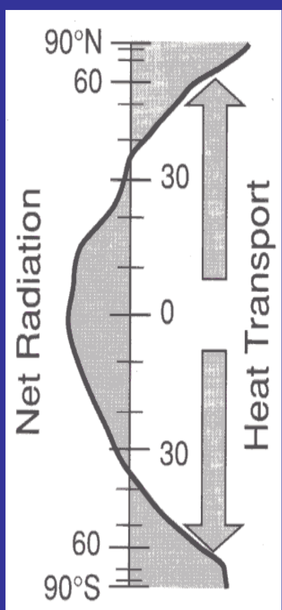
- Centrifugal Force = V^2 / R.
  V = wind speed
  R = the radius of the curvature

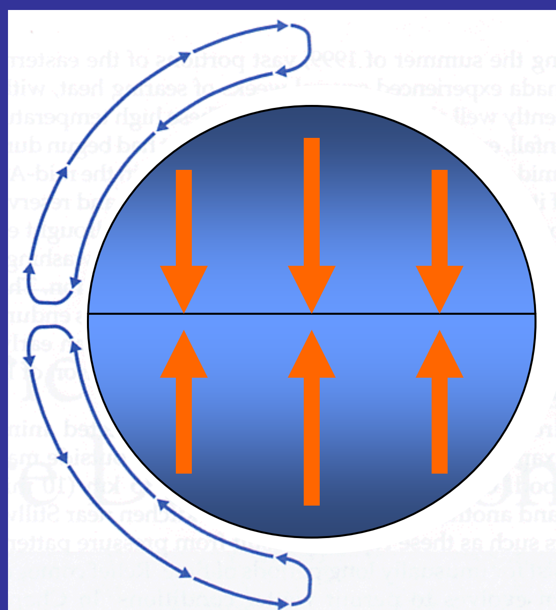
July



Single-Cell Model:
Explains Why There are Tropical Easterlies

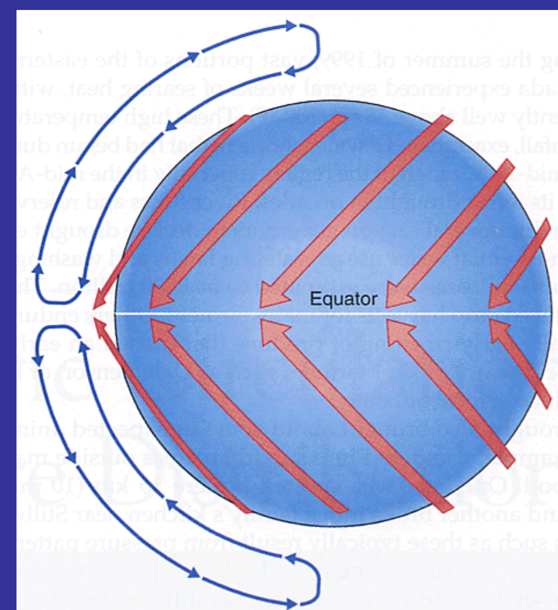
Without Earth Rotation





Coriolis Force

With Earth Rotation



(Figures from *Understanding Weather & Climate* and *The Earth System*)

Breakdown of the Single Cell → Three-Cell Model

- Absolute angular momentum at **Equator** = Absolute angular momentum at **60°N**

- The observed zonal velocity at the equatoru is u_{eq} = -5 m/sec.
  Therefore, the total velocity at the equator is U=rotational velocity ($U_0 + u_{Eq}$)

- The zonal wind velocity at 60°N (u_{60N}) can be determined by the following:

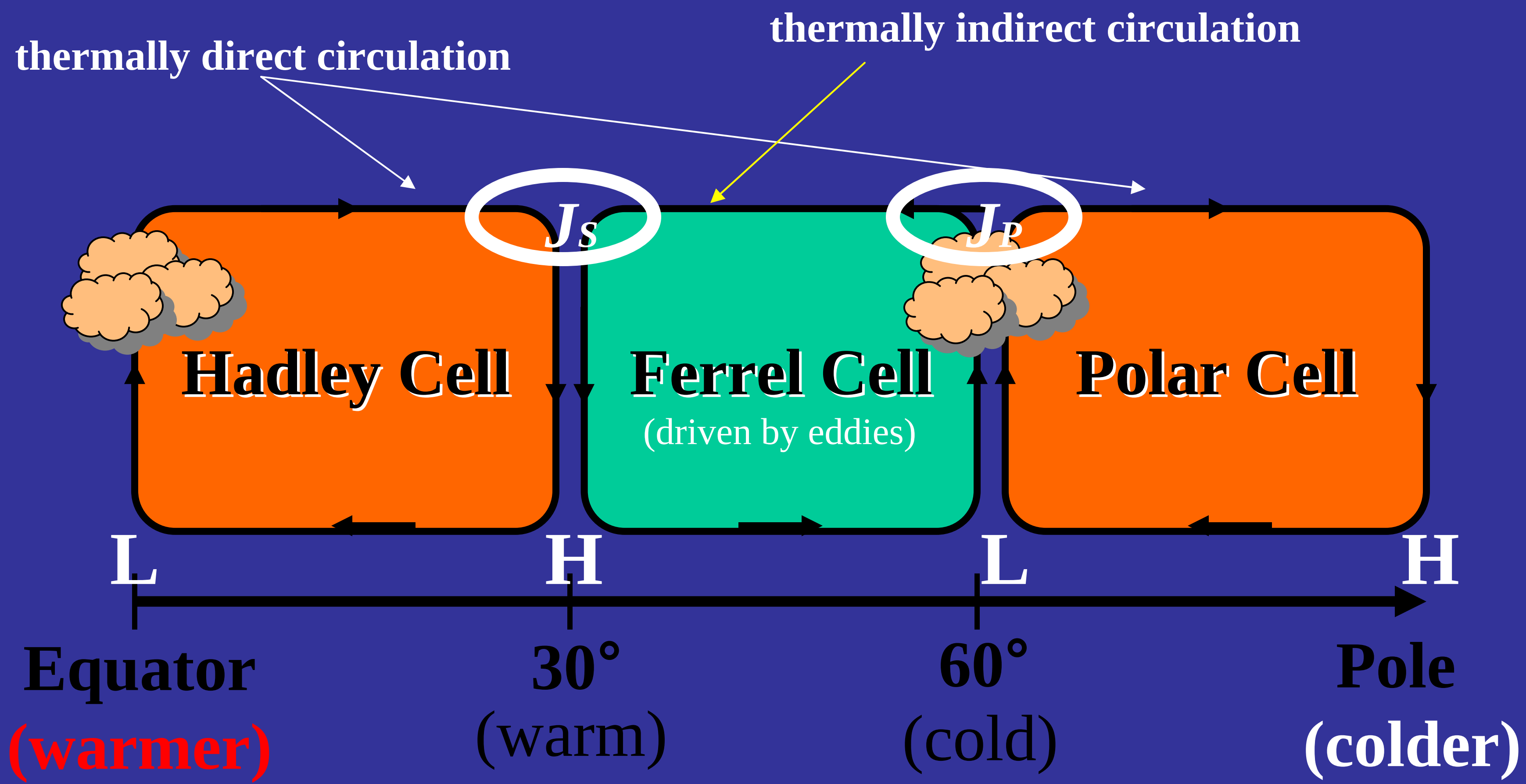
$$(U_0 + u_{Eq}) * a * \text{Cos}(0°) = (U_{60N} + u_{60N}) * a * \text{Cos}(60°)$$

$$(\Omega * a * \text{Cos}0° - 5) * a * \text{Cos}0° = (\Omega * a * \text{Cos}60° + u_{60N}) * a * \text{Cos}(60°)$$

u_{60N} = 687 m/sec !!!!

This high wind speed is not observed!

Properties of the Three Cells



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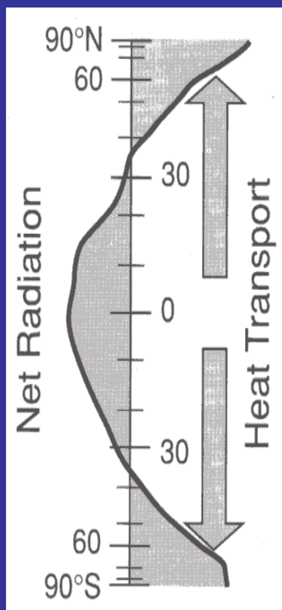
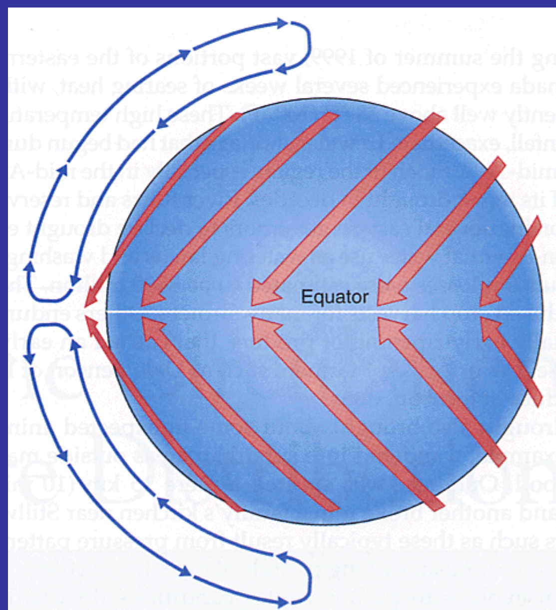
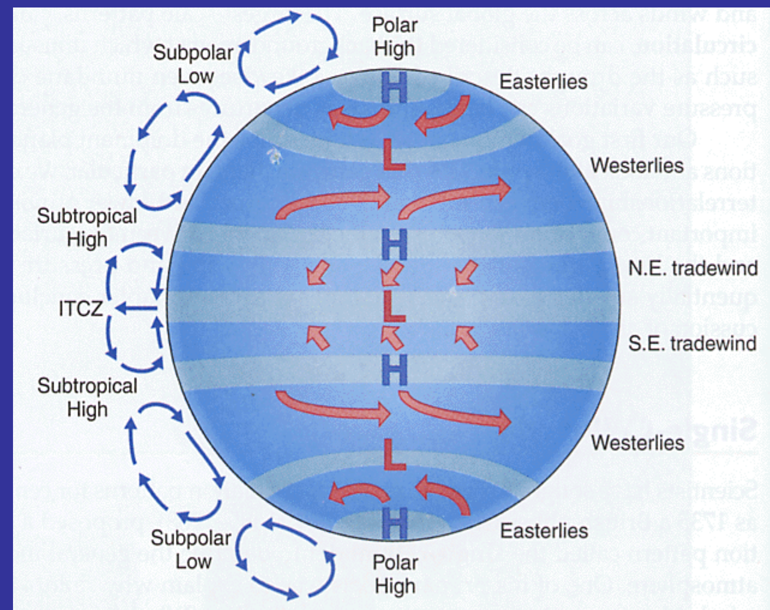
Atmospheric Circulation: Zonal-mean Views



Single-Cell Model

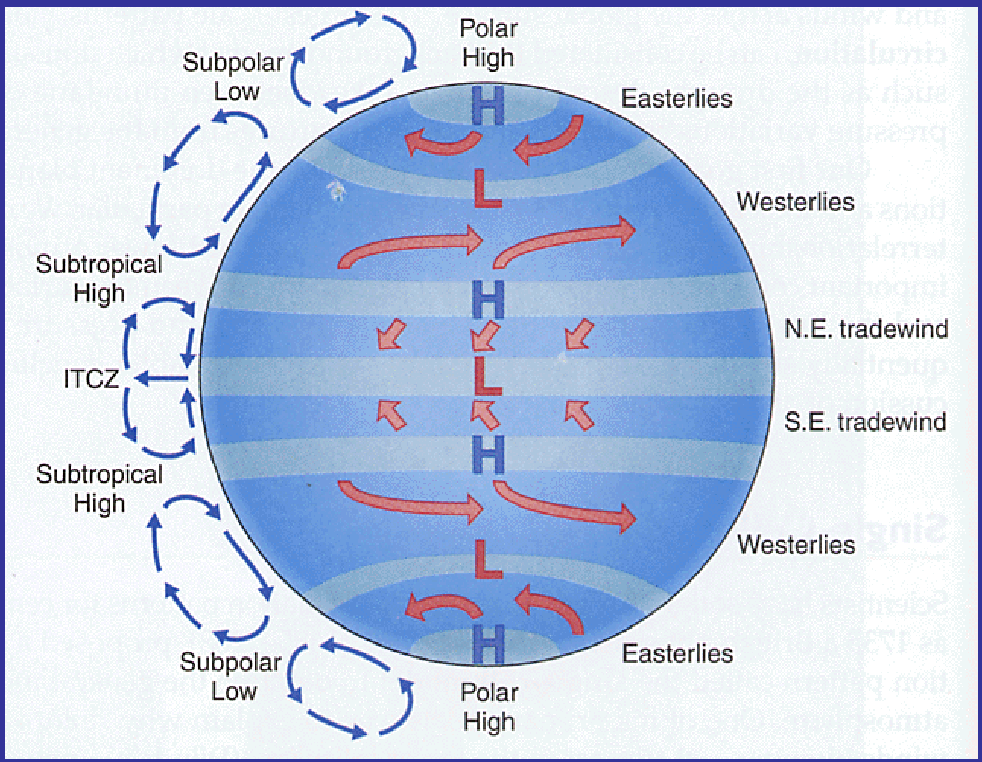


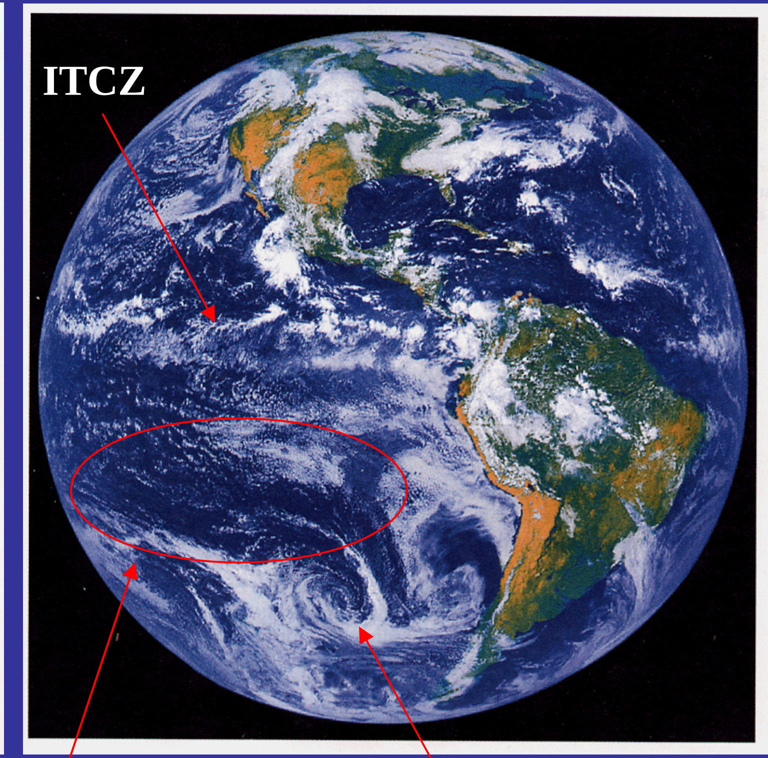
Three-Cell Model



(Figures from *Understanding Weather & Climate* and *The Earth System*)

The Three Cells





Subtropical High

midlatitude Weather system

(Figures from *Understanding Weather & Climate* and *The Earth System*)

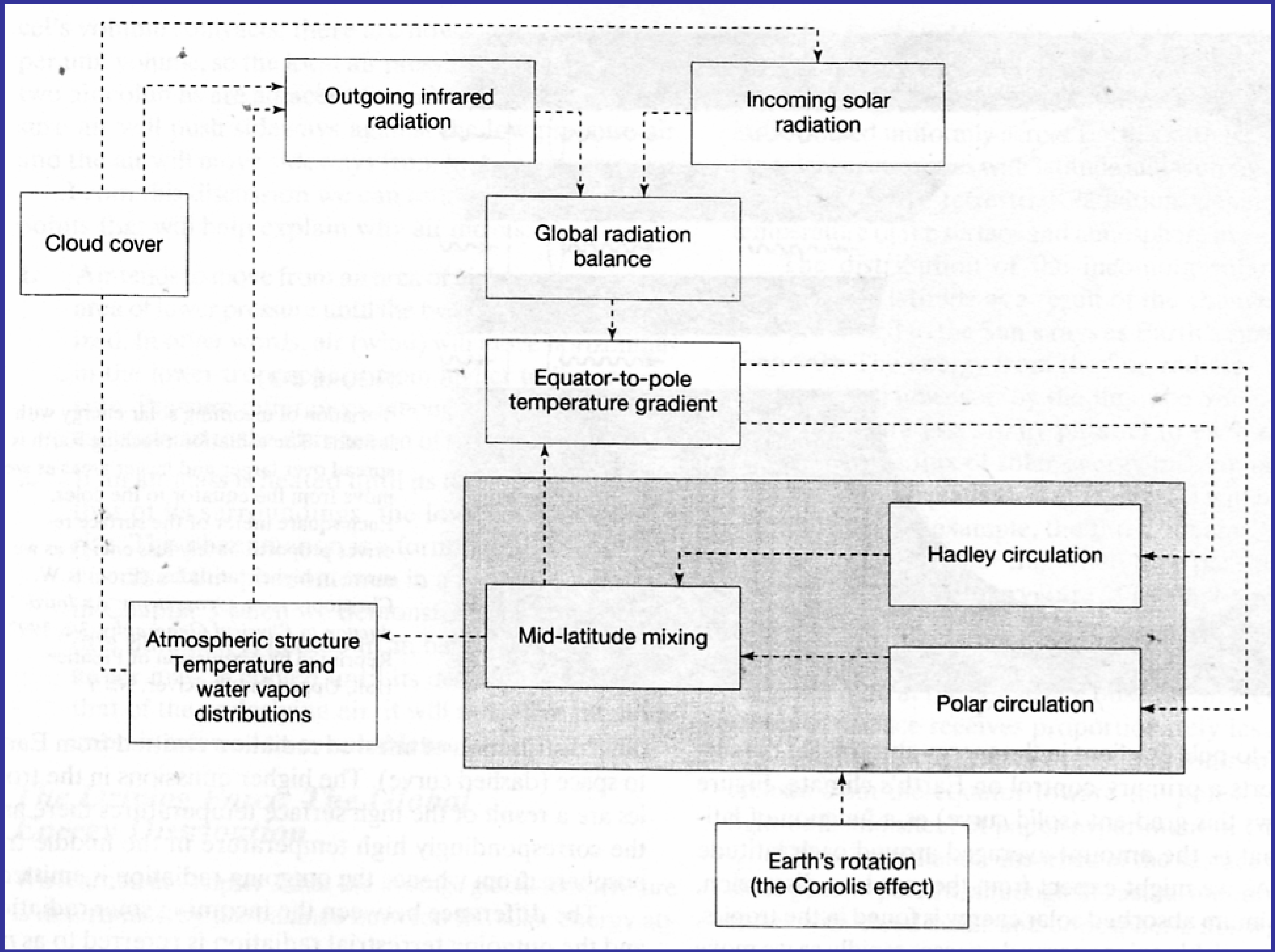
Thermally Direct/Indirect Cells

- **Thermally Direct Cells (Hadley and Polar Cells)**

  Both cells have their rising branches over warm temperature zones and sinking braches over the cold temperature zone. Both cells directly convert thermal energy to kinetic energy.

- **Thermally Indirect Cell (Ferrel Cell)**

  This cell rises over cold temperature zone and sinks over warm temperature zone. The cell is not driven by thermal forcing but driven by eddy (weather systems) forcing.



(from *The Earth System*)

Is the Three-Cell Model Realistic?

- ***Yes and No!***
  (Due to sea-land contrast and topography)

Yes: the three-cell model explains reasonably well the surface wind distribution in the atmosphere.

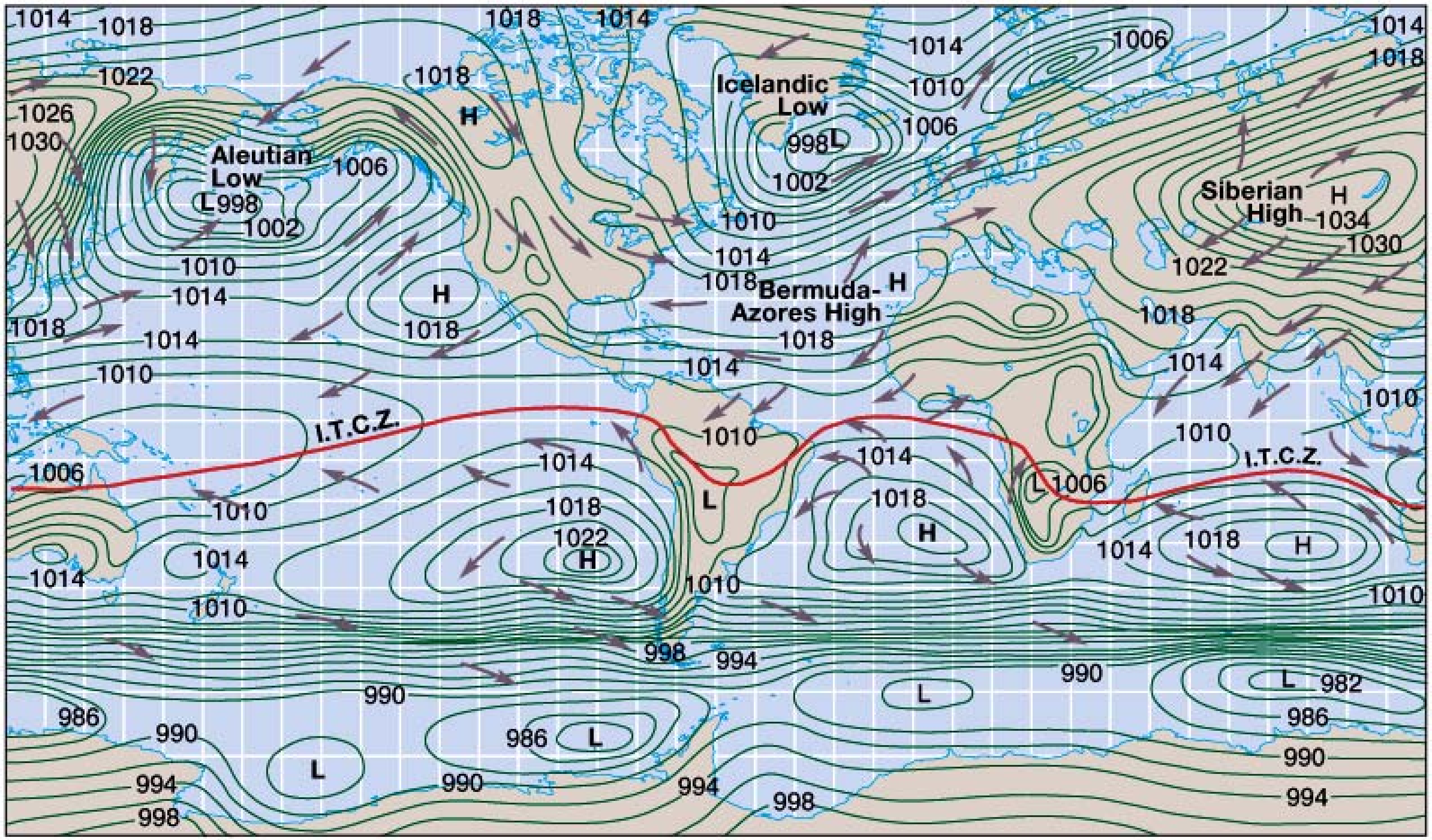
No: the three-cell model can not explain the circulation pattern in the upper troposphere. (planetary wave motions are important here.)

