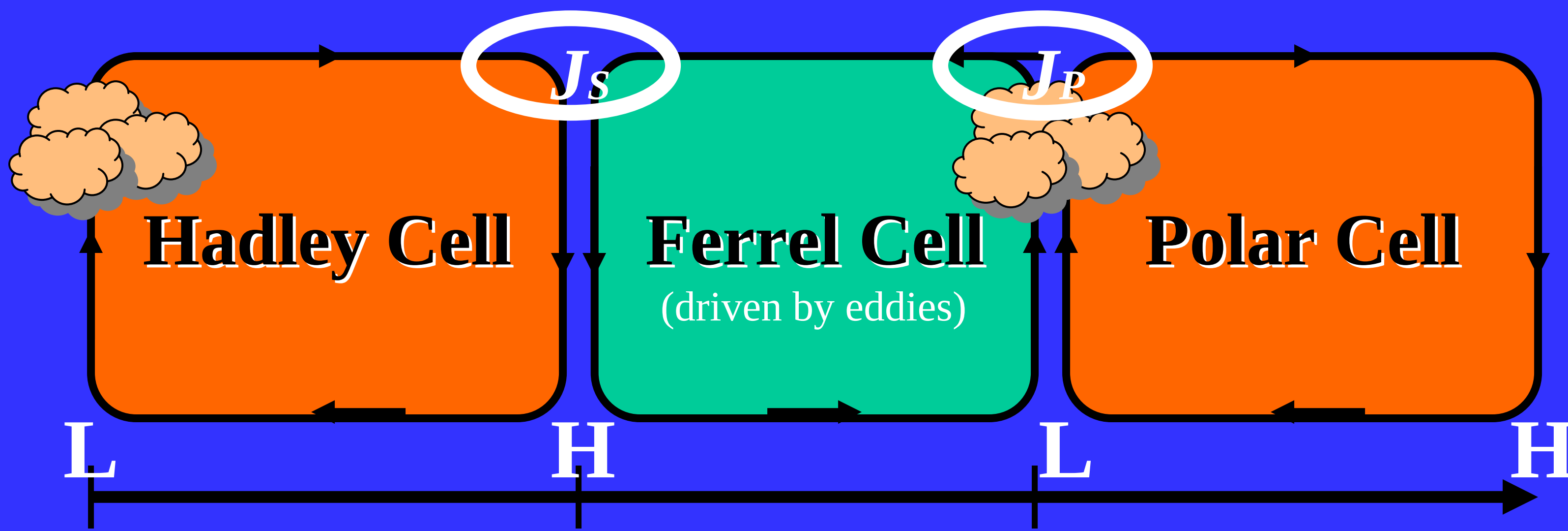
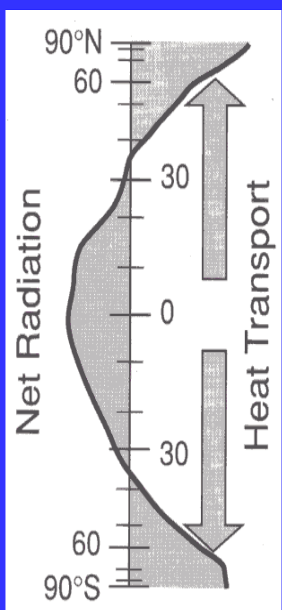
Lecture 5: Atmospheric General Circulation

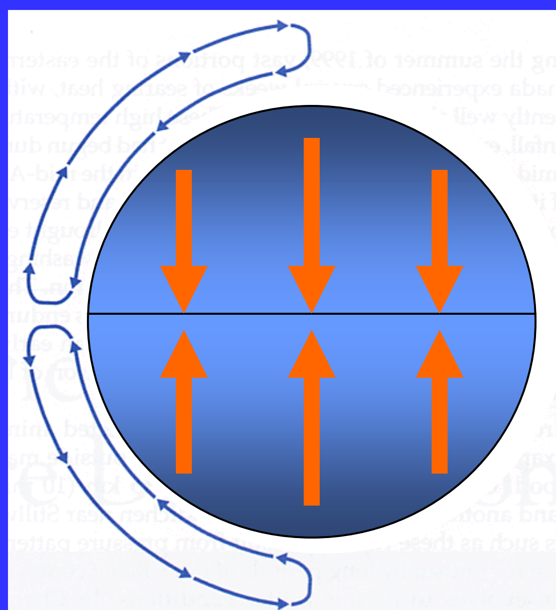


- Basic Structures and Dynamics
- General Circulation in the Troposphere
- General Circulation in the Stratosphere
- Wind-Driven Ocean Circulation

Single-Cell Model:
Explains Why There are Tropical Easterlies

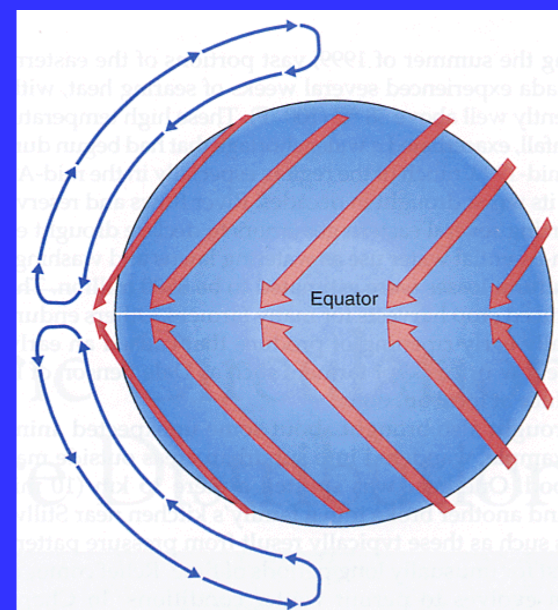
Without Earth Rotation





Coriolis Force

With Earth Rotation



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

ESS55
Prof. Jin-Yi Yu

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:

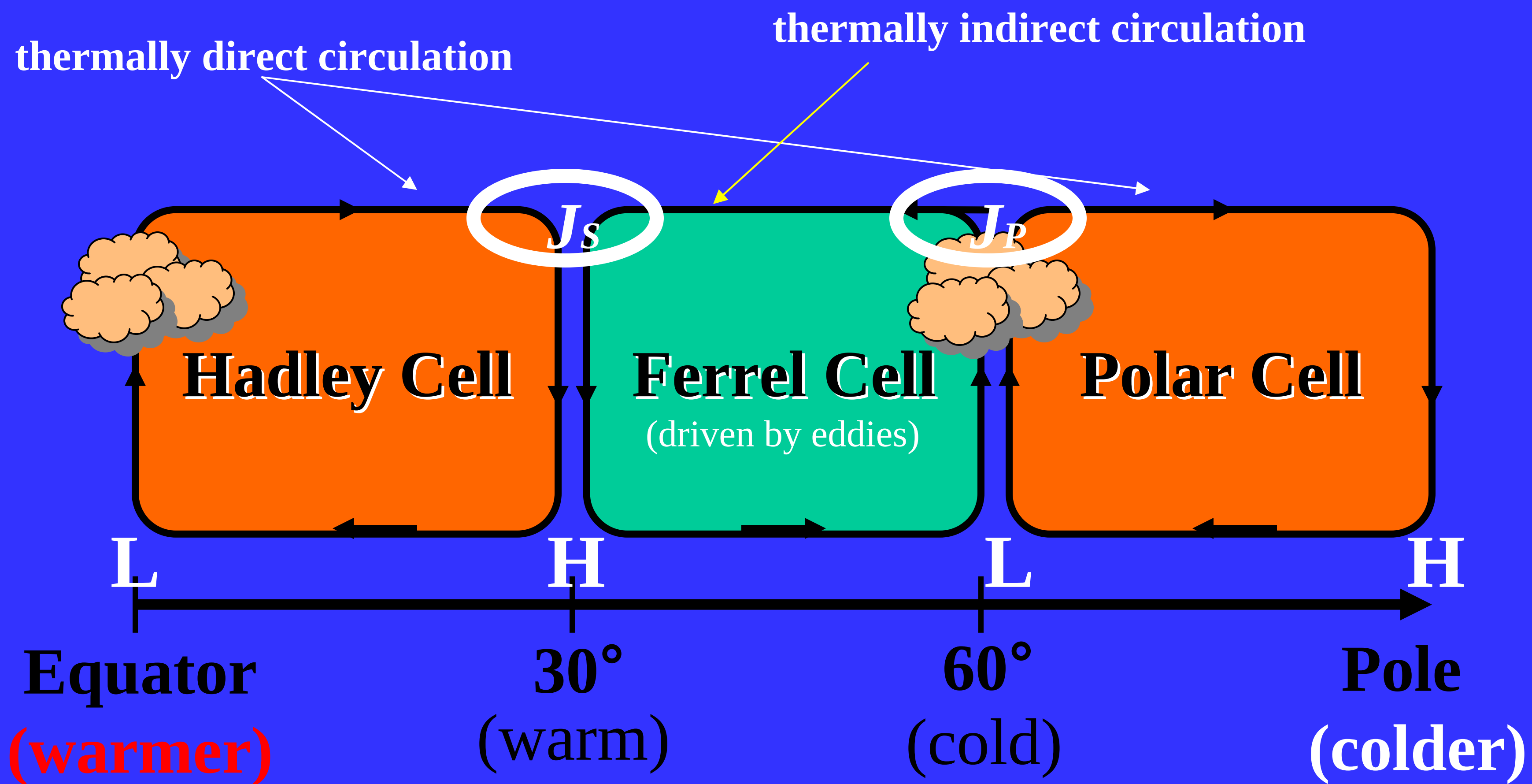
$$(U_0 + u_{Eq}) * a * Cos(0°) = (U_{60N} + u_{60N}) * a * Cos(60°)$$

$$(\Omega*a*Cos0° - 5) * a * Cos0° = (\Omega*a*Cos60° + u_{60N}) * a * Cos(60°)$$

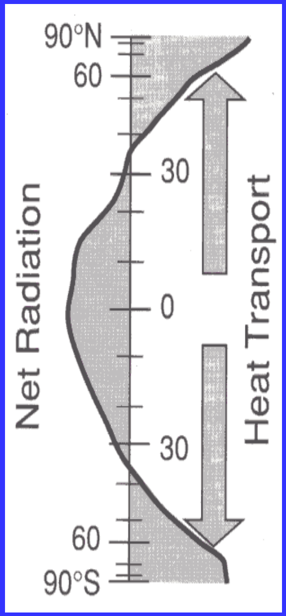
$$\boxed{u_{60N} = 687 \text{ m/sec !!!!}}$$

This high wind speed is not observed!

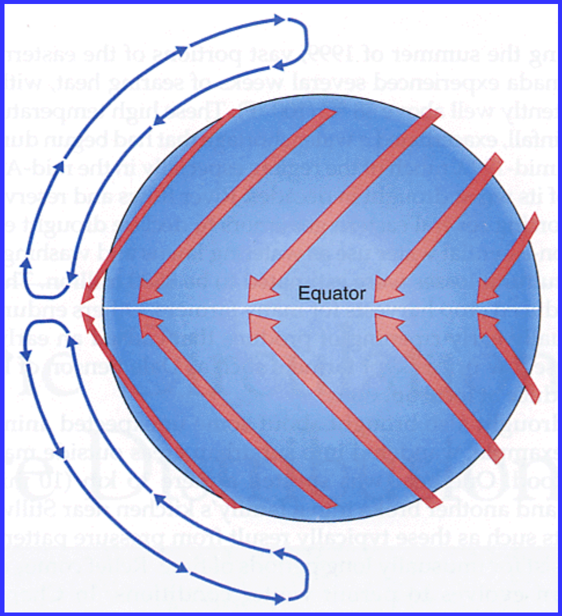
Properties of the Three Cells



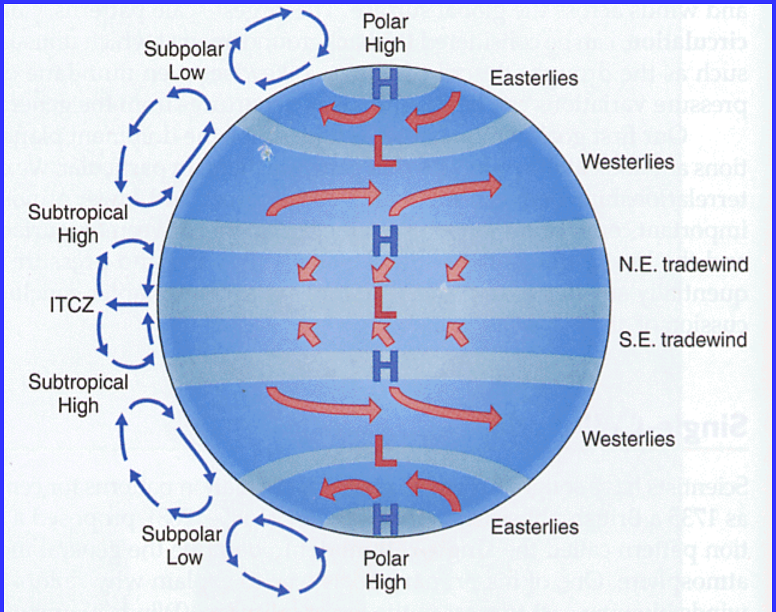
Atmospheric Circulation: Zonal-mean Views



Single-Cell Model

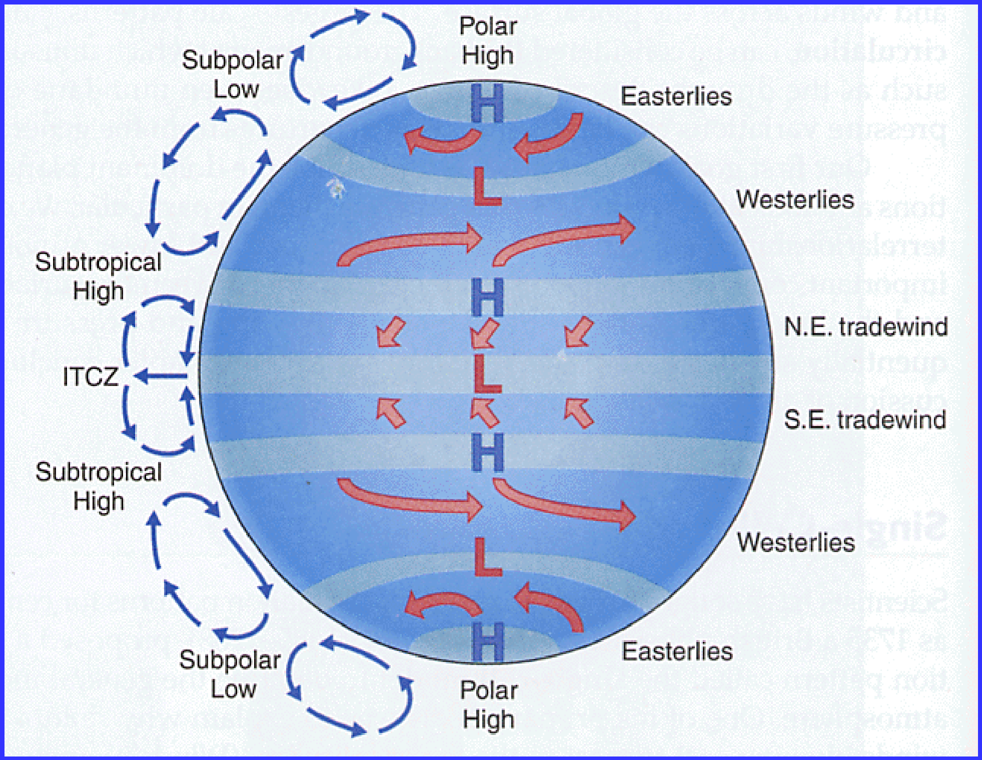


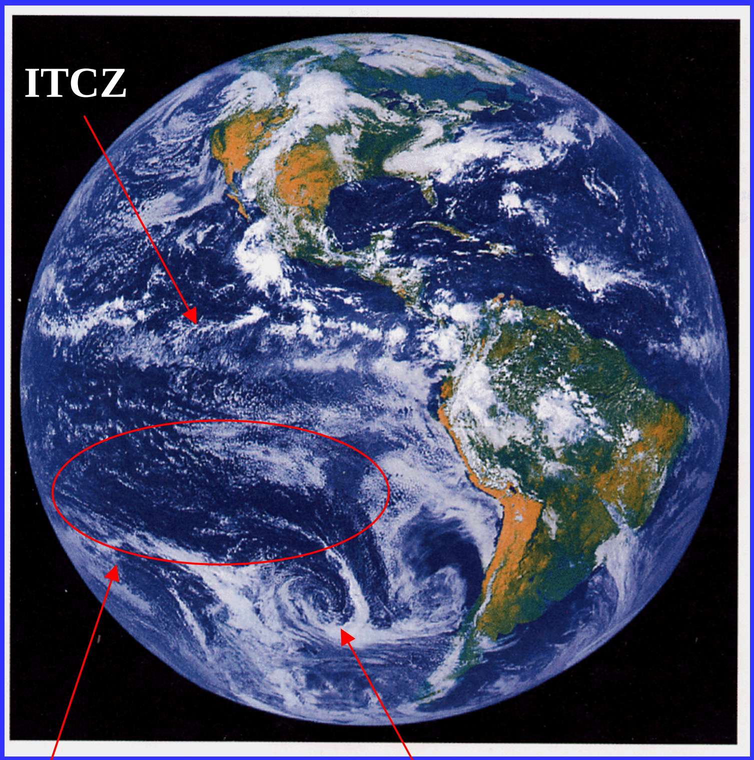
Three-Cell Model



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

The Three Cells





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

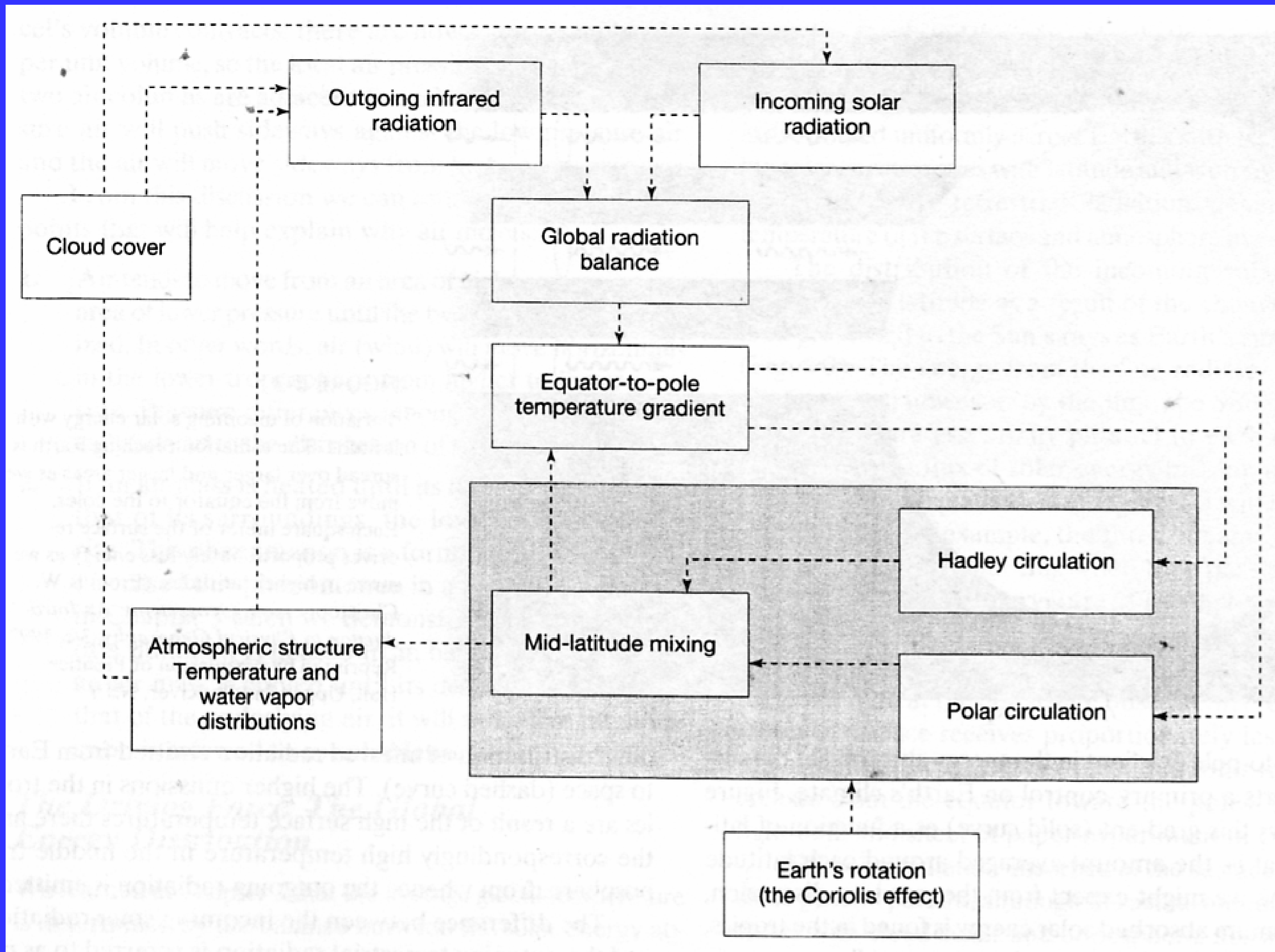
Thermally Direct/Indirect Cells

- **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)*

ESS55
Prof. Jin-Yi Yu

Is the Three-Cell Model Realistic?

