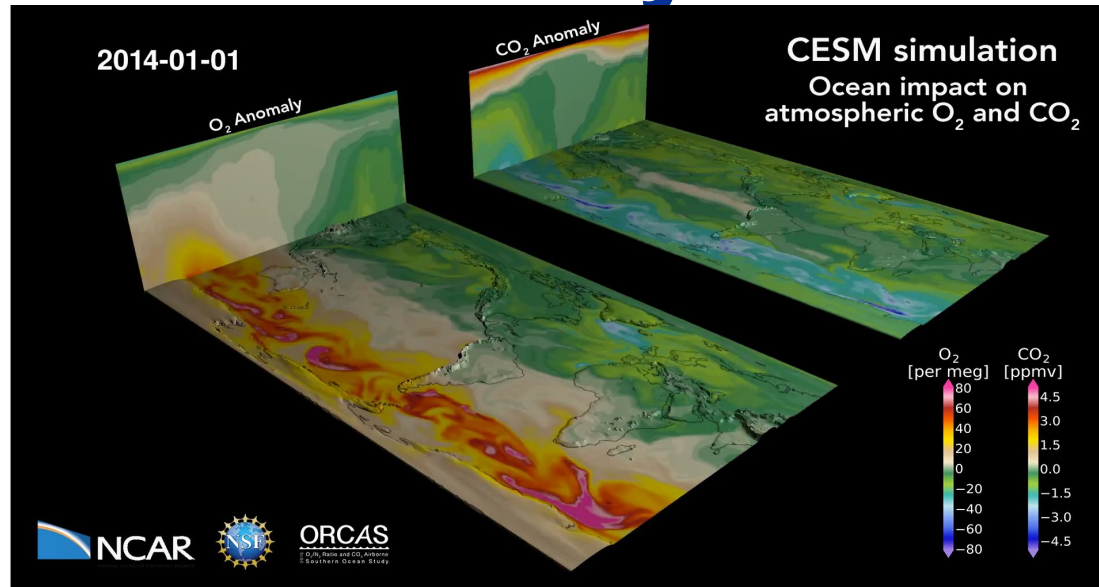


Global System



<https://www.youtube.com/watch?v=s6ZbV-jMdq8>

- Basic Structures and Dynamics
- General Circulation in the Troposphere
- El Nino, Monsoon
- Wind-Driven Ocean Circulation

Yu-heng Tseng

Institute of Oceanography, National Taiwan University, Taiwan

Tel: +886.2.33661374, Fax: +886.2.33661620, email: tsengyh@ntu.edu.tw

<http://coda.oc.ntu.edu.tw/coda>

Education

1991-1995 (B.S.)	National Taiwan University, Mechanical Engineering
1997-1999 (M.S.)	Stanford University, Department of Mechanical Engineering
1999-2003 (Ph.D)	Stanford University, Department of Civil and Environmental Engineering.

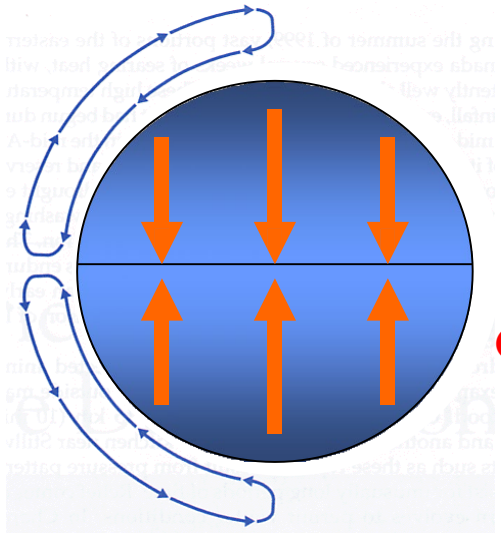
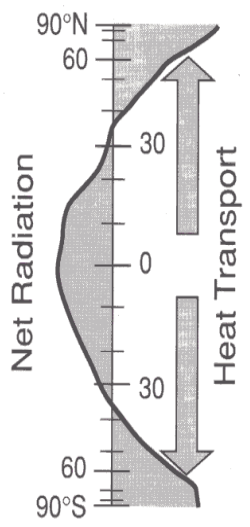
Professional Experiences

2003-2004	Johns Hopkins University, Mechanical Engineering
2004-2006	Lawrence Berkeley National Laboratory, Computational Research Division
2006-2012	National Taiwan University, Department of Atmospheric Sciences
2012-2017	National Center for Atmospheric Research, Climate and Global Dynamics Laboratory
2017-	National Taiwan University, Institute of Oceanography
2021-	National Taiwan University, Ocean Center (Director)

Research interesting: turbulence and mixing, high-order numerical method, non-hydrostatic model, regional and global ocean circulation model, air-sea (ocean-atmosphere) interaction, climate model development and parameterization

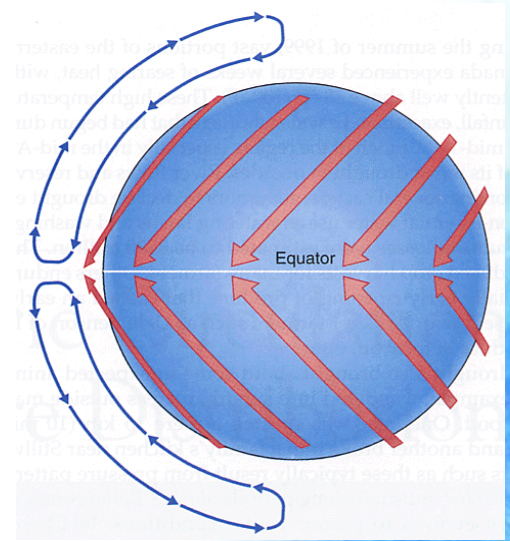
Single-Cell Model: Explains Why There are Tropical Easterlies

Without Earth Rotation



Coriolis Force

With Earth Rotation



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 equator is $u_{eq} = -5$ m/sec.
Therefore, the total velocity at the equator is $U = \text{rotational velocity} (U_0 + u_{Eq})$
- The zonal wind velocity at 60°N (u_{60N}) can be determined by the following:

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

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

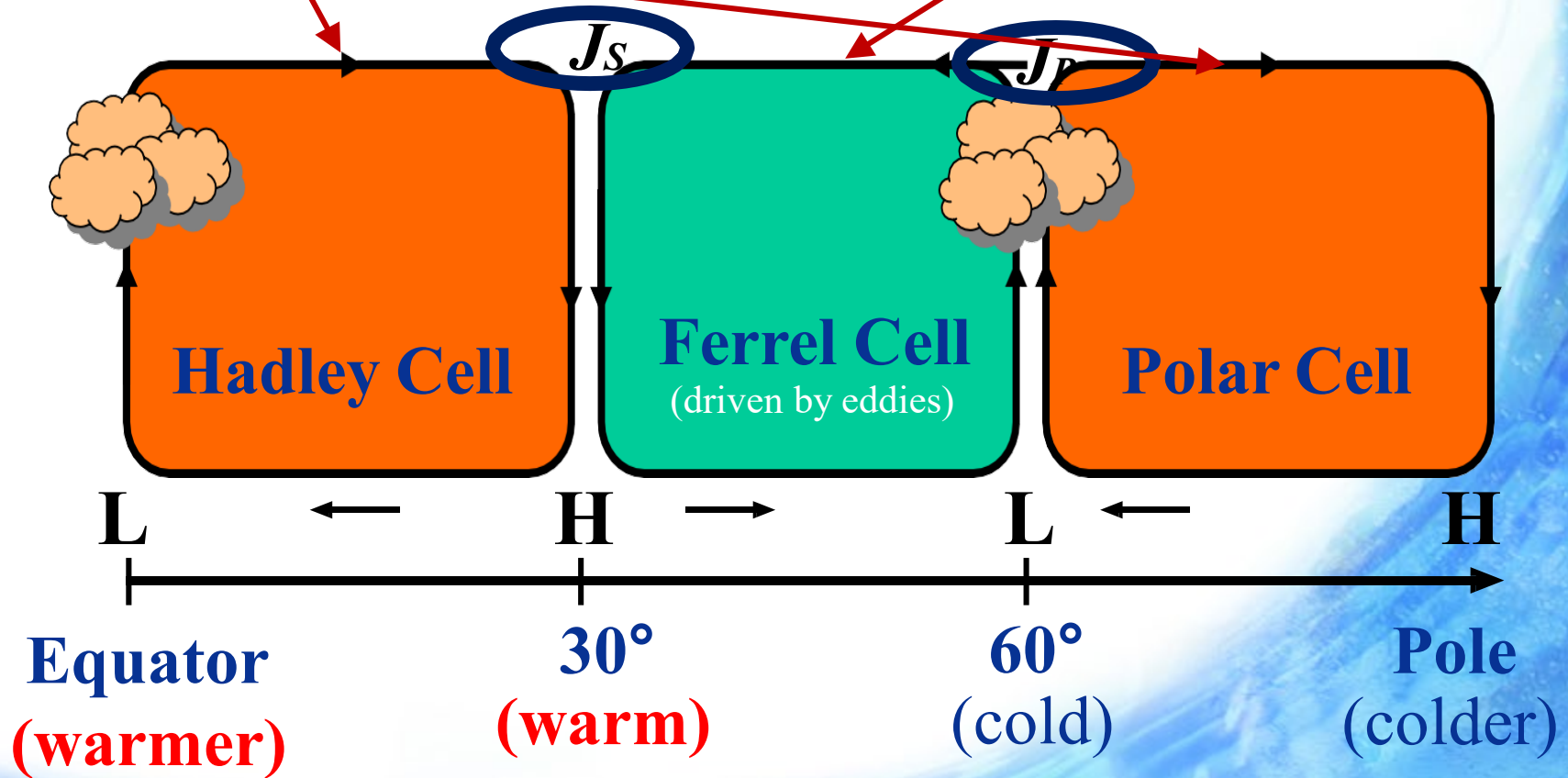
$$u_{60N} = 687 \text{ m/sec !!!!}$$

This high wind speed is not observed!

Properties of the Three Cells

thermally direct circulation

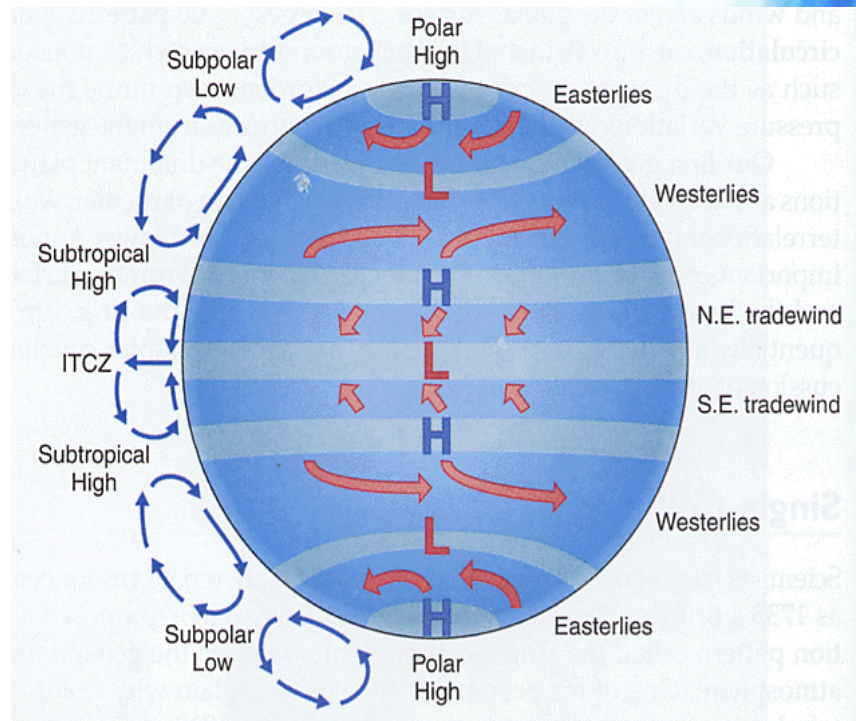
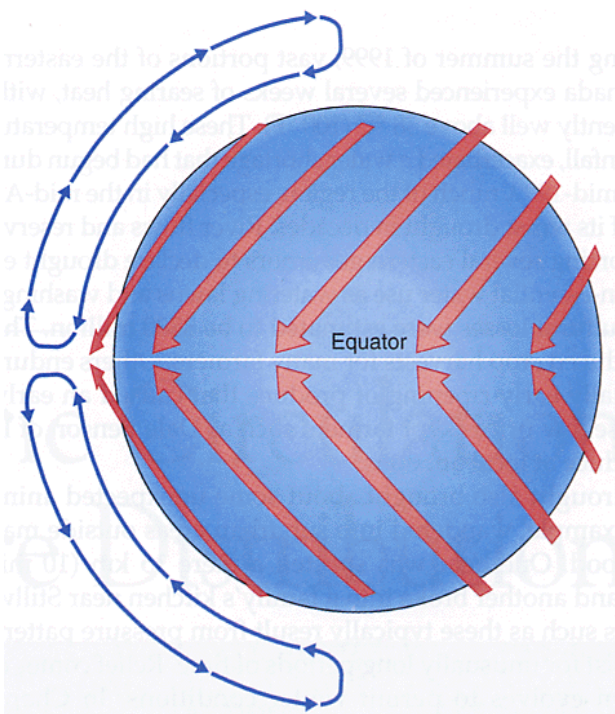
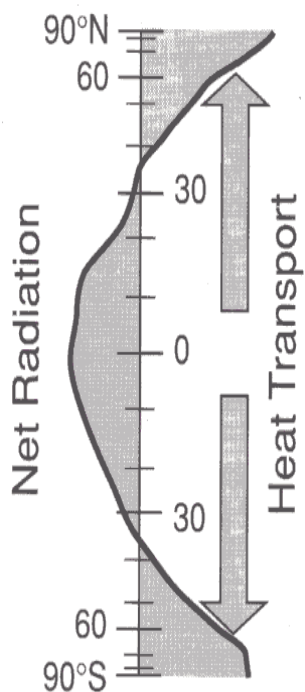
thermally indirect circulation



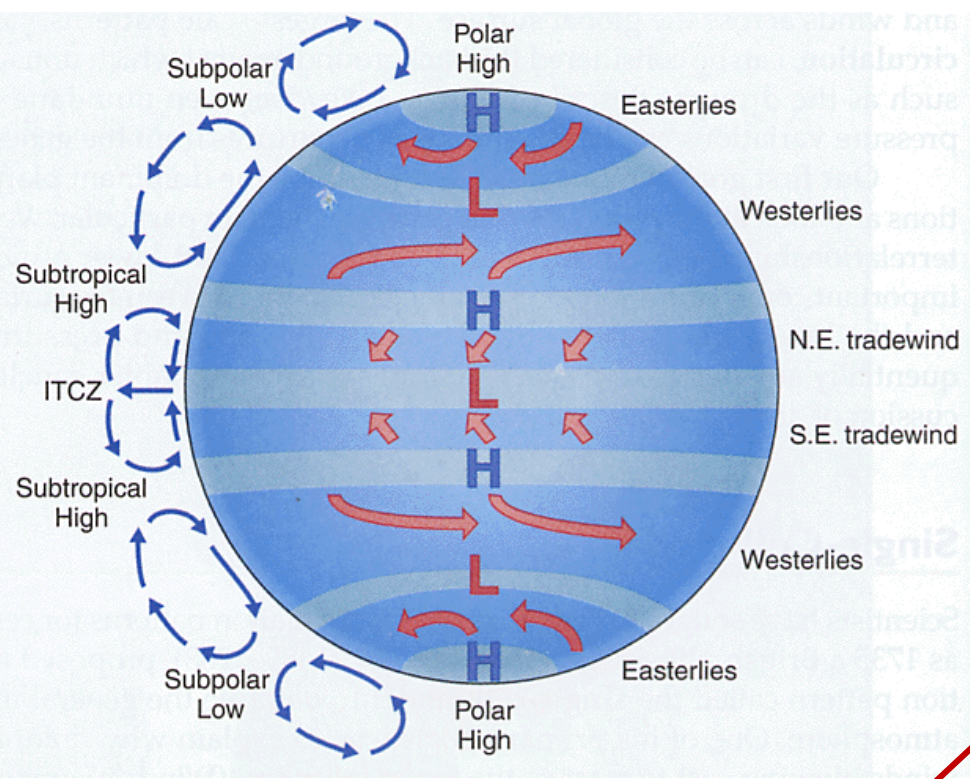
Atmospheric Circulation: Zonal-mean Views