Semi-Permanent Pressure Cells

- **The Aleutian, Icelandic, and Tibetan lows**
  - The oceanic (continental) lows achieve maximum strength during winter (summer) months
  - The summertime Tibetan low is important to the east-Asia monsoon

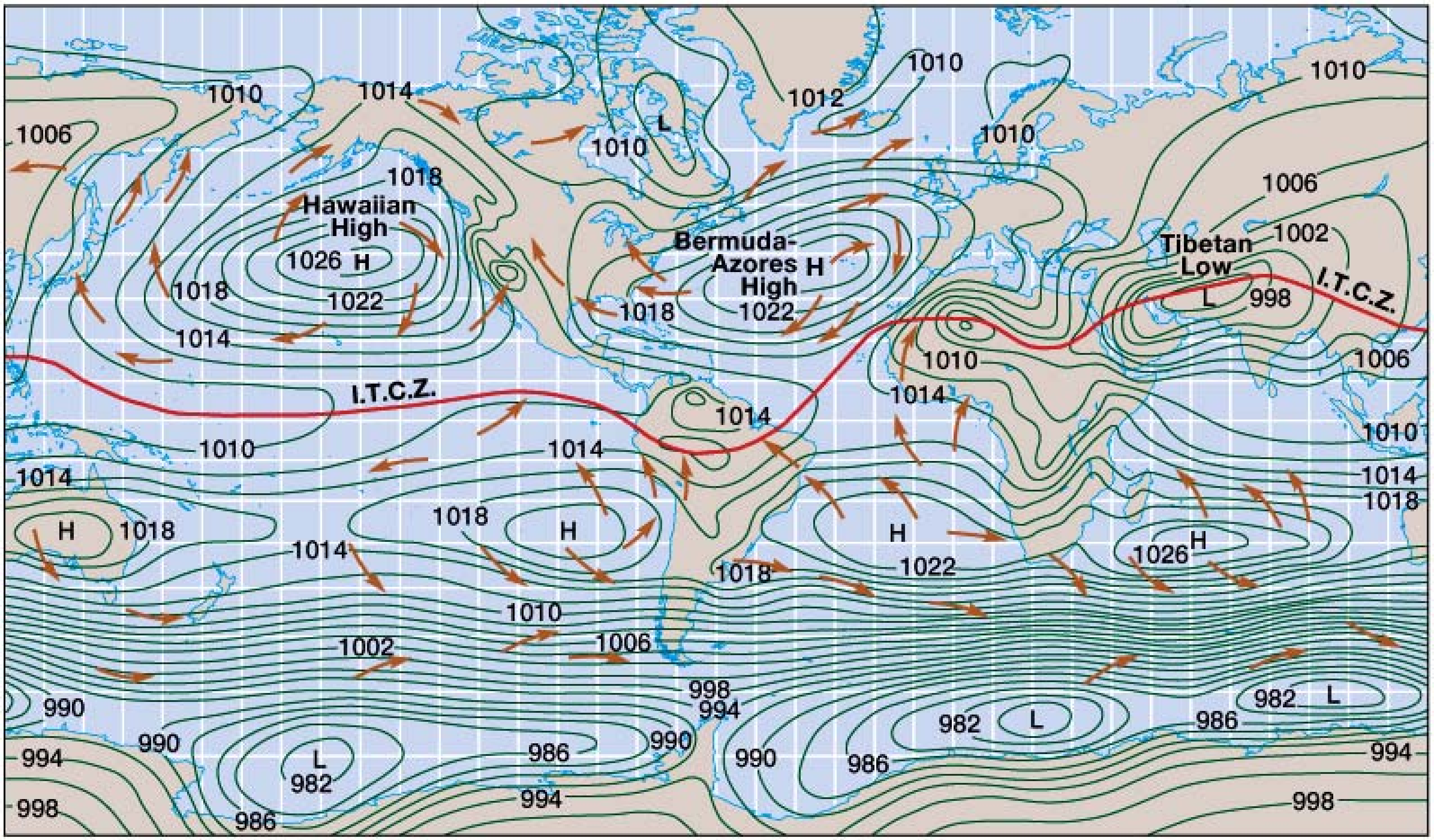
- **Siberian, Hawaiian, and Bermuda-Azores highs**
  - The oceanic (continental) highs achieve maximum strength during summer (winter) months

January

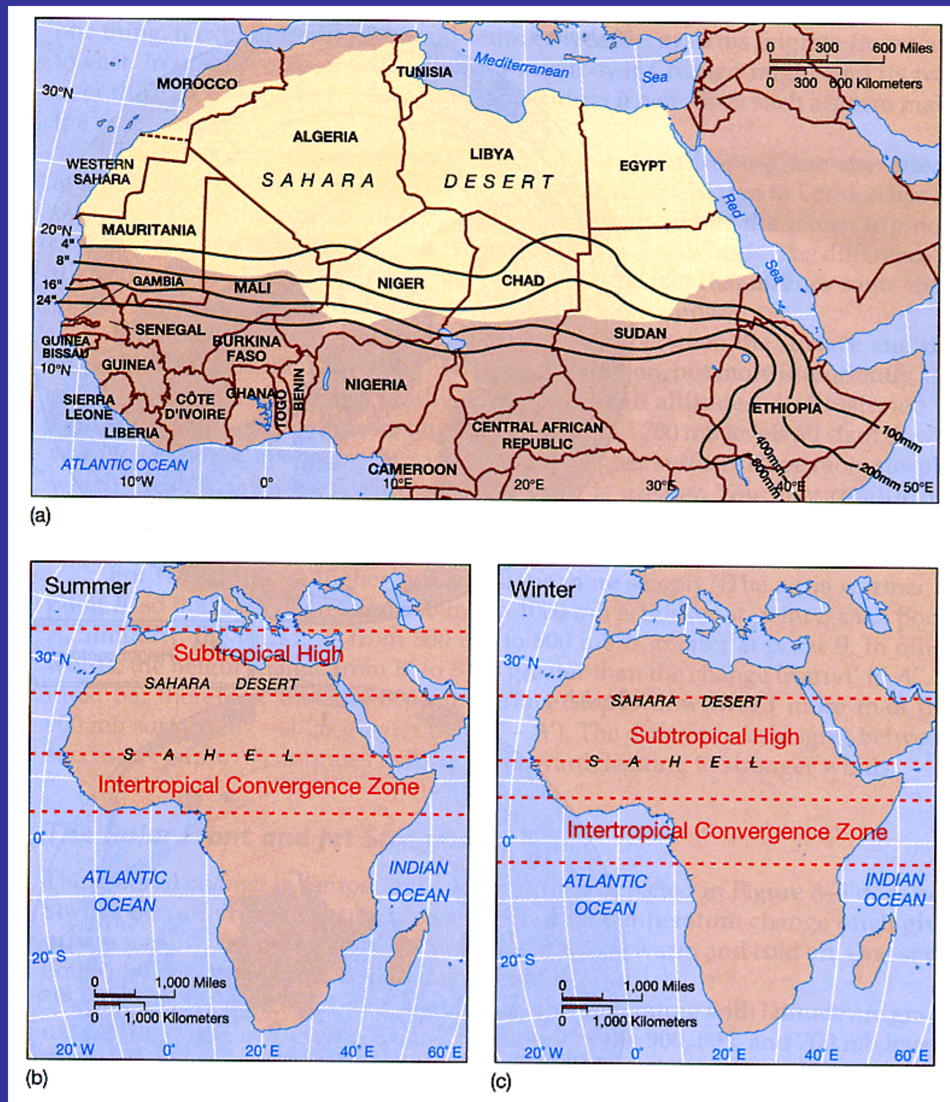


Aleutian Low
Icelandic Low
Bermuda-Azores High
Siberian High
I.T.C.Z.

July


Hawaiian High
1026 H
Bermuda-Azores High
H
Tibetan Low
L
I.T.C.Z.
I.T.C.Z.
1010
1014
1018
1022
1006
1012
1002
998
990
994
986
982

Sinking Branches and Deserts



(from *Weather & Climate*)

Global Distribution of Deserts

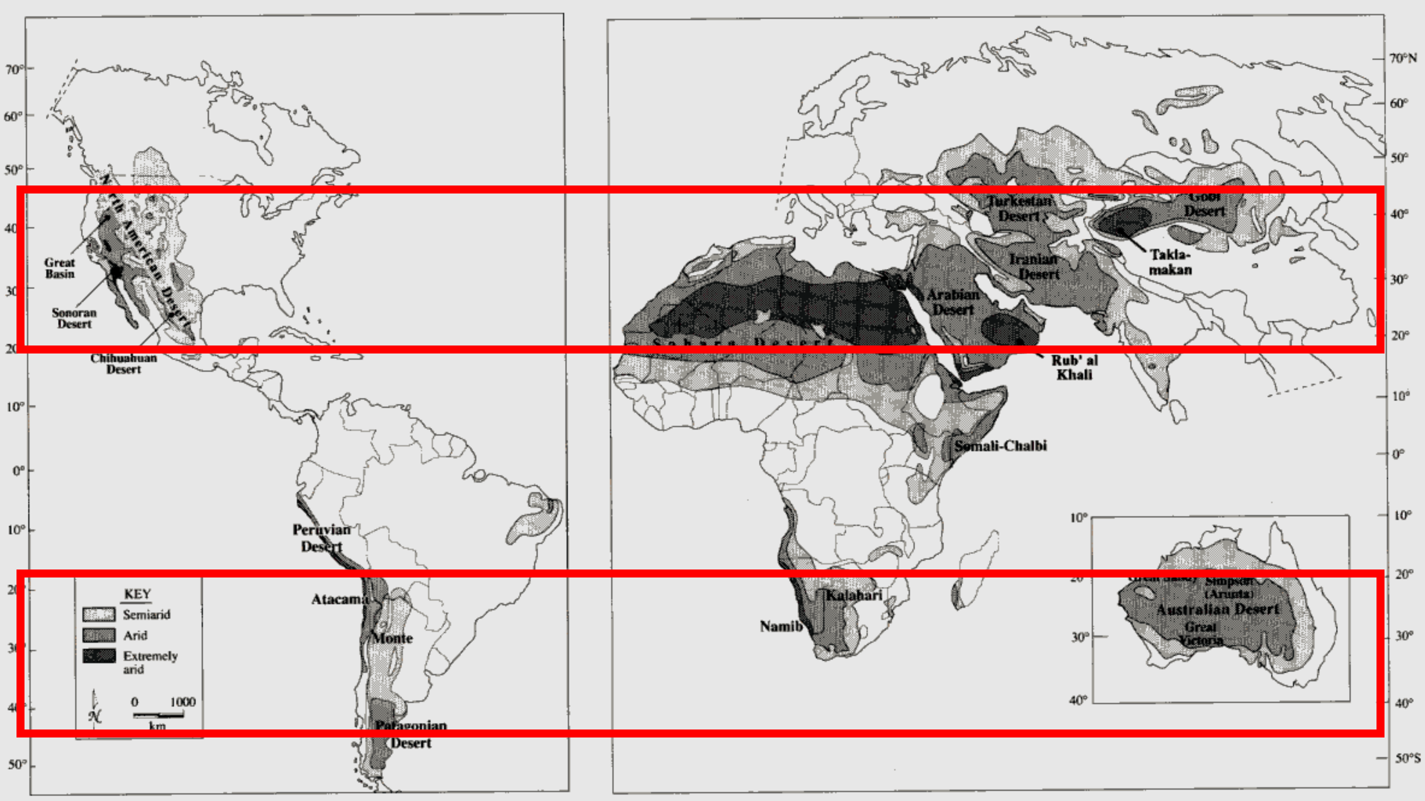
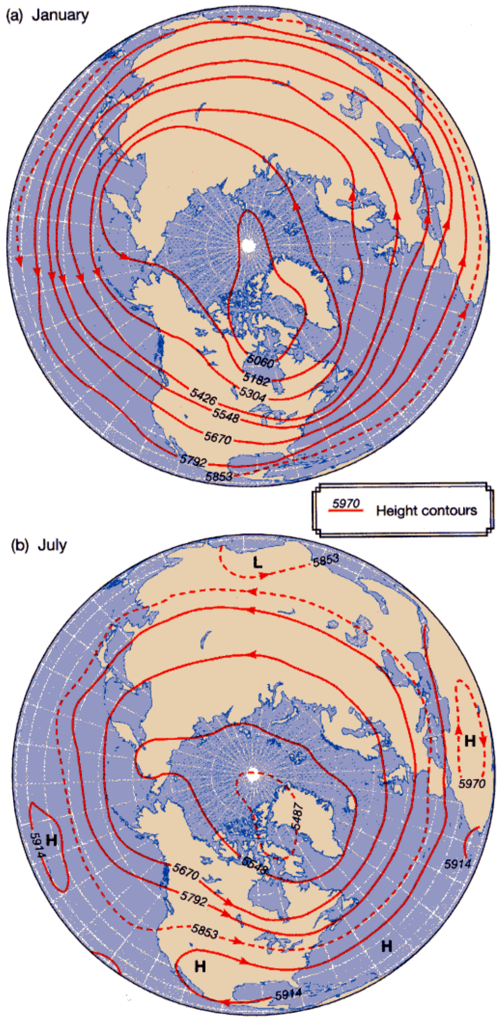


Fig. 6.21 Map showing arid lands around the world. Meigs classification taken from *Mosaic* magazine (Vol. 8, Jan/Feb 1977). [See McGinnies *et al.*, eds., (1968). Permission granted by the Office of Arid Lands Studies.]

(from *Global Physical Climatology*)

Upper Tropospheric Circulation



▶ **Figure 8–5**
The mean heights of the 500 mb levels for January (a) and July (b). The pattern is mostly zonal with decreasing heights toward the poles.

(from *Weather & Climate*)

❑ Only the Hadley Cell can be identified in the lower latitude part of the circulation.

❑ Circulation in most other latitudes are dominated by westerlies with wave patterns.

❑ Dominated by large-scale waver patterns (wave number 3 in the Northern hemisphere).

Subtropical and Polar Jet Streams

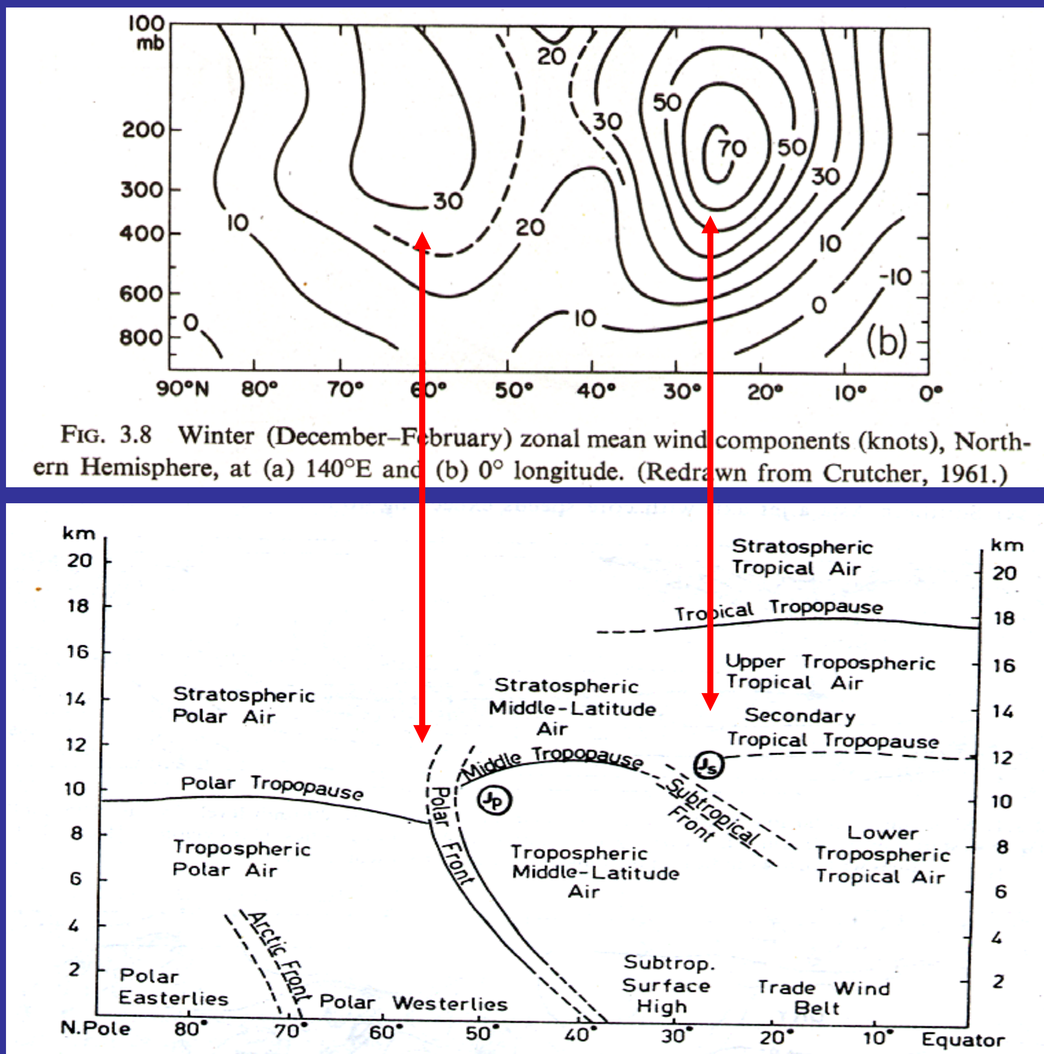


FIG. 3.8 Winter (December–February) zonal mean wind components (knots), Northern Hemisphere, at (a) 140°E and (b) 0° longitude. (Redrawn from Crutcher, 1961.)

(from *Atmospheric Circulation Systems*)

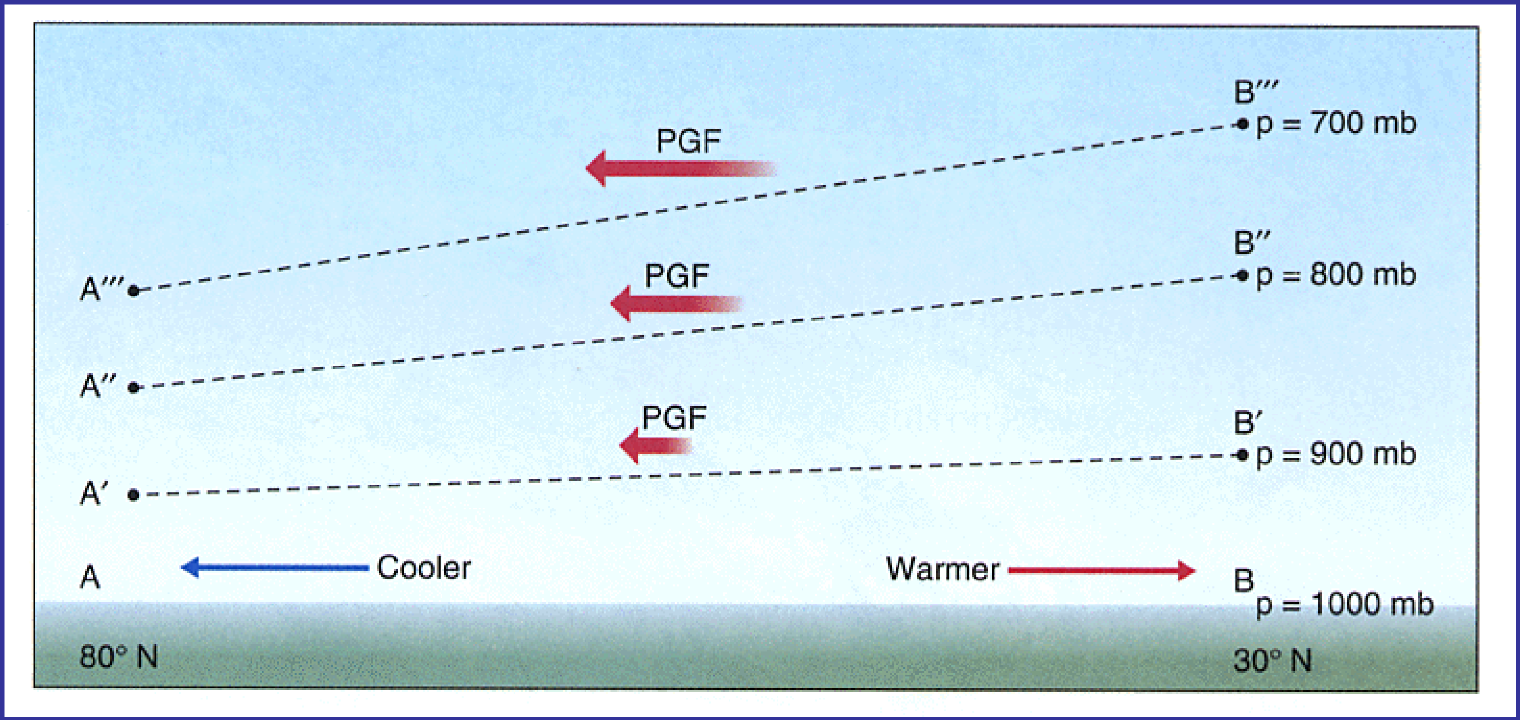
❑ Subtropical Jet

Located at the higher-latitude end of the Hadley Cell. The jet obtain its maximum wind speed (westerly) due the conservation of angular momentum.

❑ Polar Jet

Located at the thermal boundary between the tropical warm air and the polar cold air. The jet obtain its maximum wind speed (westerly) due the latitudinal thermal gradient (thermal wind relation).

Thermal Wind Relation



(from *Weather & Climate*)

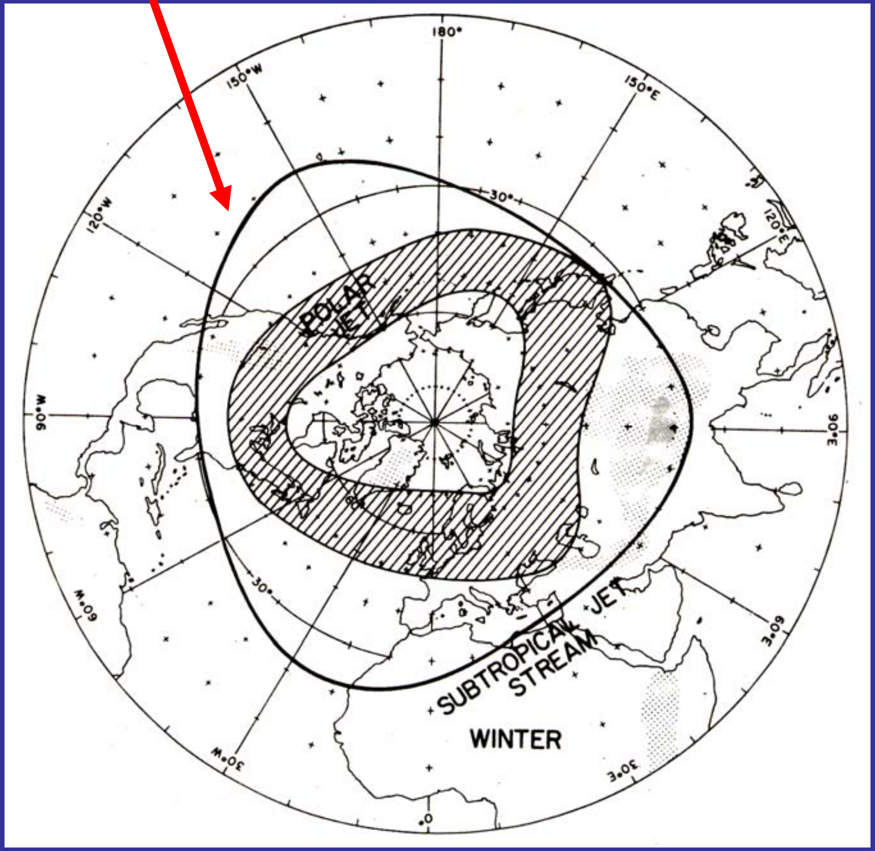
Thermal Wind Equation

$$\partial U/\partial z \propto -\partial T/\partial y$$

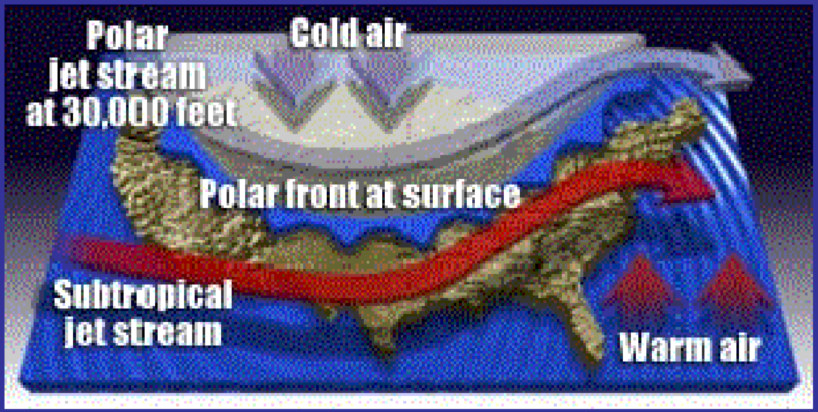
- The vertical shear of zonal wind is related to the latitudinal gradient of temperature.
- Jet streams usually are formed above baroclinic zone (such as the polar front).