- ***Yes and No!***

  (Due to sea-land contrast and topography)

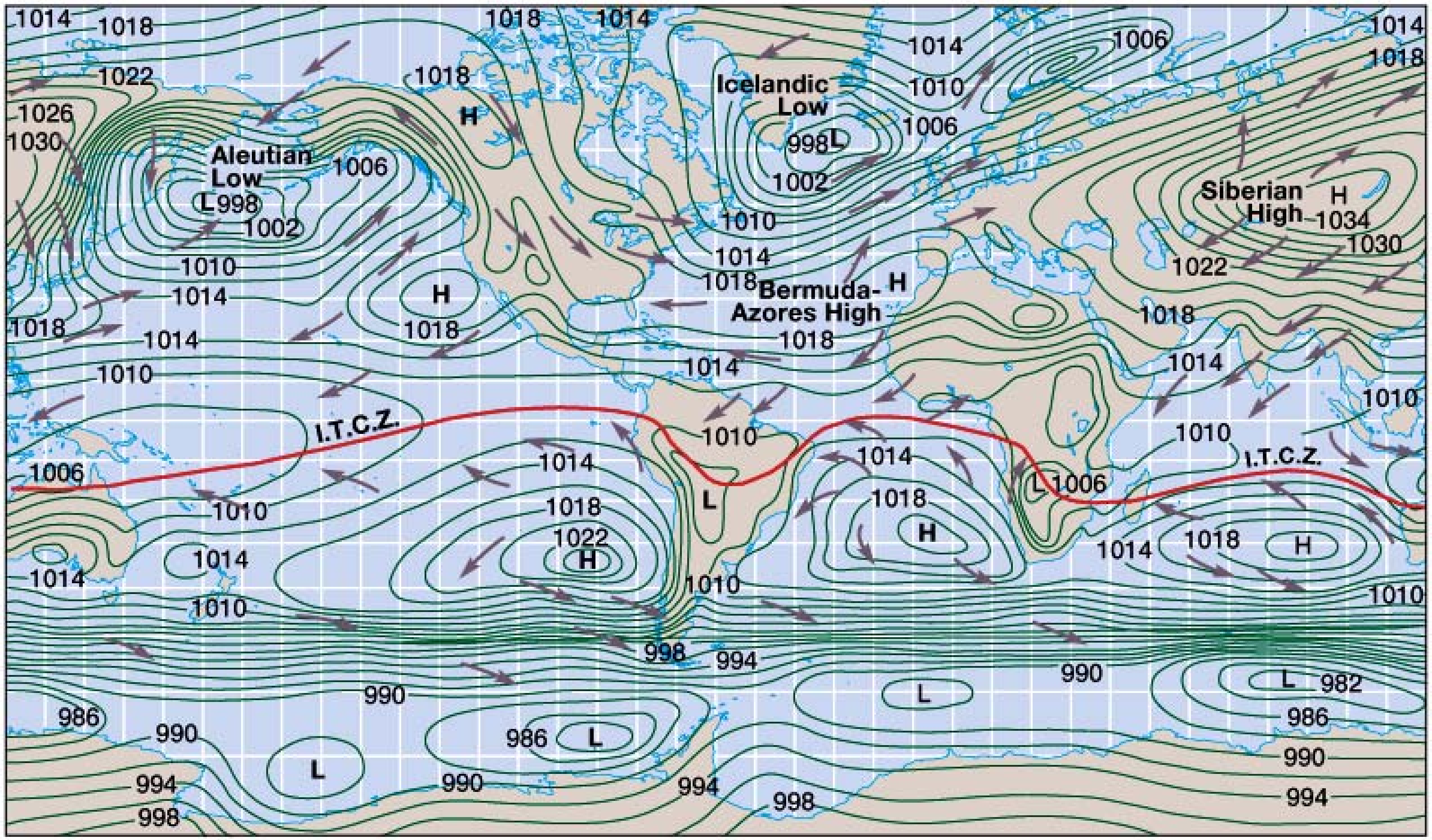
Yes: the three-cell model explains reasonably well the surface wind distribution in the atmosphere.

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

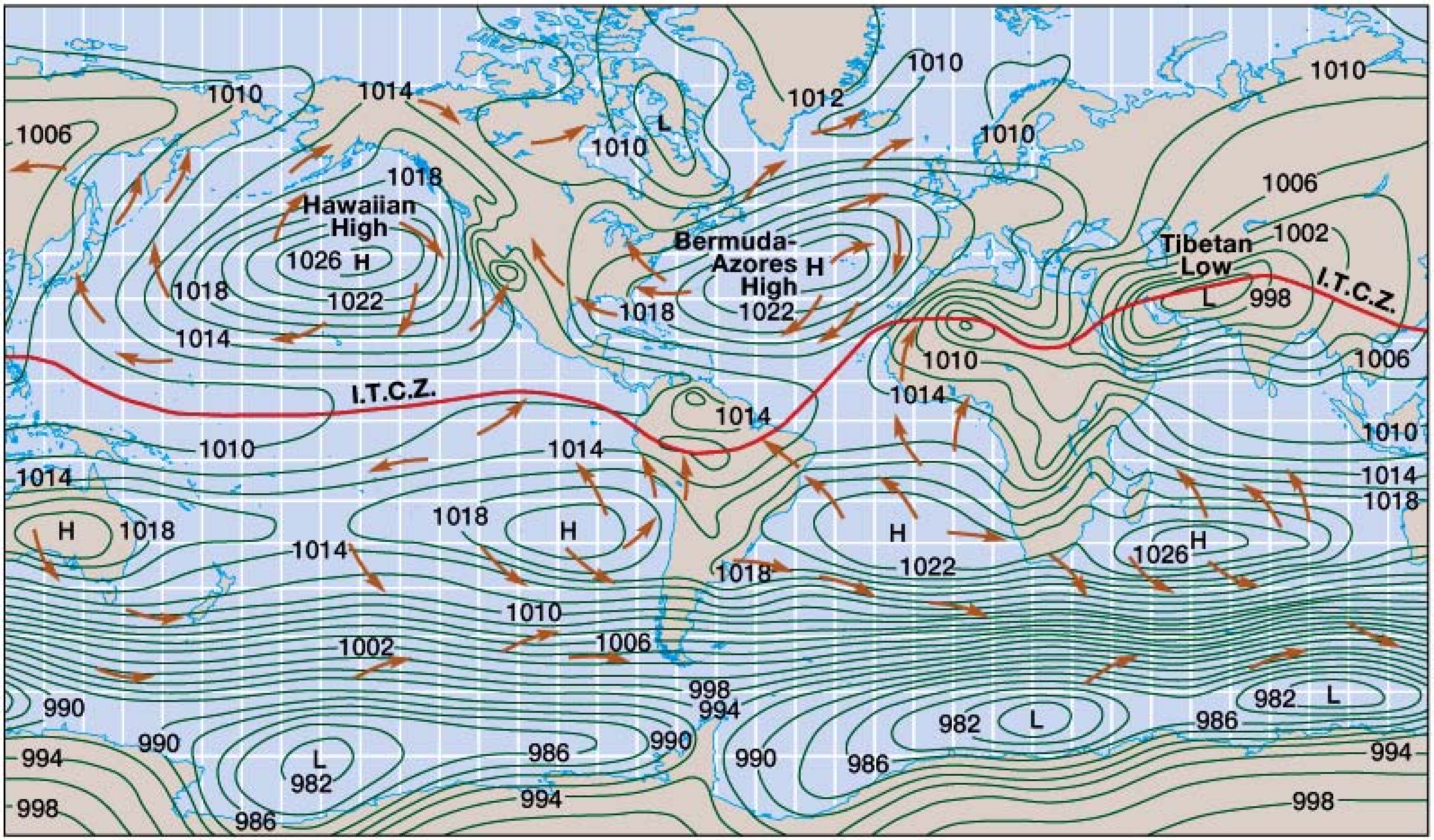
- **The Aleutian, Icelandic, and Tibetan lows**
  - The oceanic (continental) lows achieve maximum strength during winter (summer) months
  - The summertime Tibetan low is important to the east-Asia monsoon
- **Siberian, Hawaiian, and Bermuda-Azores highs**
  - The oceanic (continental) highs achieve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

January

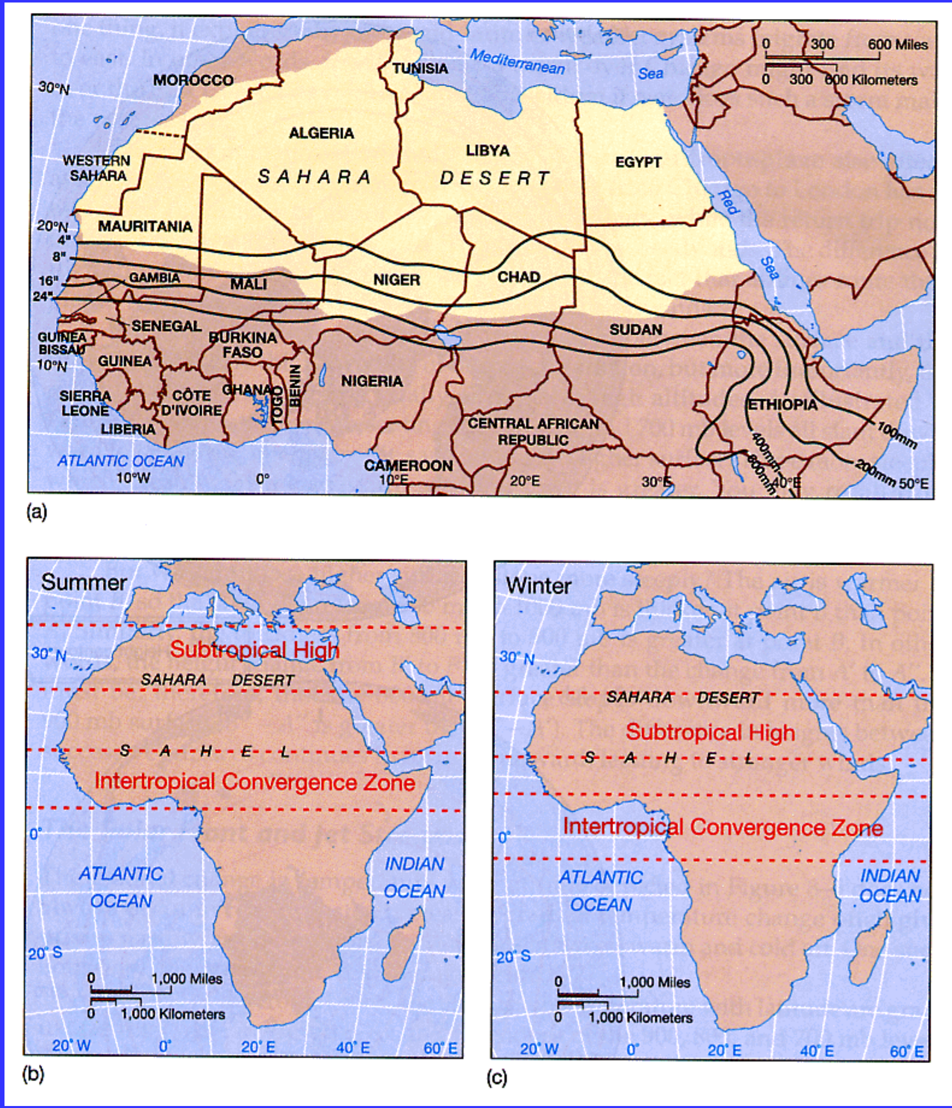


Aleutian Low
Icelandic Low
Bermuda-Azores High
Siberian High
I.T.C.Z.

July


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

Sinking Branches and Deserts



(from *Weather & Climate*)

ESS55
Prof. Jin-Yi Yu

Global Distribution of Deserts

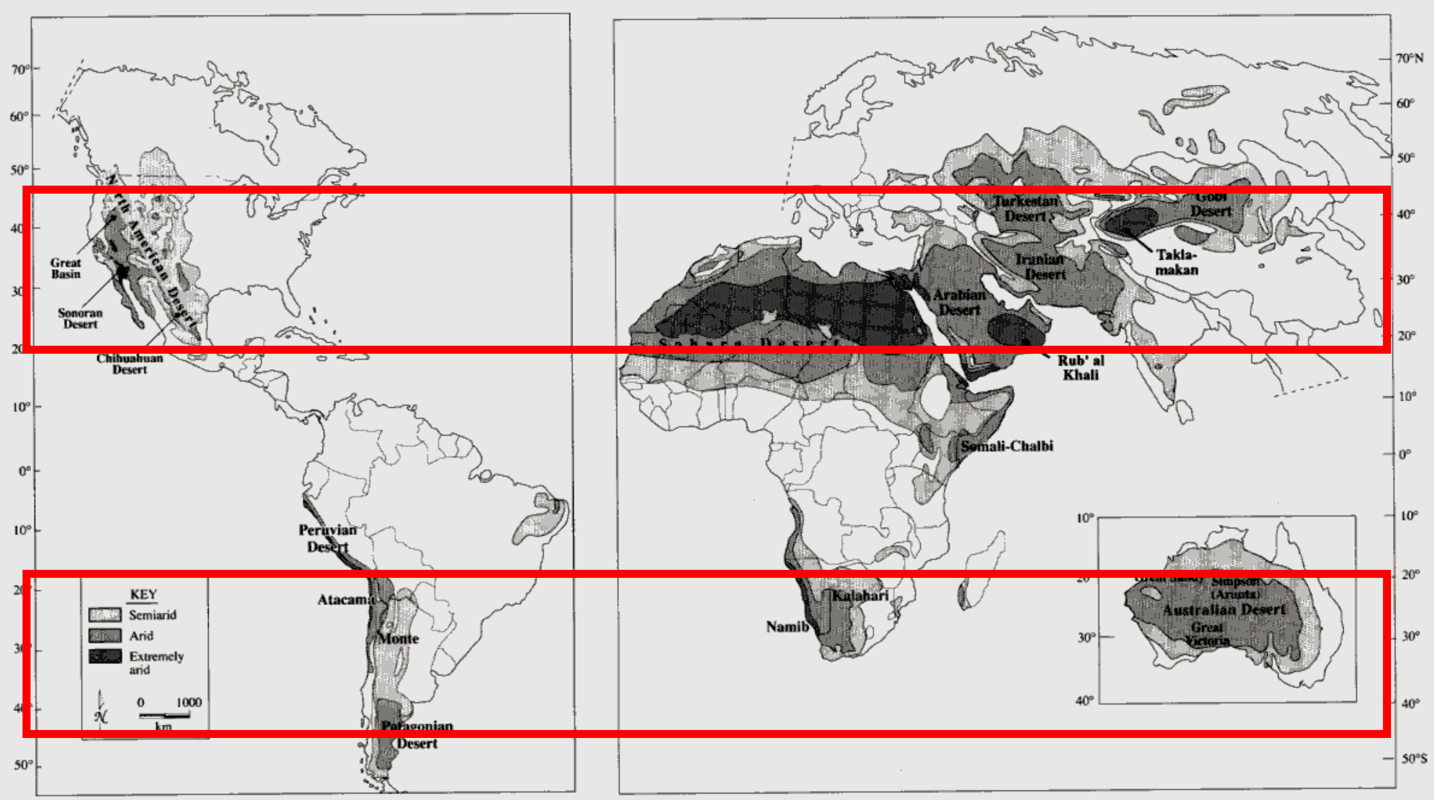
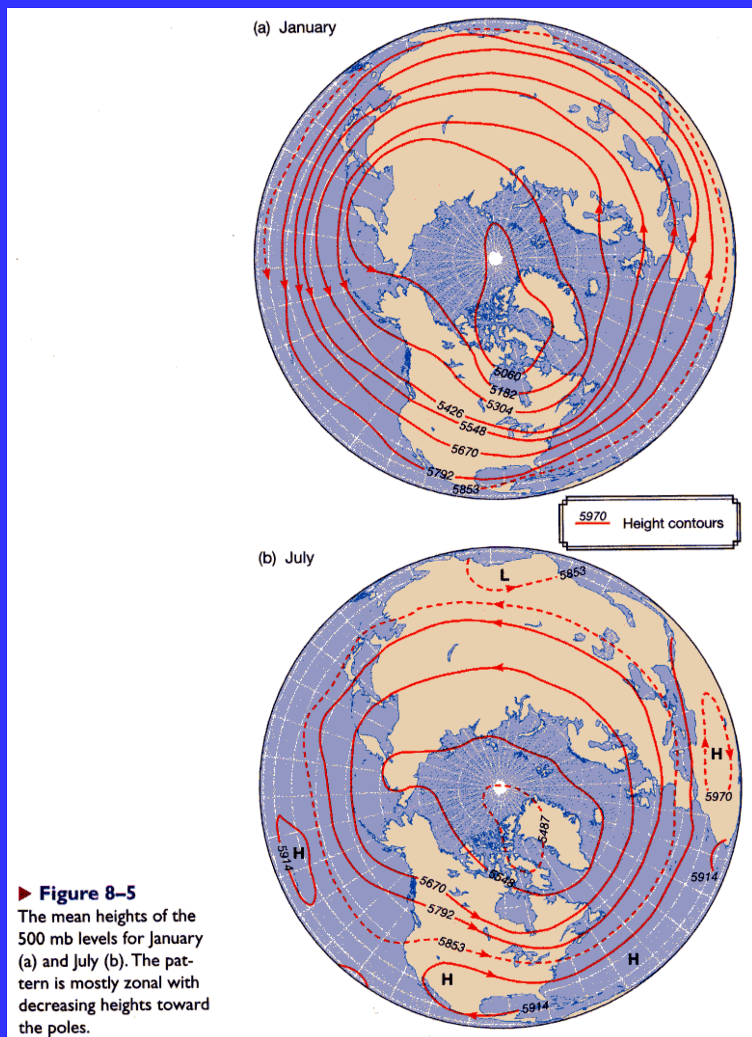


Fig. 6.21 Map showing arid lands around the world. Meigs classification taken from *Mosaic* magazine (Vol. 8, Jan/Feb 1977). [See McGinnies *et al.*, eds., (1968). Permission granted by the Office of Arid Lands Studies.]

(from *Global Physical Climatology*)

Upper Tropospheric Circulation

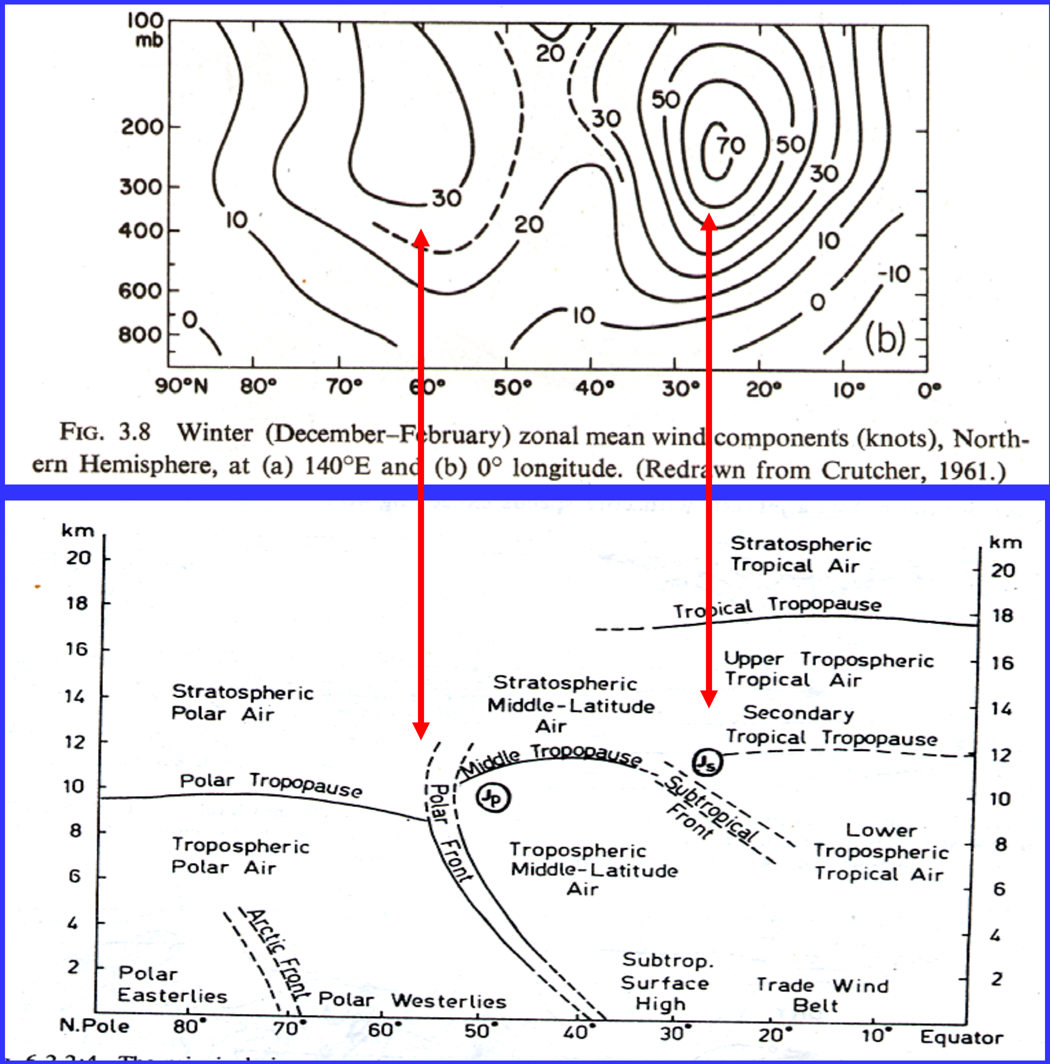


▶ **Figure 8–5**
The mean heights of the 500 mb levels for January (a) and July (b). The pattern is mostly zonal with decreasing heights toward the poles.