Single-Cell Model

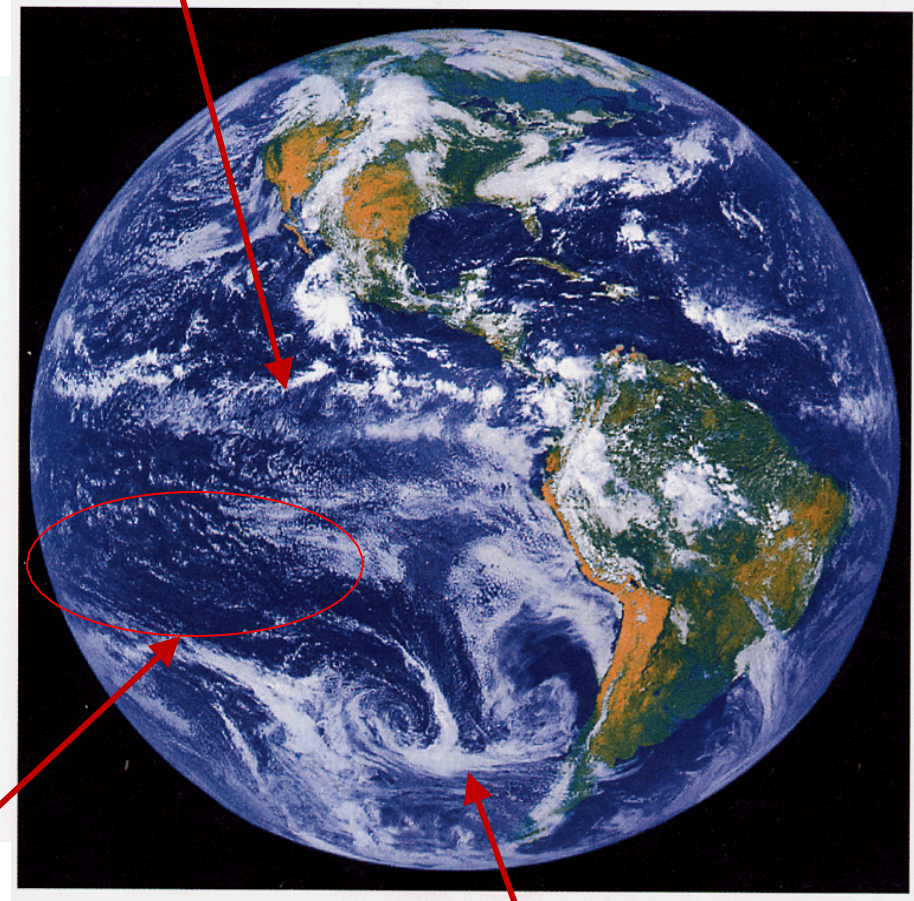
Three-Cell Model



The three cells



ITCZ



Subtropical High

midlatitude Weather system

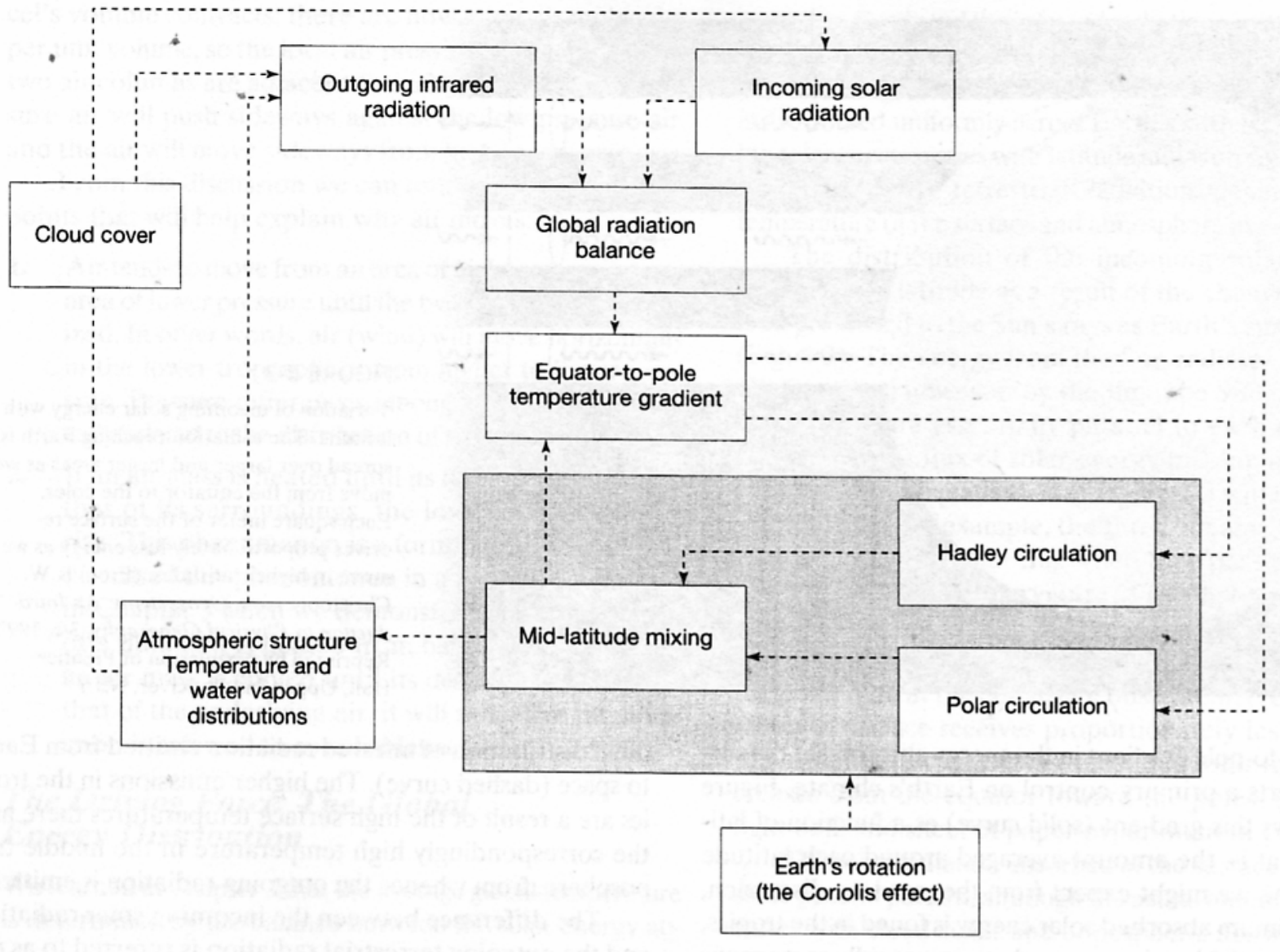
Thermally direct/indirect cells

□ Thermally Direct Cells (Hadley and Polar Cells)

Both cells have their rising branches over warm temperature zones and sinking branches 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.



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

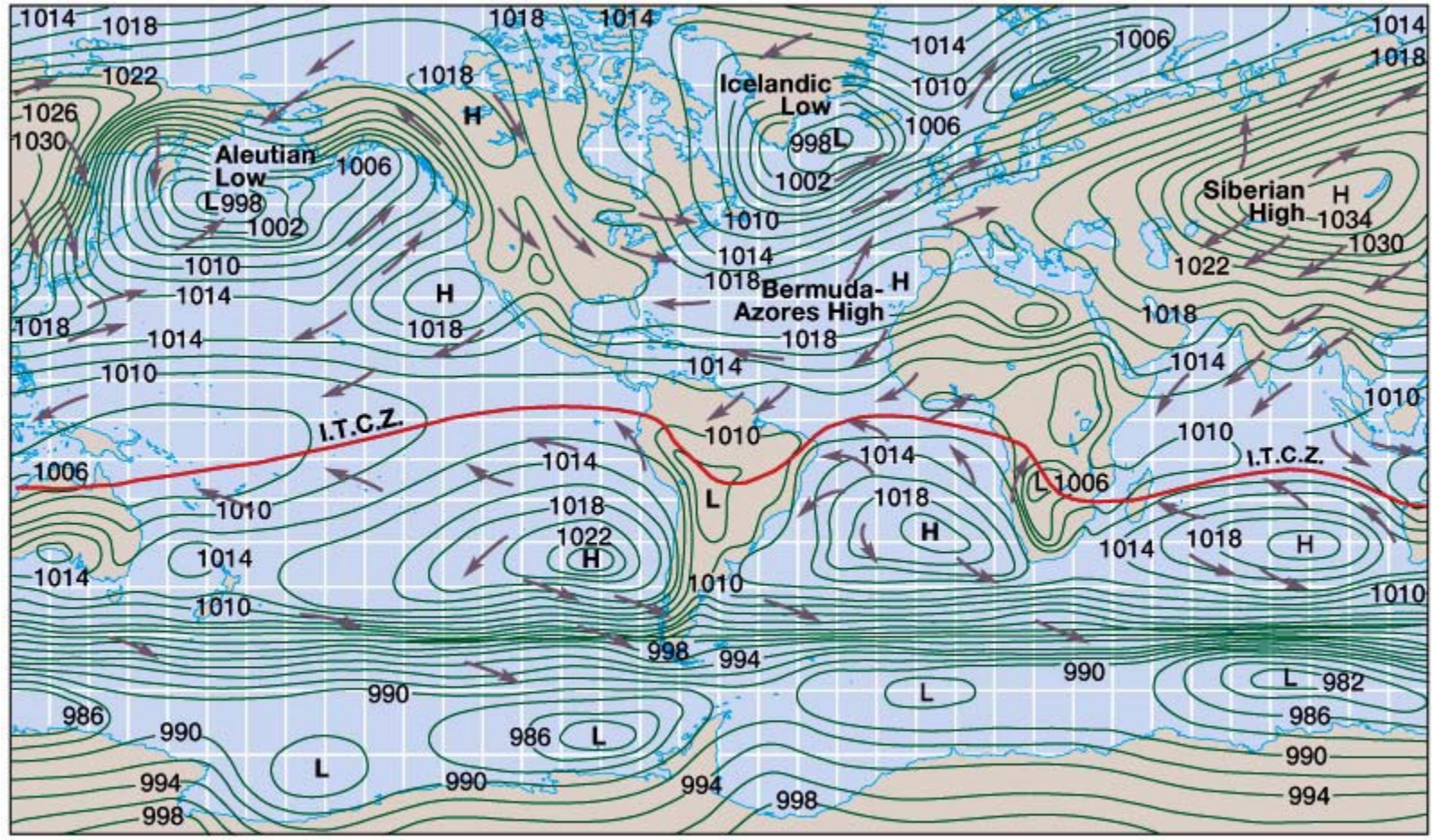
The Aleutian, Icelandic, and Tibetan lows

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

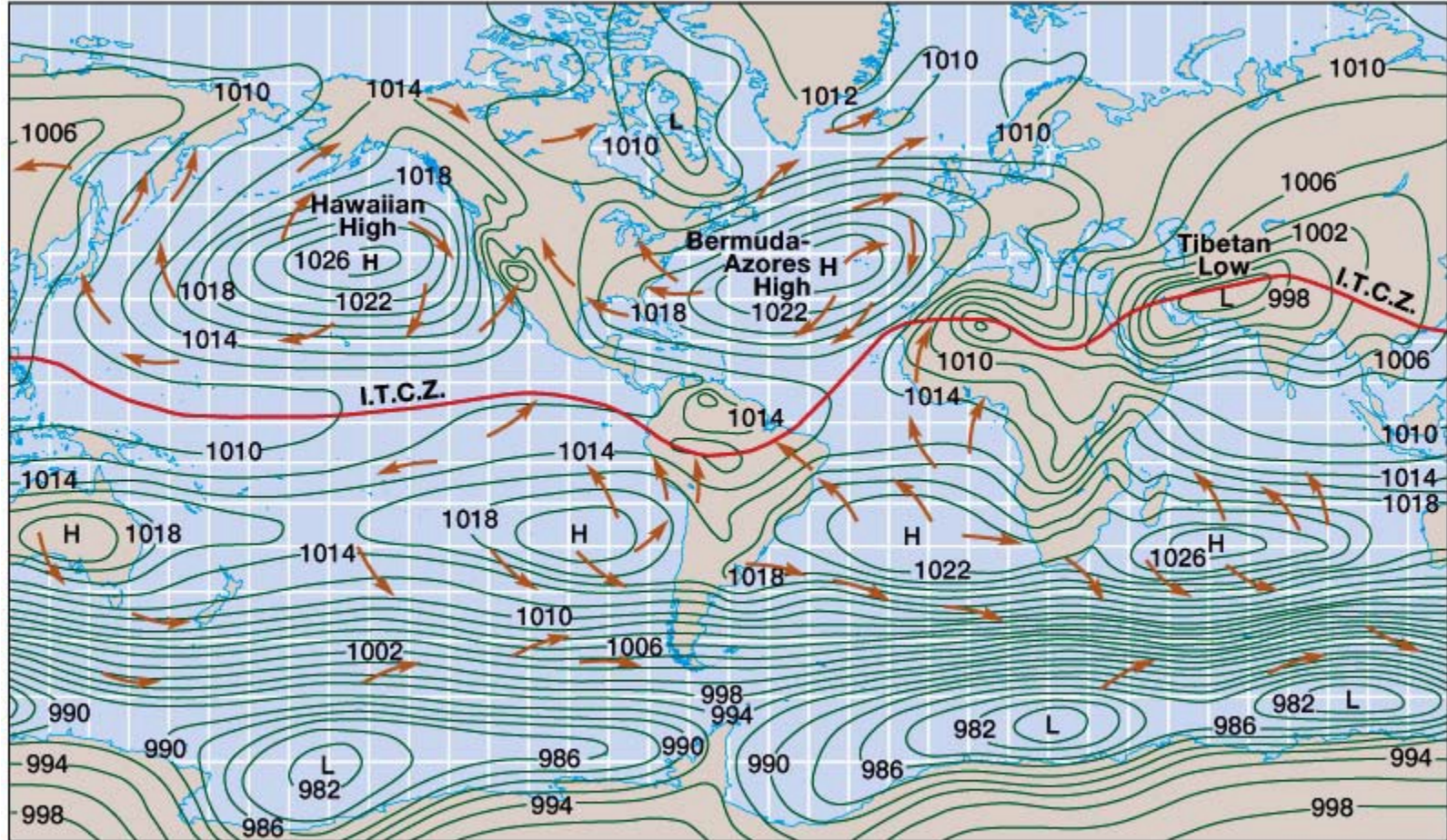
Siberian, Hawaiian, and Bermuda-Azores highs

- The oceanic (continental) highs achieve maximum strength during summer (winter) months