Jet Streams Near the Western US

Pineapple Express



(from *Riehl (1962), Palmen and Newton (1969)*)

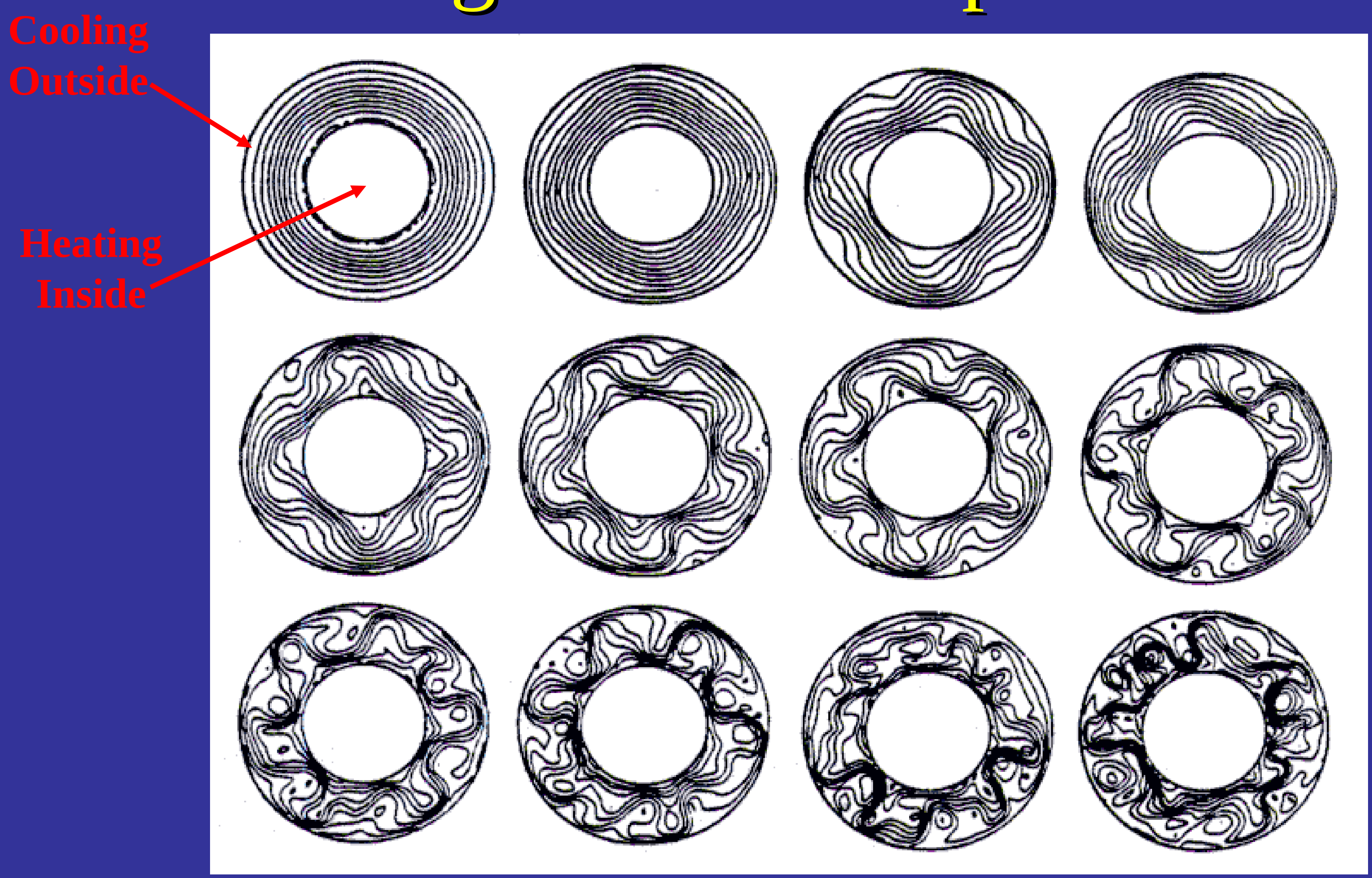


- ❑ Both the polar and subtropical jet streams can affect weather and climate in the western US (such as California).
- ❑ El Nino can affect western US climate by changing the locations and strengths of these two jet streams.

Parameters Determining Mid-latitude Weather

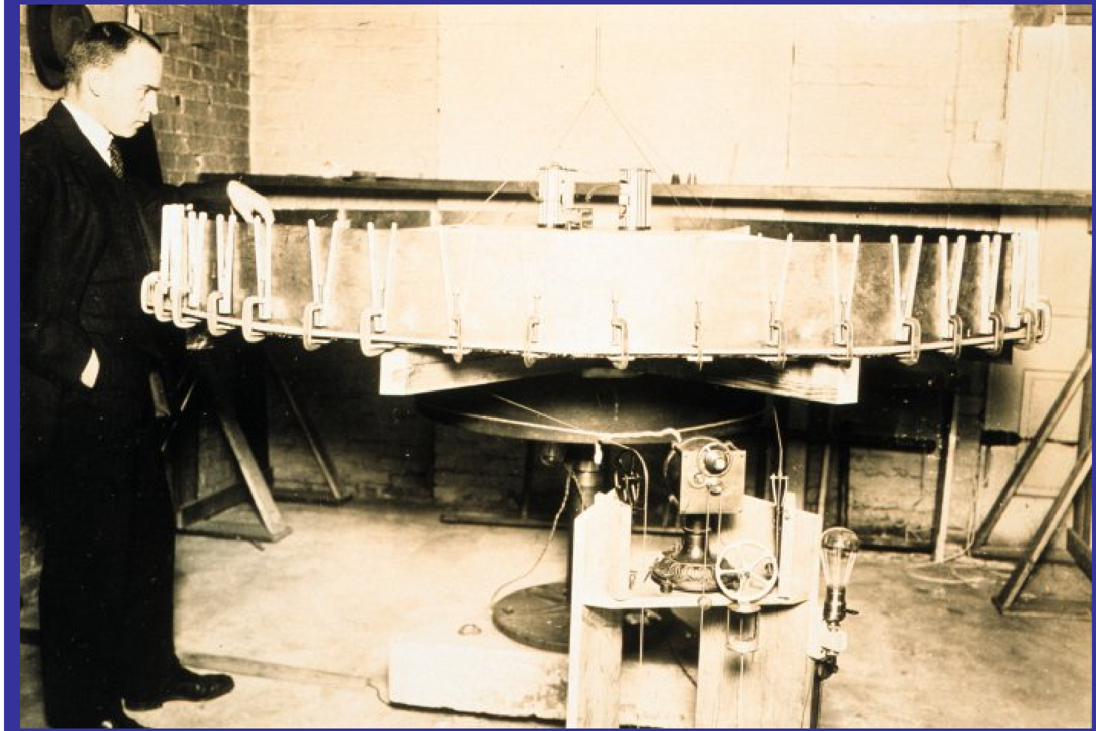
- Temperature differences between the equator and poles
- The rate of rotation of the Earth.

Rotating Annulus Experiment



(from *"Is The Temperature Rising?"*)

New Understanding of Cyclone after WWII



Carl Gustav Rossby (1898-1957)

- Carl Rossby mathematically expressed relationships between mid-latitude cyclones and the upper air during WWII.
- Mid-latitude cyclones are a large-scale waves (now called Rossby waves) that grow from the “baroclinic” instabiloity associated with the north-south temperature differences in middle latitudes.

Polar Front Theory

Vilhelm Bjerknes (1862-1951)

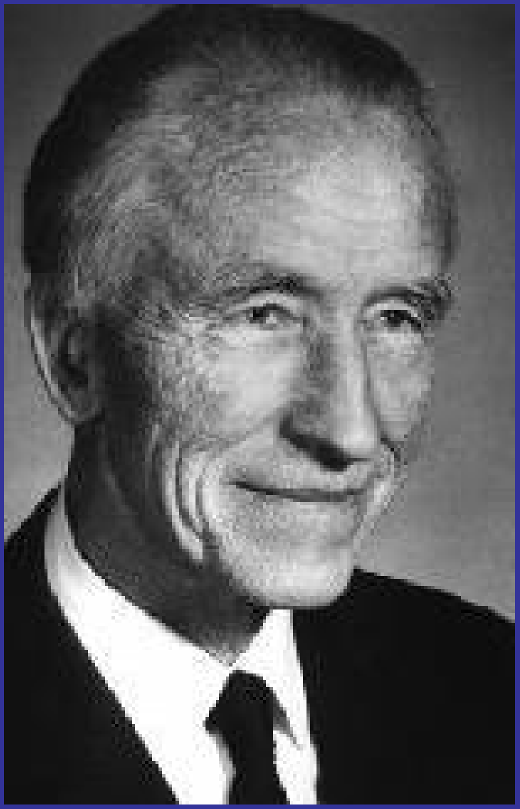
- ***Bjerknes,*** the founder of the Bergen school of meteorology, developed polar front theory during WWI to describe the formation, growth, and dissipation of mid-latitude cyclones.

El Nino and Southern Oscillation

❑ Jacob Bjerknes was the first one to recognizes that El Nino is not just an oceanic phenomenon (in his 1969 paper).

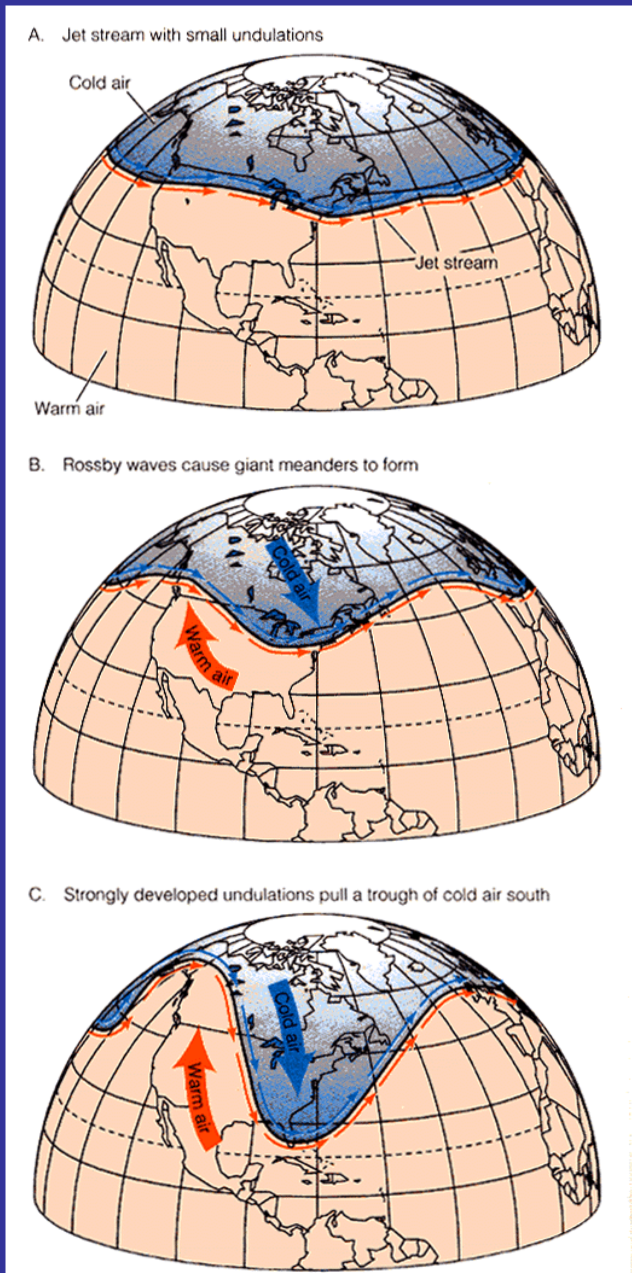
❑ In stead, he hypothesized that the warm waters of El Nino and the pressure seasaw of Walker’s Southern Oscillation are part and parcel of the same phenomenon: the ENSO.

❑ Bjerknes’s hypothesis of coupled atmosphere-ocean instability laid the foundation for ENSO research.



Jacob Bjerknes

(From *The Blue Planet*)



How Cyclone Grows?

Potential Energy ➔ Available P. Energy

(cold/warm air moves south/north)

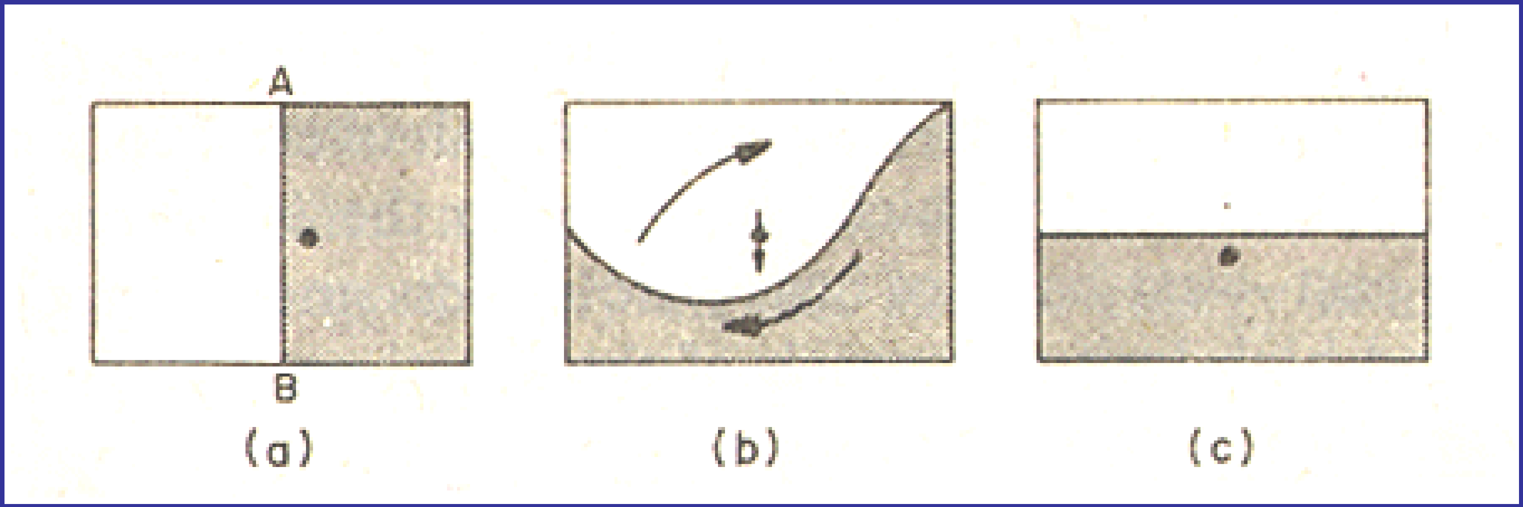
($V^*T^* > 0$)

Available Energy ➔ Kinetic Energy

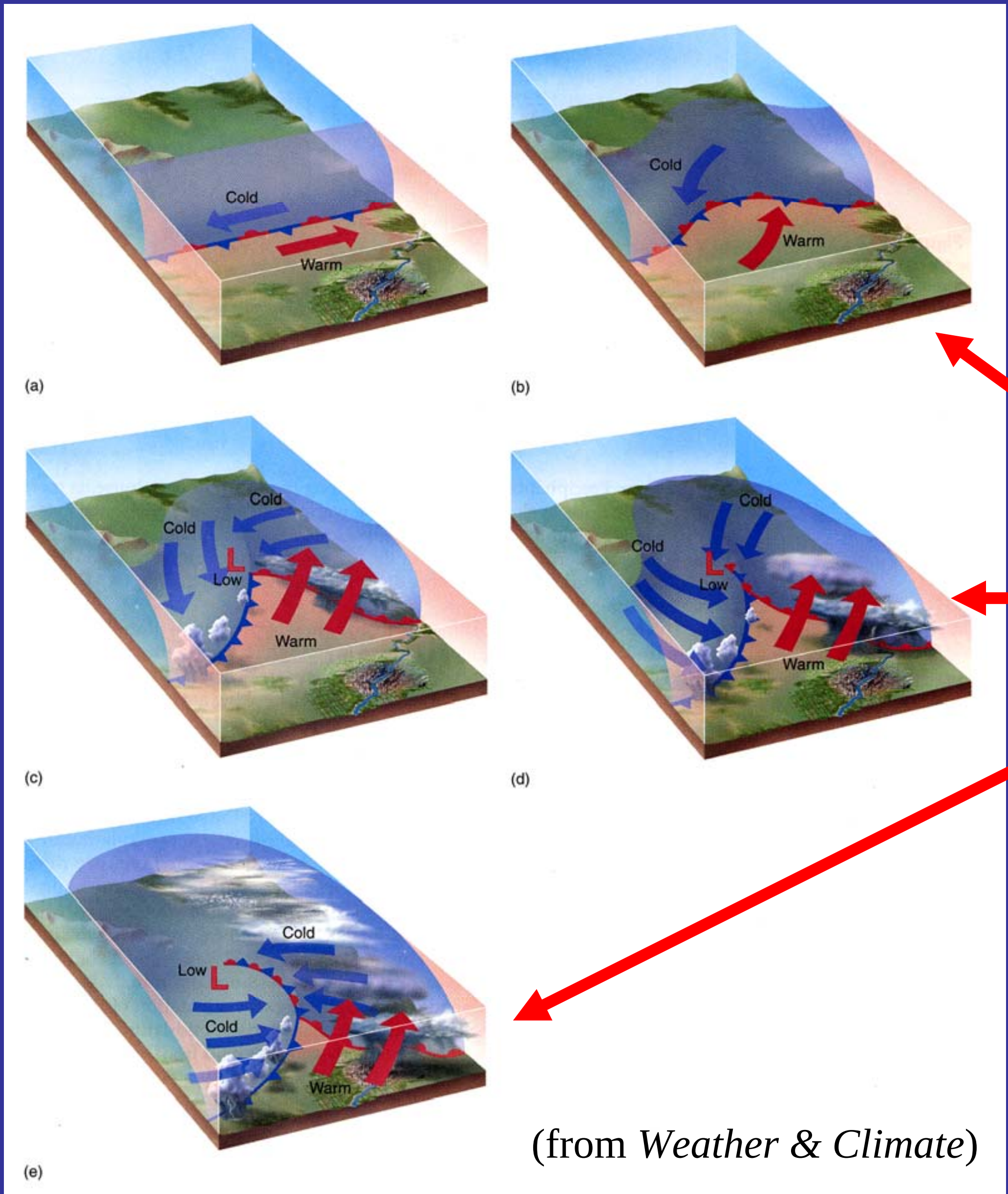
(cold/warm air moves down/up)

($W^*T^*>0$)

Available Potential Energy



Life Cycle of Mid-Latitude Cyclone



(from *Weather & Climate*)

- Cyclogenesis
- Mature Cyclone
- Occlusion

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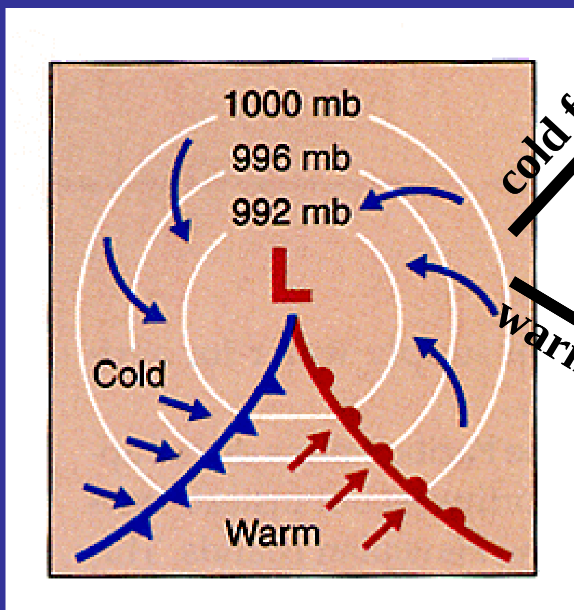
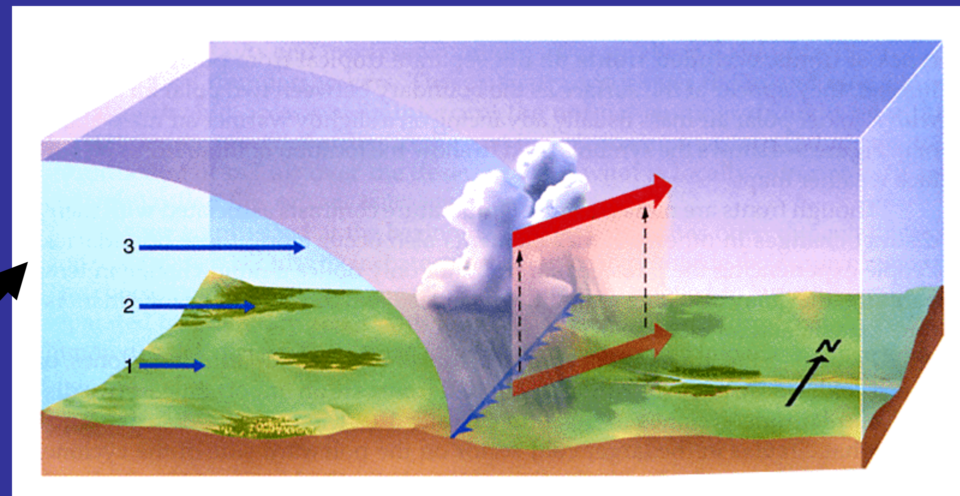
Cold and Warm Fronts