(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



(from *Atmospheric Circulation Systems*)

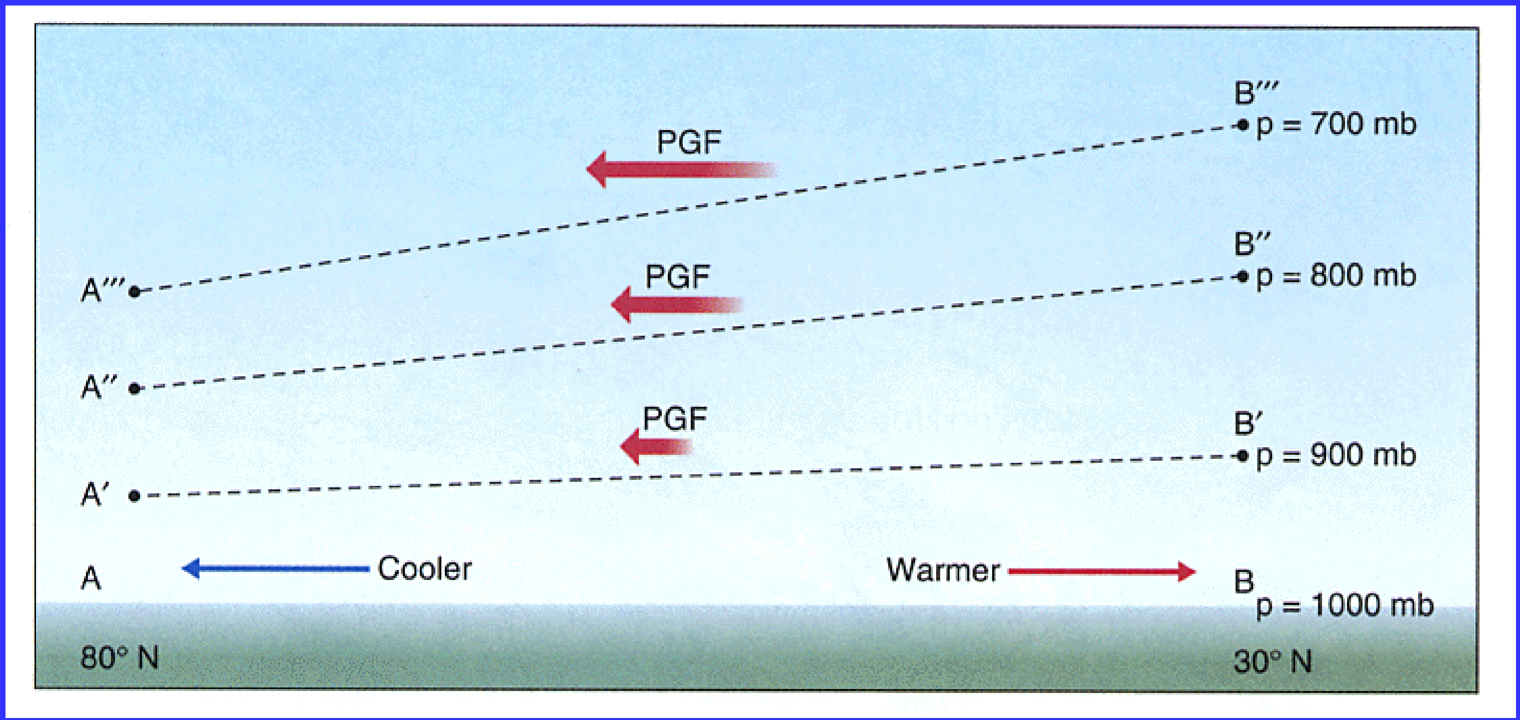
- **Subtropical Jet**

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*)

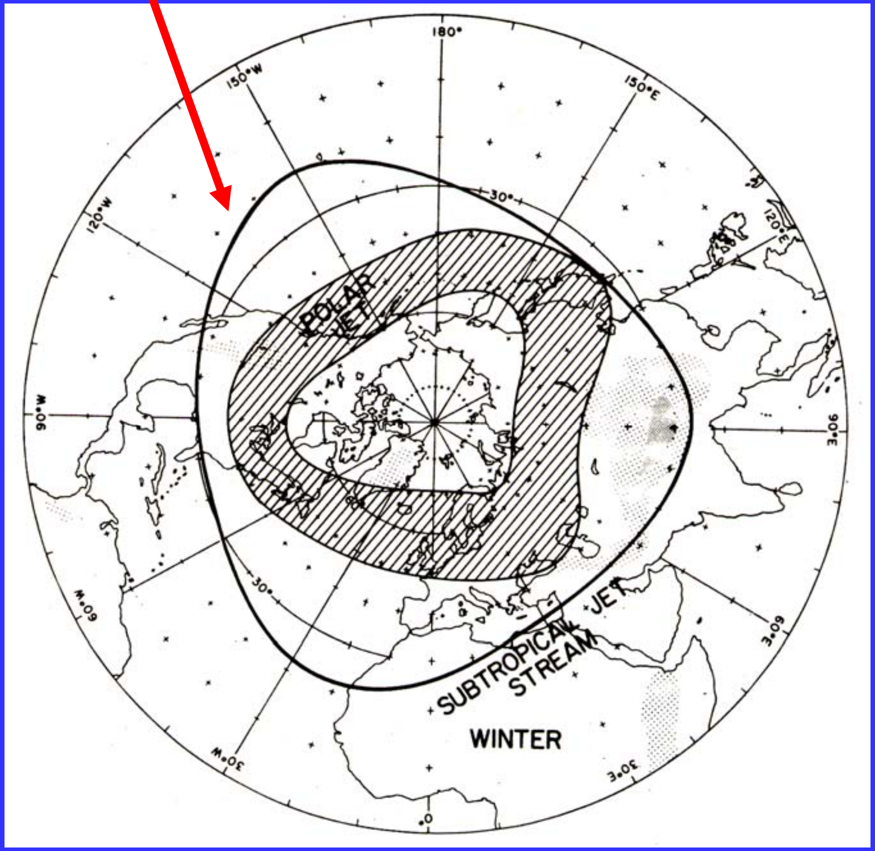
Thermal Wind Equation

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

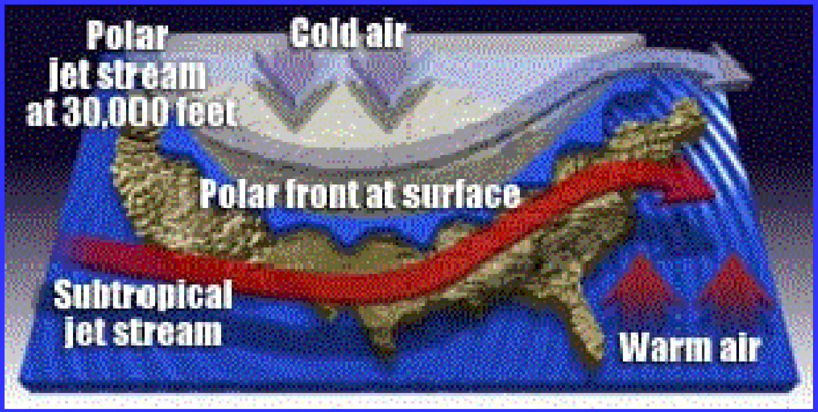
- The vertical shear of zonal wind is related to the latitudinal gradient of temperature.
- Jet streams usually are formed above baroclinic zone (such as the polar front).

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.

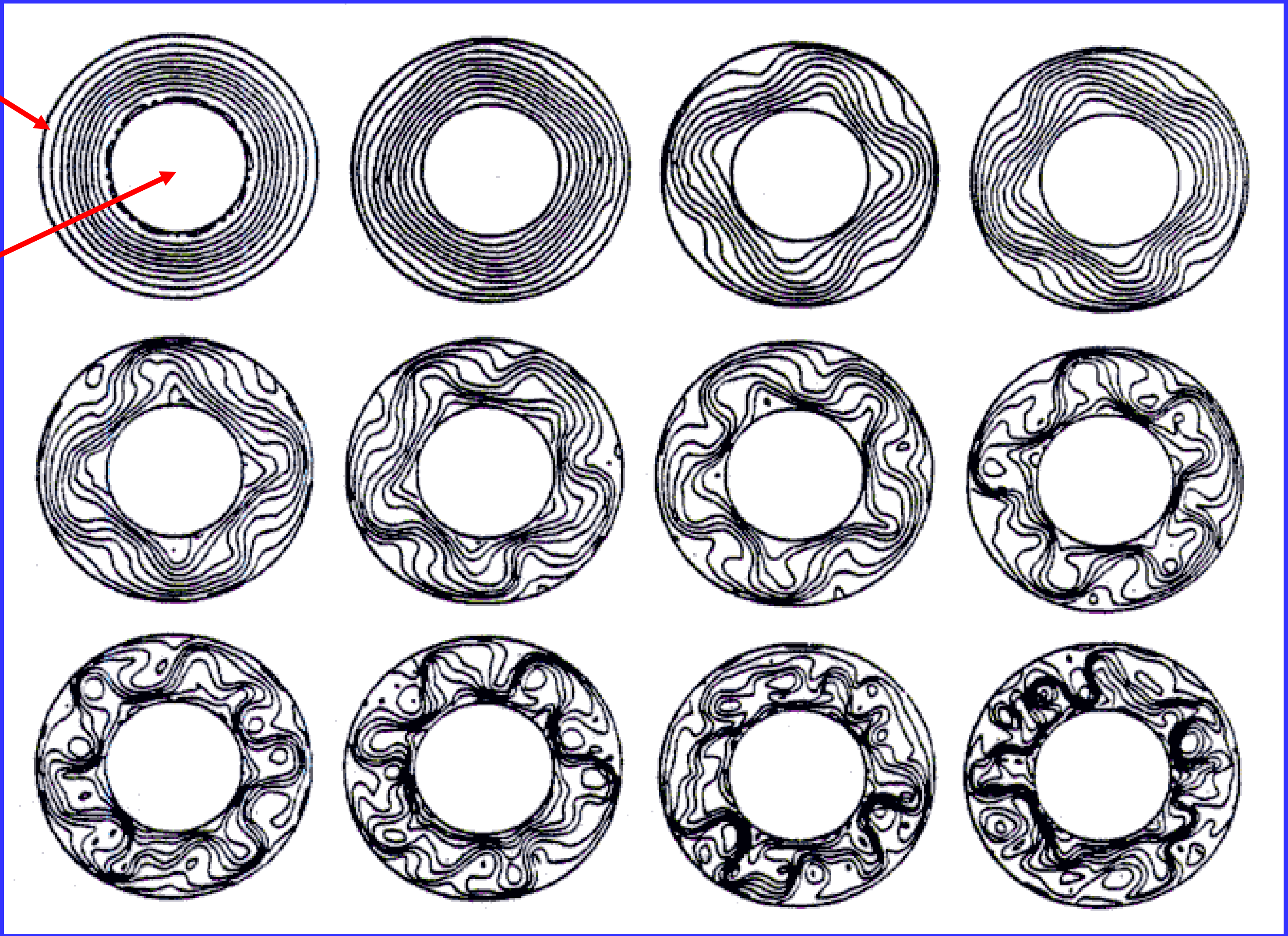
Parameters Determining Mid-latitude Weather

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

Rotating Annulus Experiment

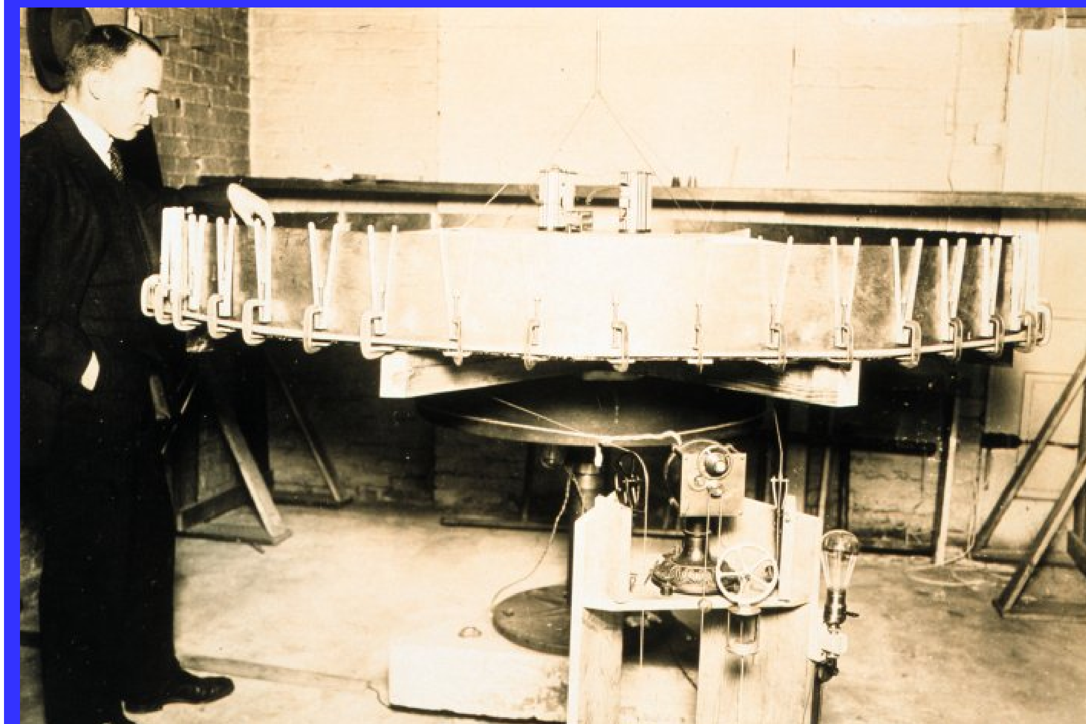
Cooling Outside

Heating Inside



(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.

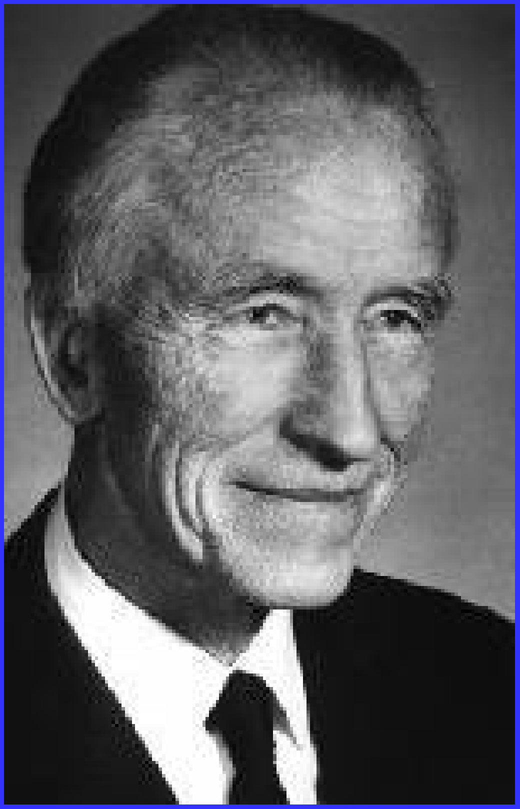
Polar Front Theory

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.

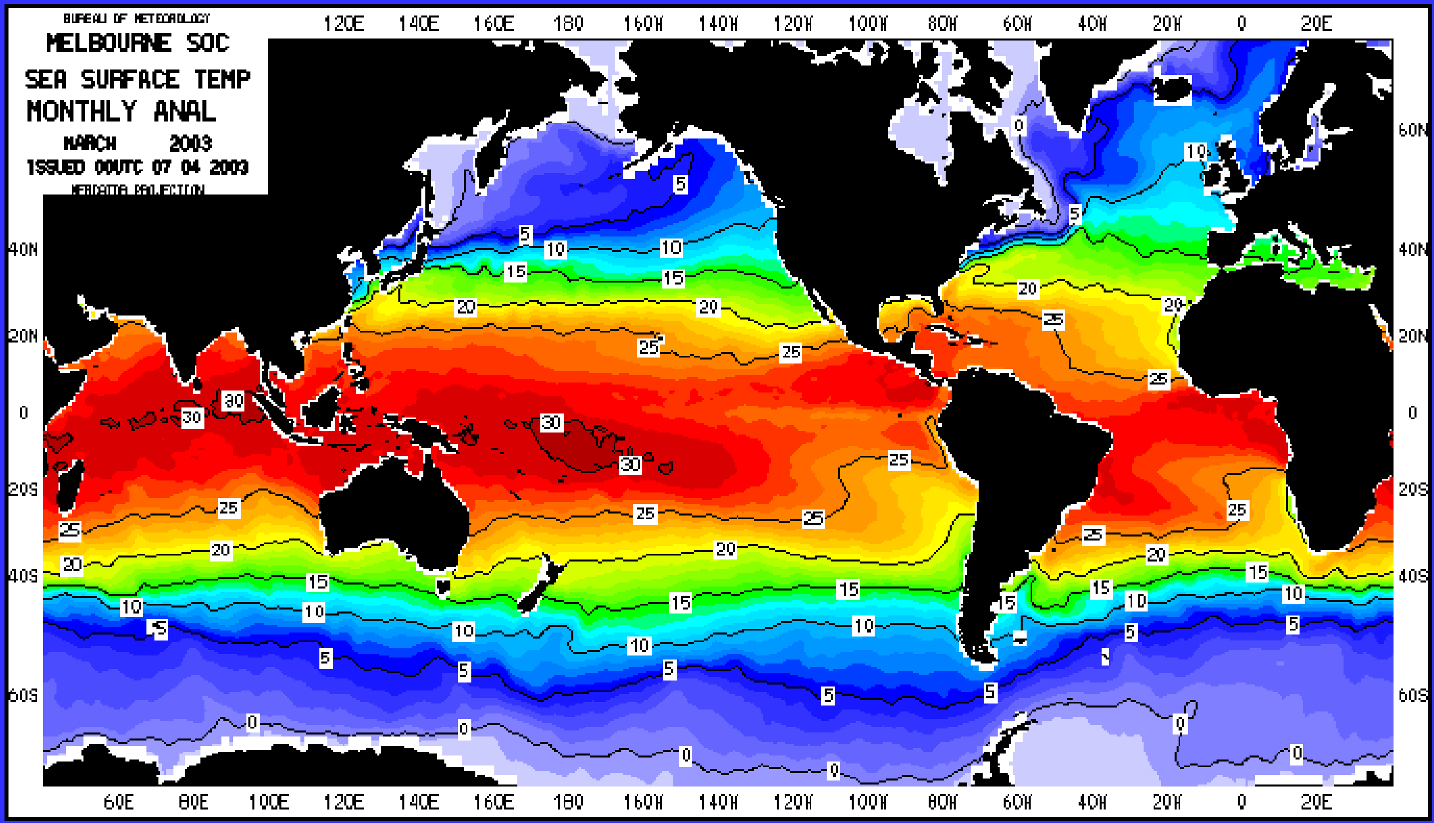
El Nino and Southern Oscillation

- 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

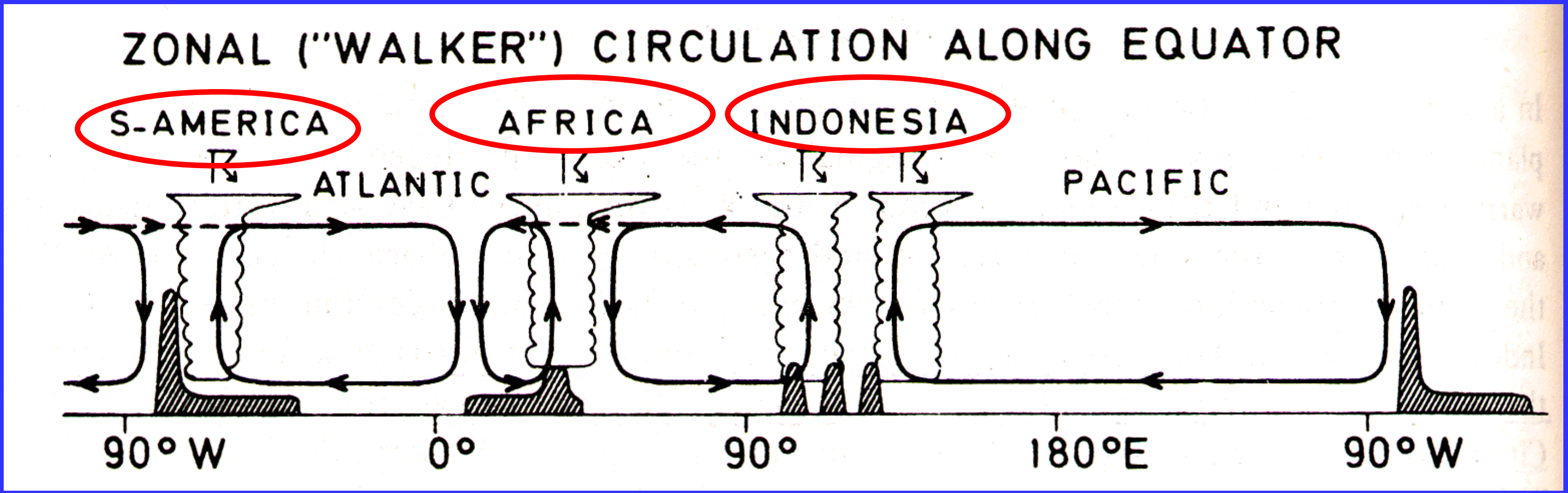
Walker Circulation and Ocean Temperature