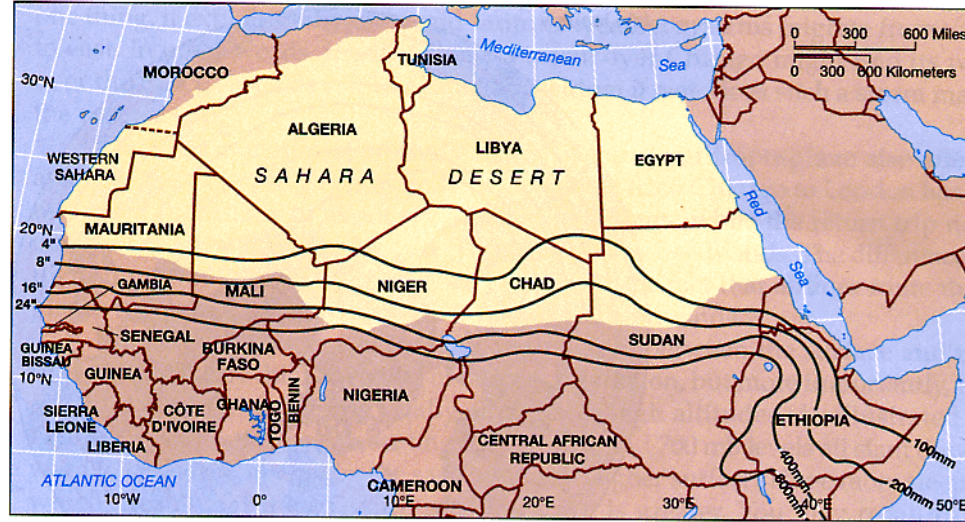
January



July



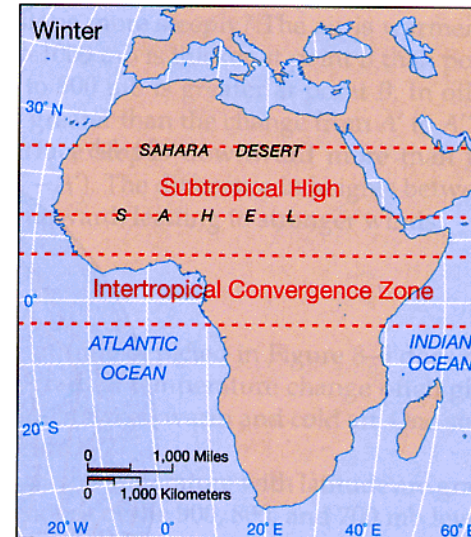
Sinking Branches and Deserts



(a)



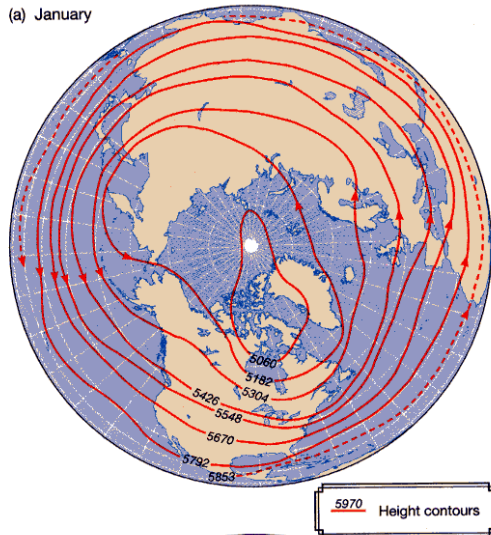
(b)



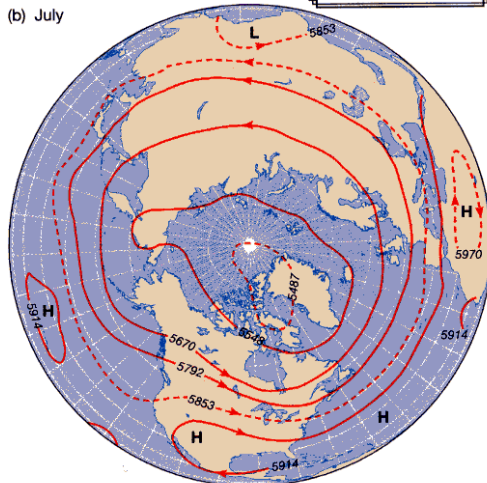
(c)

Upper Tropospheric Circulation

(a) January



(b) July



□ 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).

► **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.

Subtropical and Polar Jet Streams

□ 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.

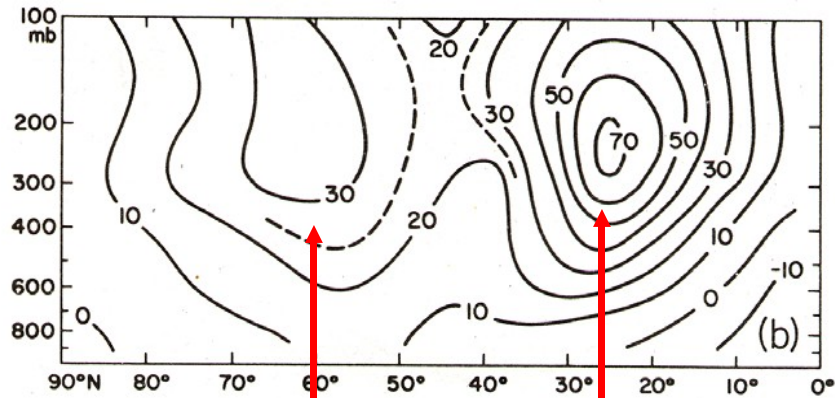
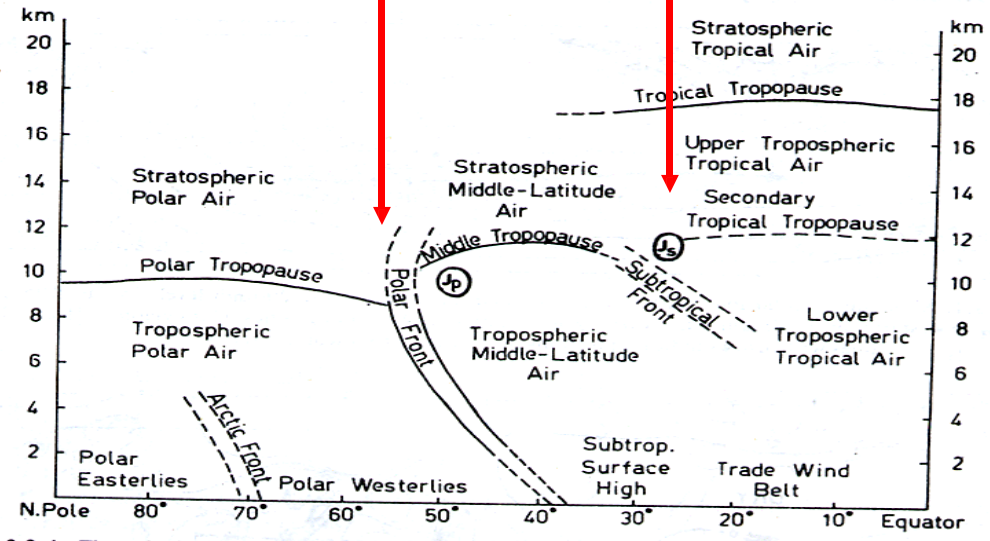


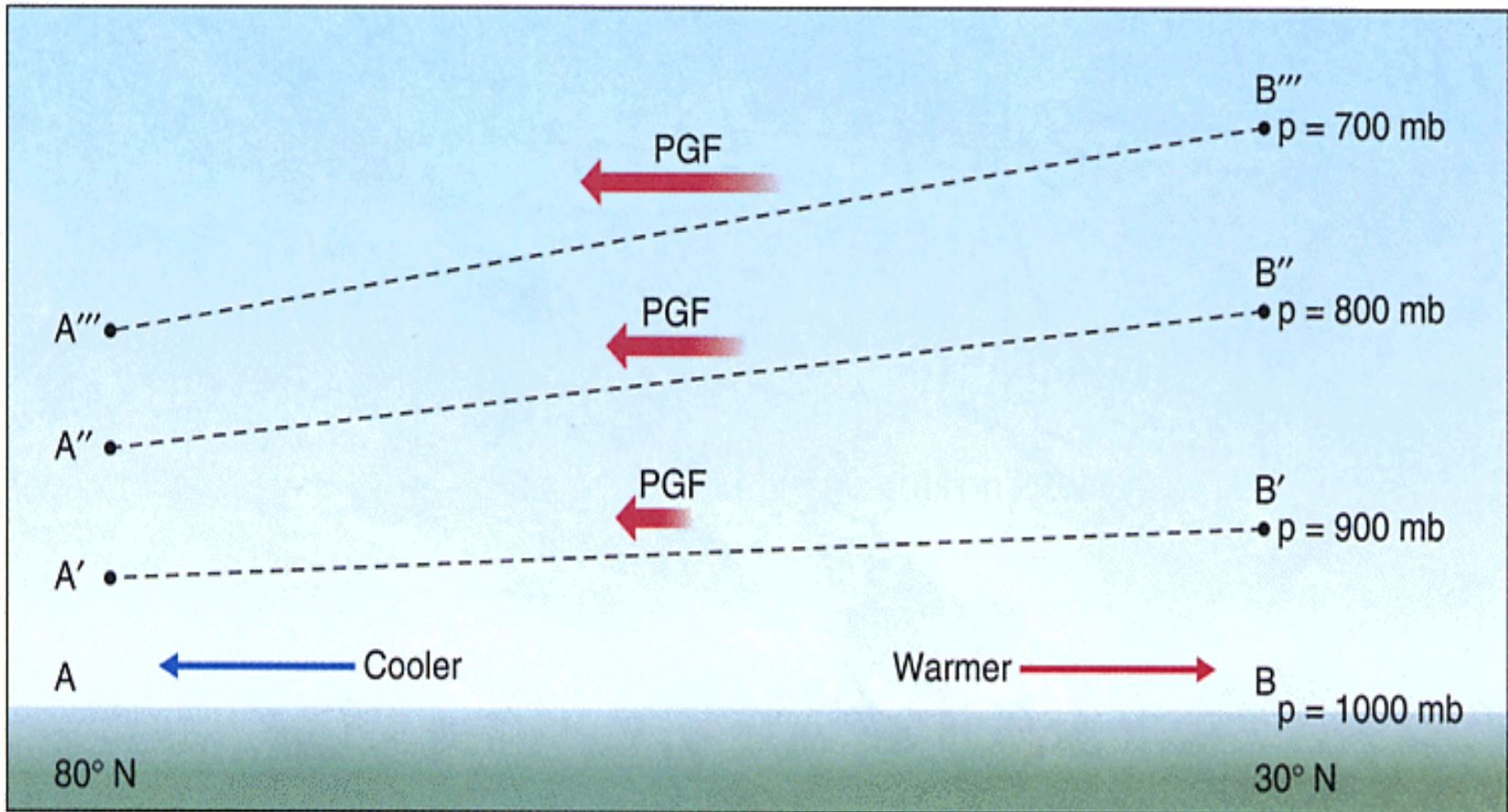
FIG. 3.8 Winter (December–February) zonal mean wind components (knots), Northern Hemisphere, at (a) 140°E and (b) 0° longitude. (Redrawn from Crutcher, 1961.)

□ 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



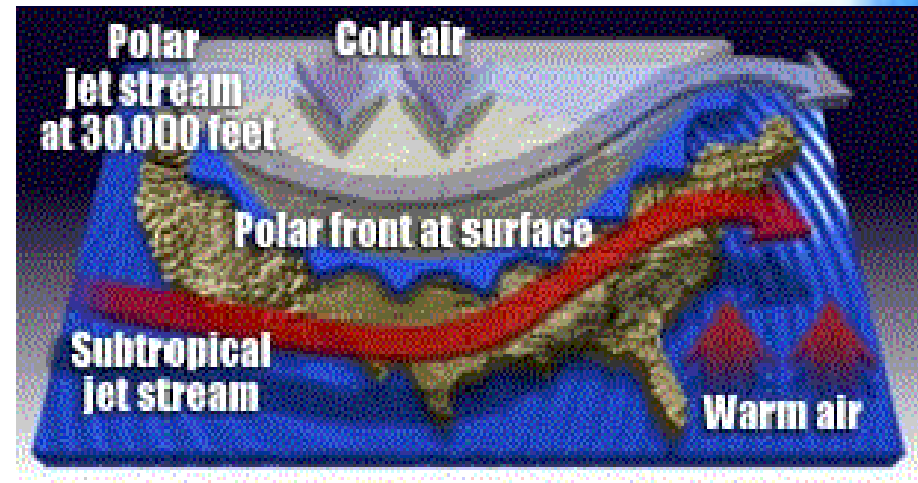
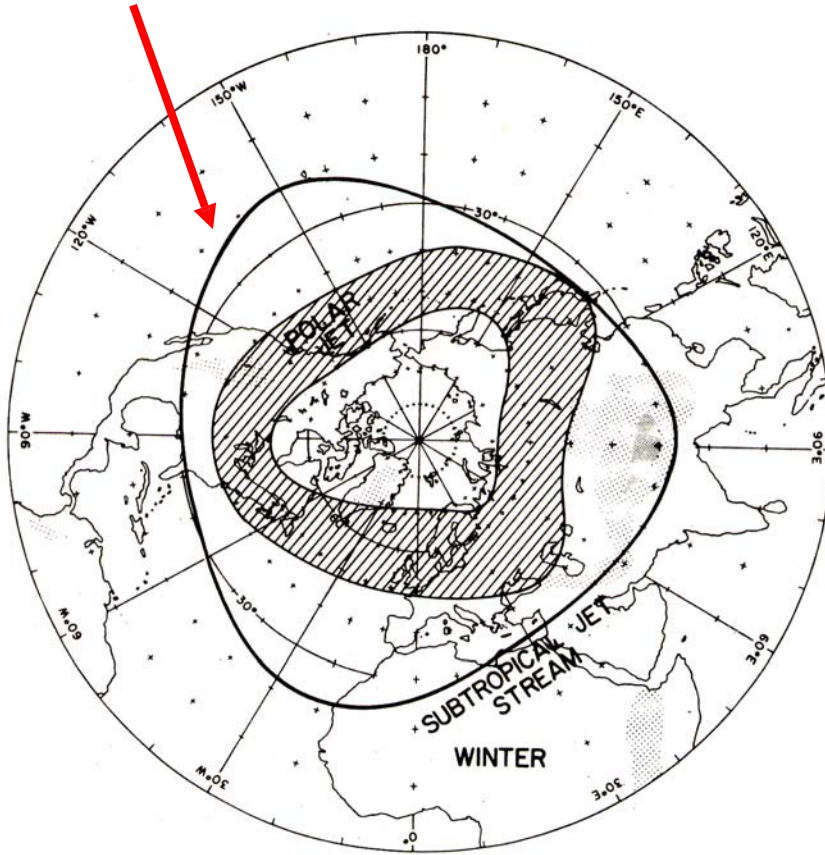
Thermal Wind Equation

$$\underline{\frac{\partial U}{\partial z} \propto - \frac{\partial T}{\partial y}}$$

- 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

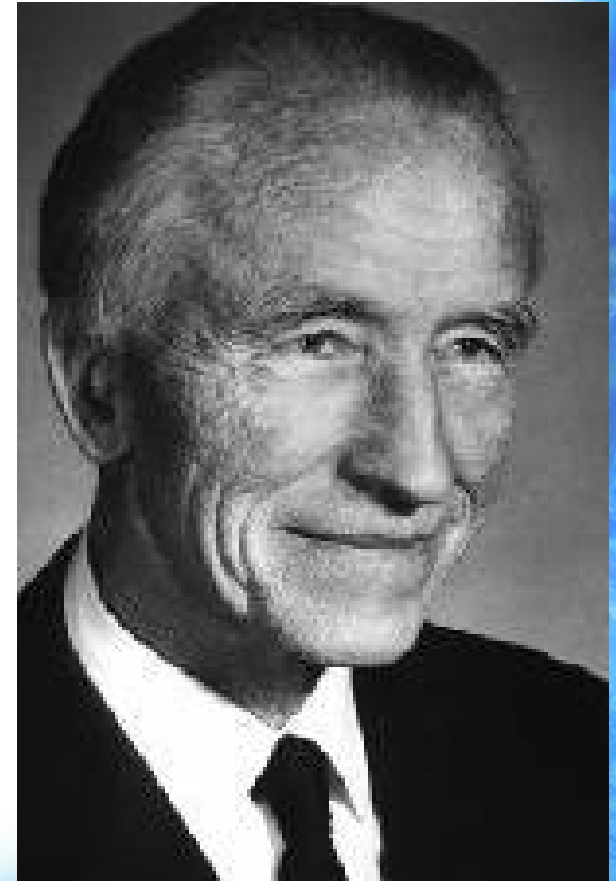


- Both the polar and subtropical jet streams can affect weather and climate in the western US (such as California).
- El Nino can affect western US climate by changing the locations and strengths of these two jet streams.