Mid-Latitude Cyclone

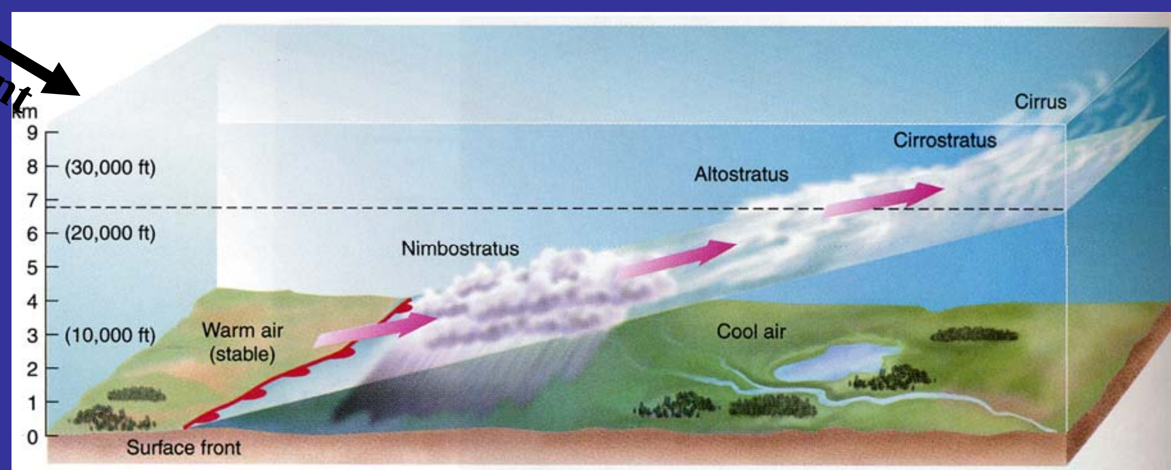


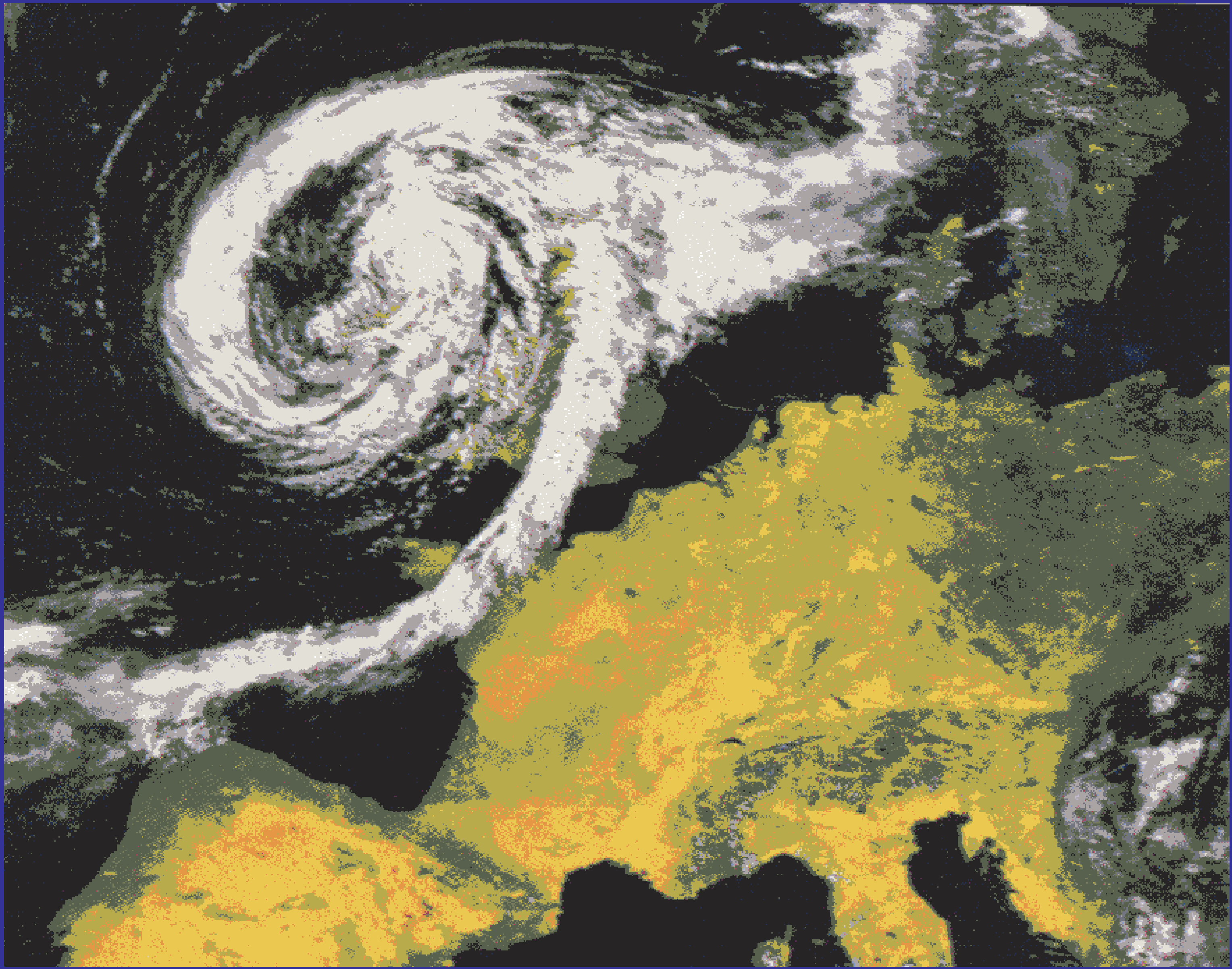
(From *Weather & Climate*)

cold front

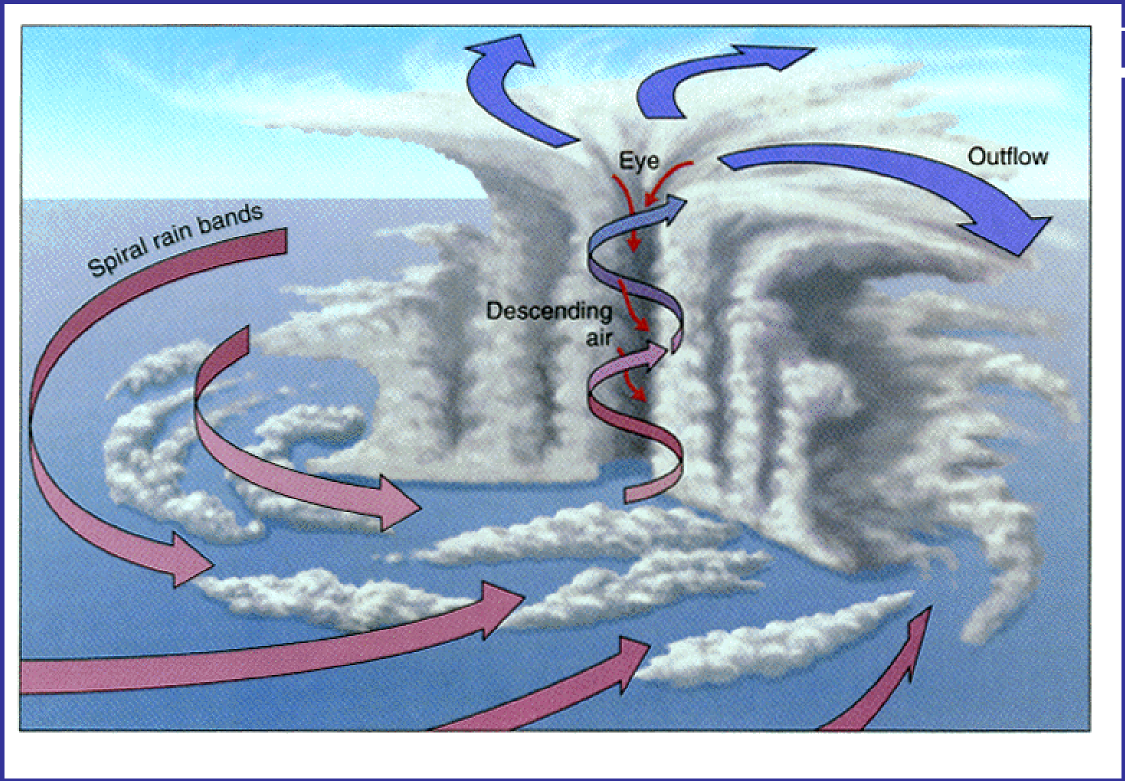


warm front





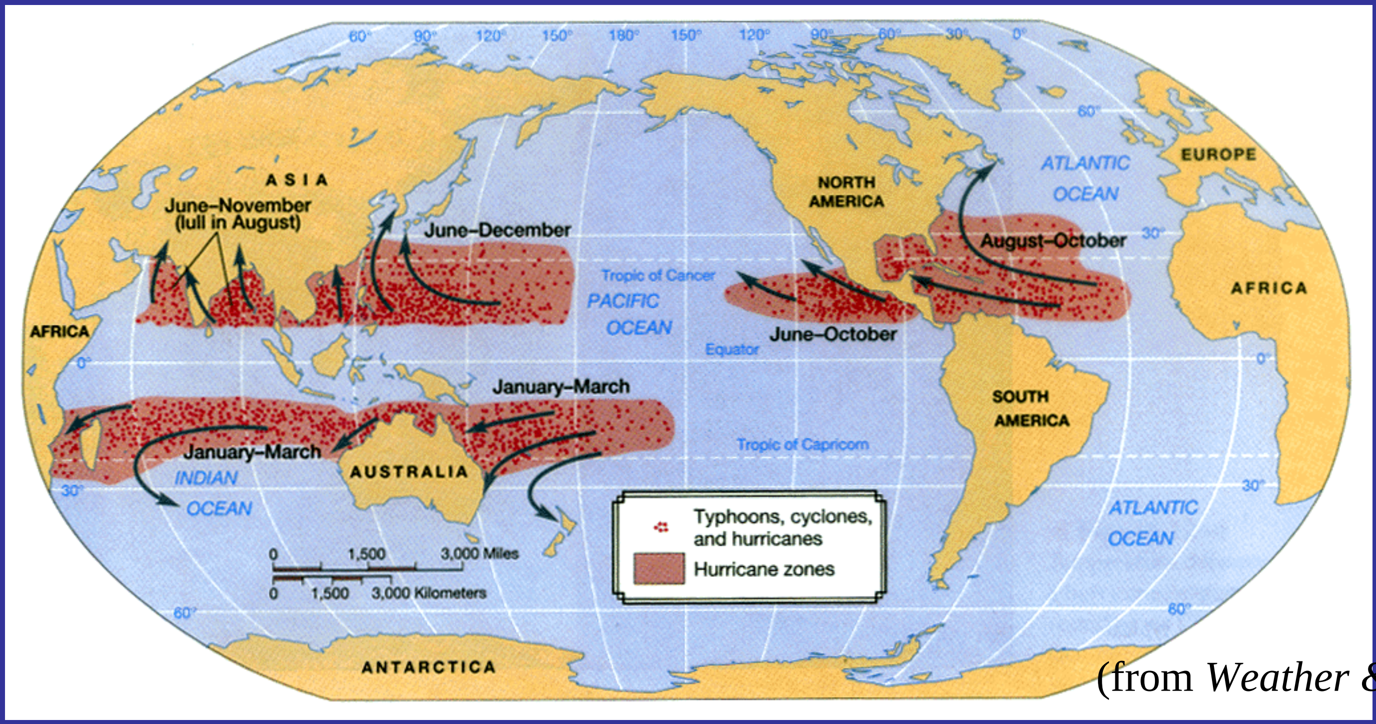
Tropical Hurricane



(from Understanding *Weather & Climate*)

- The hurricane is characterized by a strong thermally direct circulation with the rising of warm air near the center of the storm and the sinking of cooler air outside.

They Are the Same Things…

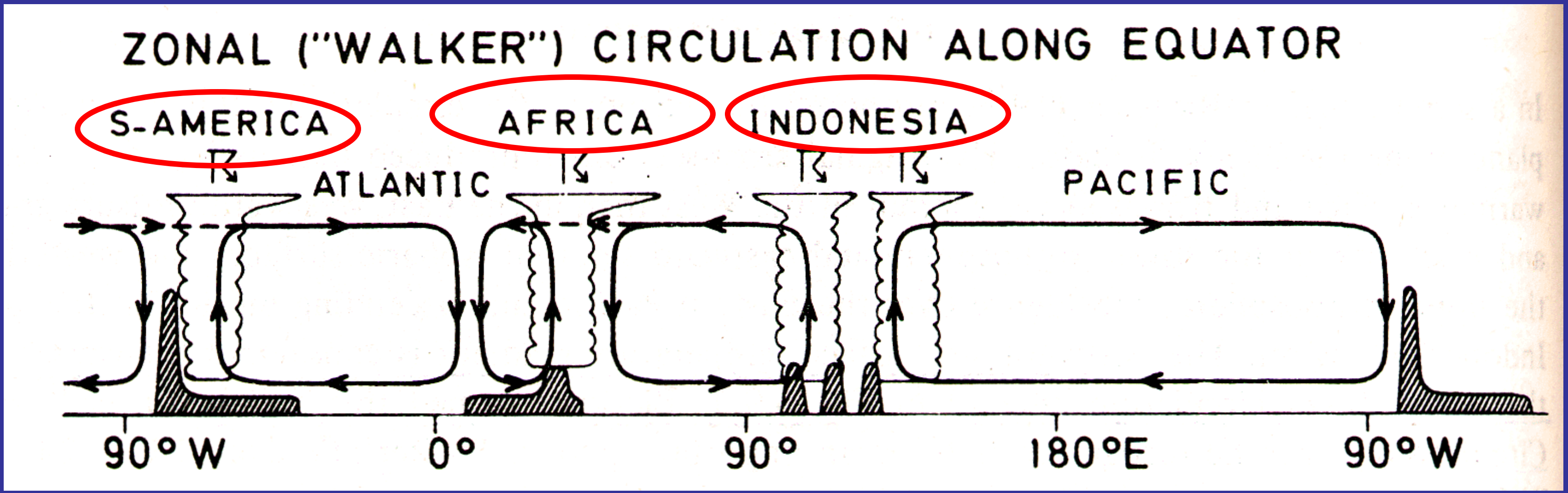


(from *Weather & Climate*)

- ***Hurricanes:*** extreme tropical storms over Atlantic and eastern Pacific Oceans.
- ***Typhoons:*** extreme tropical storms over western Pacific Ocean.
- ***Cyclones:*** extreme tropical storms over Indian Ocean and Australia.

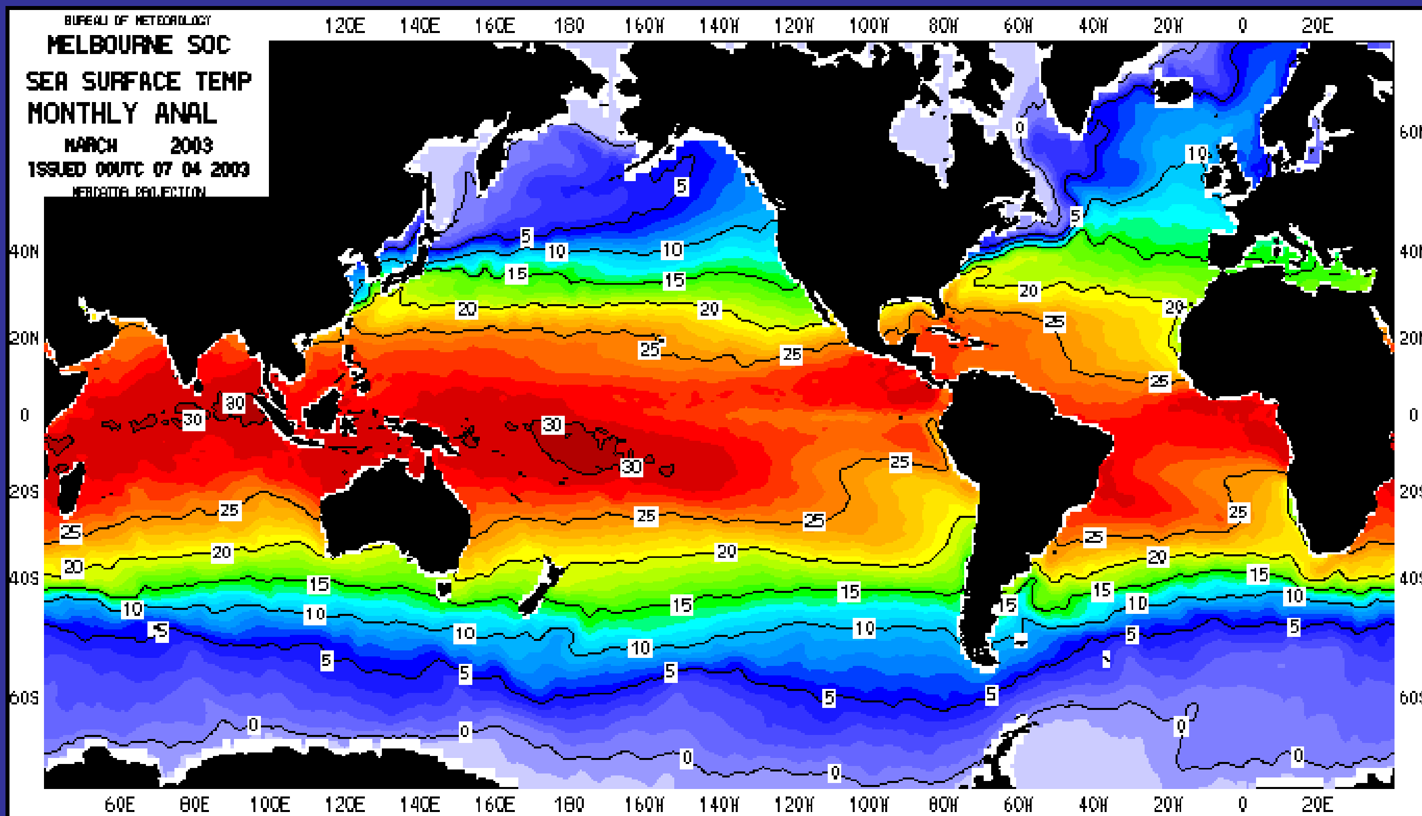
East-West Circulation

(from *Flohn (1971)*)



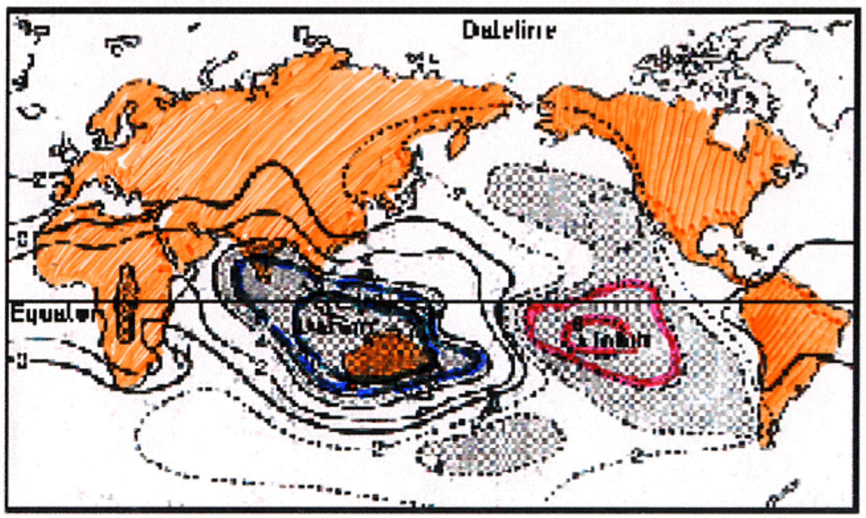
❑ The east-west circulation in the atmosphere is related to the sea/land distribution on the Earth.

Walker Circulation and Ocean Temperature



Southern Oscillation: an atmospheric phenomenon

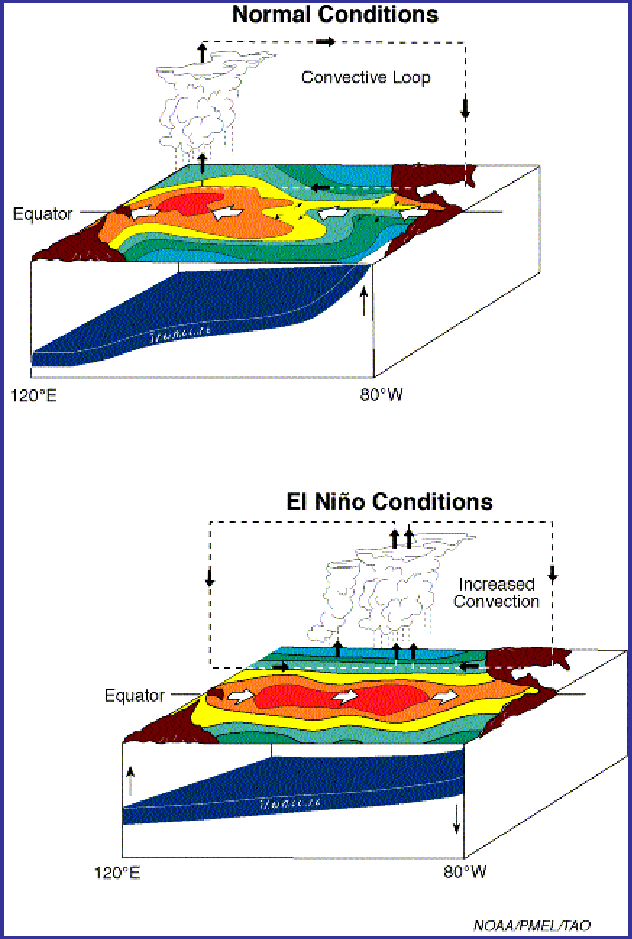
In 1910s, Walker found a connection between barometer readings at stations on the eastern and western sides of the Pacific (Tahiti and Darwin). He coined the term **Southern Oscillation** to dramatize the ups and downs in this east-west seesaw effect.