ESS55
Prof. Jin-Yi Yu

East-West Circulation

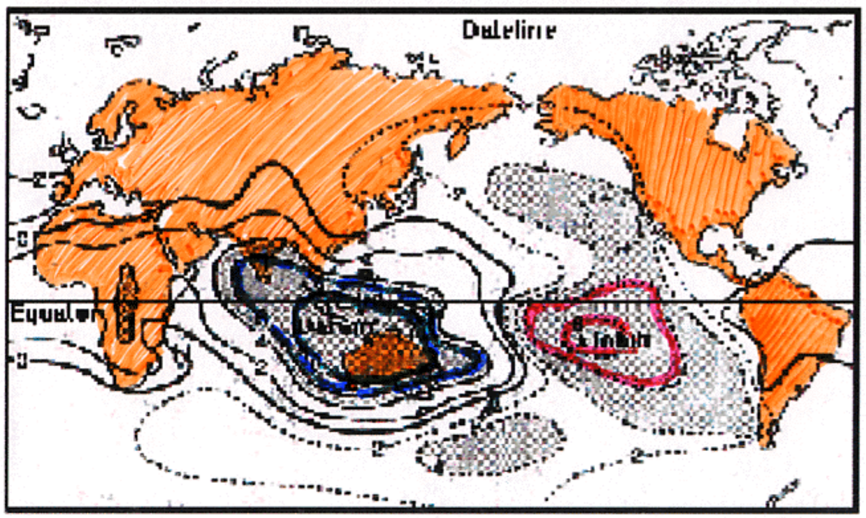
(from *Flohn (1971)*)



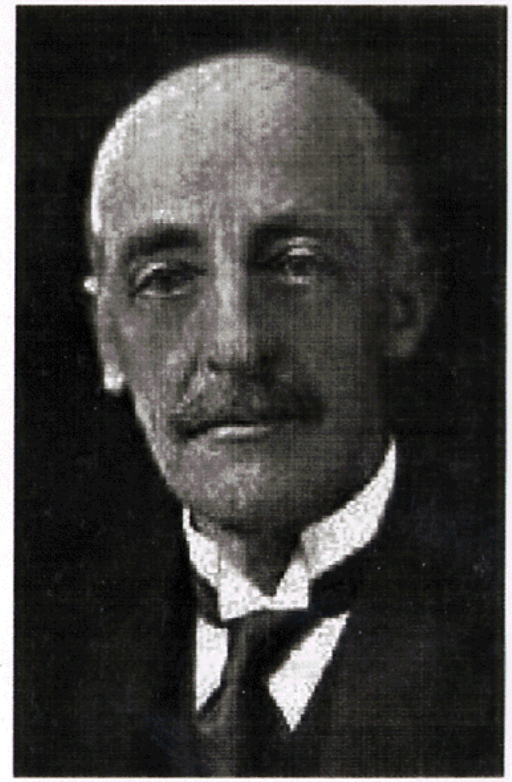
❑ The east-west circulation in the atmosphere is related to the sea/land distribution on the Earth.

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.

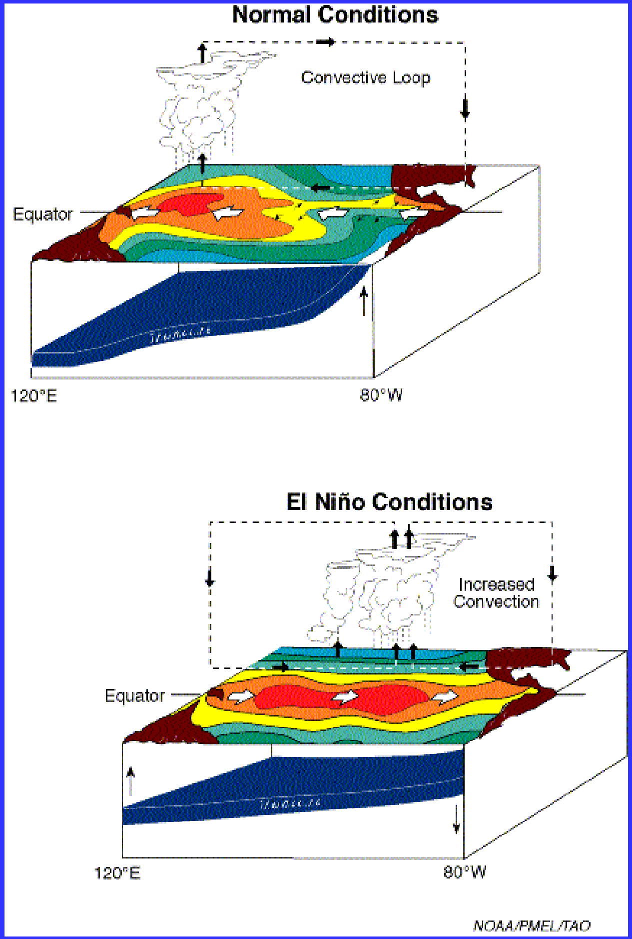


(from Rasmusson 1984)

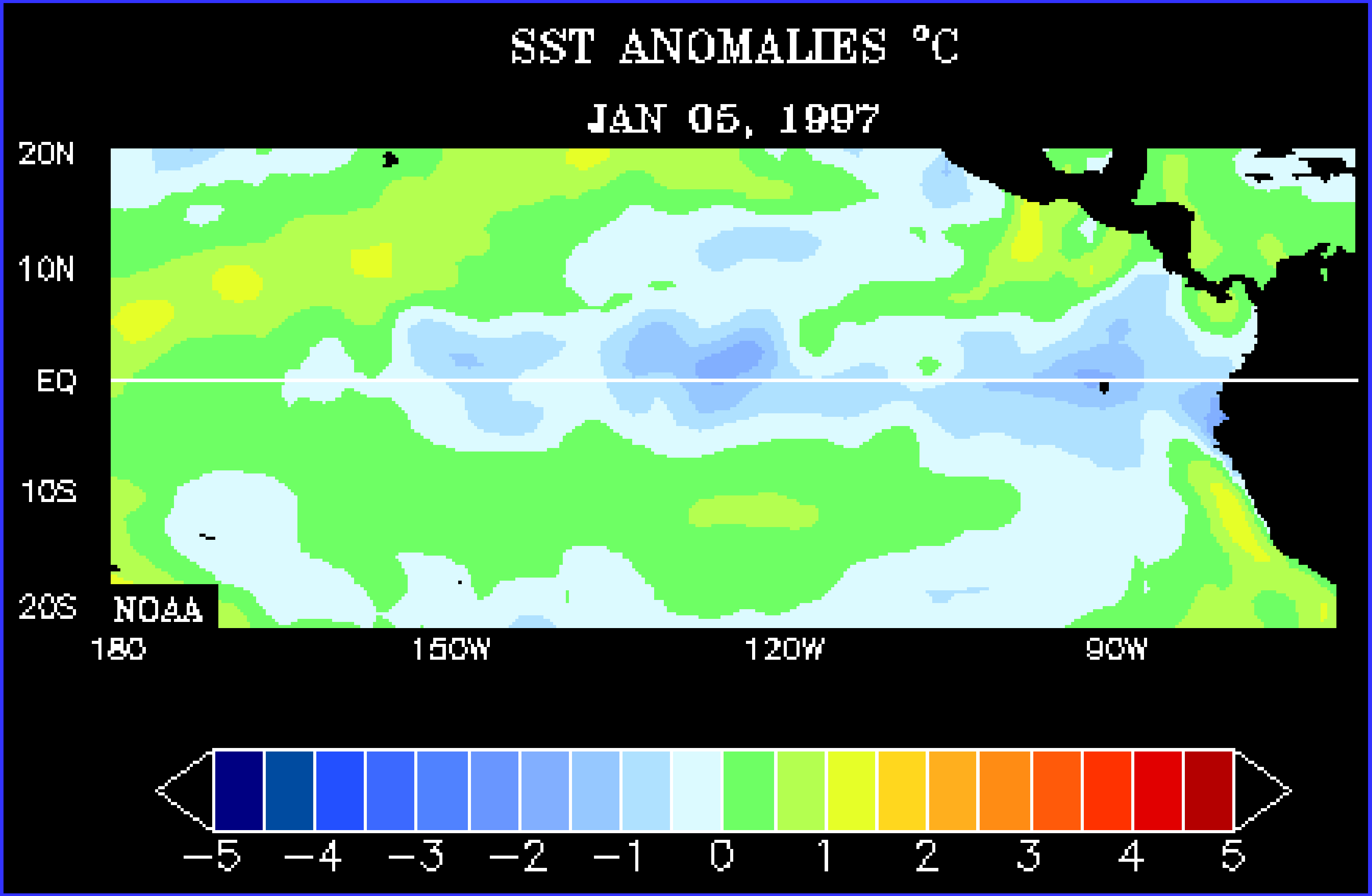


Sir Gilbert Walker

Walker Circulation and Ocean

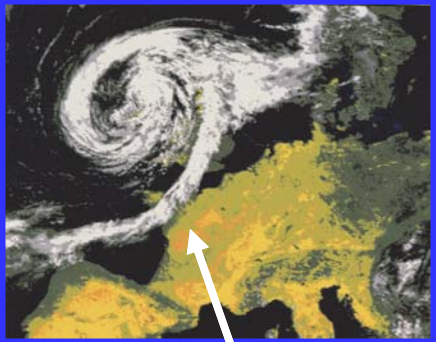


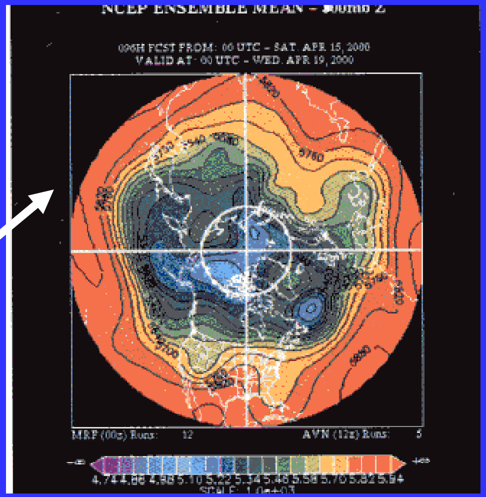
1997-98 El Nino

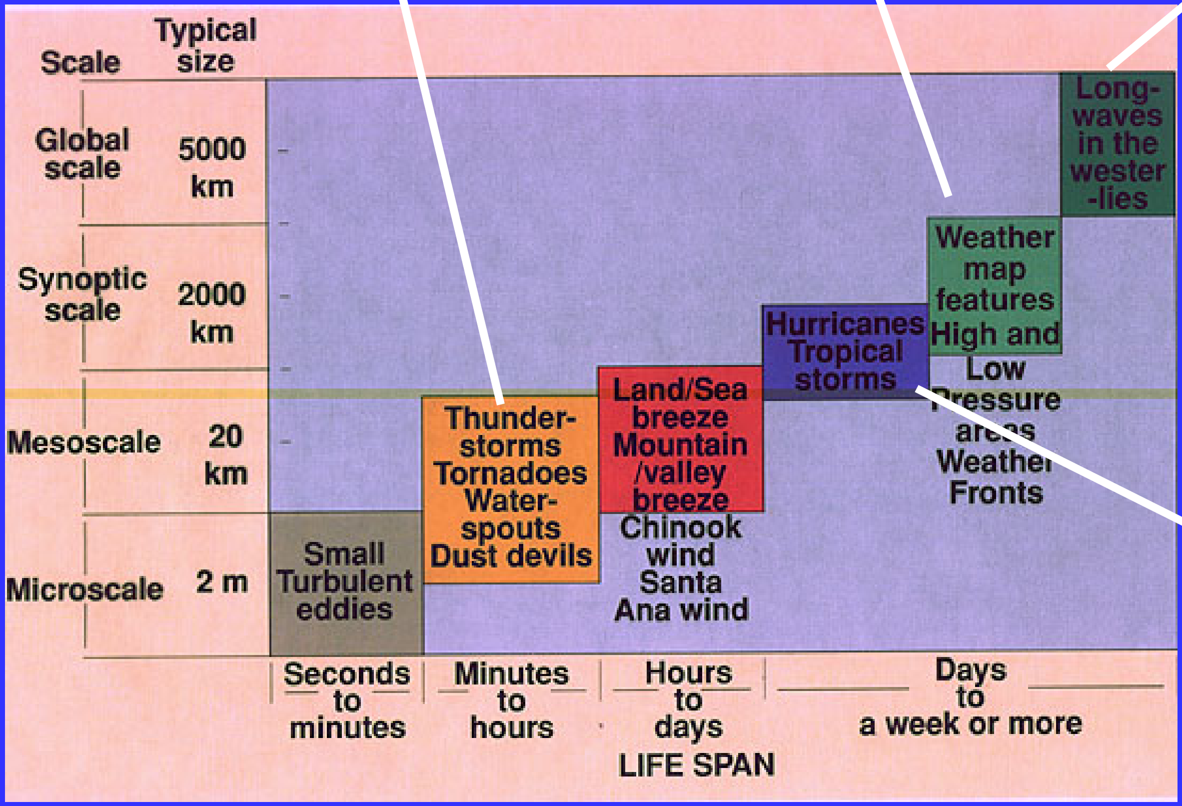


ESS55
Prof. Jin-Yi Yu

Scales of Motions in the Atmosphere

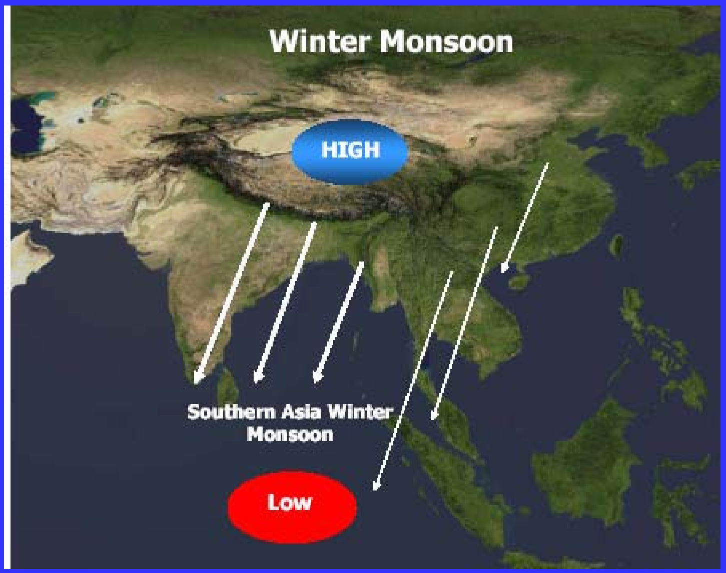




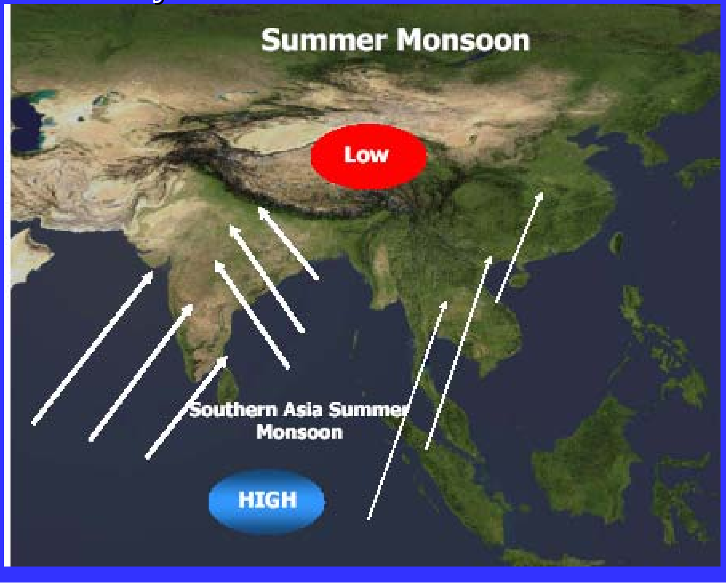


ESS55
Prof. Jin-Yi Yu

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.

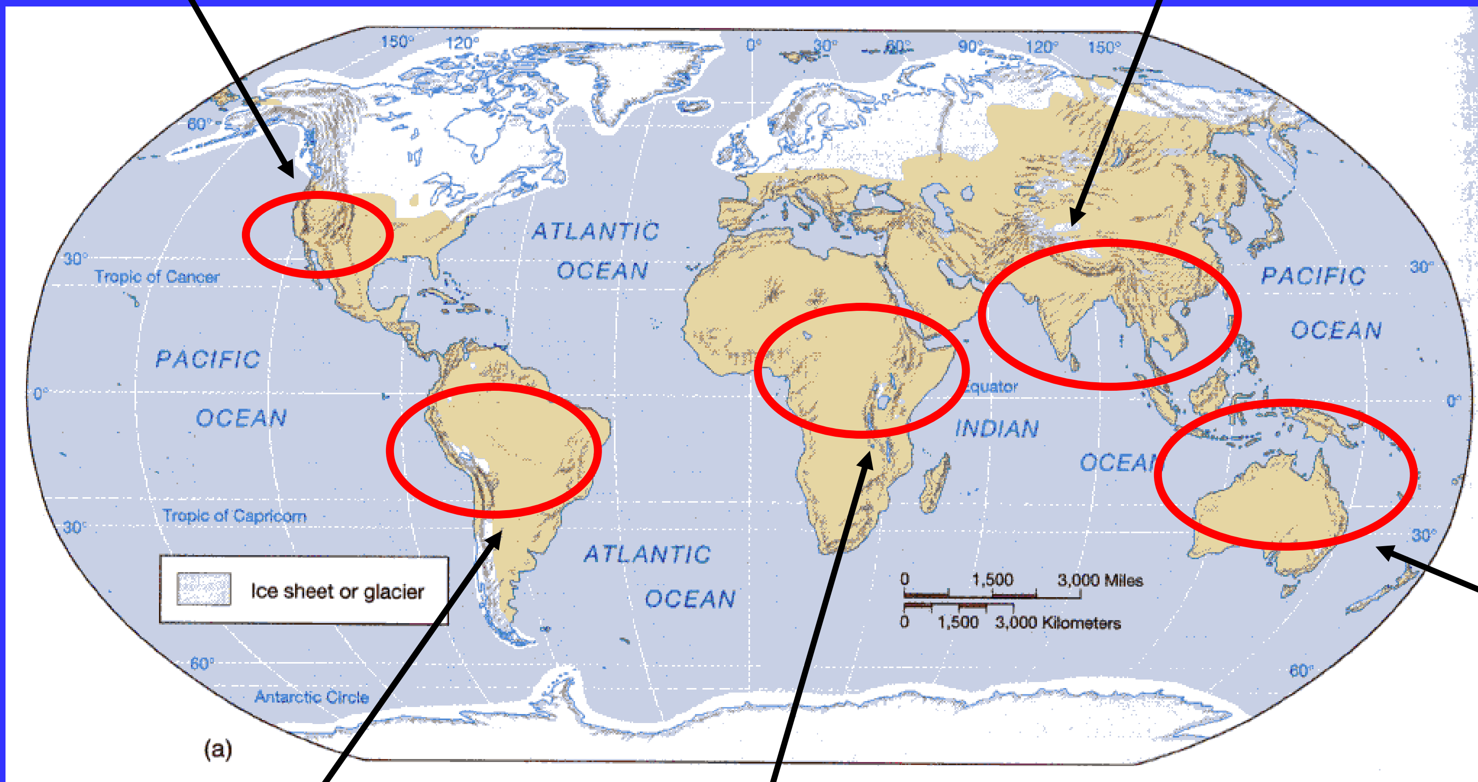
❑ During summer seasons, land surface heats up faster than the ocean. Low pressure center is established over land while high pressure center is established over oceans. Winds blow from ocean to land and bring large amounts of water vapor to produce heavy precipitation over land: A rainy season.