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

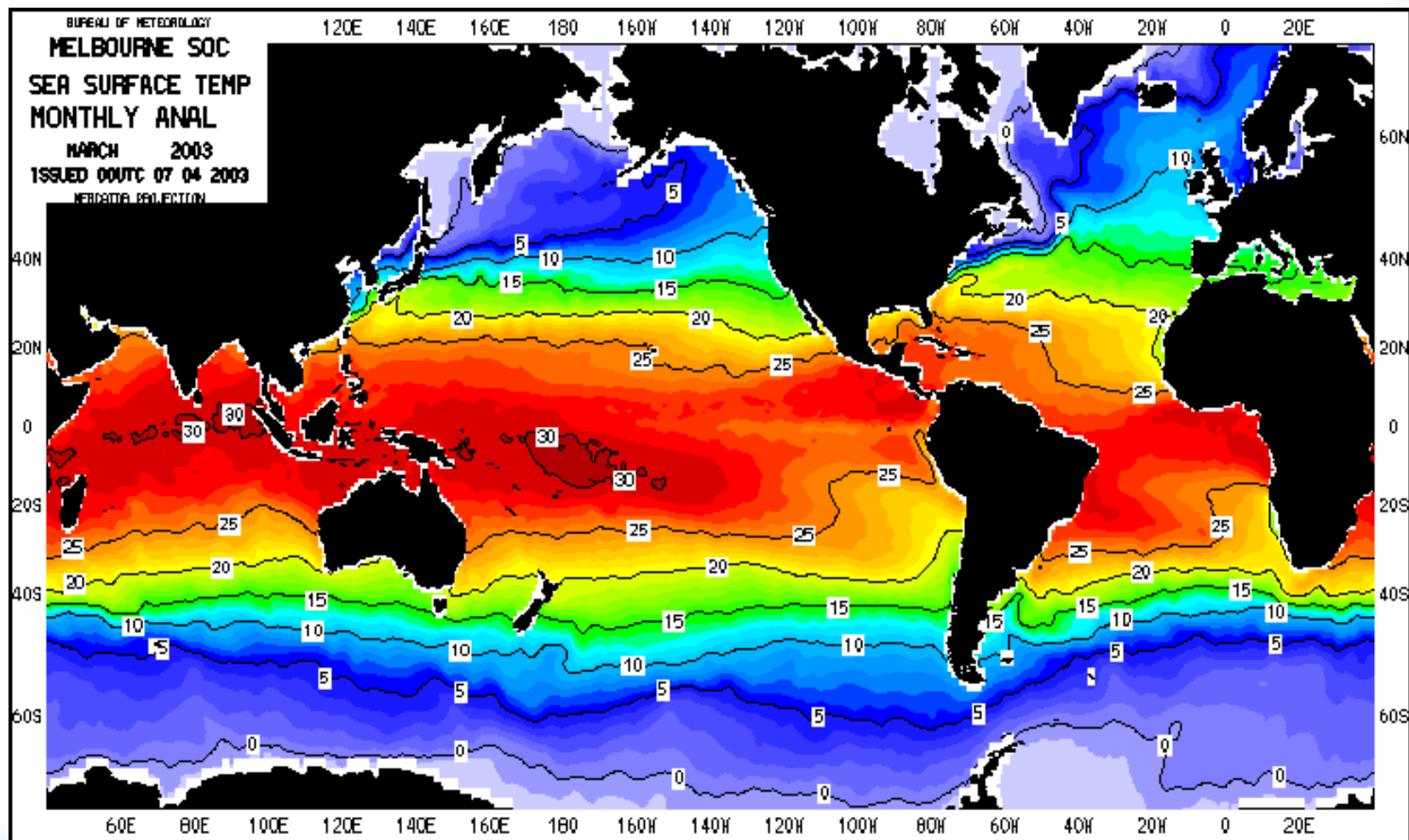
El Nino and Southern Oscillation

- Jacob Bjerknes was the first one to recognize 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

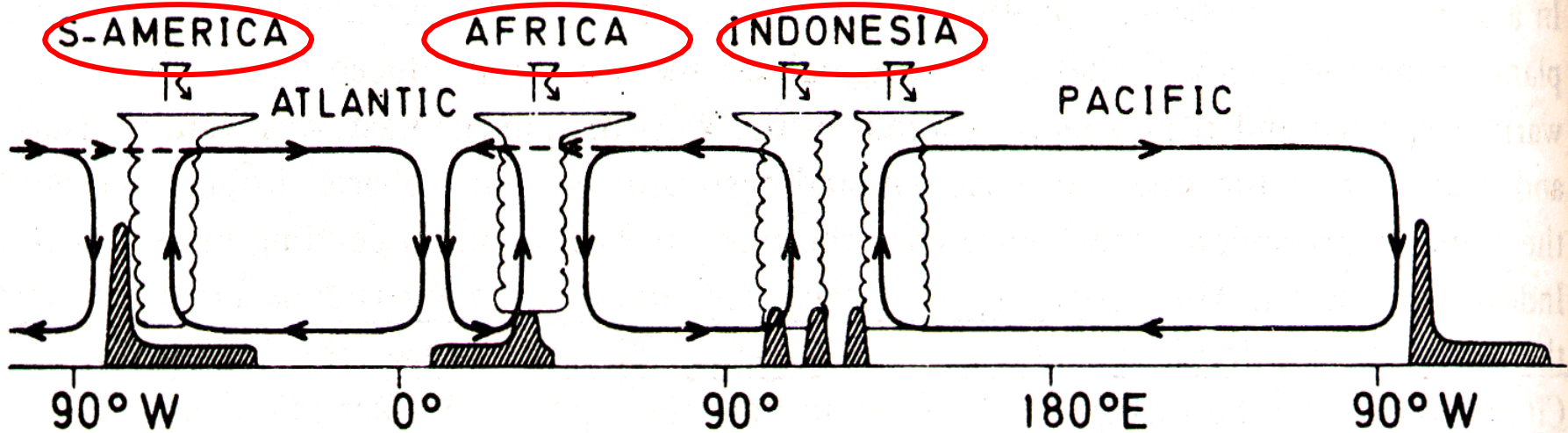
Walker Circulation and Ocean Temperature



East-West Circulation

(from Flohn (1971))

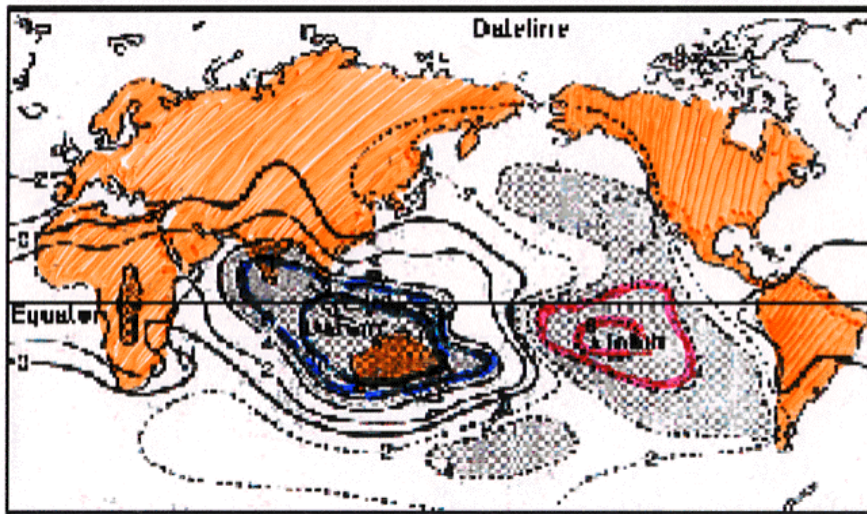
ZONAL ("WALKER") CIRCULATION ALONG EQUATOR



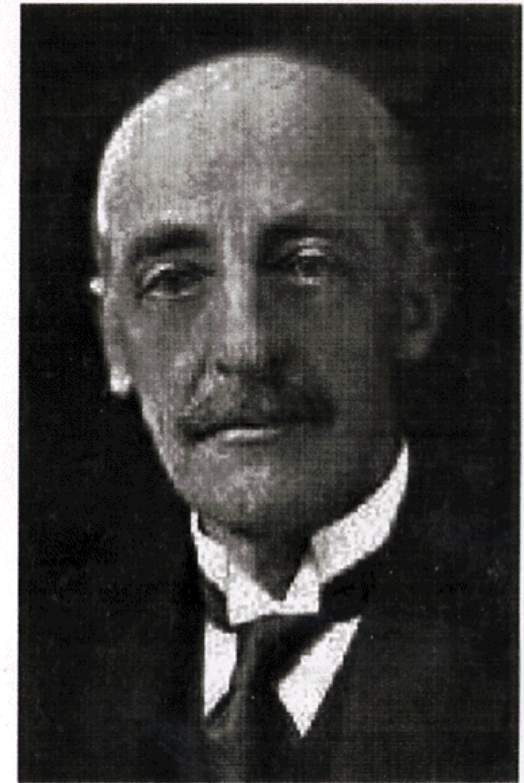
□ The east-west circulation in the atmosphere is related to the sea/land distribution on the Earth.

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.

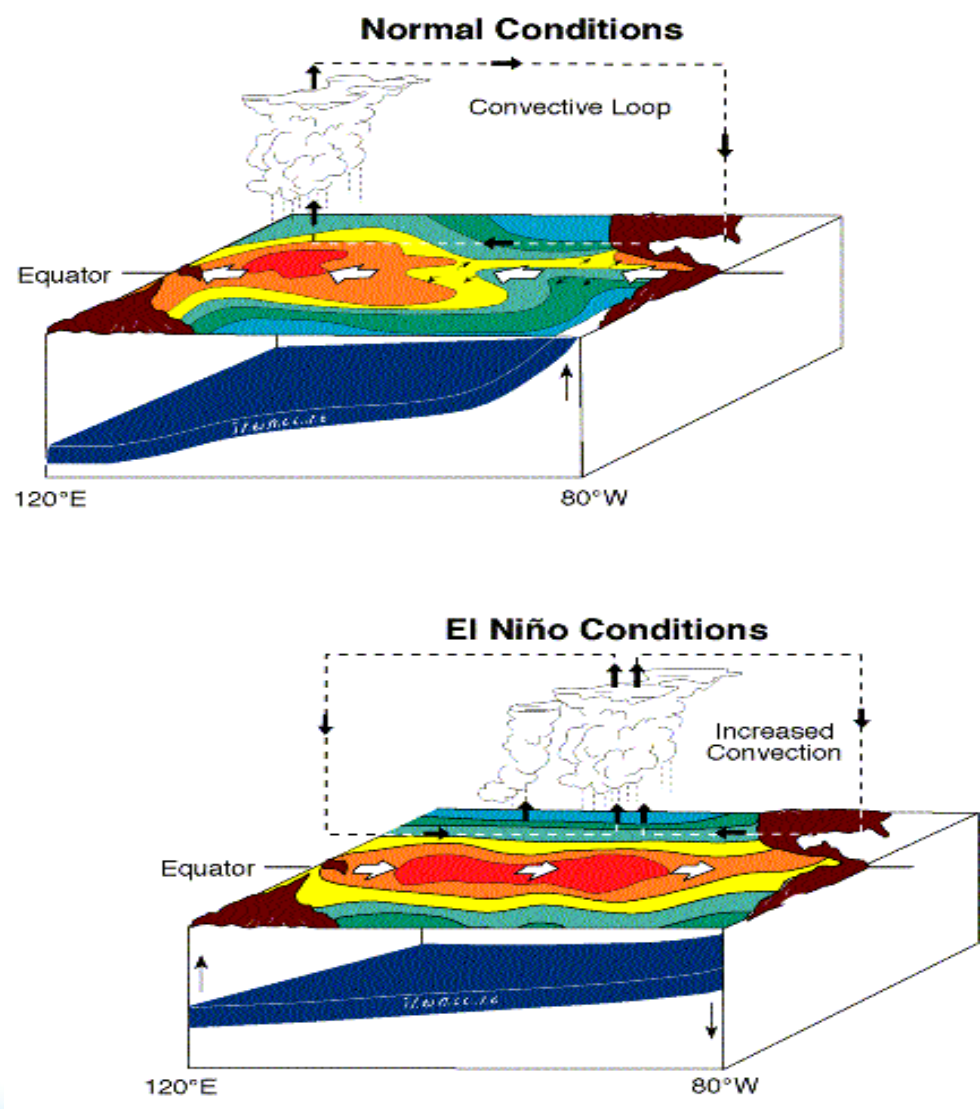


(from Rasmusson 1984)