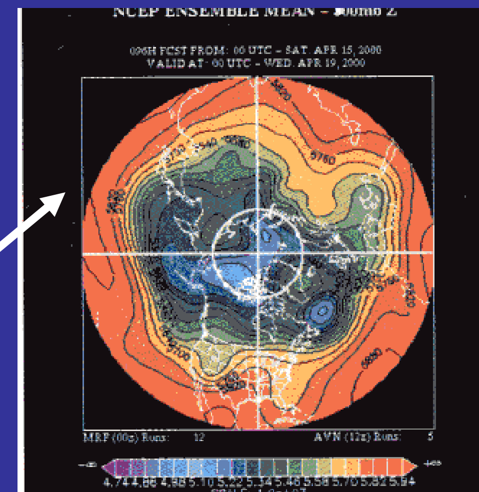
(from Rasmusson 1984)

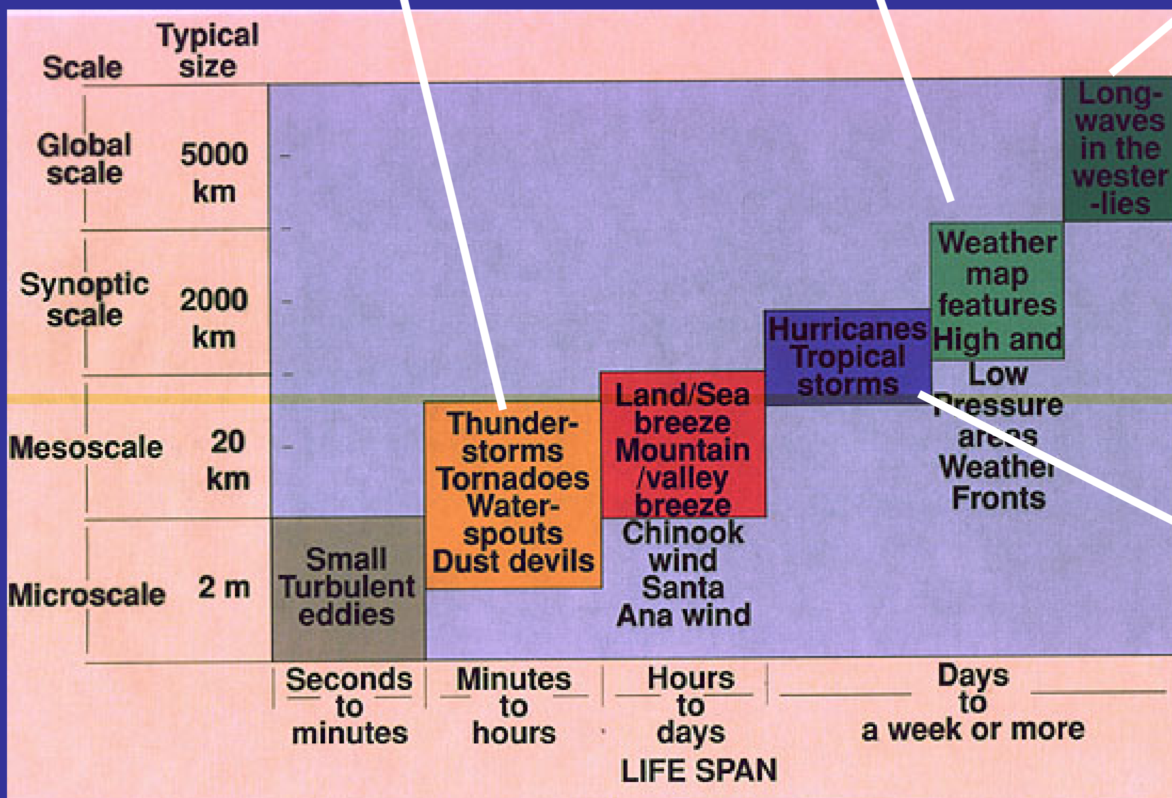
Sir Gilbert Walker

Walker Circulation and Ocean

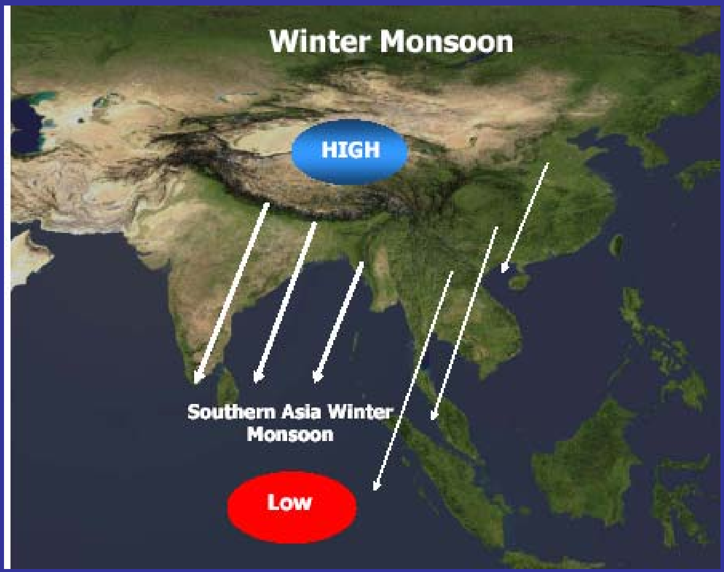


Scales of Motions in the Atmosphere

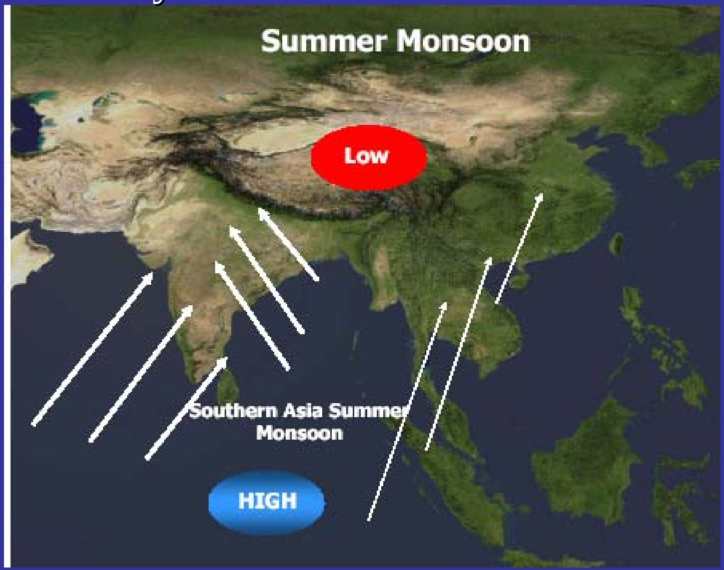




Monsoon: Sea/Land-Related Circulation

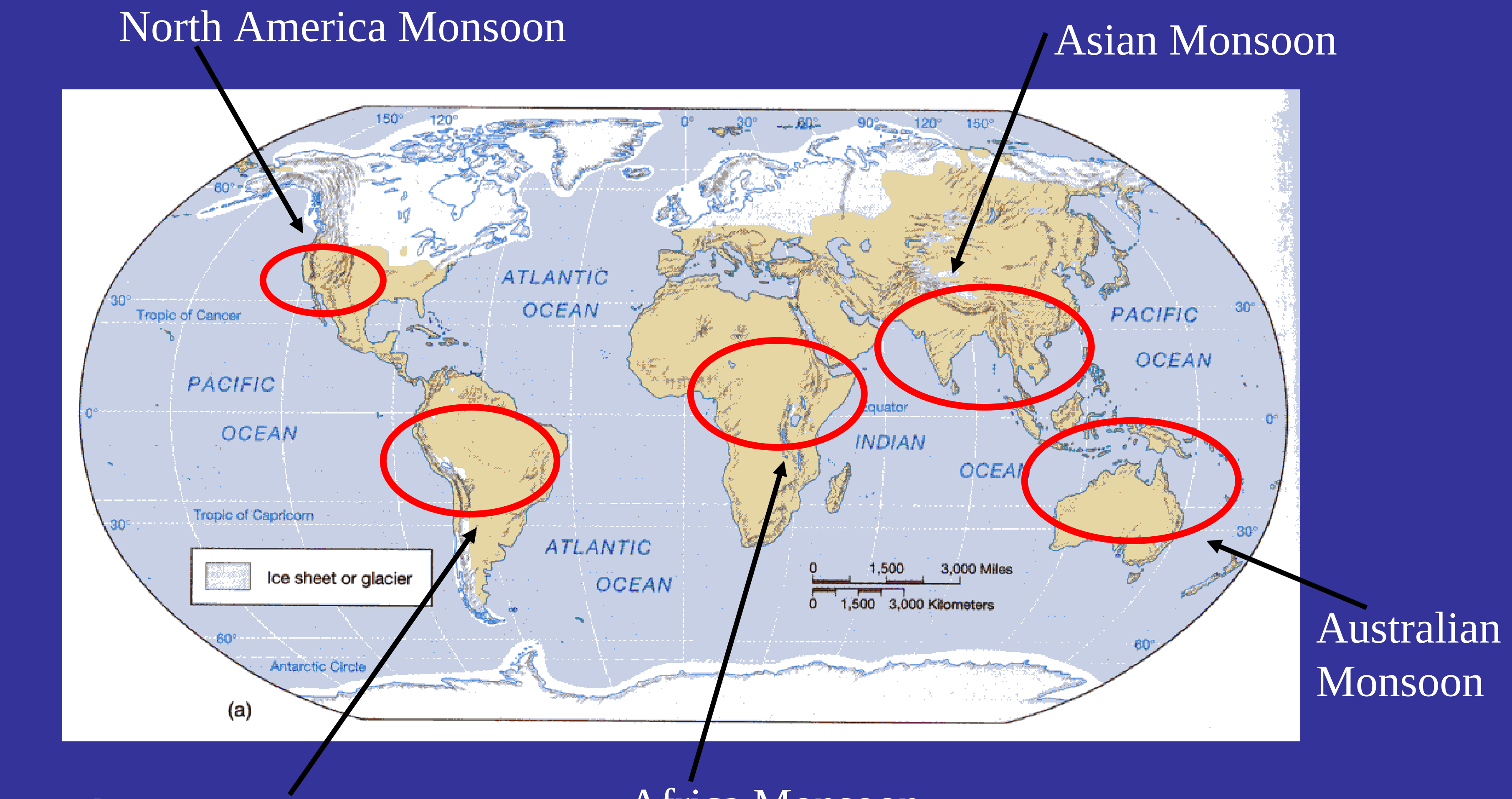


Courtesy of Kevin G. Cannariato



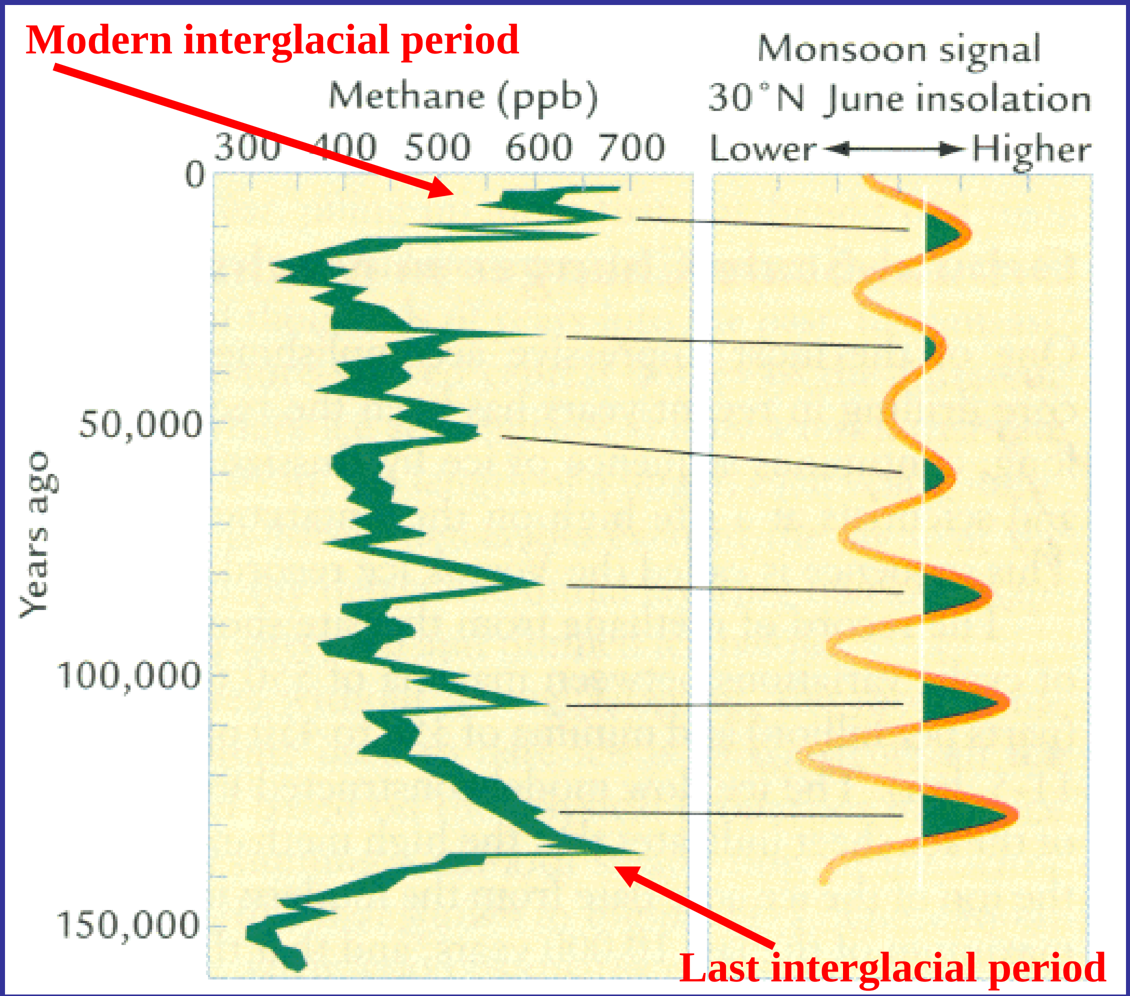
- ❑ Monsoon (Arabic “season”)
- ❑ Monsoon is a climate feature that is characterized by the ***seasonal reversal in surface winds***.
- ❑ The very different heat capacity of land and ocean surface is the key mechanism that produces monsoons.
- ❑ During summer seasons, land surface heats up faster than the ocean. Low pressure center is established over land while high pressure center is established over oceans. Winds blow from ocean to land and bring large amounts of water vapor to produce heavy precipitation over land: A rainy season.
- ❑ During winters, land surface cools down fast and sets up a high pressure center. Winds blow from land to ocean: a dry season.

How Many Monsoons Worldwide?



(figure from *Weather & Climate*)

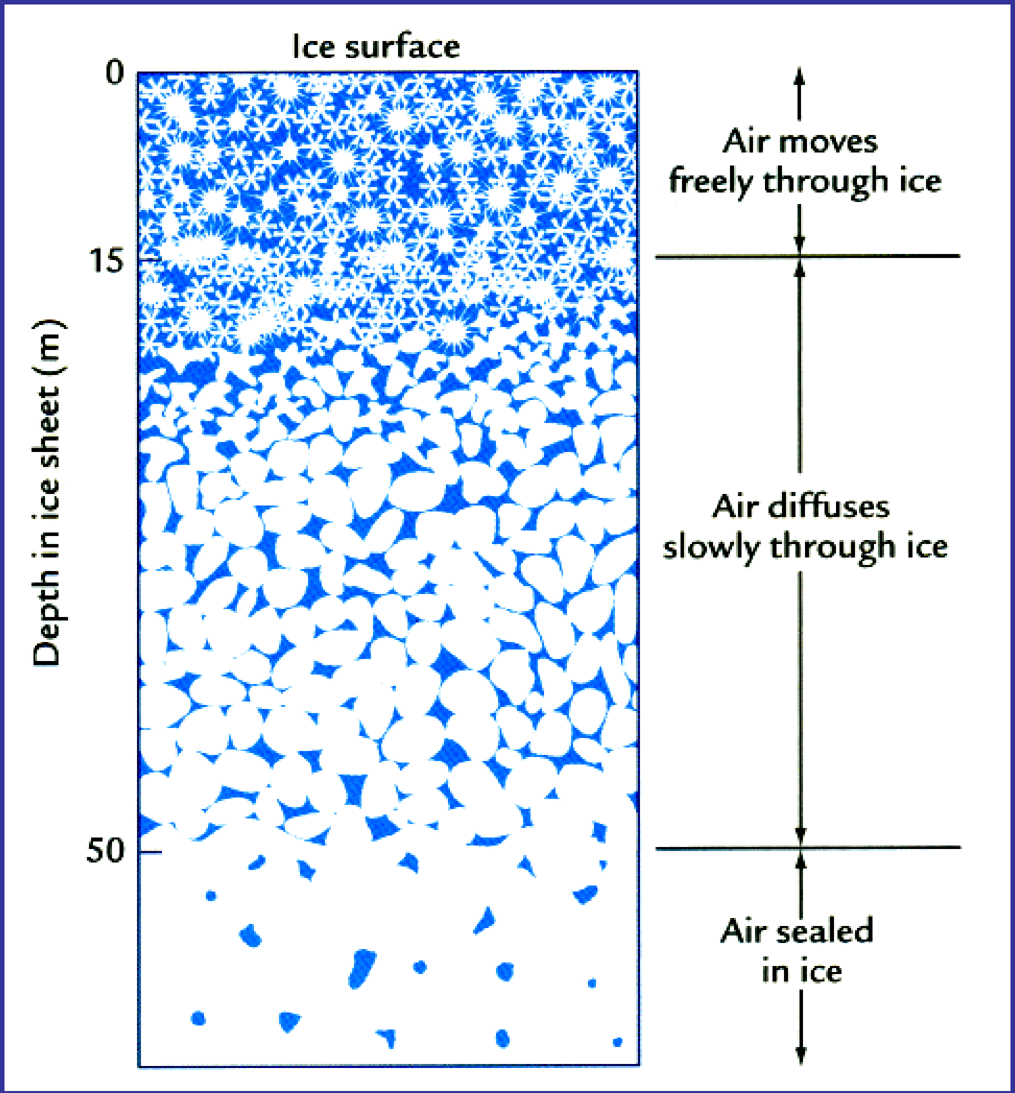
Orbital-Scale Changes in Methane



(from *Earth's Climate: Past and Future*)

- The Vostok ice record shows a series of cyclic variations in methane concentration, ranging between 350 to 700 ppb (part per billion).
- Each CH4 cycle takes about 23,000 years.
- This cycle length points to a likely connection with changes in orbital procession.
- The orbital procession dominates insolation changes at ***lower latitudes***.

Trapping Gases in the Ice



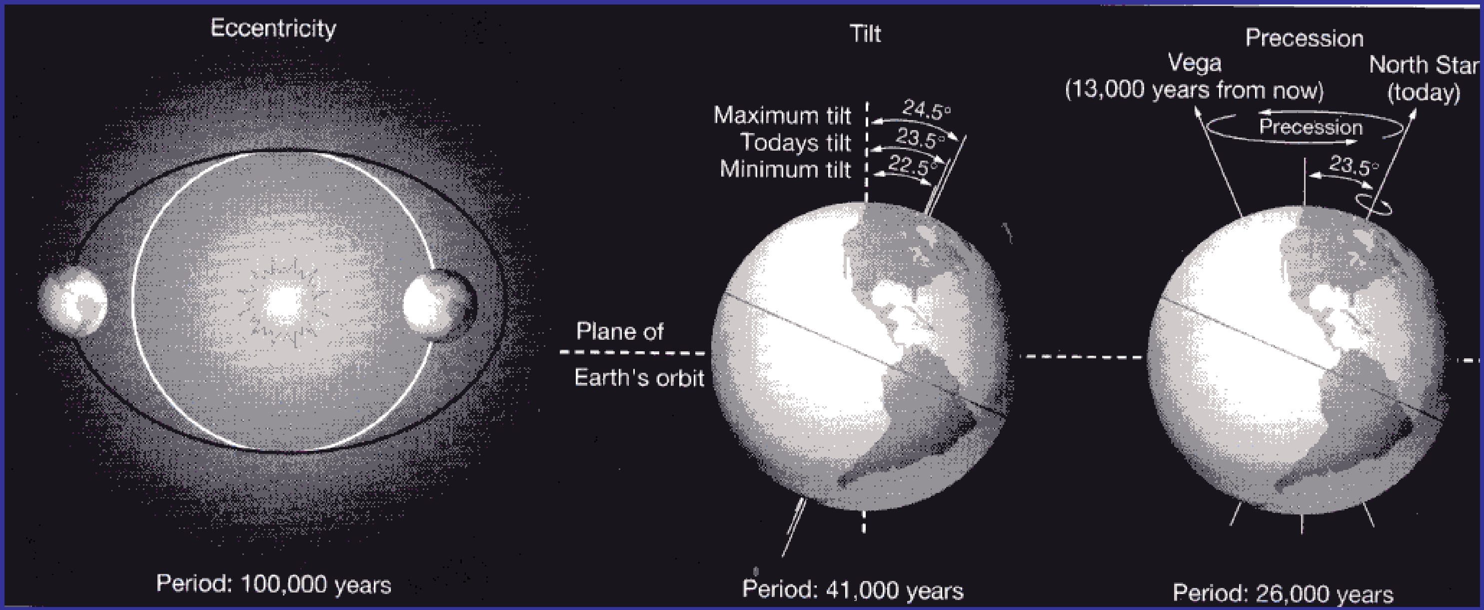
- ❑ Air moves freely through snow and ice in the upper 15 m of an ice sheet.
- ❑ Flow is increasingly restricted below this level.
- ❑ Bubbles of old air are eventually sealed off completely in ice 50 to 100 m below the surface.

(from *Earth's Climate: Past and Future*)

Monsoon and Methane

- On the 23,000-year cycle, methane variations closely resemble the variations of monsoon strength.
- The peak values of methane match the expected peaks in monsoon intensity not only in timing but also in amplitude.
- This match suggests a close connection between CH4 concentrations and the monsoon on the 23,000-year climate cycle.
- By why?

Earth's Orbit and Its Variations



(from *The Earth System*)

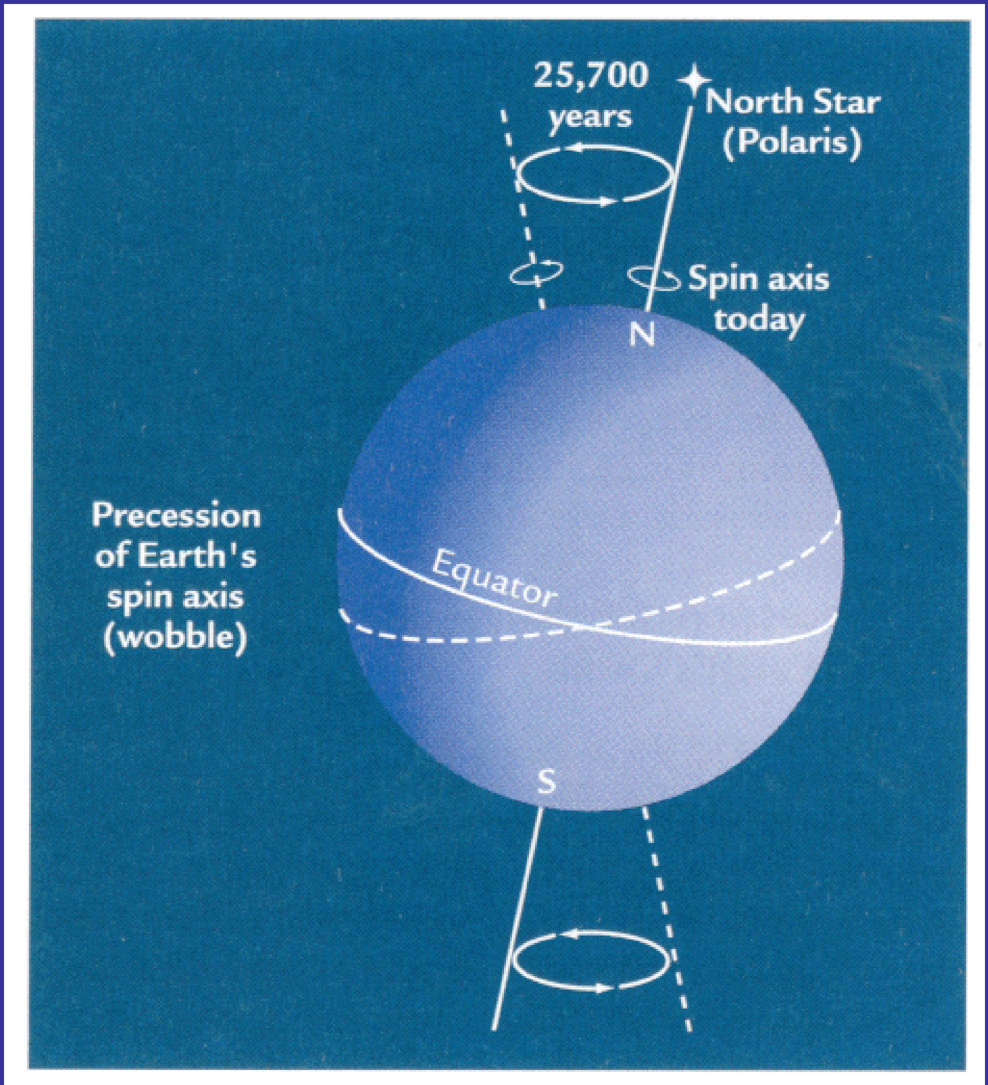
- First, Earth spins around on its axis once every day ➔ The ***Tilt.***
- Second, Earth revolves around the Sun once a year ➔ The shape of the ***Orbit***.
- Both the tilt and the shape of the orbit have changed over time and produce three types of orbital variations:

  (1) obliquity variations

  (2) eccentricity variations

  (3) precession of the spin axis.

Precession of Axis



(from *Earth's Climate: Past and Future*)

- There are two kinds of precession: (1) the precession of the spin axis and (2) the precession of the ellipse.
- Earth's wobbling motion is called the axial precession. It is caused by the gravitational pull of the Sun and Moon.
- Axial precession is a slow turning of Earth;s axis of rotation through a circular path, with a full turn every 25,700 years.