❑ 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?

North America Monsoon

Asian Monsoon



Australian Monsoon

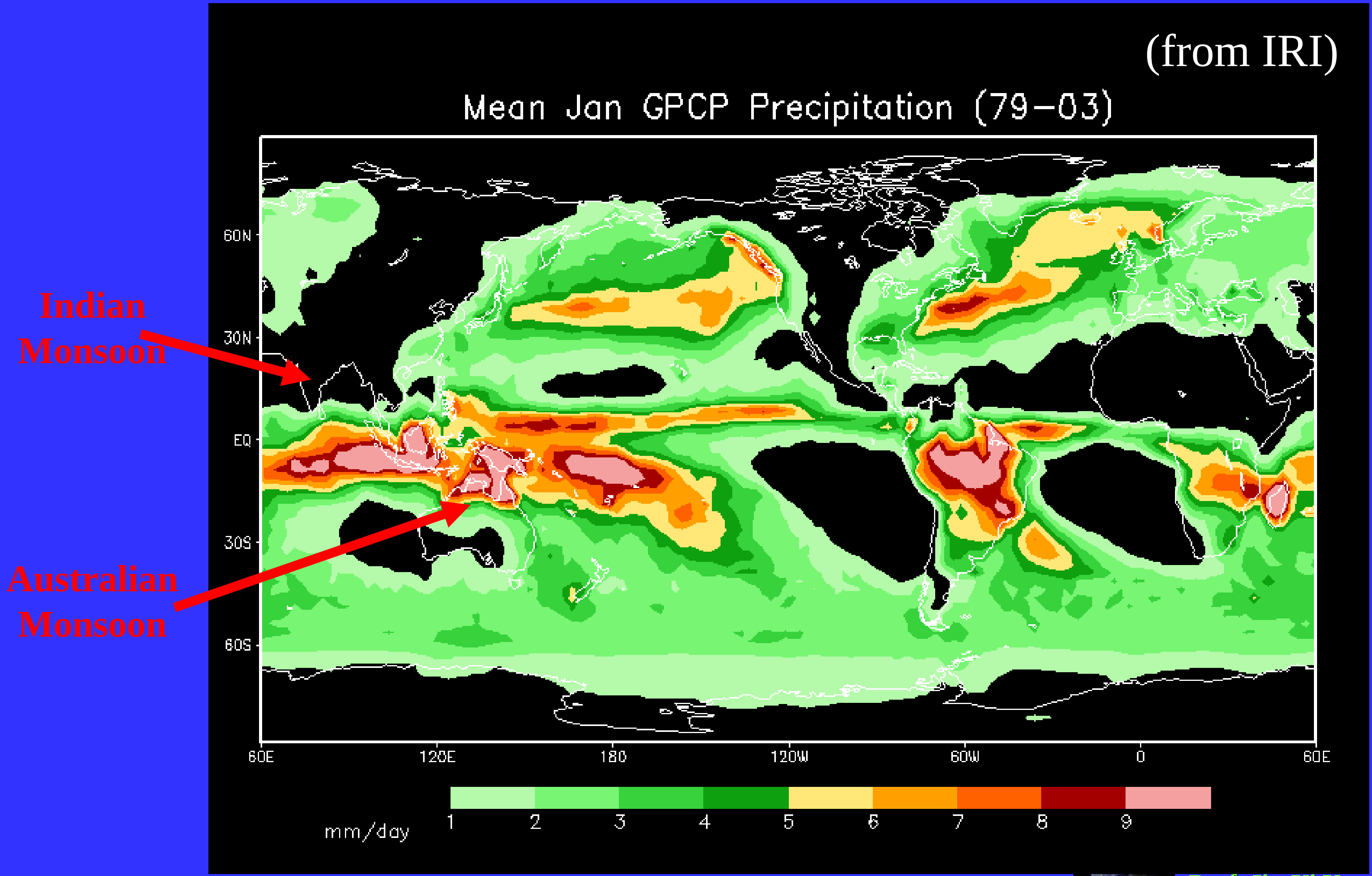
South America Monsoon

Africa Monsoon

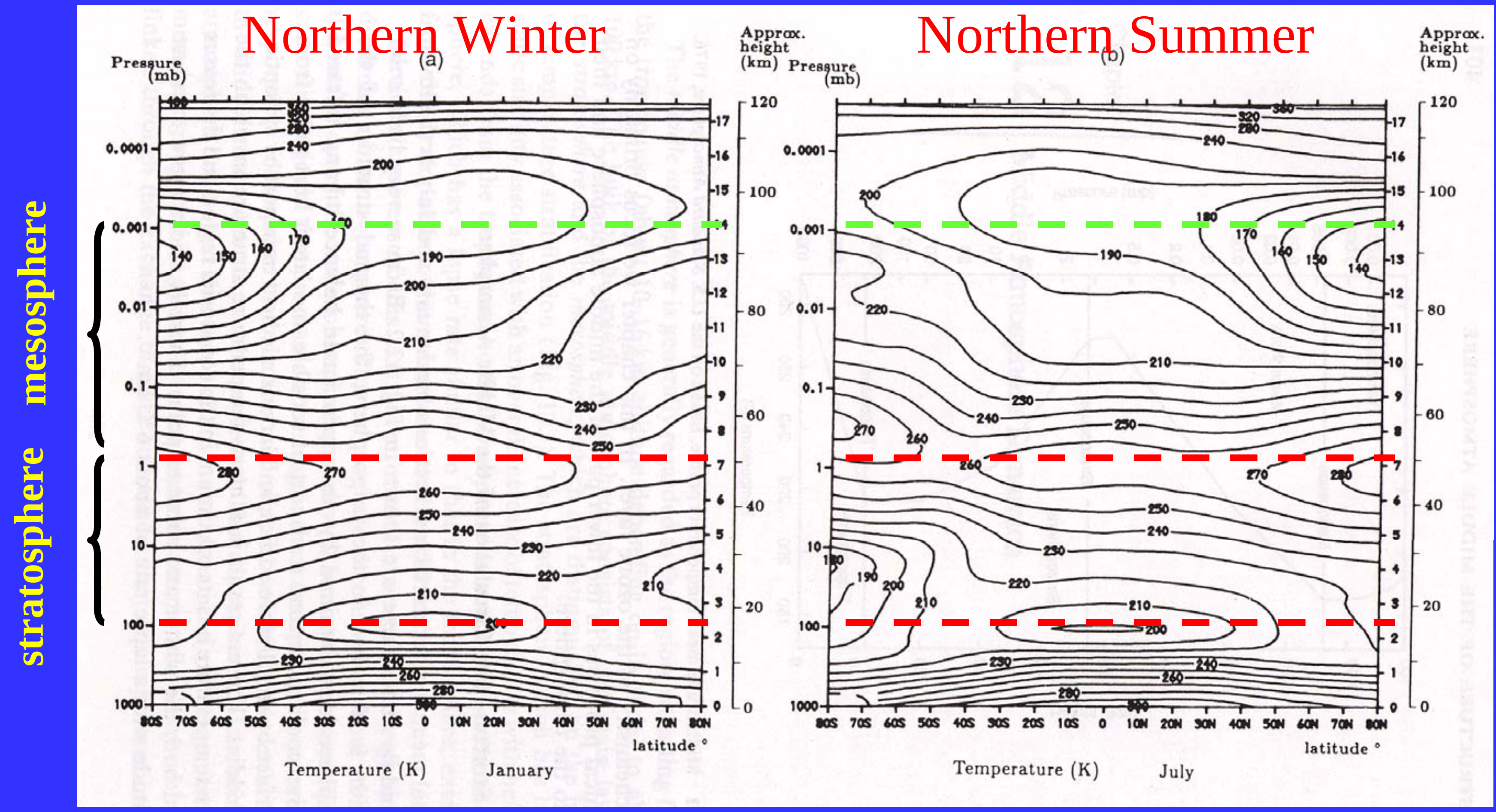
(figure from *Weather & Climate*)

ESS55
Prof. Jin-Yi Yu

Seasonal Cycle of Rainfall



Temperatures in Stratosphere



(from *Dynamic Meteorology*)

Ozone Distribution

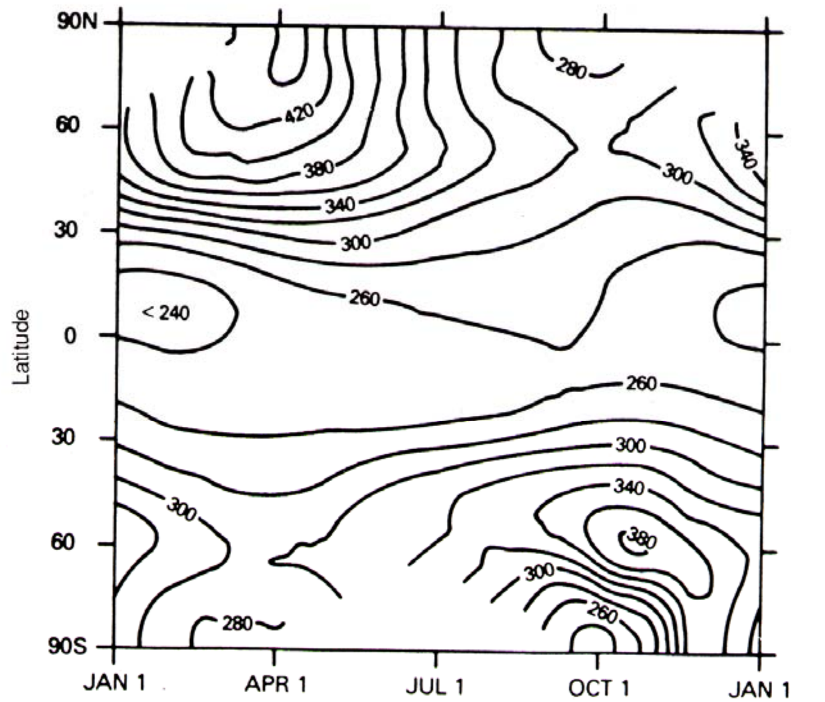
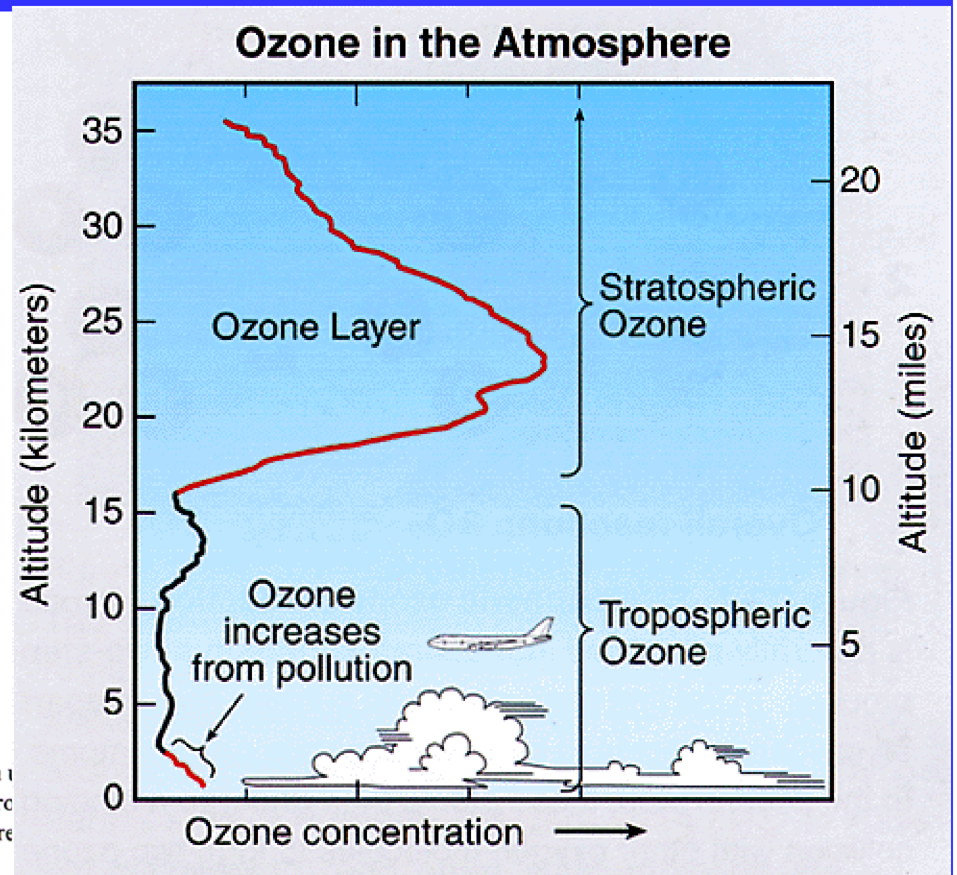


Fig. 12.13 Time–latitude section showing the seasonal variation of total ozone (Dobson u based on total ozone mapping spectrometer (TOMS) data. Note the extratro springtime maxima in both hemispheres and the minimum at 90°S centere October 1. (After Bowman and Krueger, 1985.)



Stratosphere: Circulation and Temperature

Zonal Wind

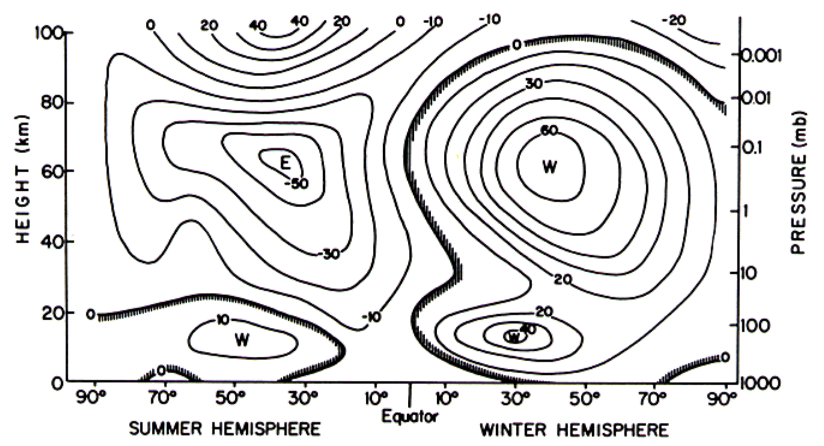


Fig. 1.4. Schematic latitude-height section of zonal mean zonal wind (m s^{-1}) for solstice conditions; W and E designate centers of westerly (from the west) and easterly (from the east) winds, respectively. (Courtesy of R. J. Reed.)

Temperature

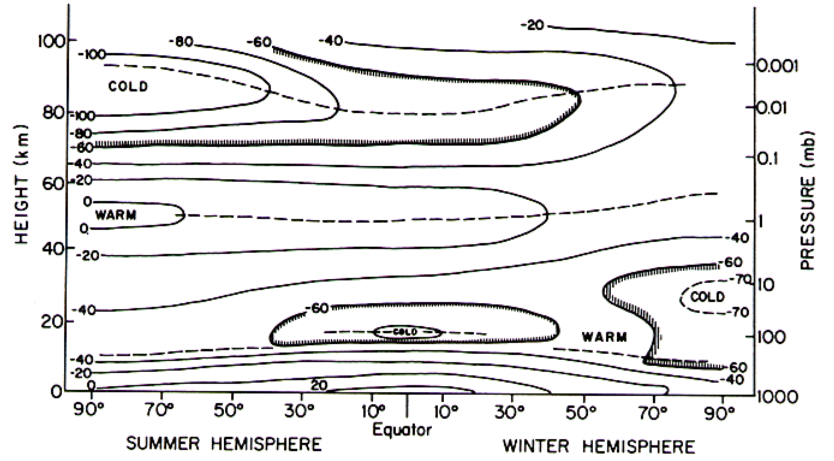
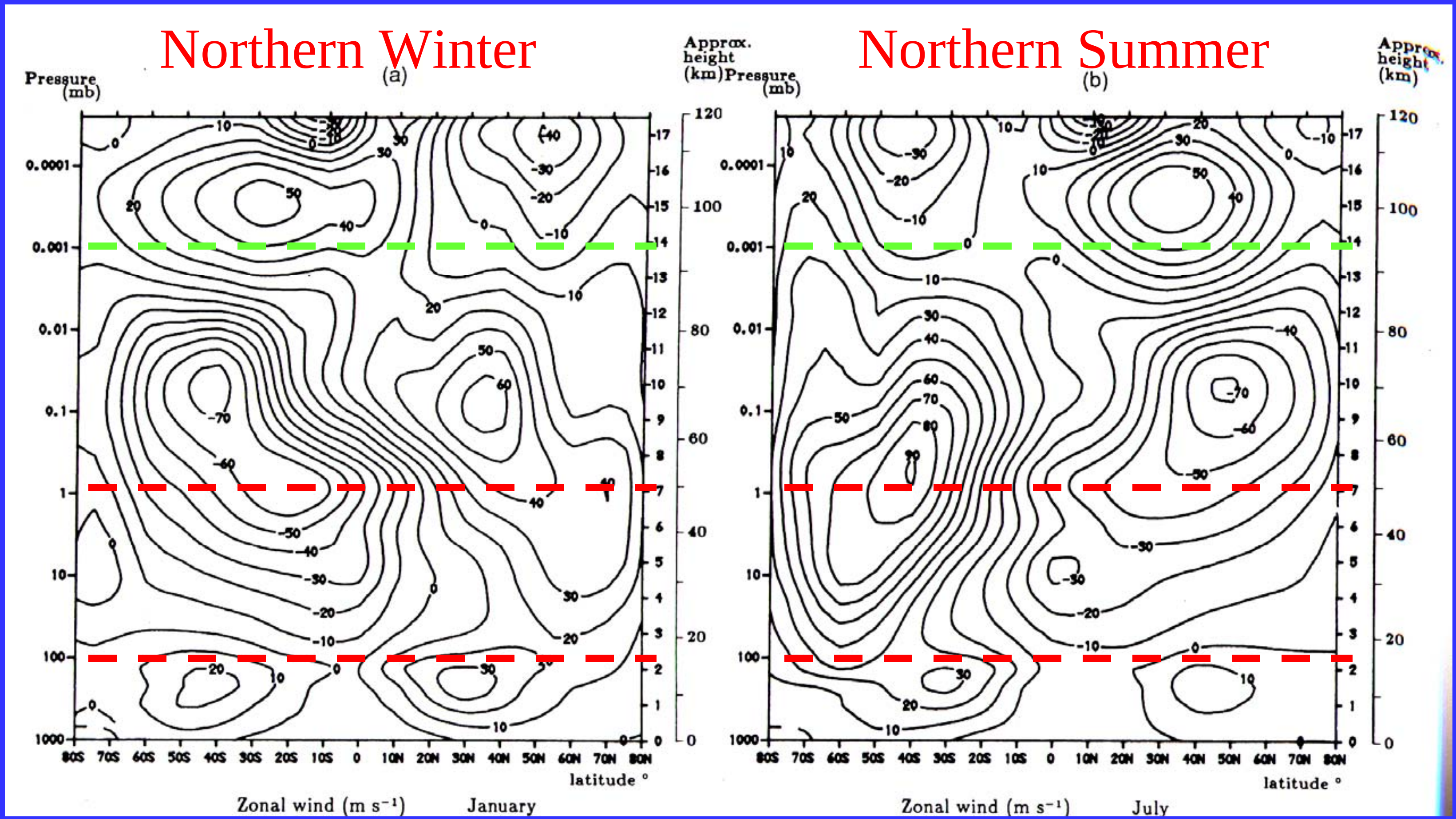


Fig. 1.3. Schematic latitude-height section of zonal mean temperatures (°C) for solstice conditions. Dashed lines indicate tropopause, stratopause, and mesopause levels. (Courtesy of R. J. Reed.)