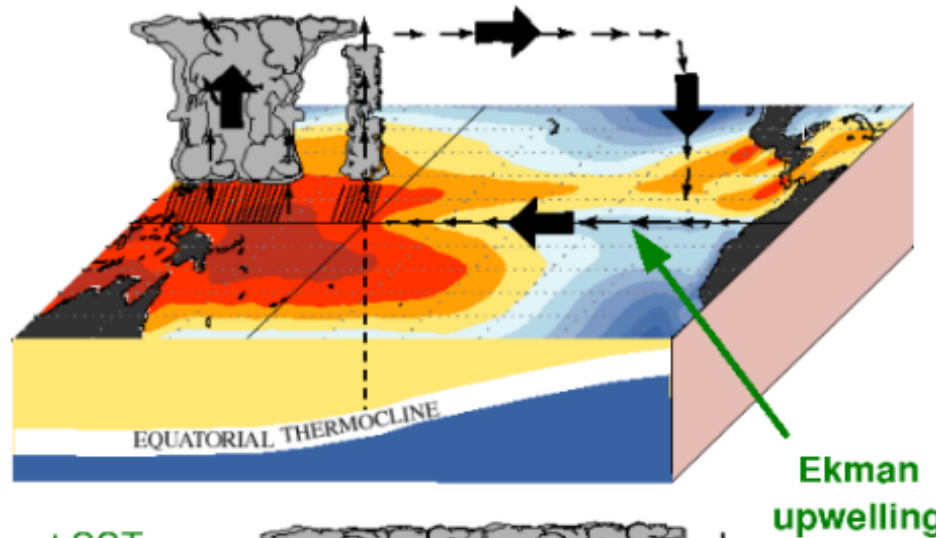
Sir Gilbert Walker

Walker Circulation and Ocean



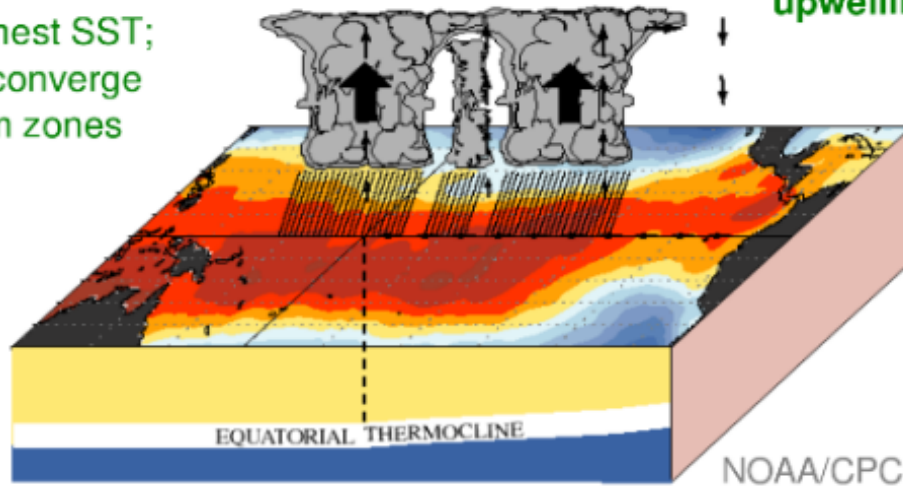
Normal v.s. El Nino

Normal



rain follows warmest SST;
 surface winds converge
 onto rainy/warm zones

El Niño

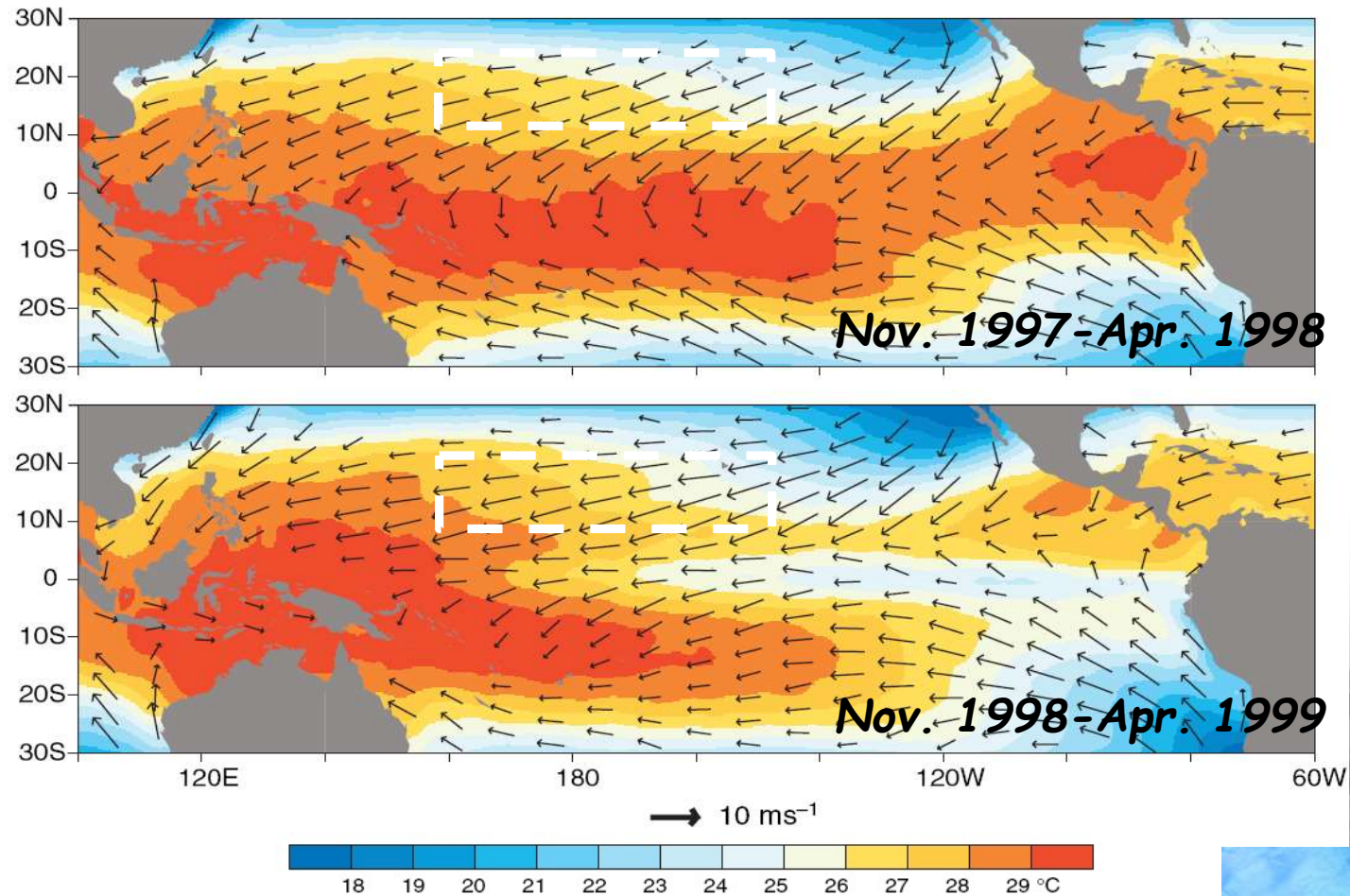


Asymmetric:
 cold tongue, warm pool;
 ITCZ north of equator;
easterly trade winds;
 sea level slopes **up** to west,
 thermocline **down** to west

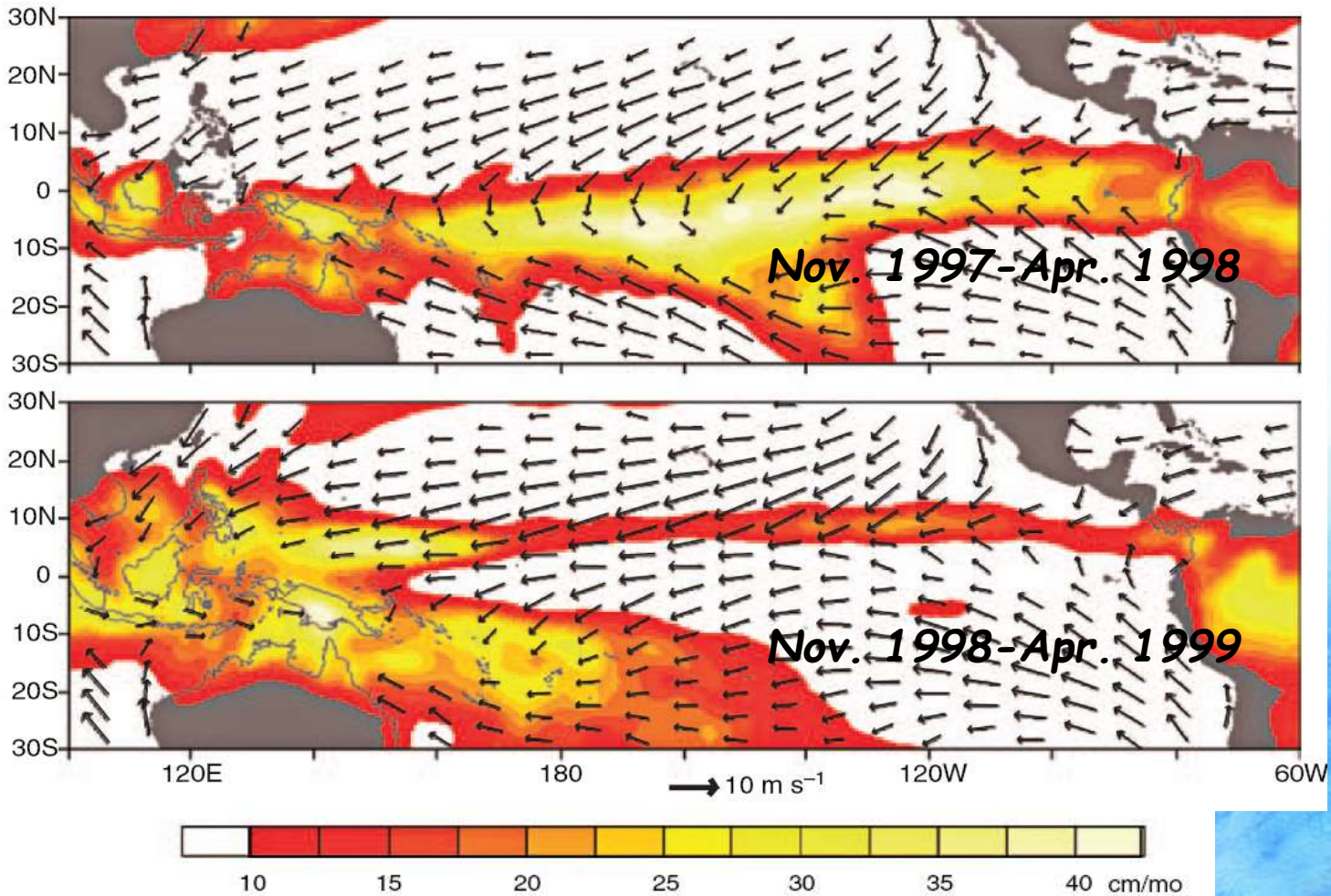
Events occur at
 irregular intervals (2-8yr);
 peak around Nov-Dec;
 last about a year;
 often followed by La Niña

ENSO schematic: Comparison of (a) normal and (b) El Niño conditions, for the tropical Pacific region in boreal winter (Dec-Jan-Feb).

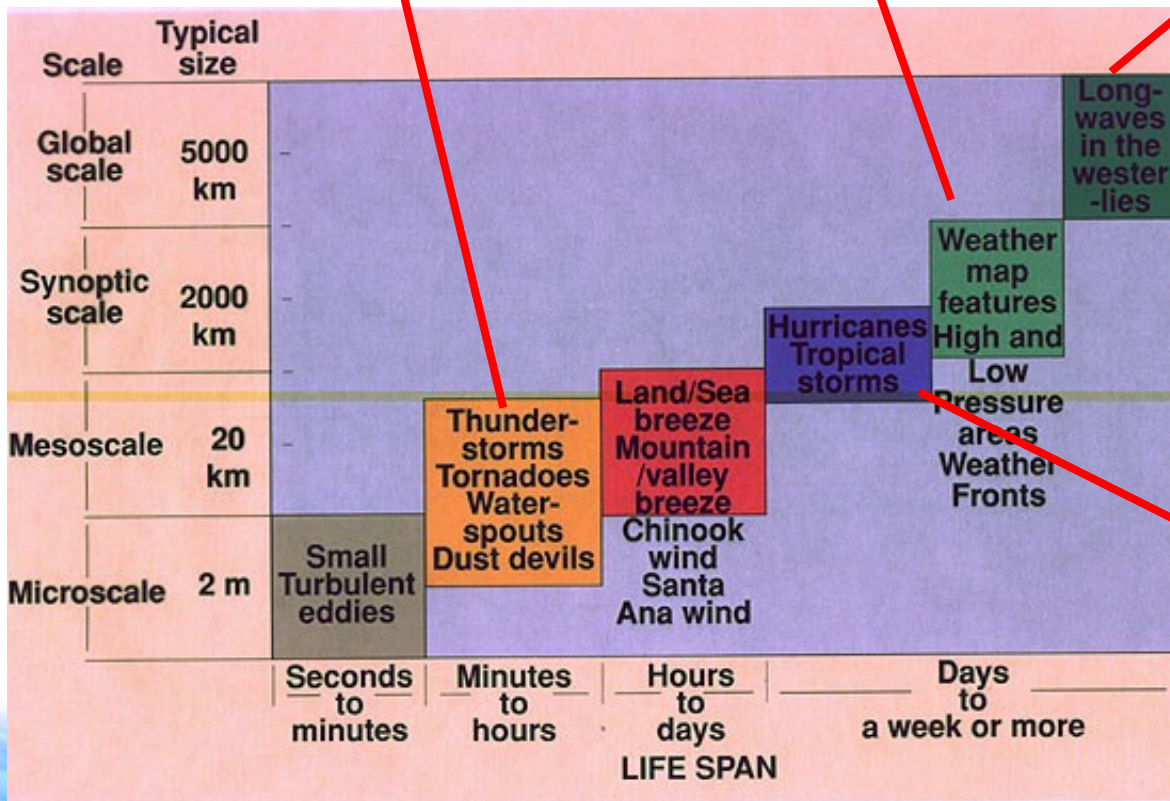
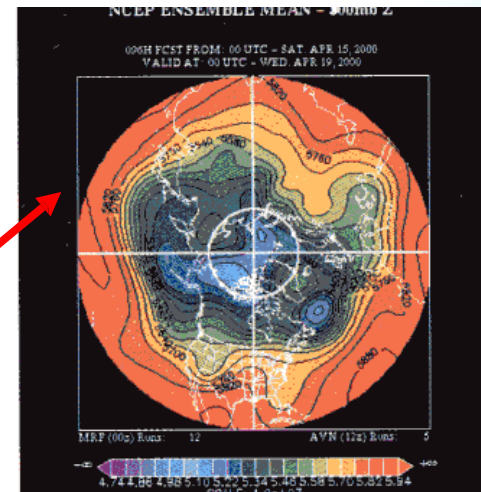
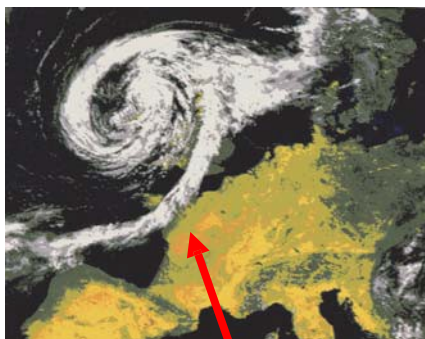
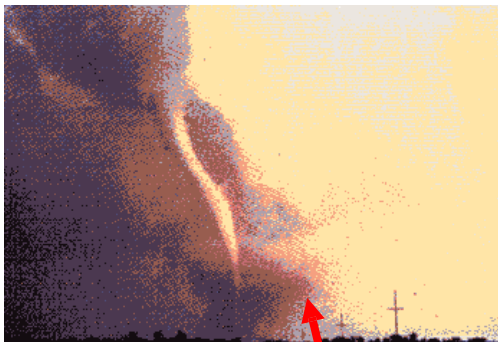
SST and surface winds during November-April of 1997-98, and 1998-99.



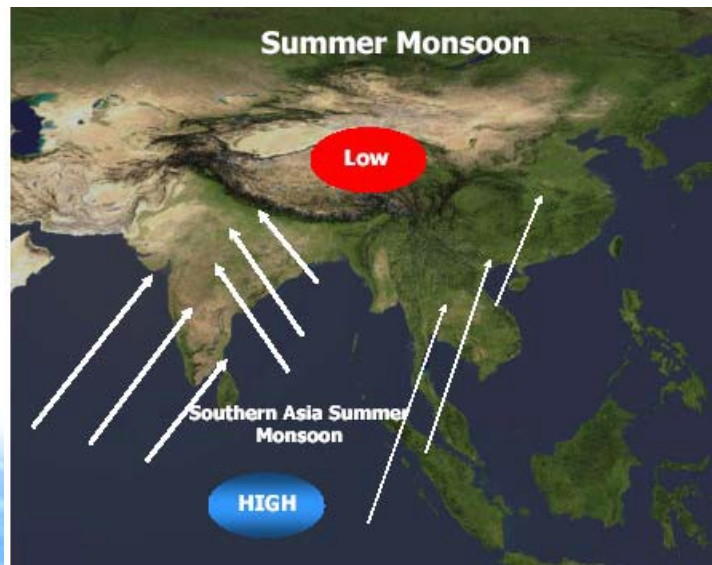
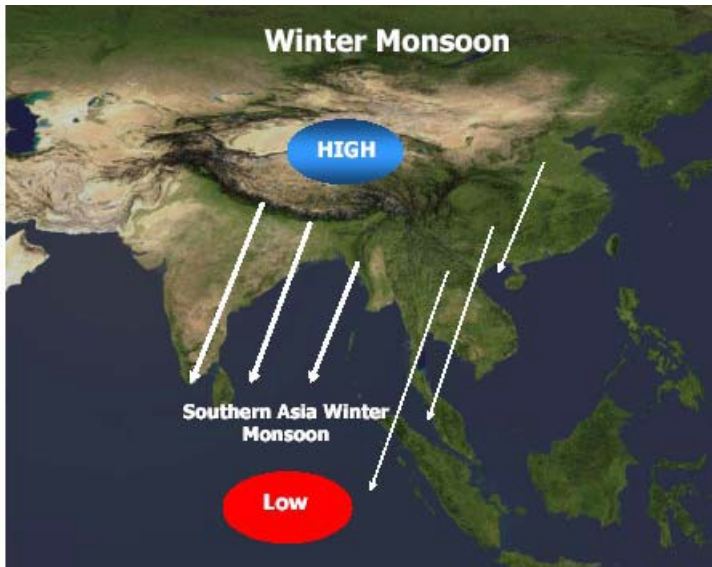
Prec. (CMAP) and surface winds (ERS-2) during November-April of 1997-98, and 1998-99.