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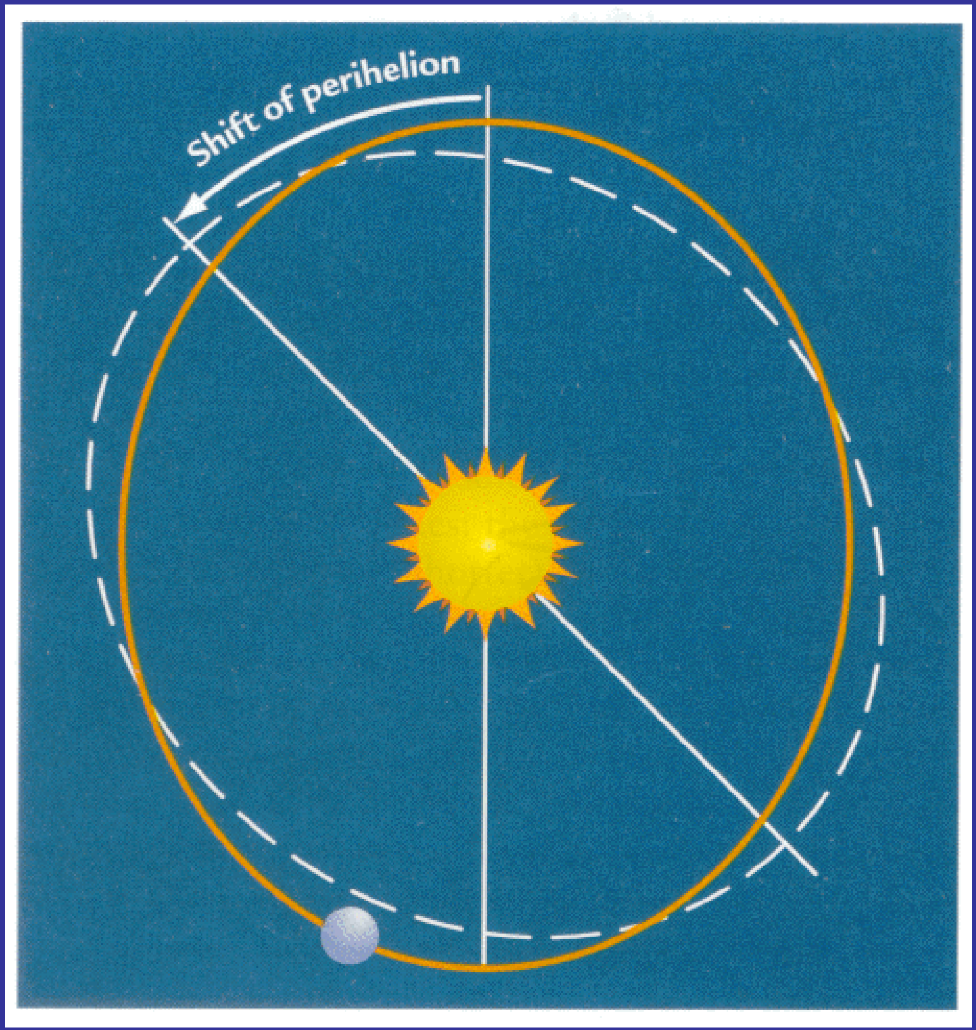
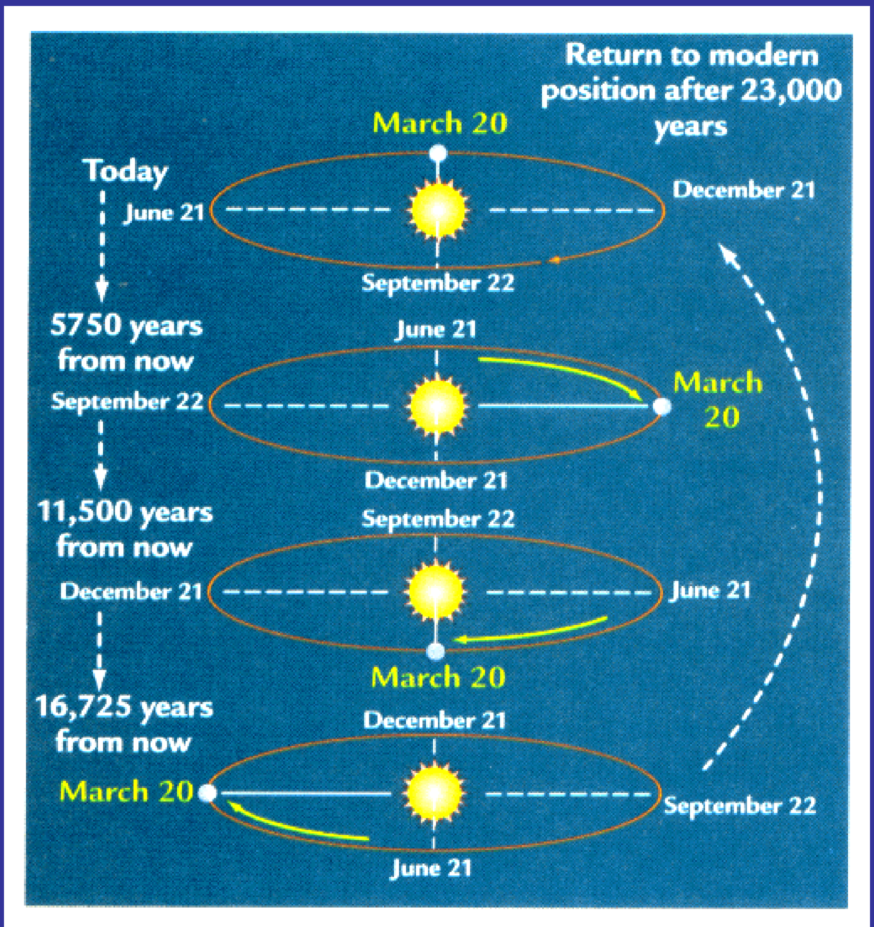
Precession of Ellipse



(from *Earth's Climate: Past and Future*)

- The precession of the ellipse is known as the elliptical shape of Earth's orbit rotates itself at a slower rate than the wobbling motion of the axial precession.

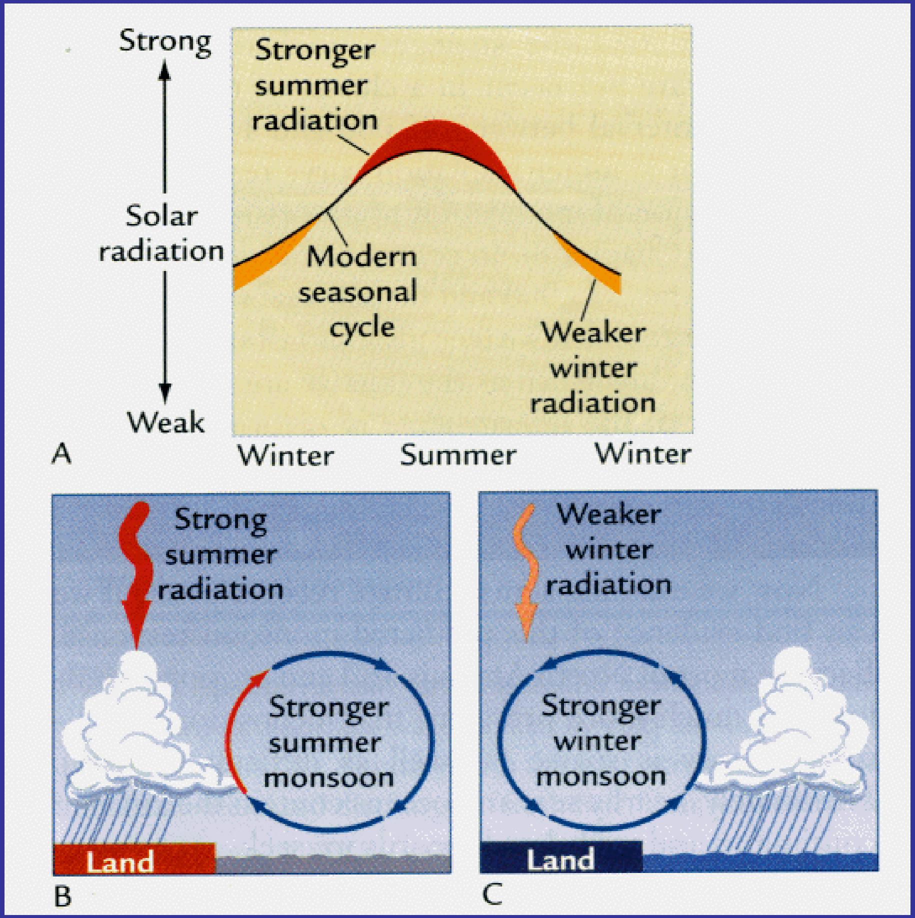
Time Scales of Precession



(from *Earth's Climate: Past and Future*)

- ❑ The combined effects of these two precessions cause the solstices and equinoxes to move around Earth's orbit, completing one full 360° orbit around the Sun every 23,000 years.

The Orbital Monsoon Hypothesis



(from *Earth's Climate: Past and Future*)

- ❑ The 23,000-year cycle of orbital procession increases (decreases) summer insolation and at the same time decreases (increases) winter insolation at low and middle latitudes.
- ❑ Departures from the modern seasonal cycle of solar radiation have driven stronger monsoon circulation in the past.
- ❑ Greater summer radiation intensified the wet summer monsoon.
- ❑ Decreased winter insolation intensified the dry winter monsoon.

How Did Monsoon Affect Methane?

- Orbital procession affects solar radiation at low latitudes

  ➔ solar radiation affects the strength of low-latitude monsoons

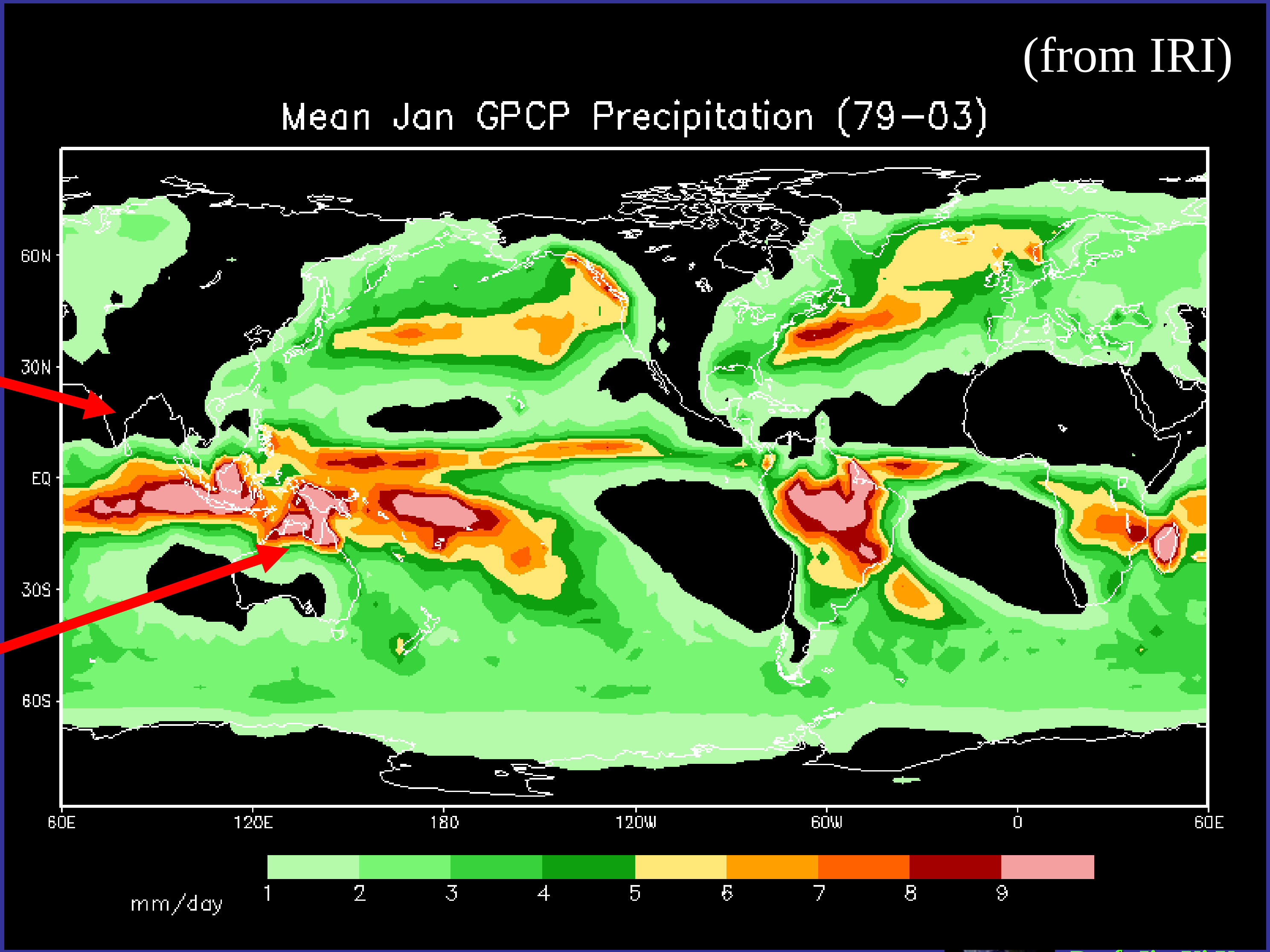
  ➔ monsoon fluctuations changes the precipitation amounts in ***Southeast Asia***

  ➔ heavy rainfalls increase the amount of standing water in bogs

  ➔ decaying vegetation used up any oxygen in the water and creates the oxygen-free conditions needed to generate methane

  ➔ the extent of these boggy area must have expanded during wet monsoon maximum and shrunk during dry monsoon minimum.

Seasonal Cycle of Rainfall

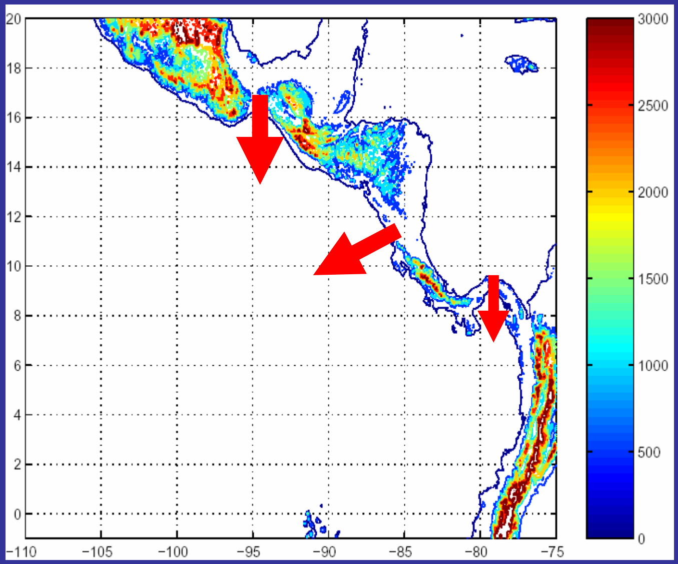


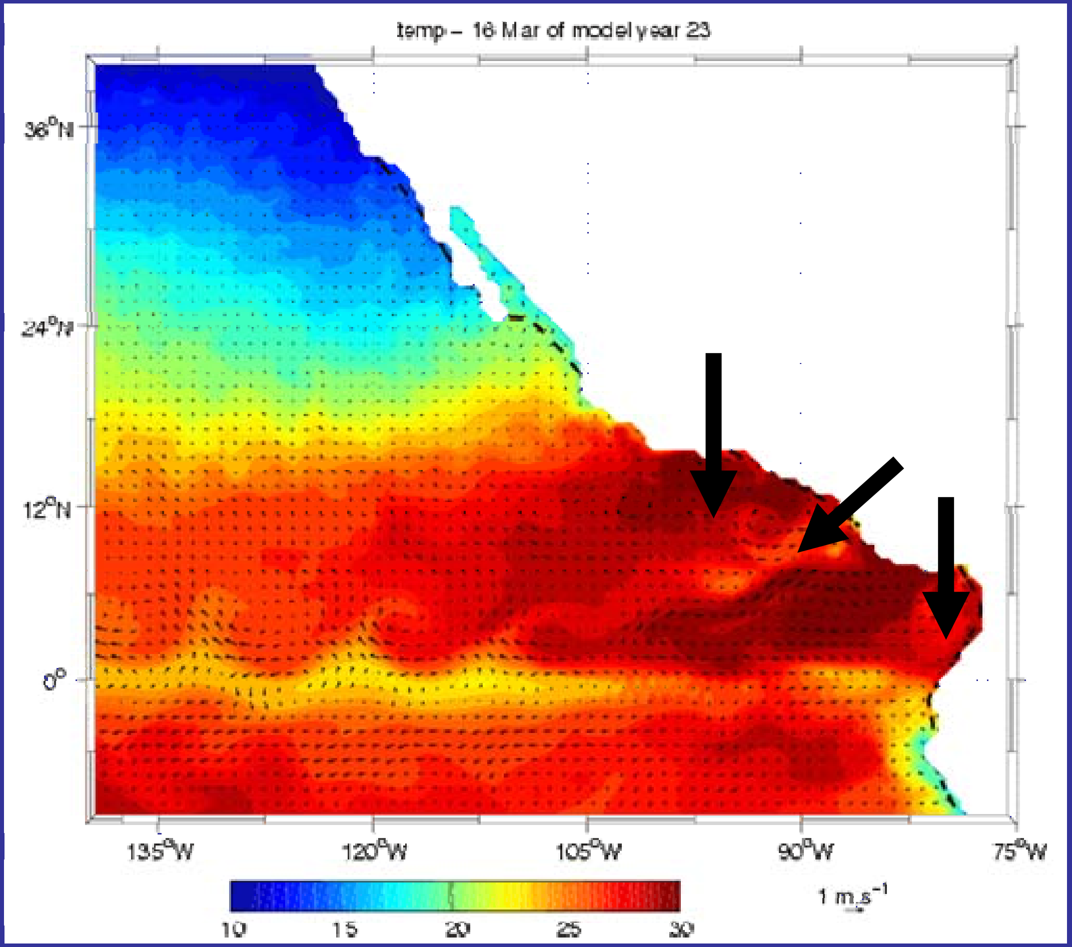
Indian Monsoon

Australian Monsoon

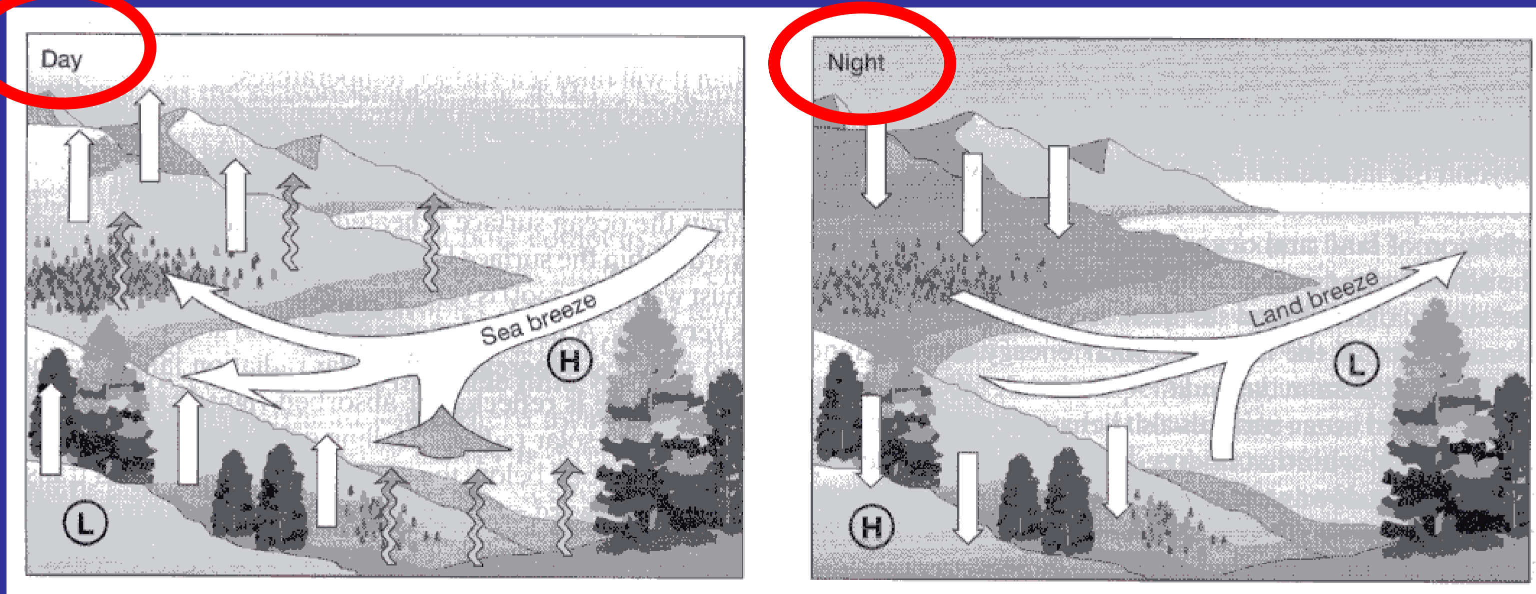
Computer Simulation of Eastern Pacific Warm Pool

Topography (meter)





Sea/Land Breeze



❑ Sea/land breeze is also produced by the different heat capacity of land and ocean surface, similar to the monsoon phenomenon.

❑ However, sea/land breeze has much shorter timescale (day and night) and space scale (a costal phenomenon) than monsoon (a seasonal and continental-scale phenomenon).

(figure from *The Earth System*)

Santa Ana Wind

This is a picture of Fremont Canyon, located in the Santa Ana Mountains in Orange County. This canyon is known for its extremely high winds during Santa Ana wind events, where the winds can gust over 100 MPH during very strong Santa Ana wind events (picture from the Orange County Register).

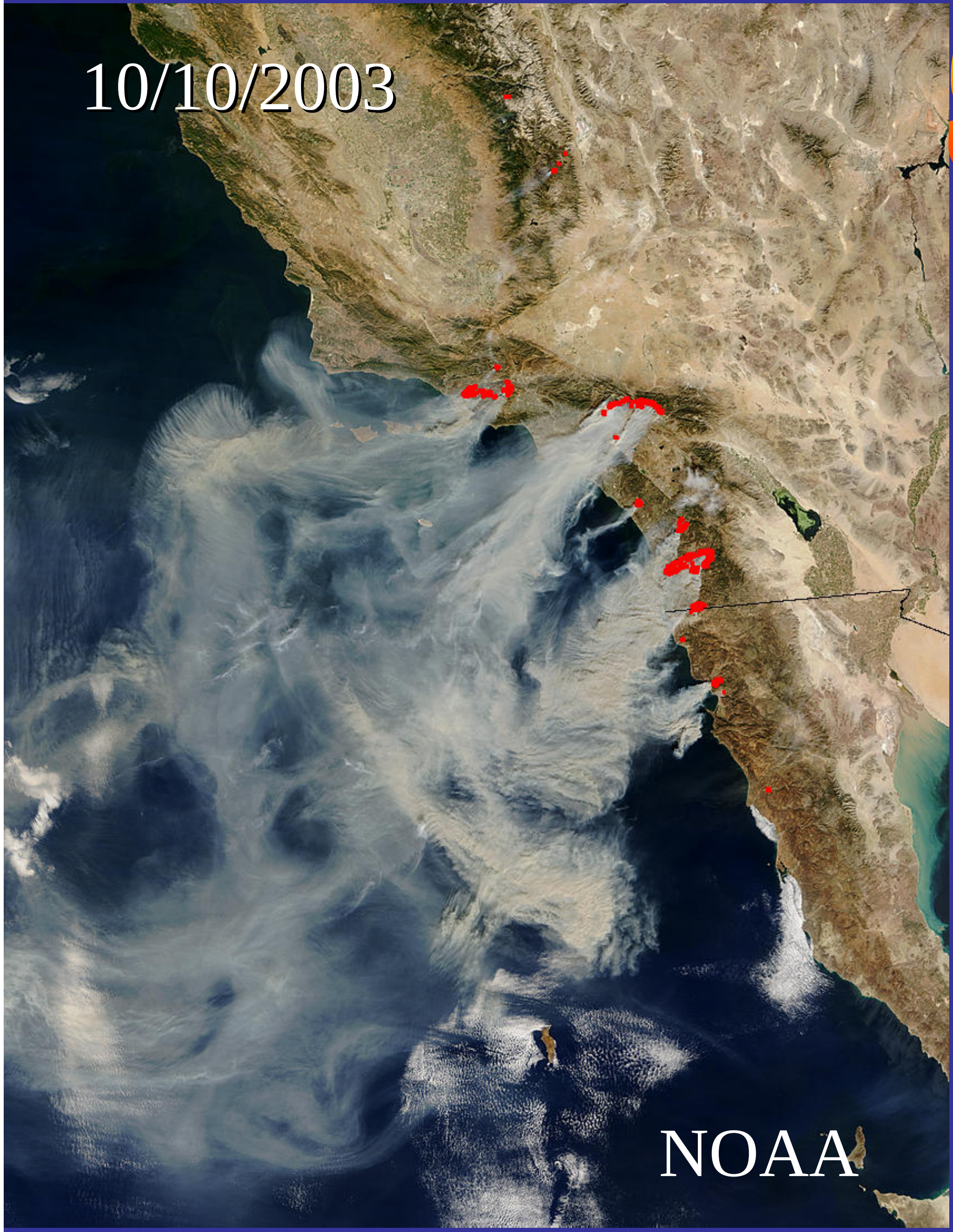
DEFINITION

Strong warm and dry winds blow over the southern California from the Great Basin, with speeds exceed 25 knots (46 km/hr).