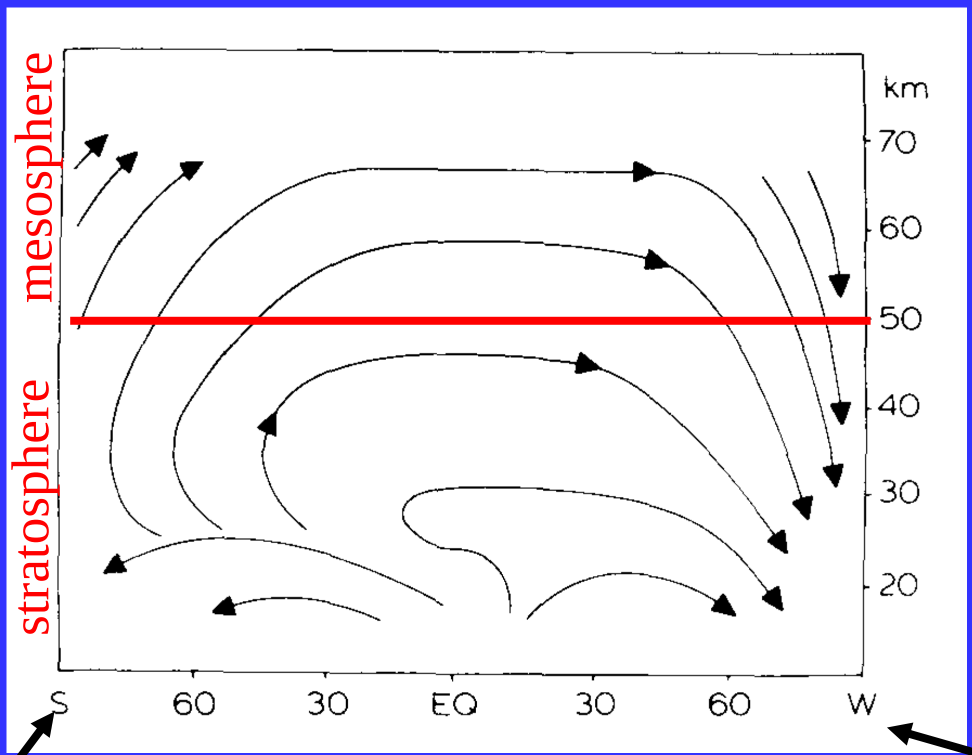
Circulation in Stratosphere



(from *Dynamic Meteorology*)

ESS55
Prof. Jin-Yi Yu

Zonal-Mean Circulation in the Stratosphere



summer

winter

ESS55
Prof. Jin-Yi Yu

Ozone Production and Destruction

(from *The Earth System*)

The Chapman Mechanism of Ozone Production and Destruction

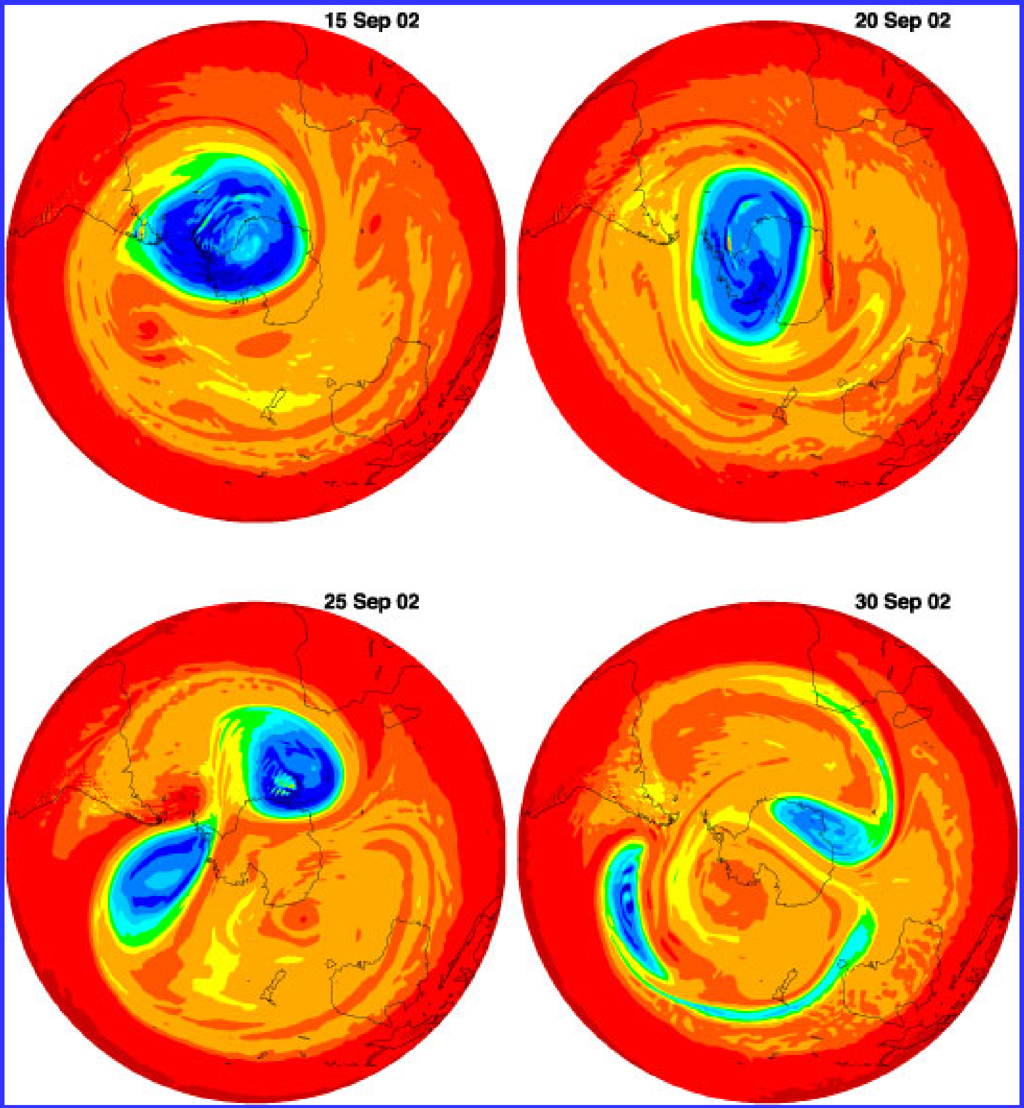
*Reaction**			*Rate*
1)	O_2 + UV photon $\rightarrow$ O + O	production	Slow
2)	O + O_2 + M $\rightarrow$ O_3 + M	production	Fast
3)	O_3 + photon $\rightarrow$ O_2 + O	destruction	Fast
4)	O + O_3 $\rightarrow$ 2 O_2	destruction	Slow

Photodissociation (or photolysis)

visible light

destroy O3 permanently

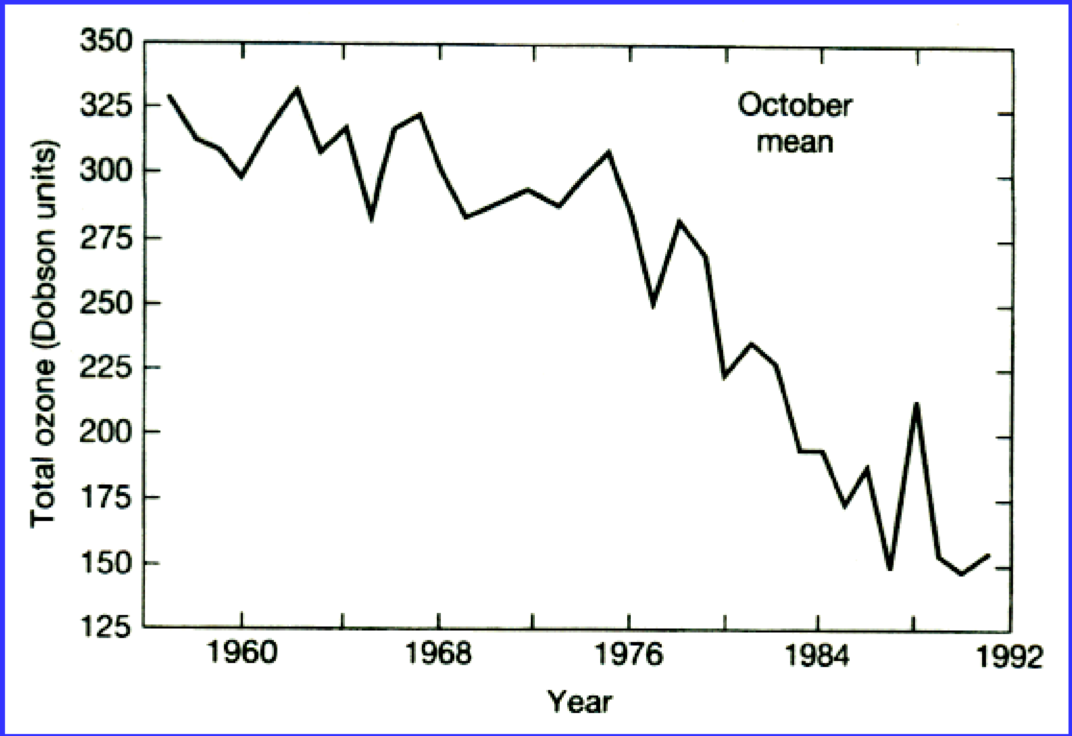
Sudden Warming



- 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!

Antarctic Ozone Hole

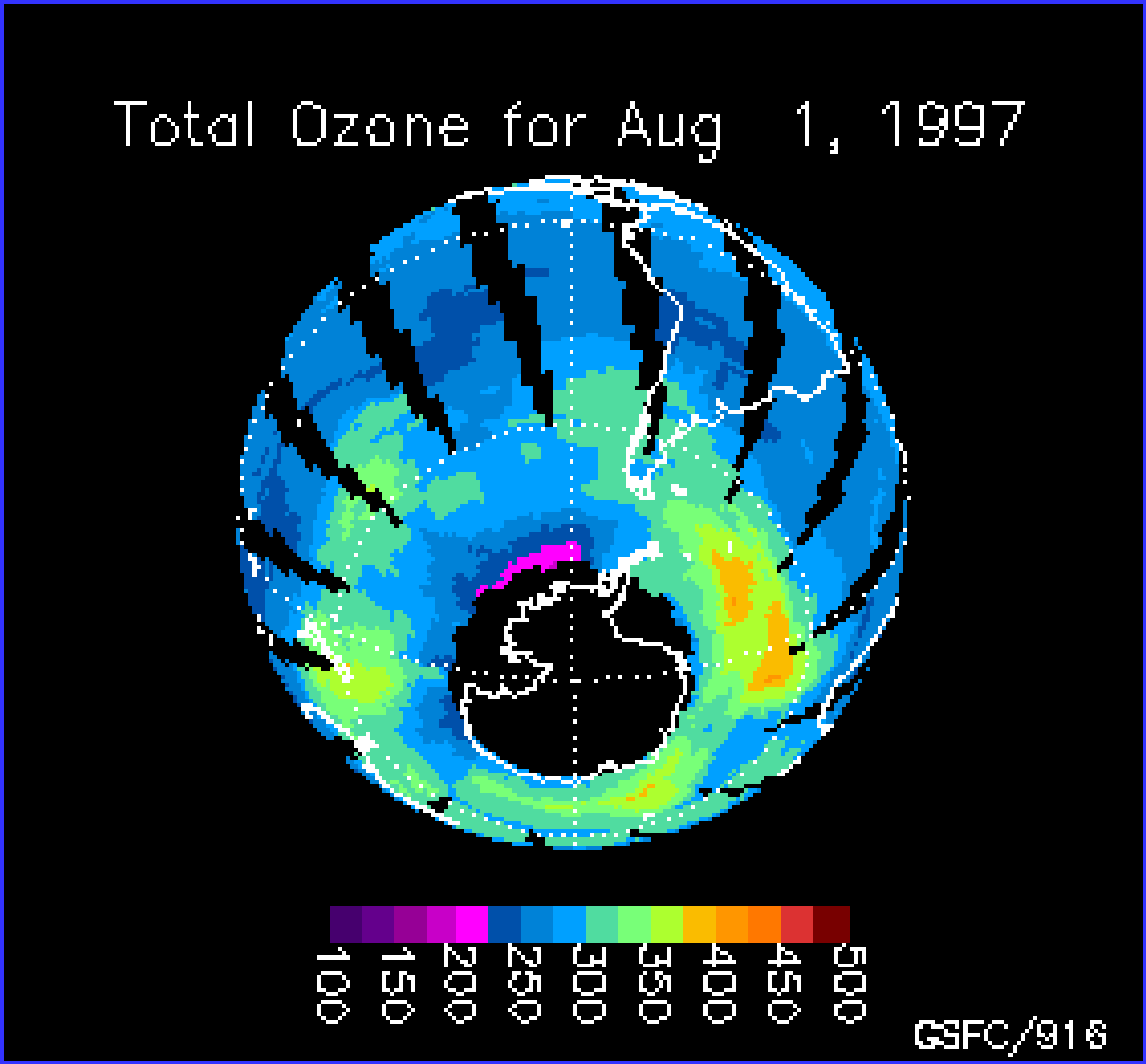
Mean Total Ozone Over Antarctic in October



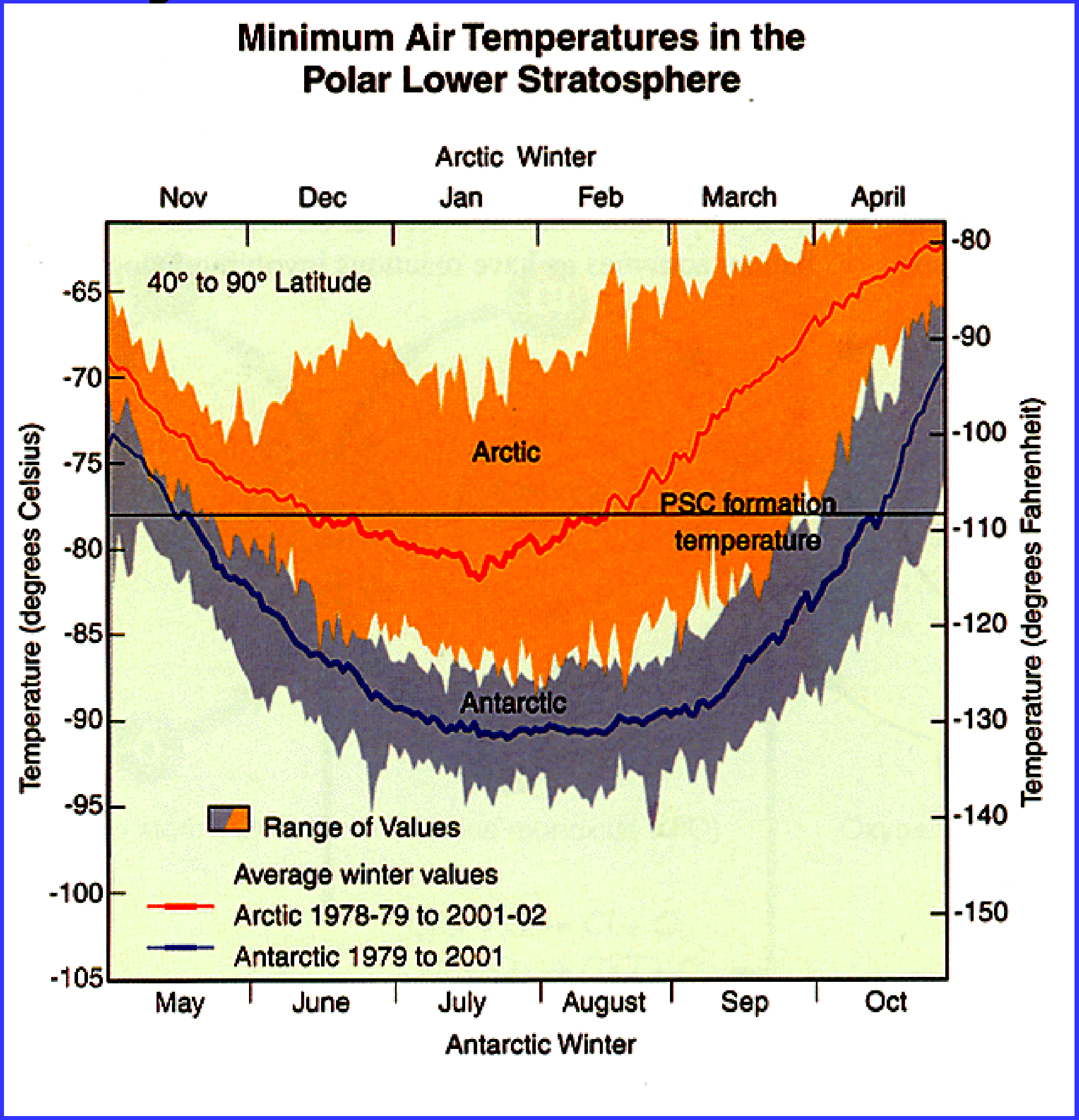
(from *The Earth System*)

- 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)

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:

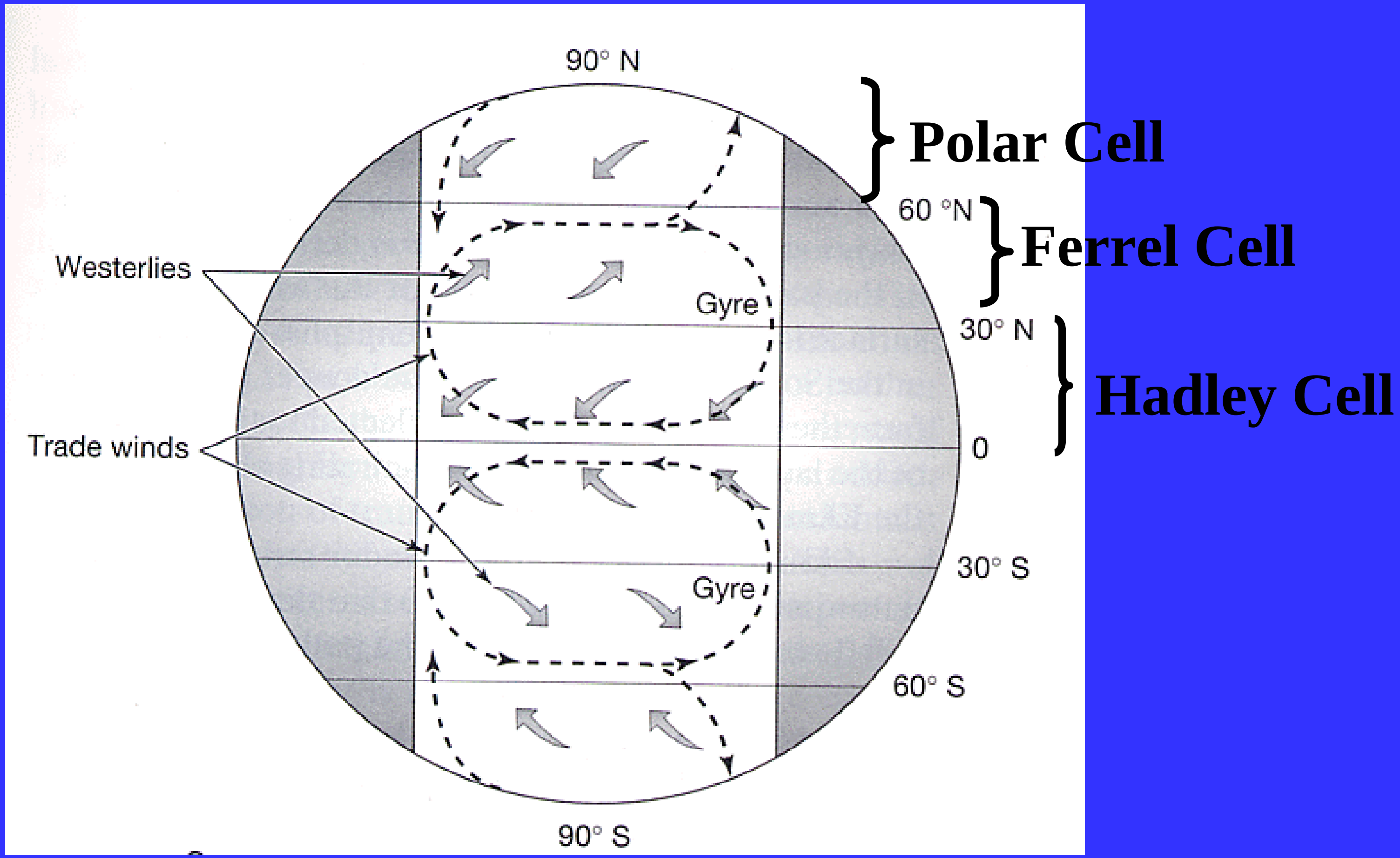
  (1) by coupling between the odd nitrogen and chlorine cycles

  (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.