Scale of Motions in the Atmosphere



Monsoon: Sea/Land-Related Circulation



□ Monsoon (Arabic “season”)

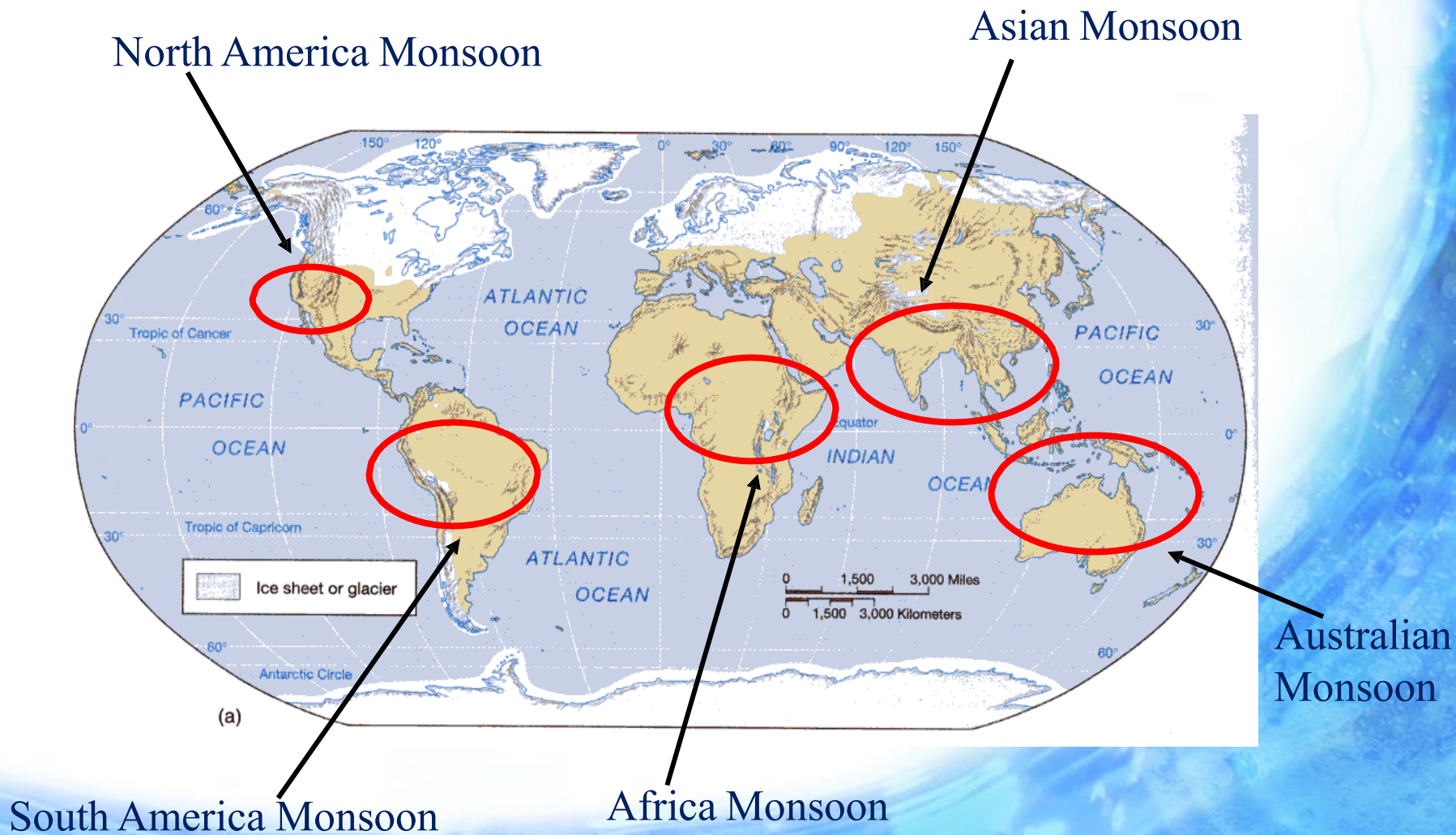
□ Monsoon is a climate feature that is characterized by the *seasonal reversal in surface winds*.

□ The very different heat capacity of land and ocean surface is the key mechanism that produces monsoons.

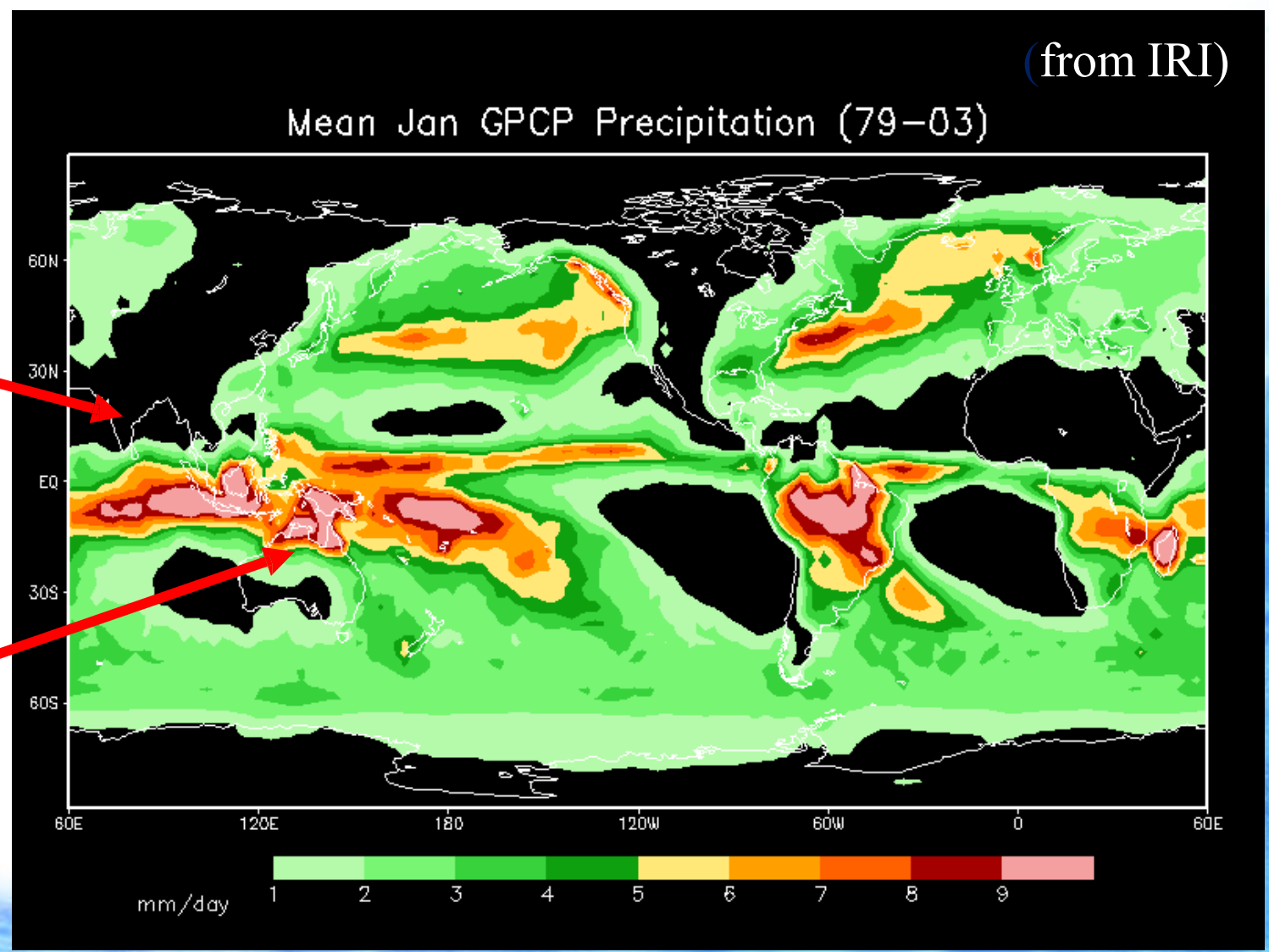
□ During summer seasons, land surface heats up faster than the ocean. Low pressure center is established over land while high pressure center is established over oceans. Winds blow from ocean to land and bring large amounts of water vapor to produce heavy precipitation over land: A rainy season.

□ During winters, land surface cools down fast and sets up a high pressure center. Winds blow from land to ocean: a dry season.

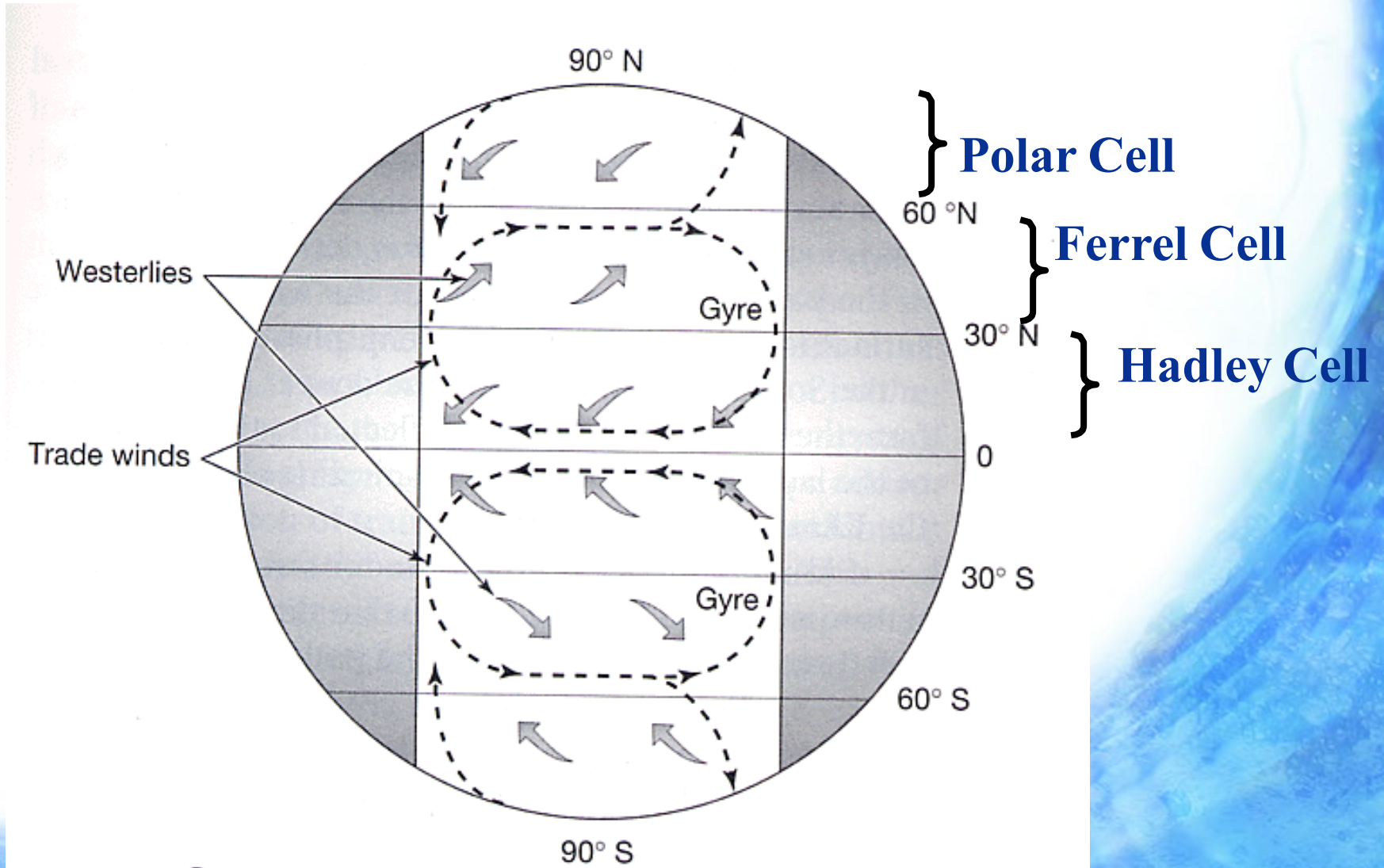
How Many Monsoons Worldwide?



Seasonal Cycle of Rainfall



Winds and Surface Currents



Basic Ocean Structures

Warm up by sunlight!

□ Upper Ocean (~100 m)

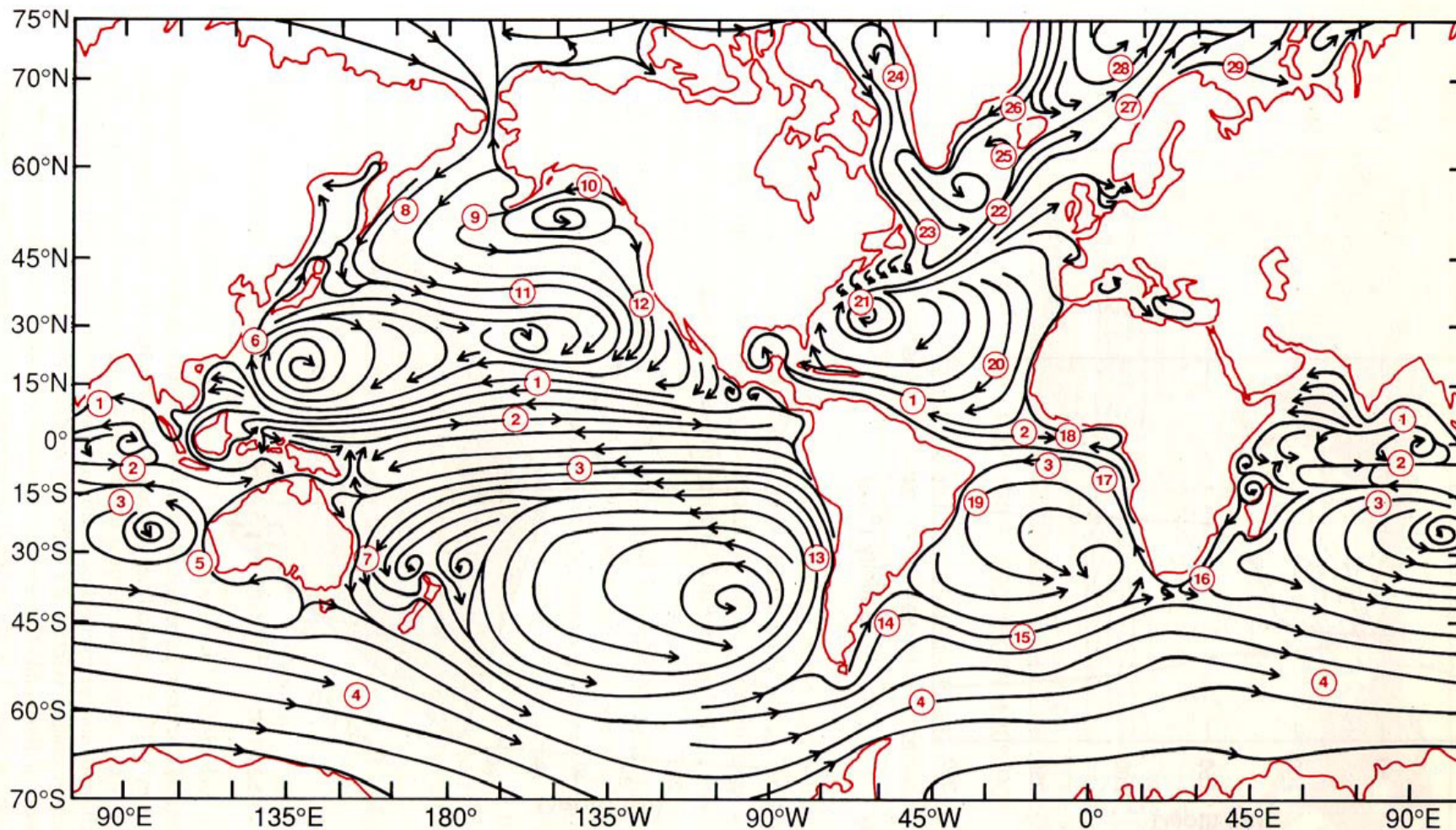
Shallow, warm upper layer where light is abundant and where most marine life can be found.