Generation Mechanism

(from NASA's Observatorium website)

Santa Ana Wind



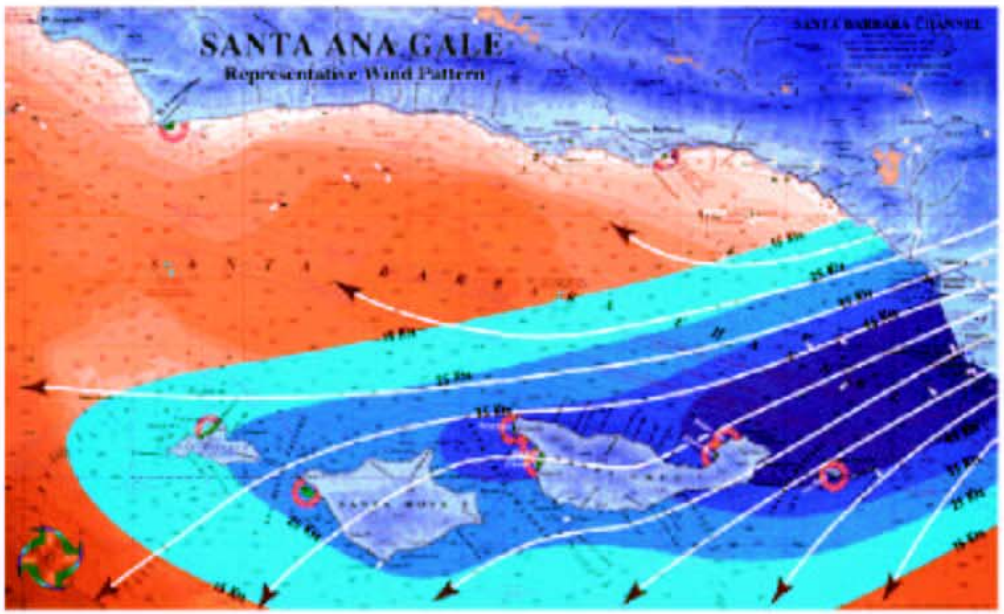
The air is forced down the mountain slopes towards the Pacific coast

Dry, low humidity and hot, with sinking air temperature 40C (104F) near the coast

Often contribute to the spread of severely destructive wild fires in California

Santa Ana Wind

Santa Ana winds on February 9, 2002
NASA MISR observation



Santa Ana Guide ©1999 Channel Crossings Press

Diurnal and Seasonal Variations

Diurnal variation:

Stronger Santa Ana wind at night and weaker Santa Ana wind on the day.

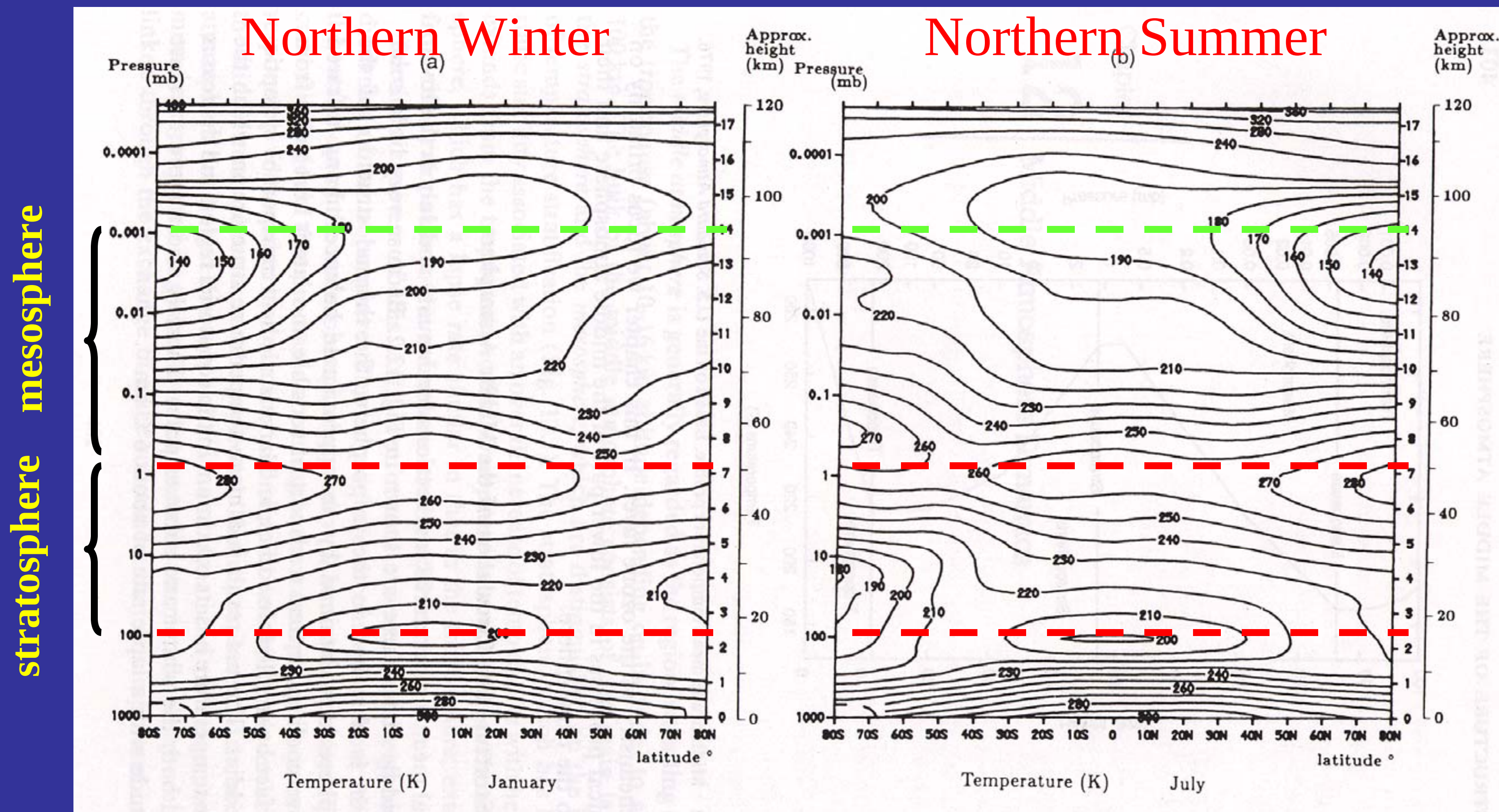
Seasonal Variation:

Occurs most frequently in winter (November to March).


10/22/2007


CALIFORNIA FIRESTORM
BREAKING NEWS
Castaic
Agua Dulce
Devore
San Bernardino
Malibu
Fontana
Orange
Potrero
2
cbs2.com

Temperatures in Stratosphere



(from *Dynamic Meteorology*)

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Ozone Distribution

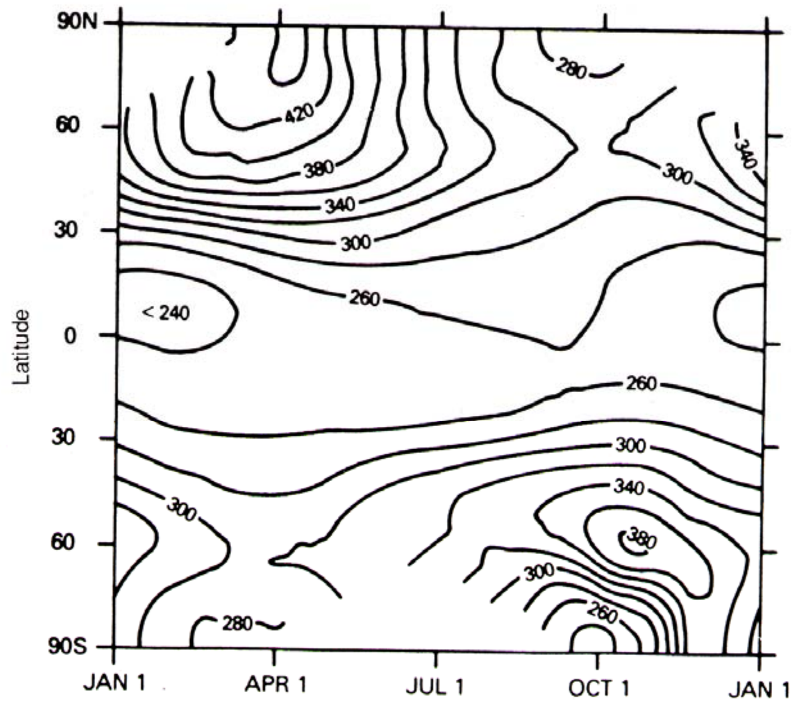
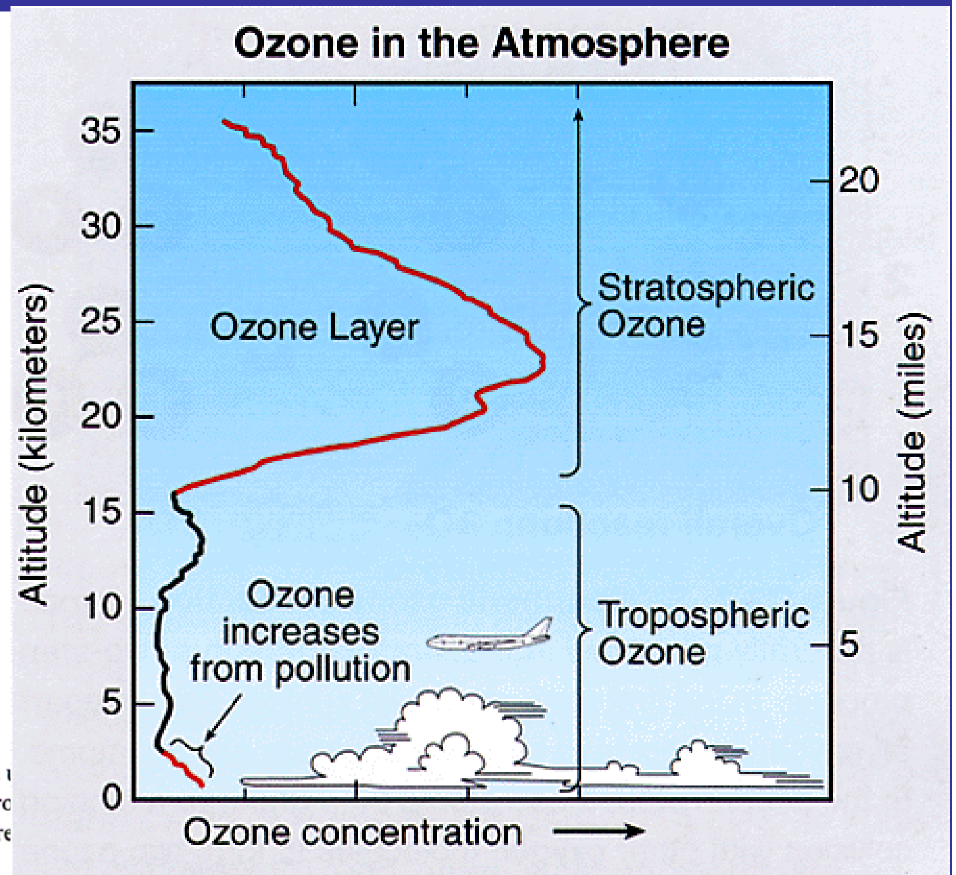


Fig. 12.13 Time–latitude section showing the seasonal variation of total ozone (Dobson u based on total ozone mapping spectrometer (TOMS) data. Note the extratro springtime maxima in both hemispheres and the minimum at 90°S centere October 1. (After Bowman and Krueger, 1985.)



Stratosphere: Circulation and Temperature

Zonal Wind

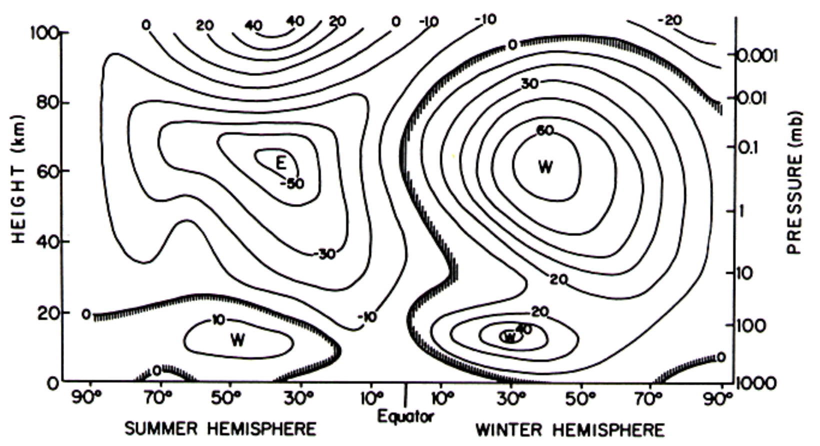


Fig. 1.4. Schematic latitude–height section of zonal mean zonal wind (m s^{-1}) for solstice conditions; W and E designate centers of westerly (from the west) and easterly (from the east) winds, respectively. (Courtesy of R. J. Reed.)

Temperature

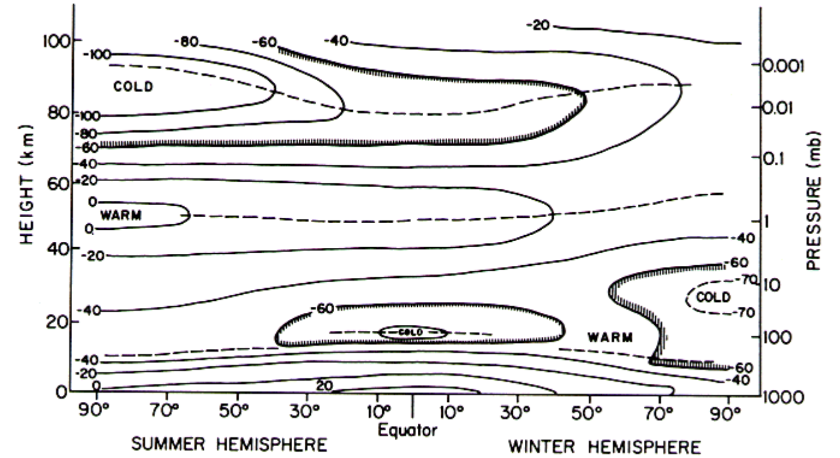
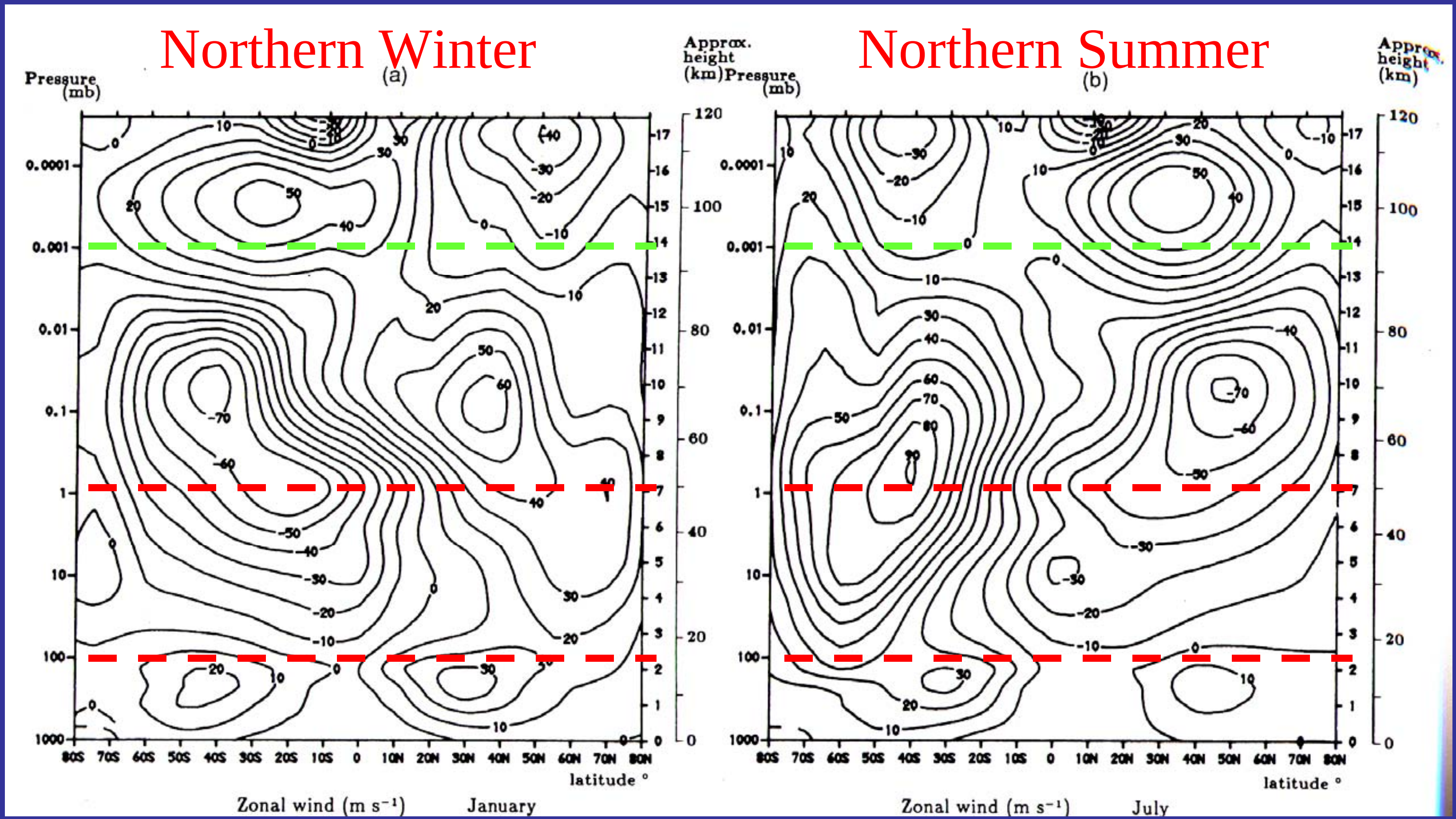


Fig. 1.3. Schematic latitude–height section of zonal mean temperatures (°C) for solstice conditions. Dashed lines indicate tropopause, stratopause, and mesopause levels. (Courtesy of R. J. Reed.)

Circulation in Stratosphere



(from *Dynamic Meteorology*)

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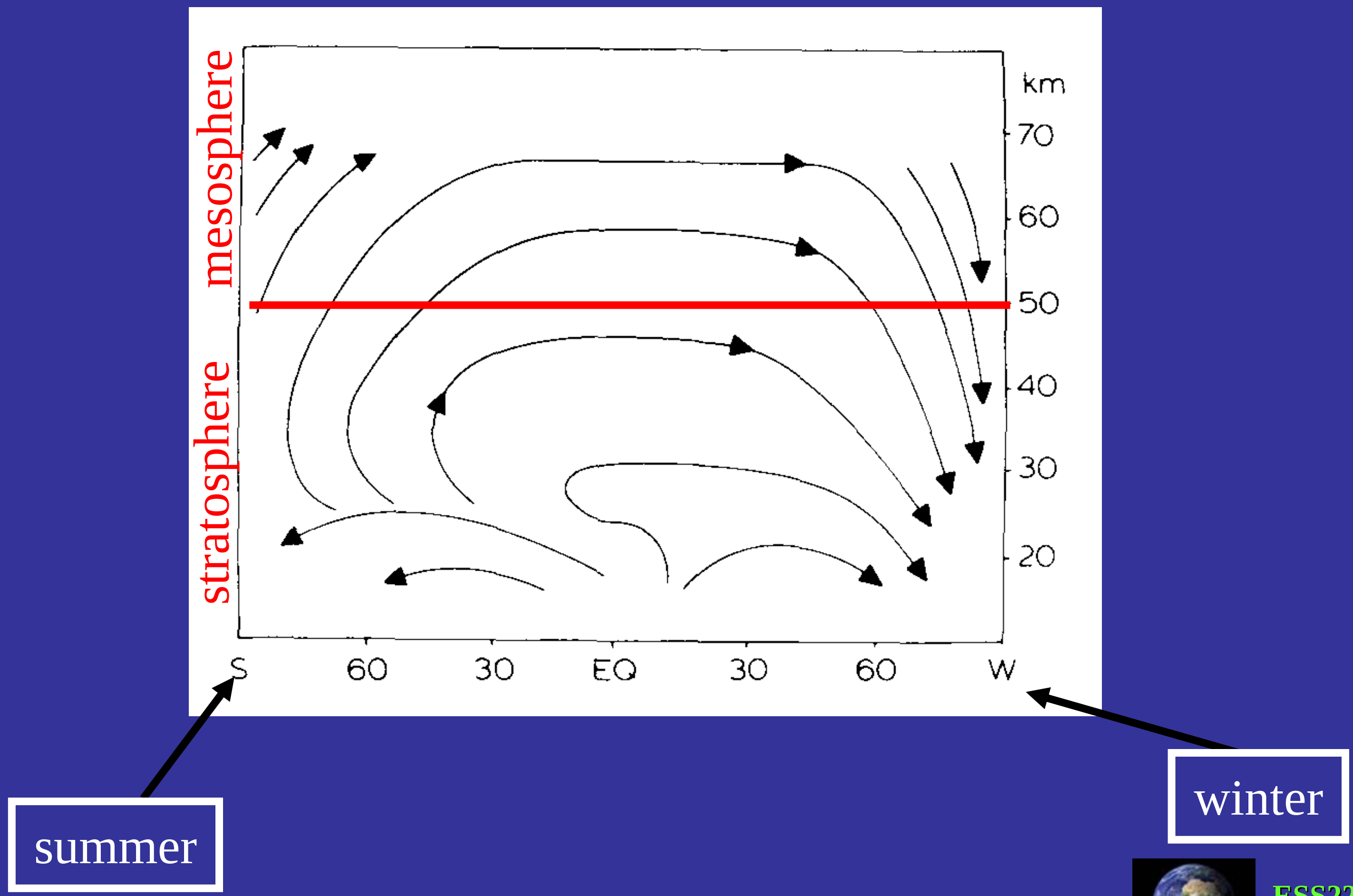
Zonal-Mean Circulation in the Stratosphere



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Ozone Production and Destruction

(from *The Earth System*)

The Chapman Mechanism of Ozone Production and Destruction

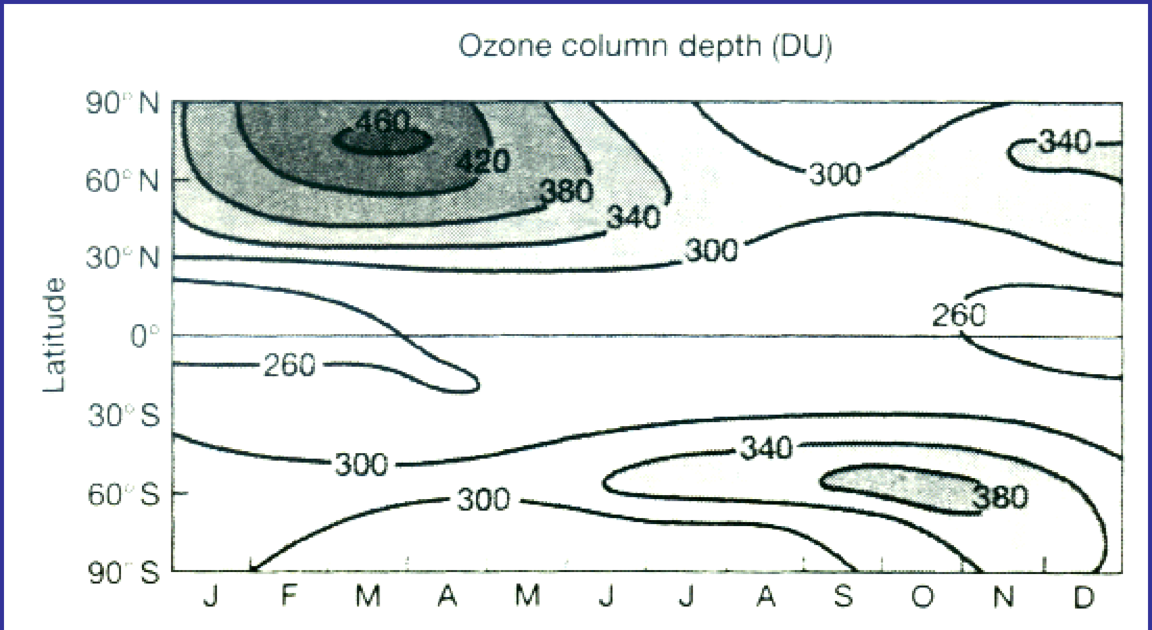
Reaction*		***Rate***
1) O_2 + UV photon → O + O	production	Slow
2) O + O_2 + M → O_3 + M	production	Fast
3) O_3 + photon → O_2 + O	destruction	Fast
4) O + O_3 → 2 O_2	destruction	Slow

Photodissociation (or photolysis)

visible light

destroy O3 permanently

Ozone Distribution



(from *The Earth System*)

- The greatest production of ozone occurs in the tropics, where the solar UV flux is the highest.
- However, the general circulation in the stratosphere transport ozone-rich air from the tropical upper stratosphere to mid-to-high latitudes.
- Ozone column depths are highest during springtime at mid-to-high latitudes.
- Ozone column depths are the lowest over the equator.