Winds and Surface Currents



(Figure from *The Earth System*)

Basic Ocean Structures

Warm up by sunlight!

- **Upper Ocean (~100 m)**

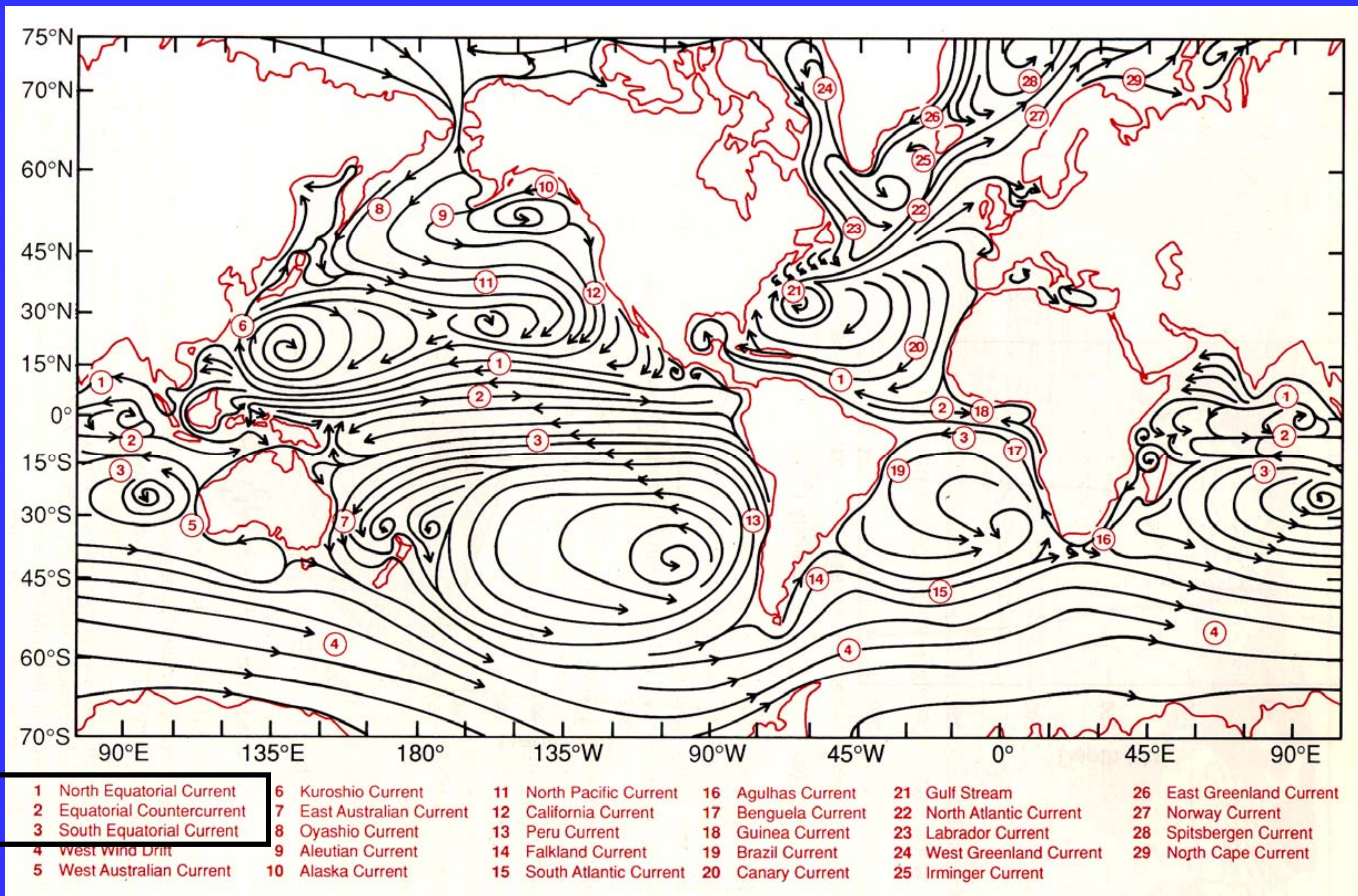
  Shallow, warm upper layer where light is abundant and where most marine life can be found.

- **Deep Ocean**

  Cold, dark, deep ocean where plenty supplies of nutrients and carbon exist.

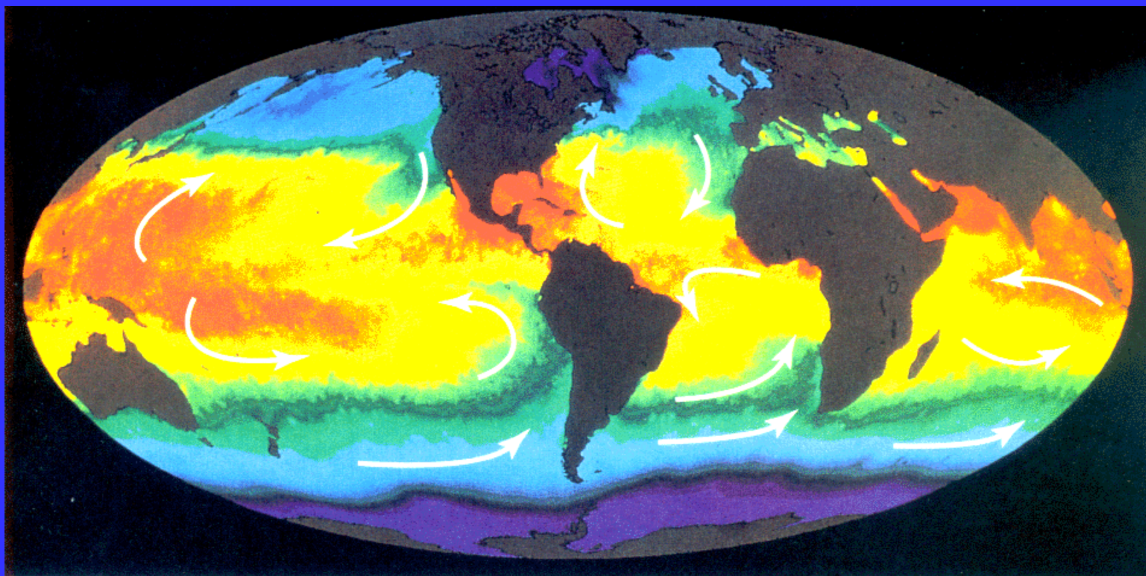
No sunlight!

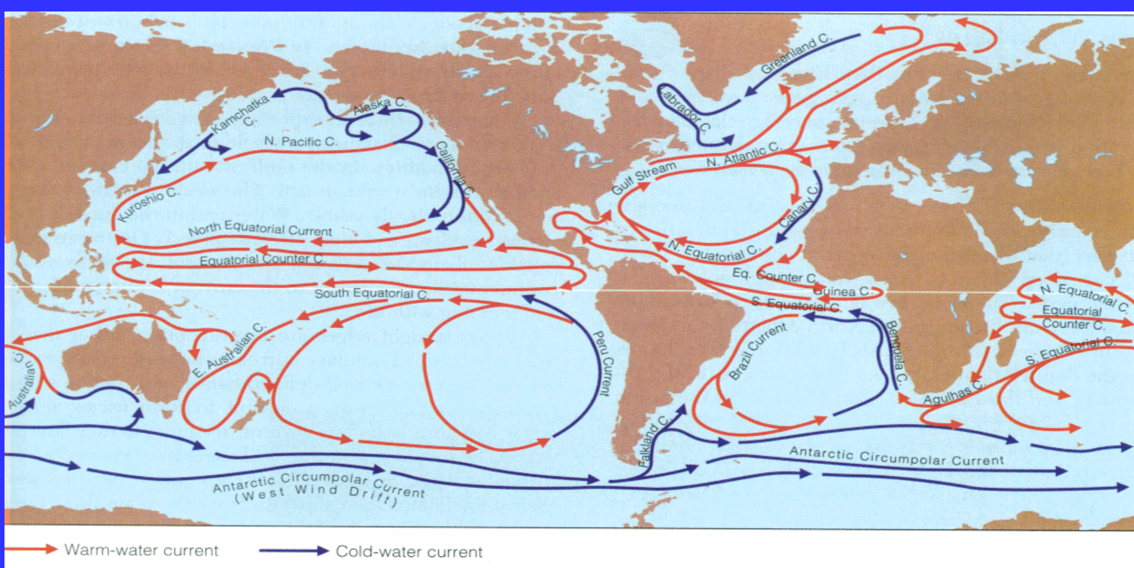
Global Surface Currents



(from *Climate System Modeling*)

Six Great Current Circuits in the World Ocean





❑ **5 of them are geostrophic gyres:**

North Pacific Gyre

South Pacific Gyre

North Atlantic Gyre

South Atlantic Gyre

Indian Ocean Gyre

❑ **The 6th and the largest current:**

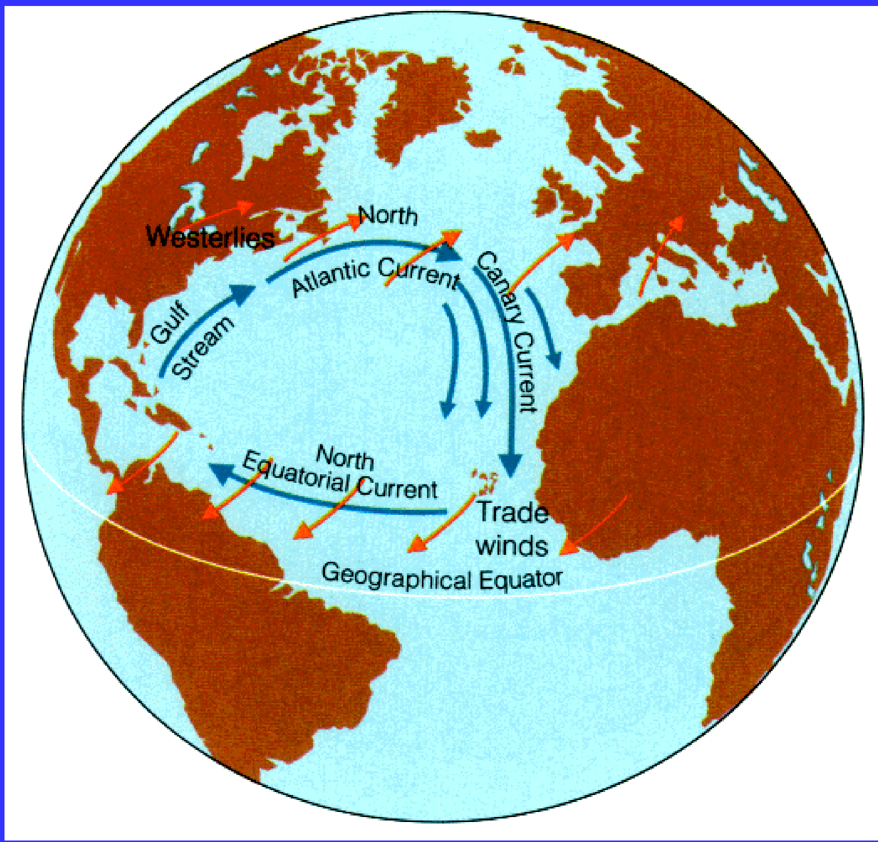
Antarctic Circumpolr Current

(also called West Wind Drift)

(Figure from *Oceanography* by Tom Garrison)

Characteristics of the Gyres

(Figure from *Oceanography* by Tom Garrison)



Volume transport unit:

1 sv = 1 Sverdrup = 1 million m^3/sec

(the Amazon river has a transport of ~0.17 Sv)

- **Currents are in geostropic balance**
- **Each gyre includes 4 current components:**

  two boundary currents: western and eastern

  two transverse currents: easteward and westward

Western boundary current (jet stream of ocean)

the fast, deep, and narrow current moves **warm** water polarward (transport ~50 Sv or greater)

Eastern boundary current

the slow, shallow, and broad current moves cold water equatorward (transport ~ 10-15 Sv)

Trade wind-driven current

the moderately shallow and broad westward current (transport ~ 30 Sv)

Westerly-driven current

the wider and slower (than the trade wind-driven current) eastward current

Major Current Names

- **Western Boundary Current**

  Gulf Stream (in the North Atlantic)
  Kuroshio Current (in the North Pacific)
  Brazil Current (in the South Atlantic)
  Eastern Australian Current (in the South Pacific)
  Agulhas Current (in the Indian Ocean)

- **Eastern Boundary Current**

  Canary Current (in the North Atlantic)
  California Current (in the North Pacific)
  Benguela Current (in the South Atlantic)
  Peru Current (in the South Pacific)
  Western Australian Current (in the Indian Ocean)

- **Trade Wind-Driven Current**

  North Equatorial Current
  South Equatorial Current

- **Westerly-Driven Current**

  North Atlantic Current (in the North Atlantic)
  North Pacific Current (in the North Pacific)

Surface Current – Geostrophic Gyre

- Mixed Layer

  Currents controlled by frictional force + Coriolis force

  → wind-driven circulation

  → Ekman transport (horizontal direction)

  → convergence/divergence

  → downwelling/upwelling at the bottom of mixed layer

- Thermocline

  downwelling/upwelling in the mixed layer

  → pressure gradient force + Coriolis force

  → geostrophic current

  → Sverdrup transport (horizontal)

Step 1: Surface Winds

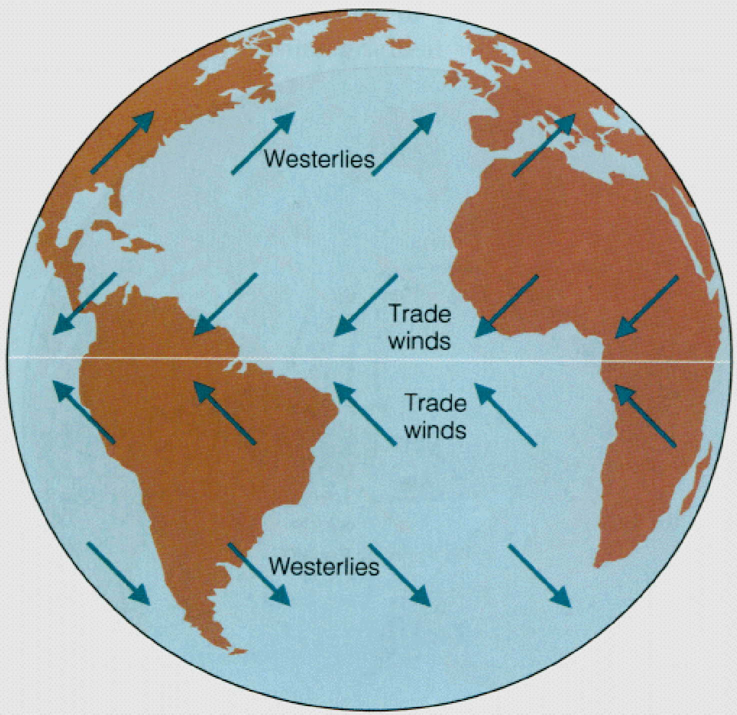


Figure 9.1 Winds, driven by uneven solar heating and Earth's spin, drive the movement of the ocean's surface currents. The prime movers are the powerful westerlies and the persistent trade winds (easterlies).

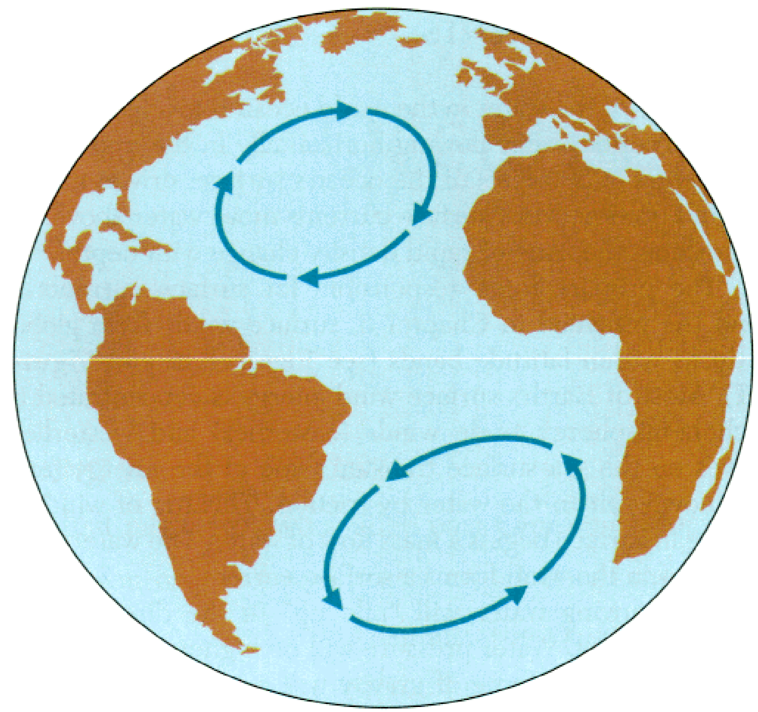
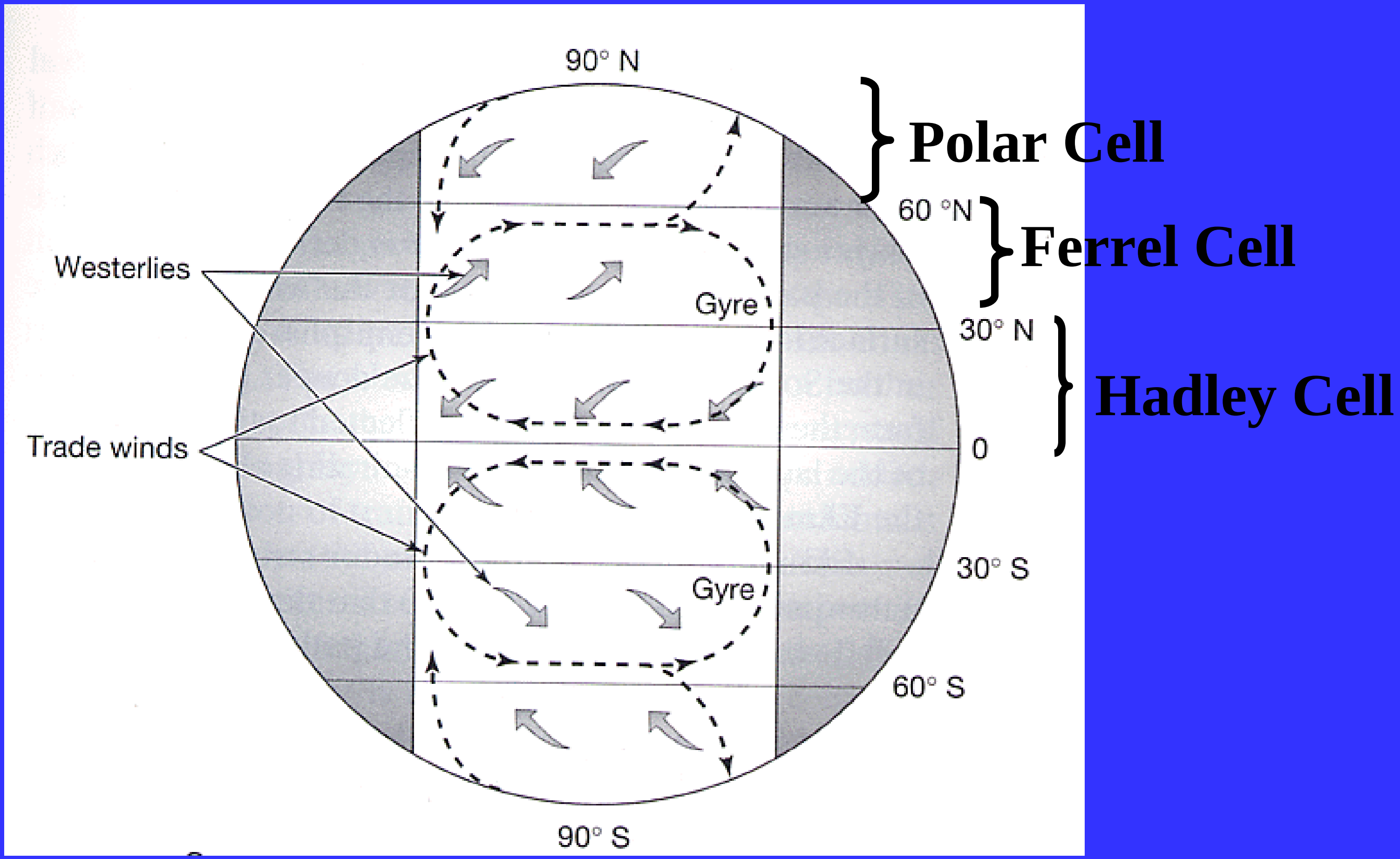


Figure 9.2 A combination of four forces—surface winds, the sun's heat, the Coriolis effect, and gravity—circulates the ocean surface clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, forming gyres.