□ Deep Ocean

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

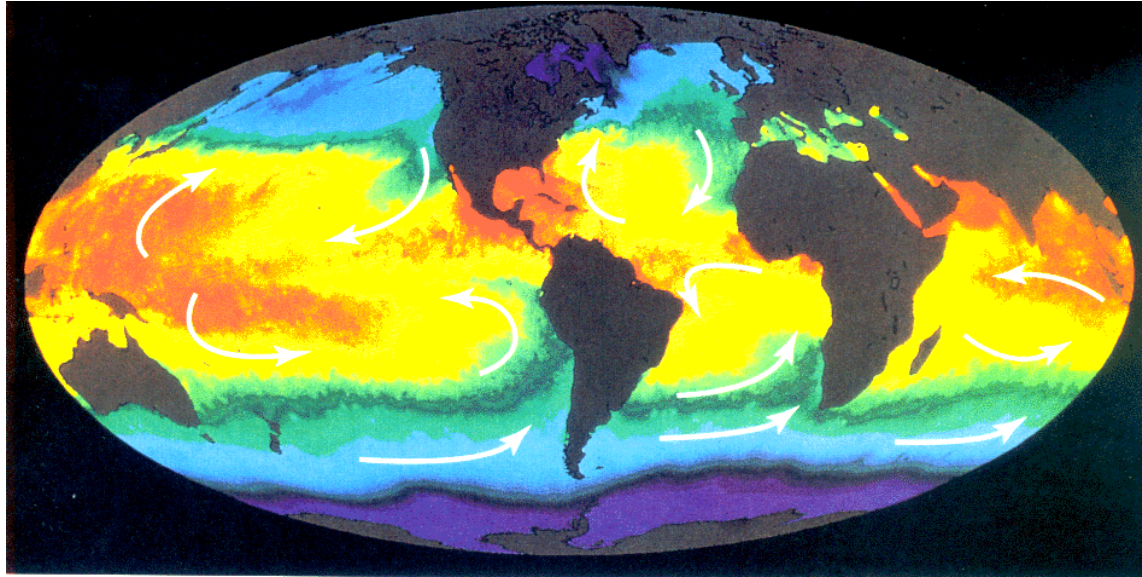
No sunlight!

Global Surface Currents



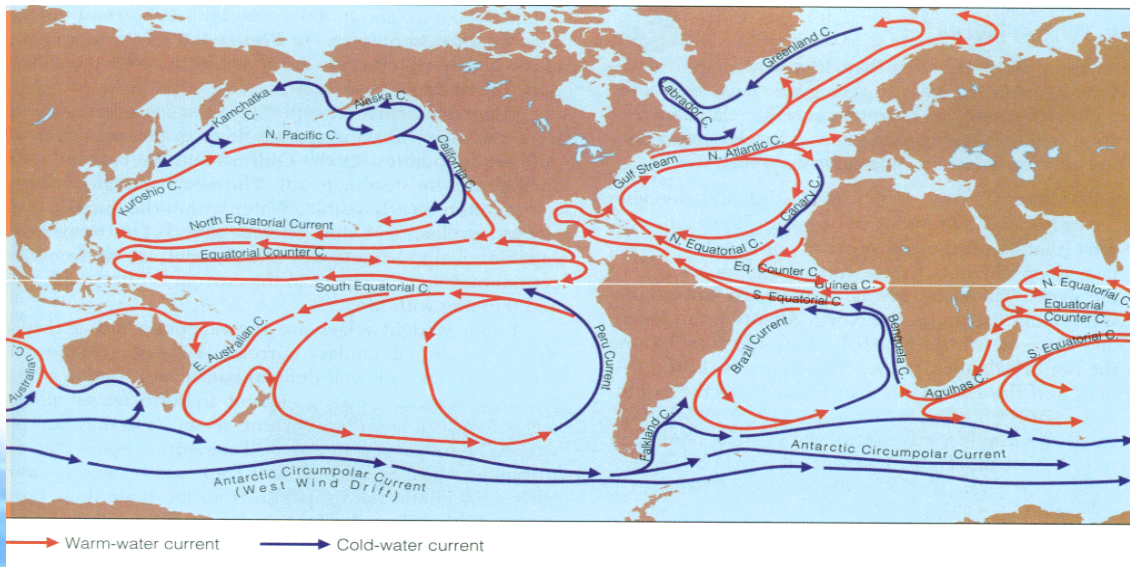
- | | | | | | |
|-----------------------------|---------------------------|---------------------------|---------------------|---------------------------|---------------------------|
| 1 North Equatorial Current | 6 Kuroshio Current | 11 North Pacific Current | 16 Agulhas Current | 21 Gulf Stream | 26 East Greenland Current |
| 2 Equatorial Countercurrent | 7 East Australian Current | 12 California Current | 17 Benguela Current | 22 North Atlantic Current | 27 Norway Current |
| 3 South Equatorial Current | 8 Oyashio Current | 13 Peru Current | 18 Guinea Current | 23 Labrador Current | 28 Spitsbergen Current |
| 4 West Wind Drift | 9 Aleutian Current | 14 Falkland Current | 19 Brazil Current | 24 West Greenland Current | 29 North Cape Current |
| 5 West Australian Current | 10 Alaska Current | 15 South Atlantic Current | 20 Canary Current | 25 Irminger Current | |

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 Circumpolar Current (also called West Wind Drift)

Characteristics of the Gyres

- **Currents are in geostrophic balance**
- **Each gyre includes 4 current components:**
 - two boundary currents: western and eastern
 - two transverse currents: eastward and westward

Western boundary current (jet stream of ocean)

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

Eastern boundary current

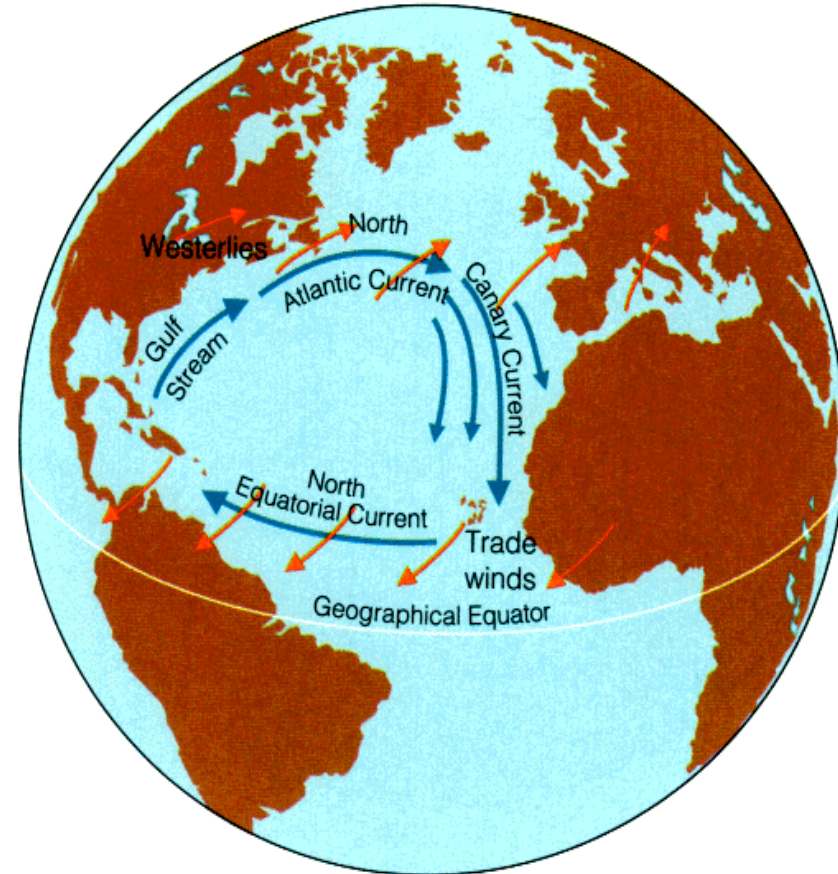
the slow, shallow, and broad current moves cold water equatorward (transport ~ 10-15 Sv)

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



Volume transport unit:

1 sv = 1 Sverdrup = 1 million m³/sec

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

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

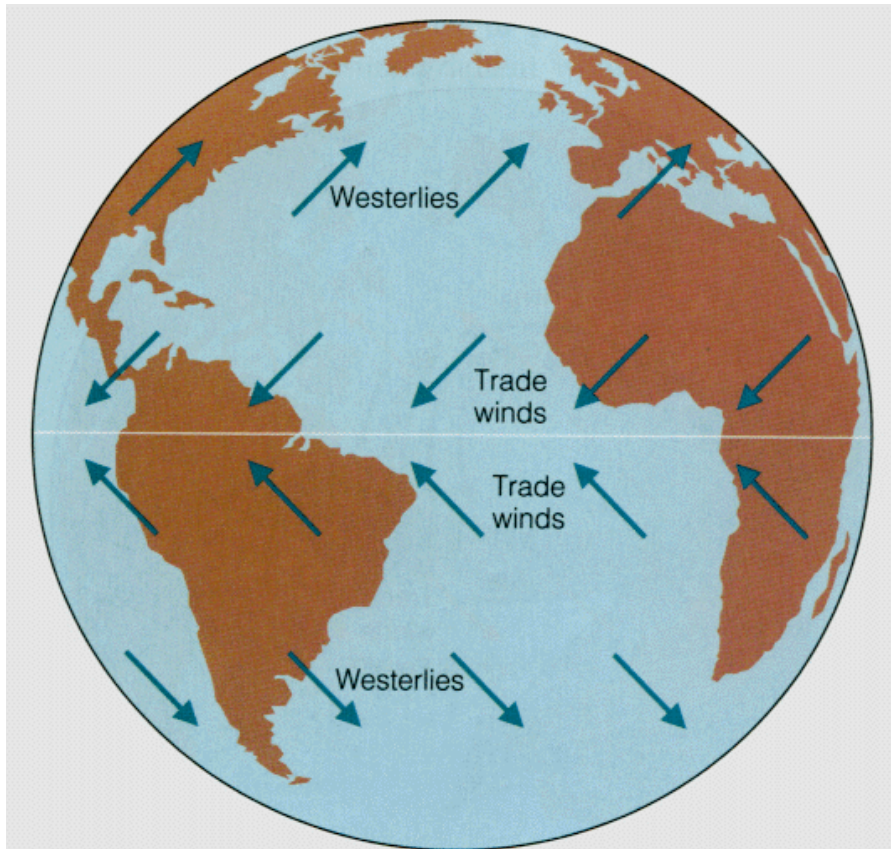


Figure 9.1 Winds, driven by uneven solar heating and Earth's spin, drive the movement of the ocean's surface currents. The prime movers are the powerful westerlies and the persistent trade winds (easterlies).