Climate Variations in Stratosphere

- ❑ Quasi-Biennial Oscillation (QBO)
- ❑ Sudden Warming: in Northern Pole
- ❑ Ozone Hole: in Southern Pole

QBO

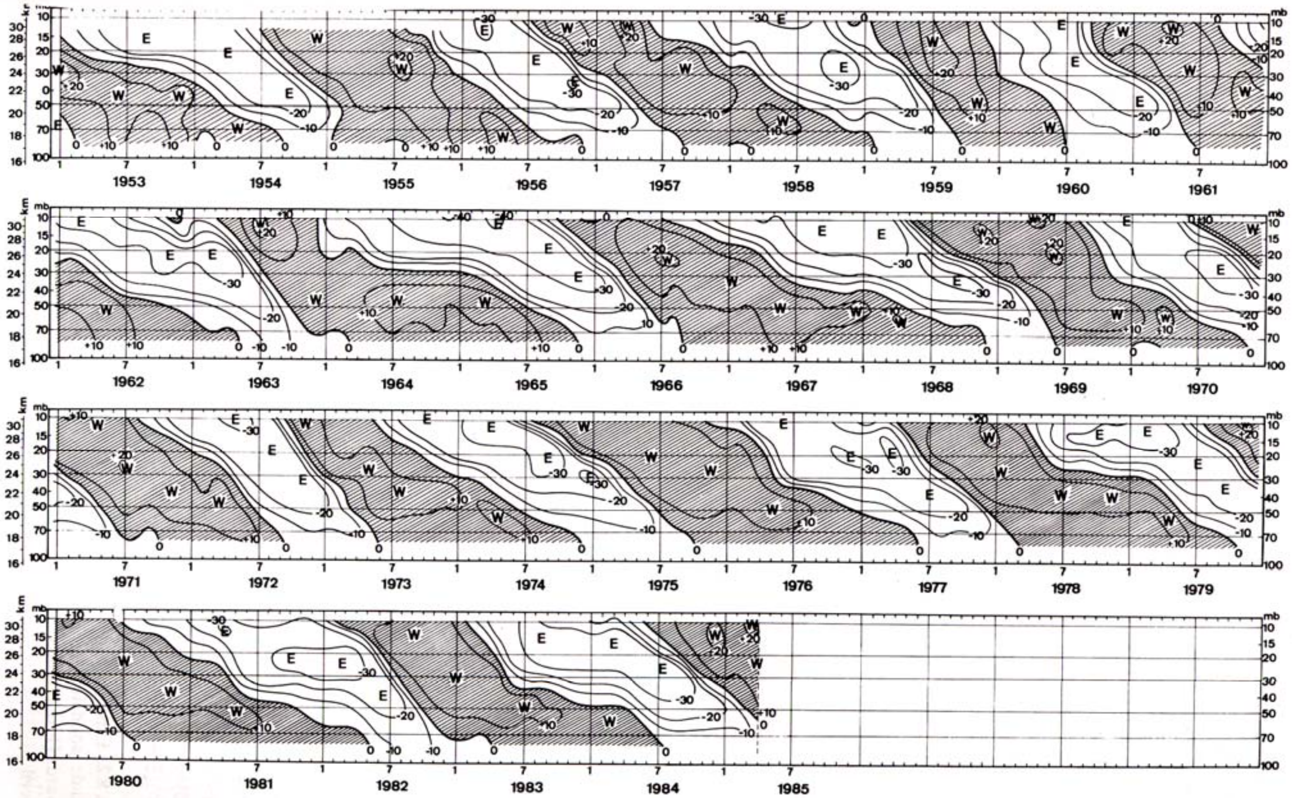


Fig. 8.1. Time-height section of monthly mean zonal winds (m s^{-1}) at equatorial stations (Jan. 1953–Aug. 1967: Canton Island, 3°S/172°W; Sept. 1967–Dec. 1975: Gan/Maldive Islands, 1°S/73°E; Jan. 1976–Apr. 1985: Singapore, 1°N/104°E). Isopleths are at 10-m s^{-1} intervals. Note the alternating downward propagating westerly (W) and easterly (E) regimes. [From Naujokat (1986), with permission.]

- Quasi-Biennial Oscillation: Easterly and westerly winds alternate every other years (approximately) in the lower to middle parts of the tropical stratosphere.

Why QBO?

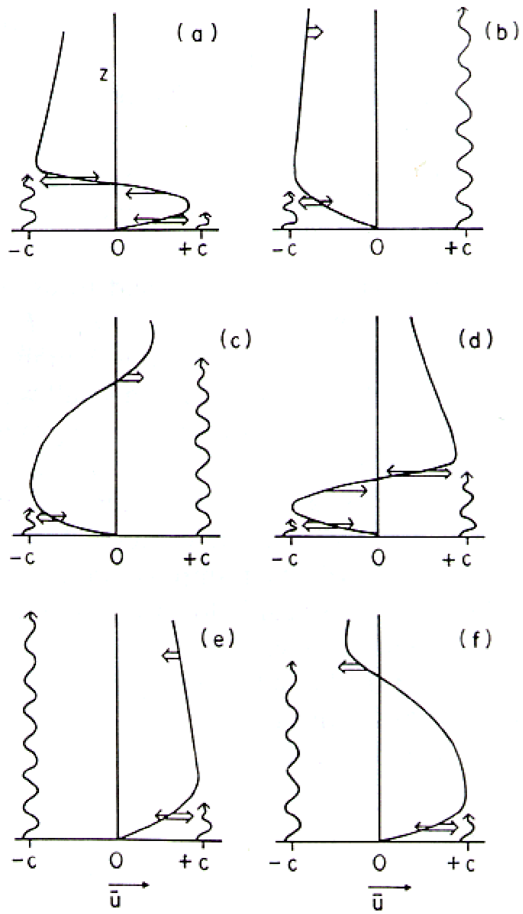
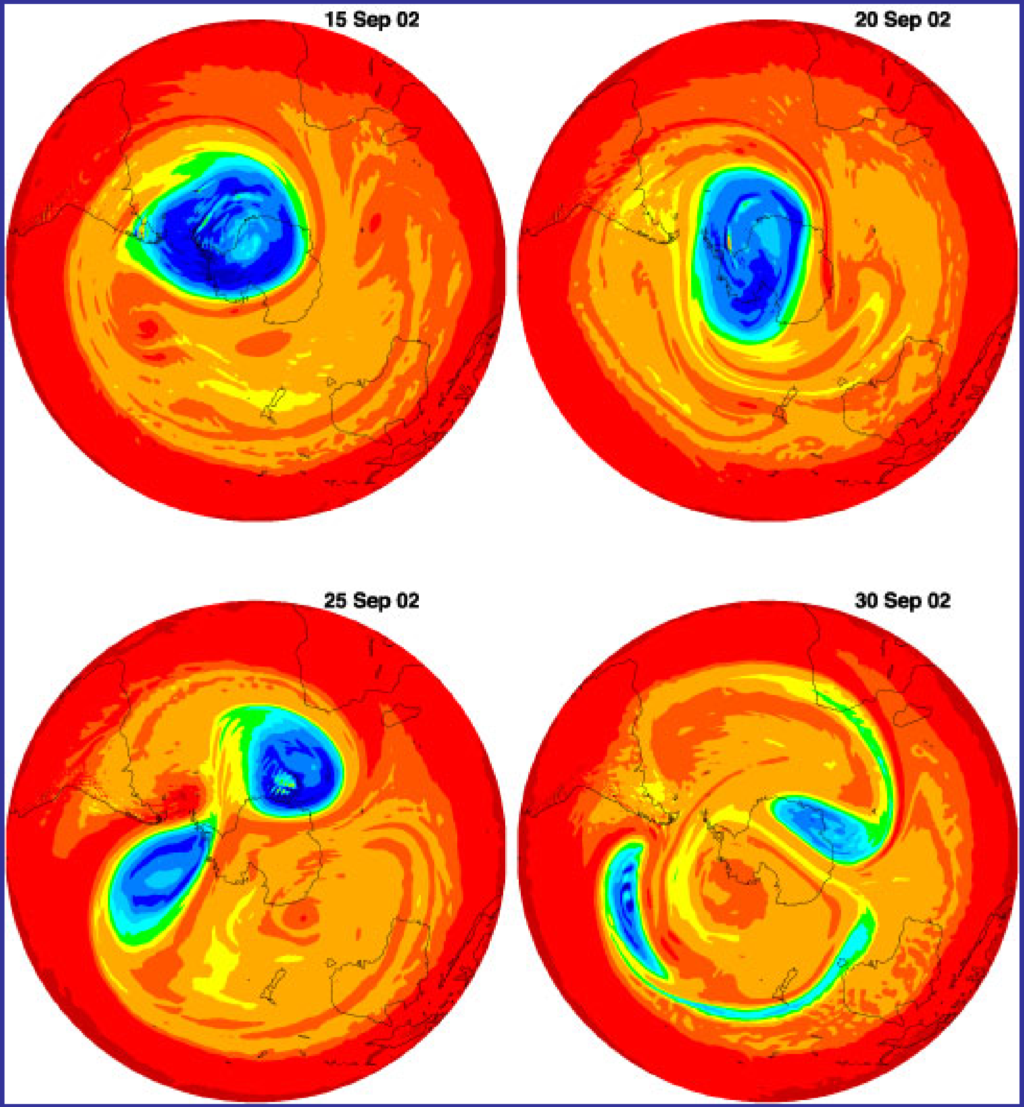


Fig. 8.7. Schematic representation of the evolution of the mean flow in Plumb's analog of the QBO. Six stages of a complete cycle are shown. Double arrows show wave-driven accelerations and single arrows show viscously driven accelerations. Wavy lines indicate relative penetration of easterly and westerly waves. See text for details. [After Plumb (1984).]

- ❑ Kevin Waves accelerate westerly.
- ❑ Rossby-Gravity Wave accelerate easterly.

Sudden Warming



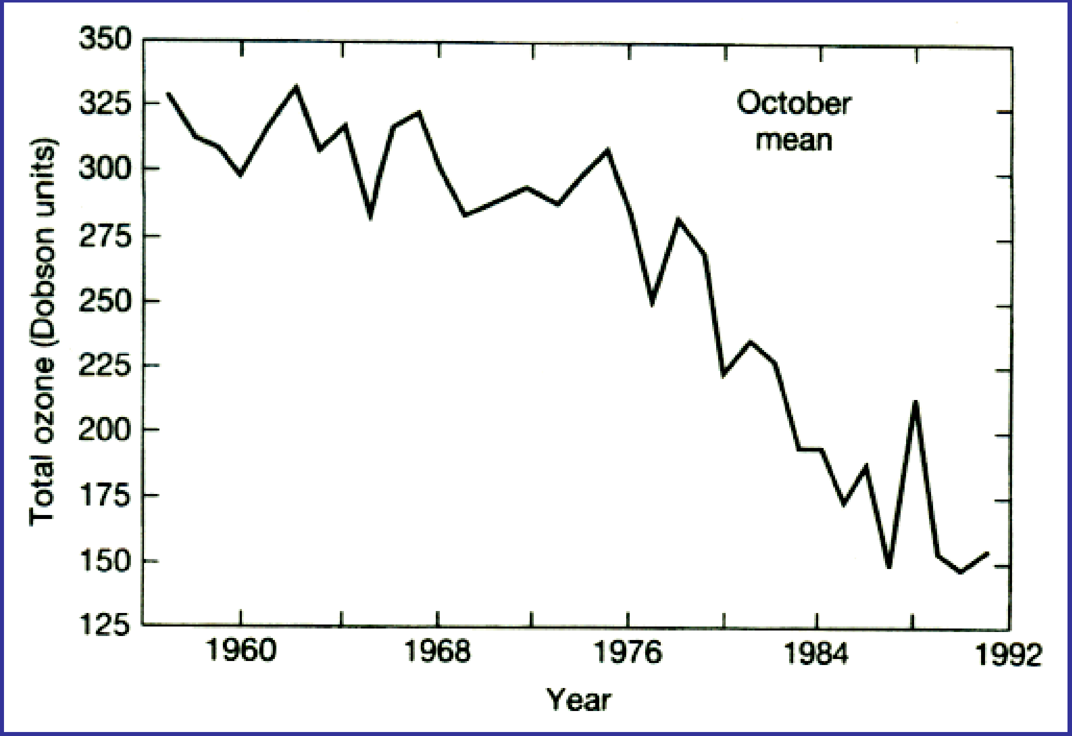
- Every other year or so the normal winter pattern of a cold polar stratosphere with a westerly vortex is interrupted in the middle winter.
- The polar vortex can completely disappear for a period of a few weeks.
- During the sudden warming period, the stratospheric temperatures can rise as much as 40°K in a few days!

Why Sudden Warming?

- Planetary-scale waves propagating from the troposphere (produced by big mountains) into the stratosphere.
- Those waves interact with the polar vortex to break down the polar vortex.
- There are no big mountains in the Southern Hemisphere to produce planetary-scale waves.
- Less (?) sudden warming in the southern polar vortex.

Antarctic Ozone Hole

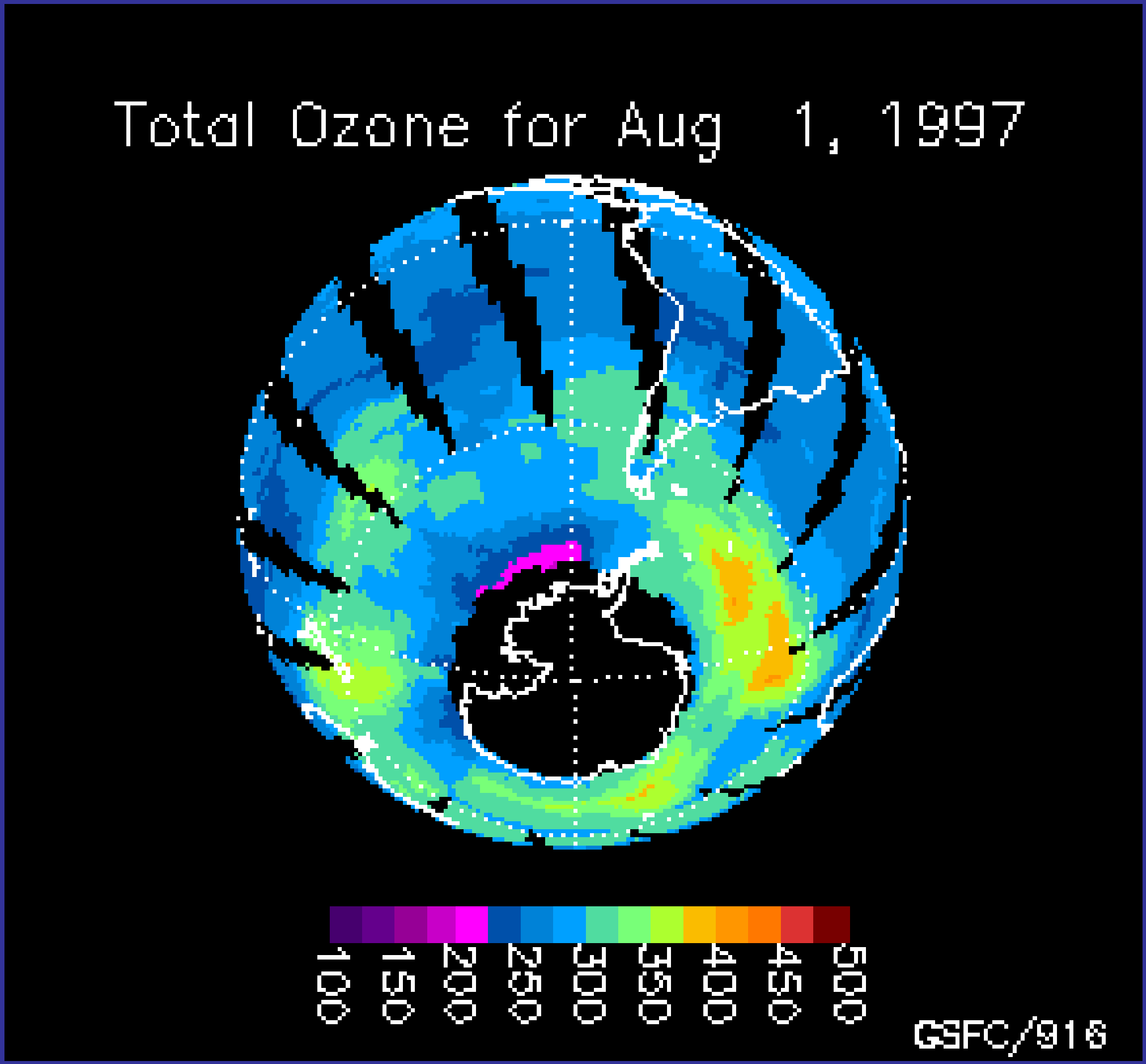
Mean Total Ozone Over Antarctic in October



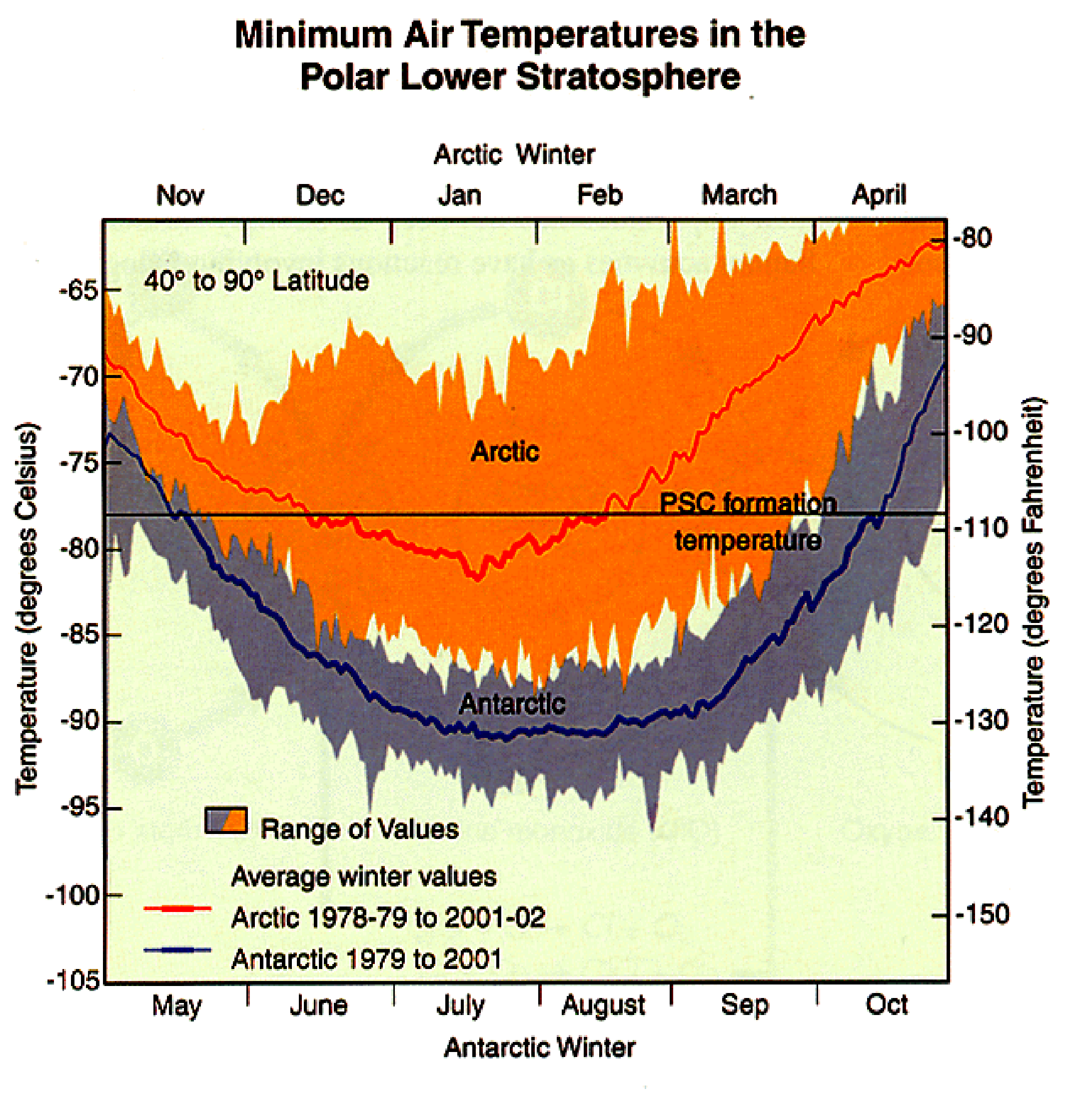
(from *The Earth System*)

- The decrease in ozone near the South Pole is most striking near the spring time (October).
- During the rest of the year, ozone levels have remained close to normal in the region.

The 1997 Ozone Hole



Why No Ozone Hole in Artic?



(from WMO Report 2003)

ESS220
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Polar Stratospheric Clouds (PSCs)

(Sweden, January 2000; from NASA website)

- In winter the polar stratosphere is so cold (-80°C or below) that certain trace atmospheric constituents can condense.
- These clouds are called "polar stratospheric clouds" (PSCs).
- The particles that form typically consist of a mixture of water and nitric acid (HNO3).
- The PSCs alter the chemistry of the lower stratosphere in two ways:

  (1) by coupling between the odd nitrogen and chlorine cycles

  (2) by providing surfaces on which heterogeneous reactions can occur.

Ozone Hole Depletion

- Long Antarctic winter (May through September)
- → The stratosphere is cold enough to form PSCs
- → PSCs deplete odd nitrogen (NO)
- → Help convert unreactive forms of chlorine (ClONO2 and HCl) into more reactive forms (such as Cl2).
- → The reactive chlorine remains bound to the surface of clouds particles.
- → Sunlight returns in springtime (September)
- → The sunlight releases reactive chlorine from the particle surface.
- → The chlorine destroy ozone in October.
- → Ozone hole appears.
- → At the end of winter, the polar vortex breaks down.
- → Allow fresh ozone and odd nitrogen to be brought in from low latitudes.
- → The ozone hole recovers (disappears) until next October.