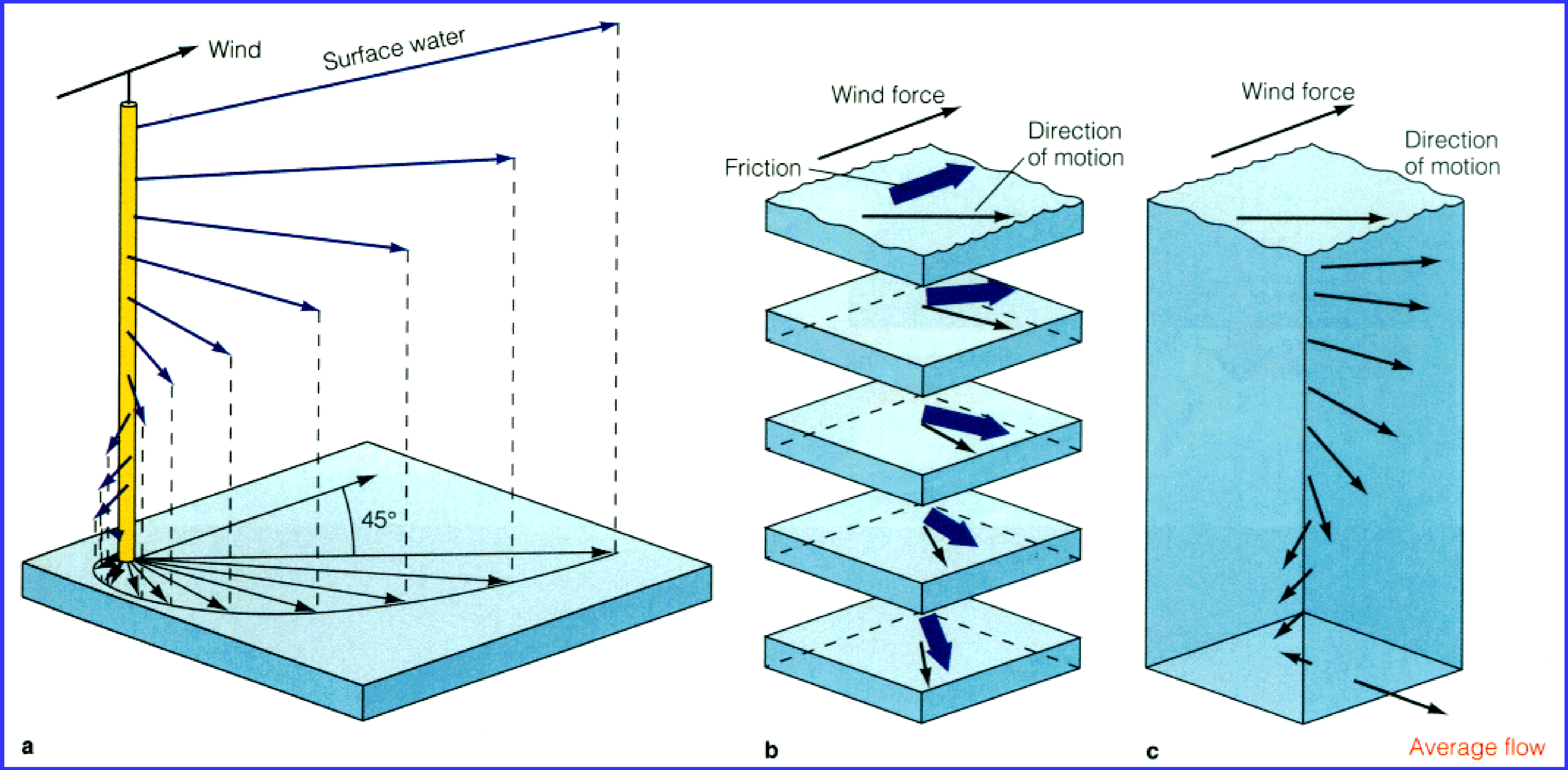
(Figure from *Oceanography* by Tom Garrison)

Winds and Surface Currents



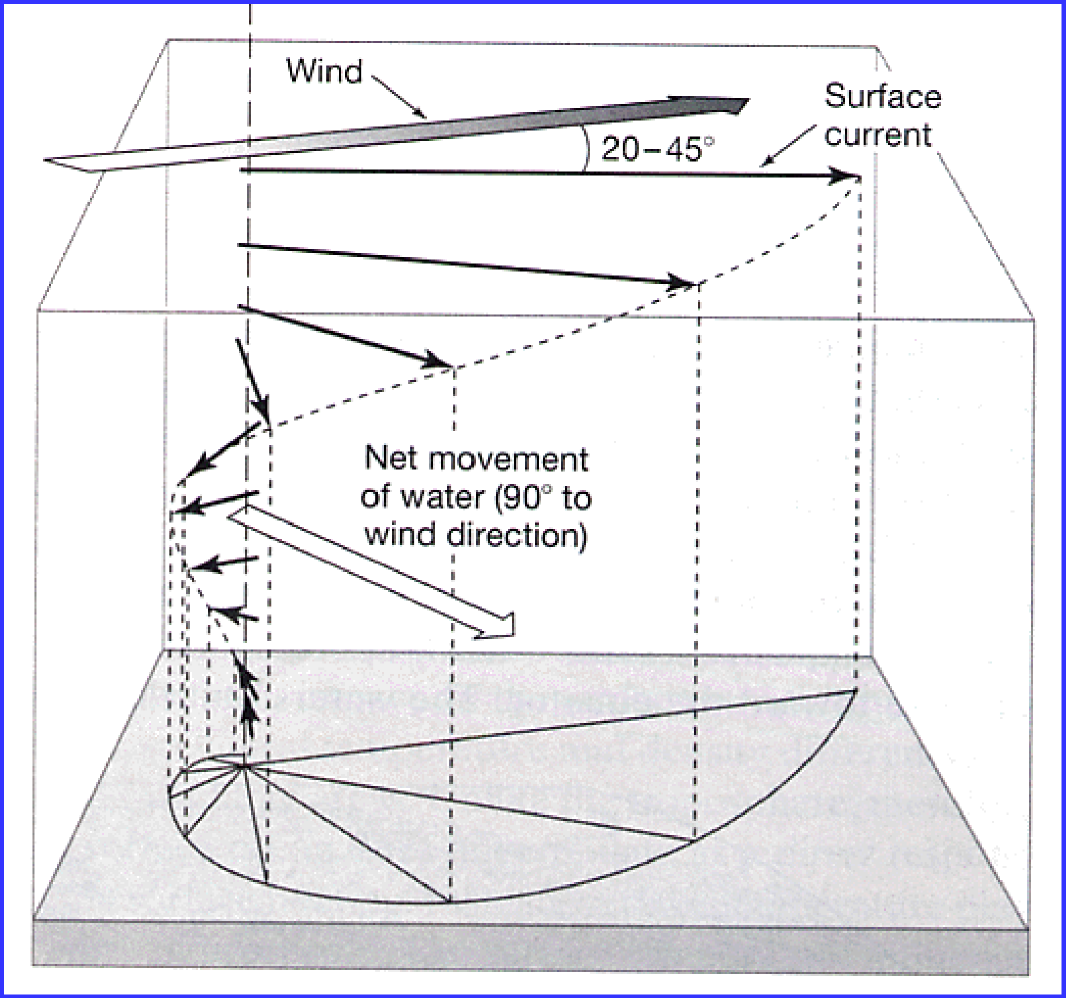
(Figure from *The Earth System*)

Step 2: Ekman Layer
(frictional force + Coriolis Force)



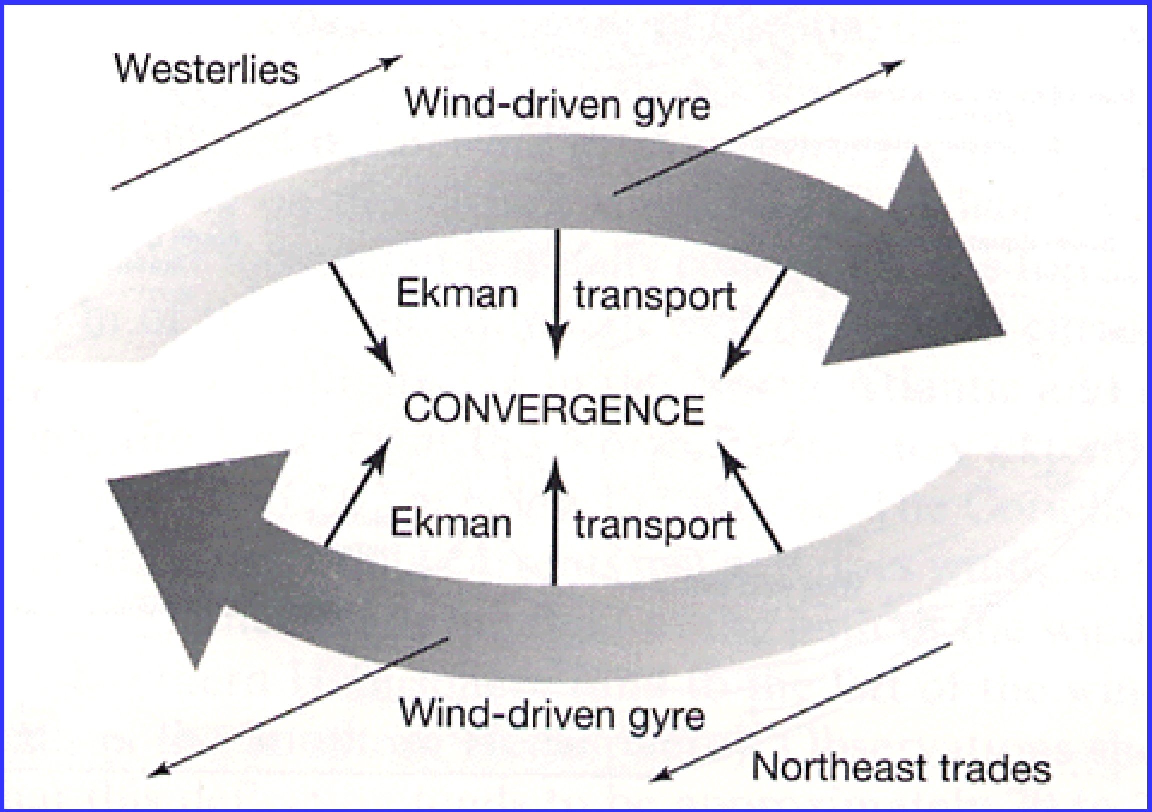
(Figure from *Oceanography* by Tom Garrison)

Ekman Spiral – A Result of Coriolis Force



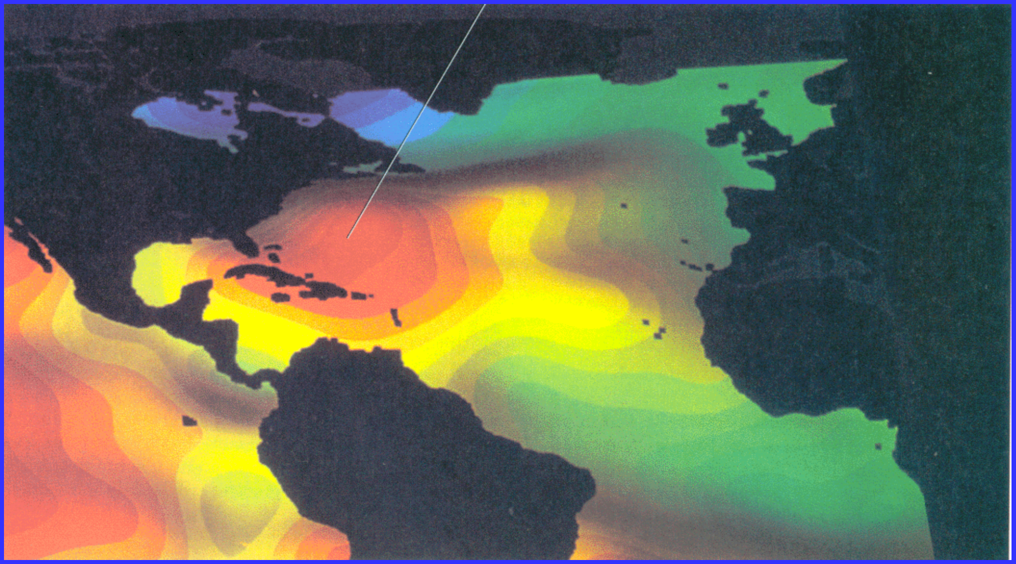
(Figure from *The Earth System*)

Ekman Transport

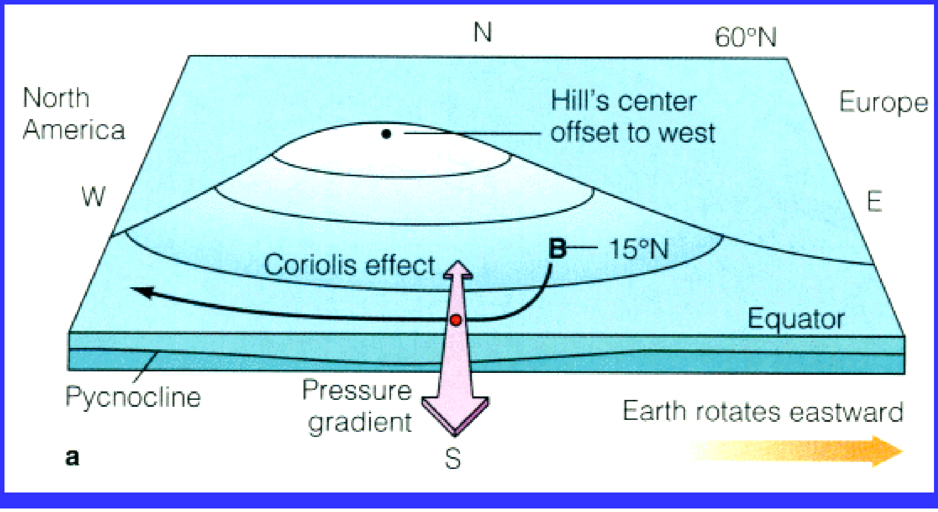


(Figure from *The Earth System*)

Step 3: Geostrophic Current
(Pressure Gradient Force + Corioils Foce)



NASA-TOPEX Observations of Sea-Level Hight



(from *Oceanography* by Tom Garrison)

ESS55
Prof. Jin-Yi Yu

Thermohaline Circulation

- Thermo → temperature
- Haline → salinity

Density-Driven Circulation

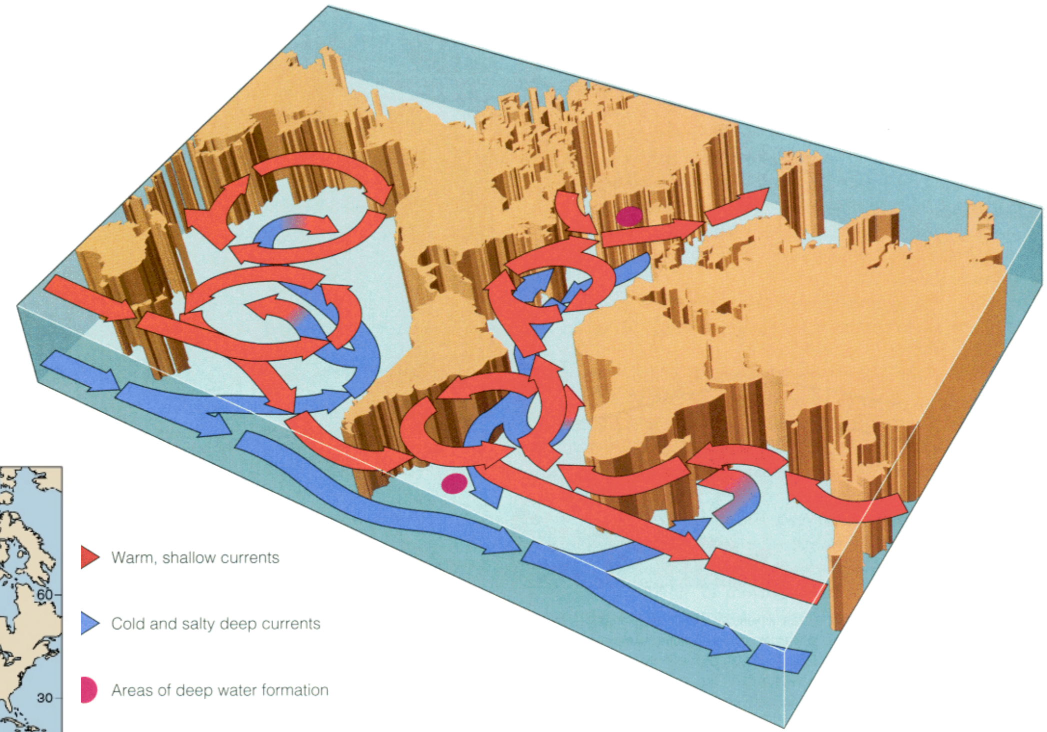
Cold and salty waters go down

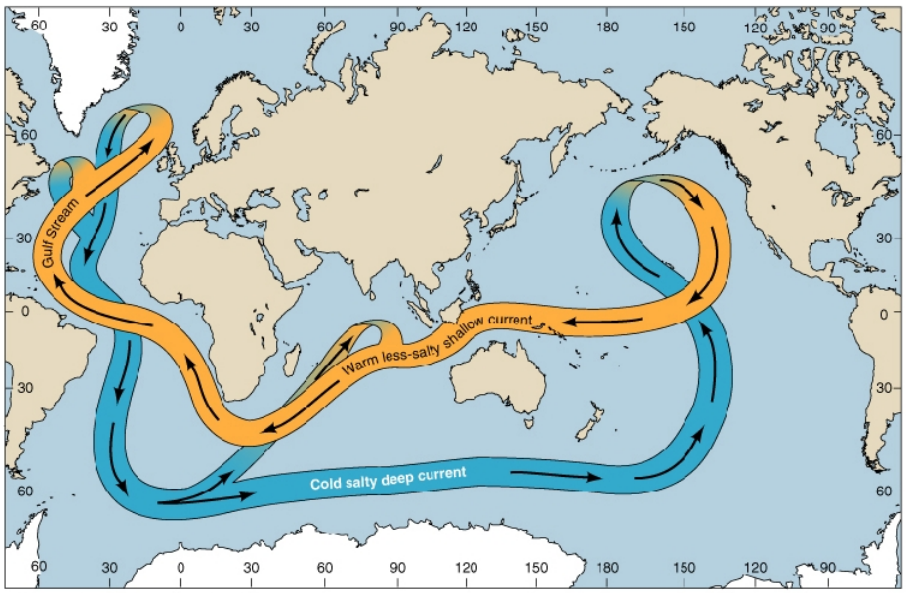
Warm and fresh waters go up

Thermohaline Conveyor Belt

❑ Typical speed for deep ocean current: 0.03-0.06 km/hour.

❑ Antarctic Bottom Water takes some 250-1000 years to travel to North Atlantic and Pacific.





(Figure from *Oceanography* by Tom Garrison)

ESS55
Prof. Jin-Yi Yu

It Takes ~1000 Years for Deep Ocean Waters to Travel Around…

- If we date a water parcel from the time that it leaves the surface and sink into the deep ocean

➔ Then the youngest water is in the deep north Atlantic, and the oldest water is in the deep northern Pacific, where its age is estimated to be 1000 year.

The Most Unpolluted Waters are..

the waters in the deep northern Pacific.

- The man-released CFC and the chemical tritium and C^{14}, which were released through atmospheric atomic bomb test in the 1950s and 1960s, entered the deep ocean in the northern Atlantic and are still moving southward slowly.

- Those pollutions just cross the equator in the Atlantic ➔ They have not reached the deep northern Pacific yet!!

Global Warming and Thermohaline Circulation

- ***If the warming is slow***

  The salinity is high enough to still produce a thermohaline circulation

- ➔ The circulation will transfer the heat to deep ocean
- ➔ The warming in the atmosphere will be deferred.

- ***If the warming is fast***

  Surface ocean becomes so warm (low water density)

- ➔ No more thermohalione circulation
- ➔ The rate of global warming in the atmosphere will increase.