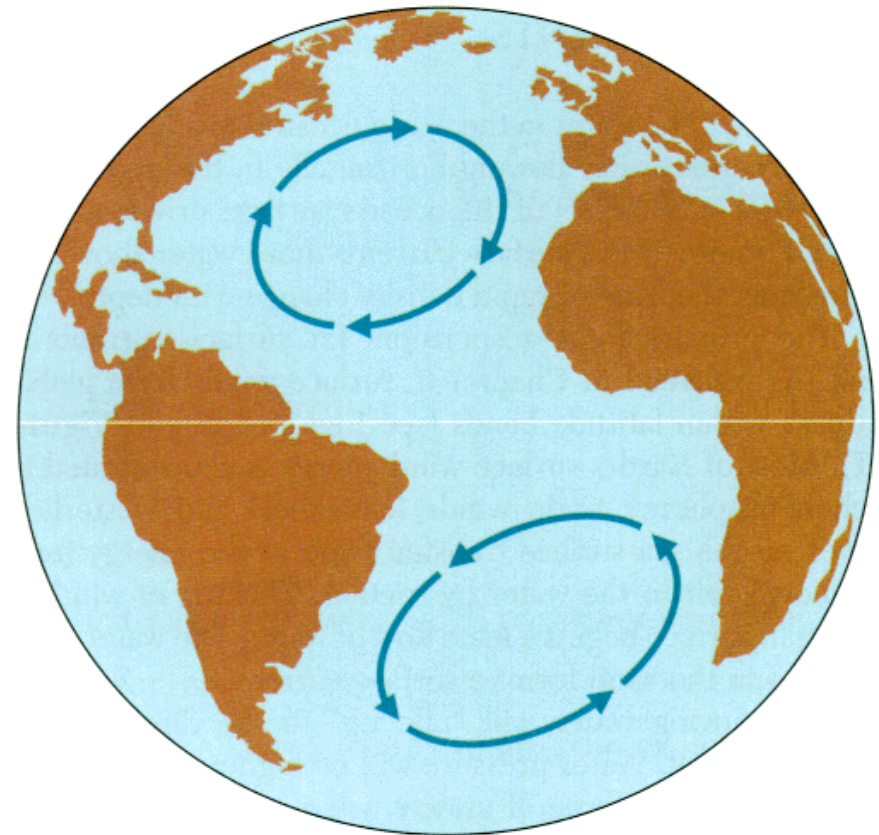
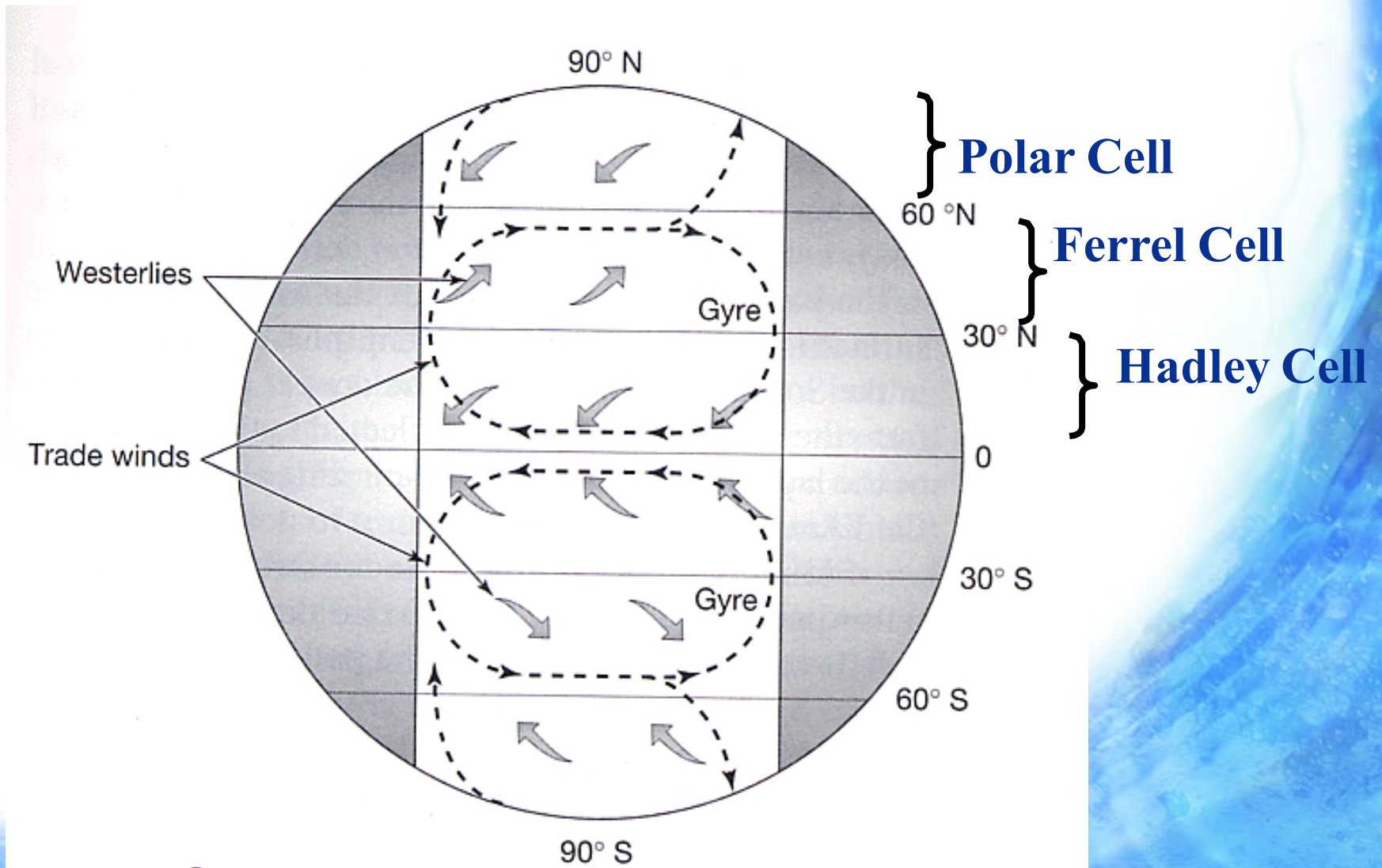
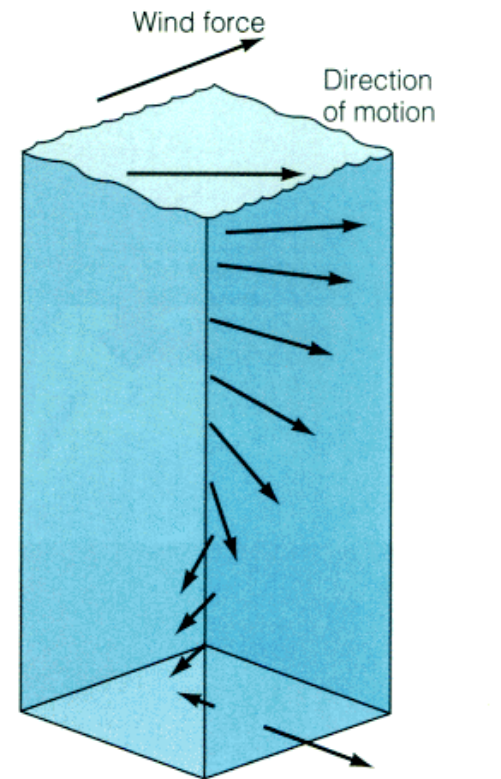
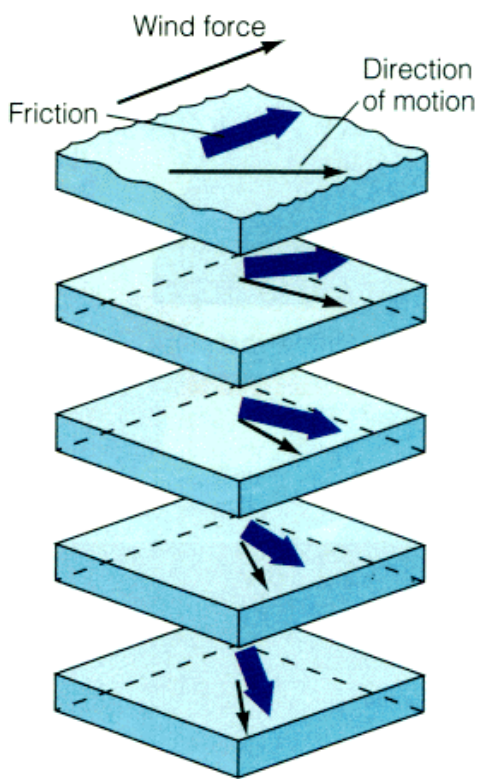
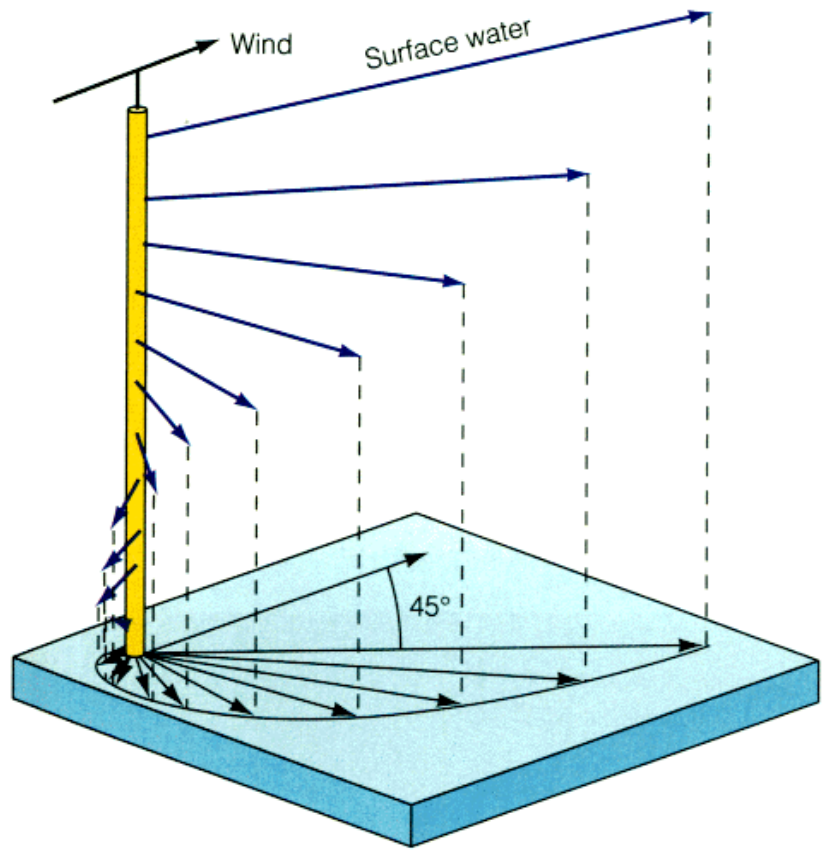


Figure 9.2 A combination of four forces—surface winds, the sun's heat, the Coriolis effect, and gravity—circulates the ocean surface clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, forming gyres.

Winds and Surface Currents

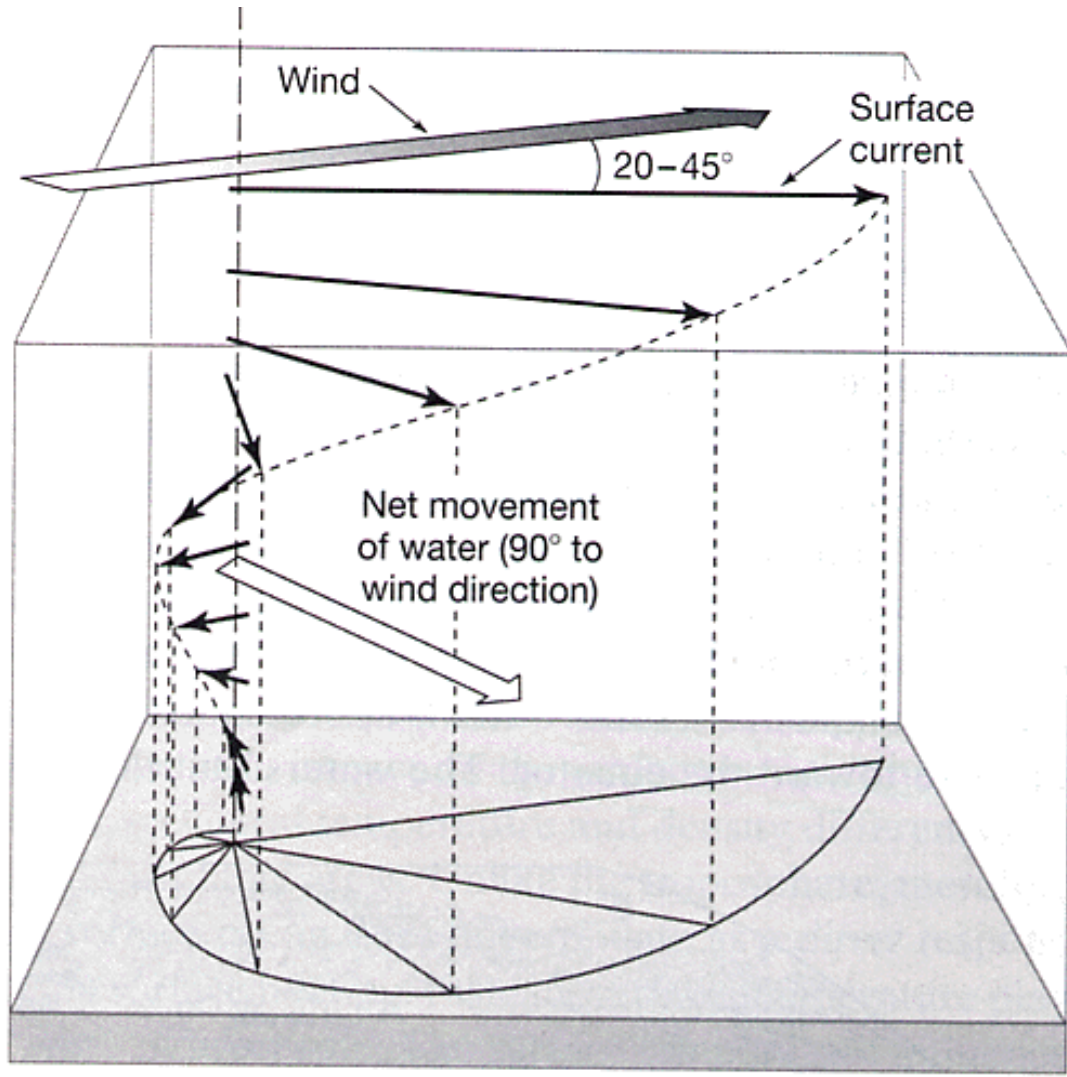


Step 2: Ekman Layer (frictional force + Coriolis Force)

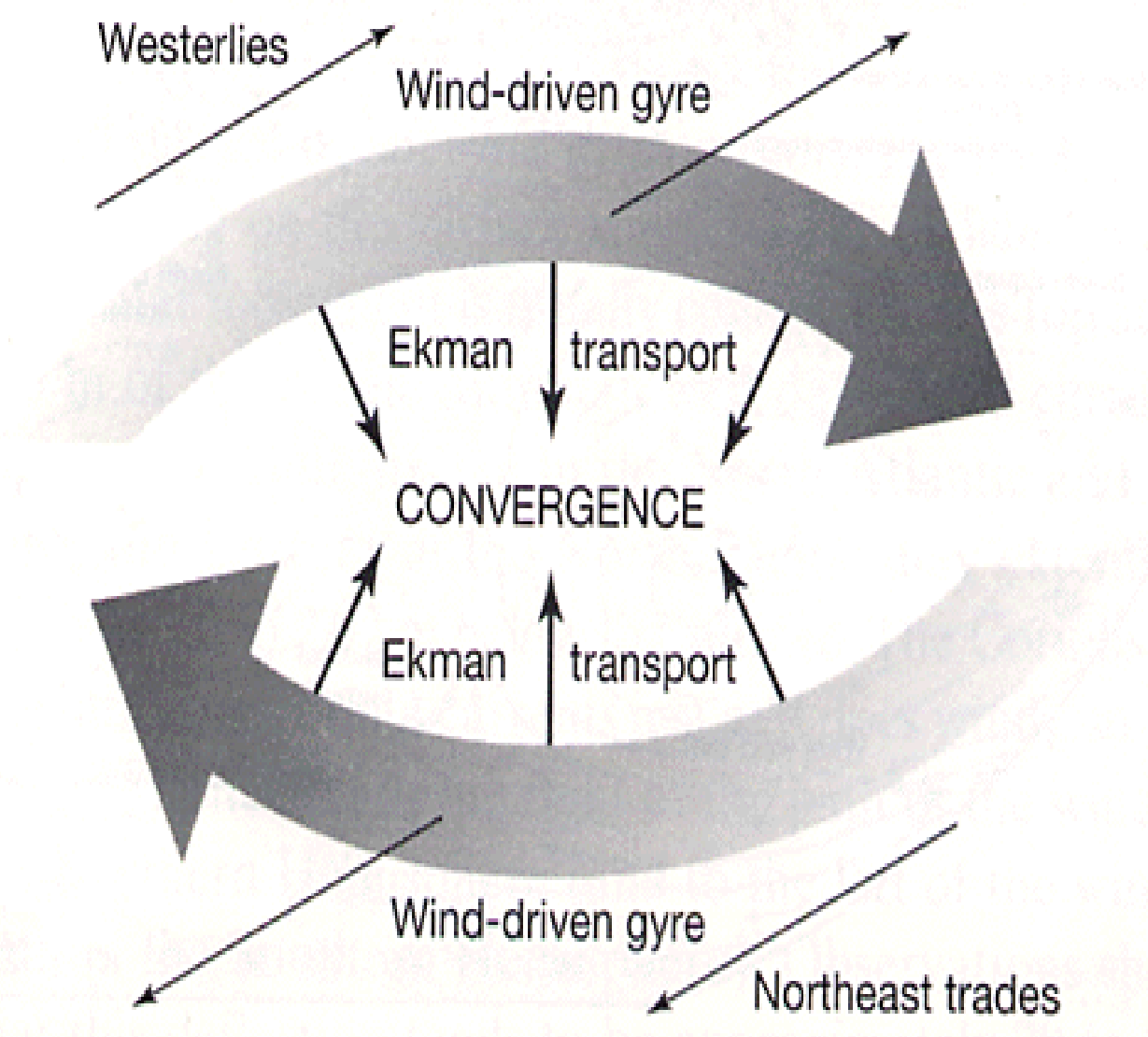


a b c Average flow

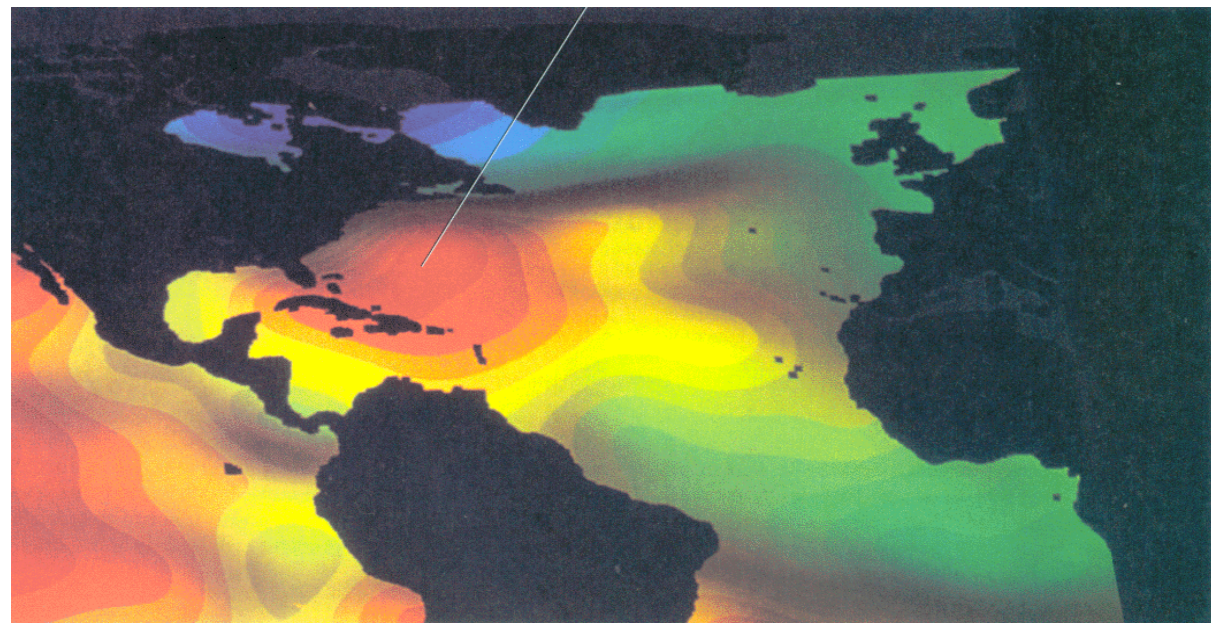
Ekman Spiral – A Result of Coriolis Force



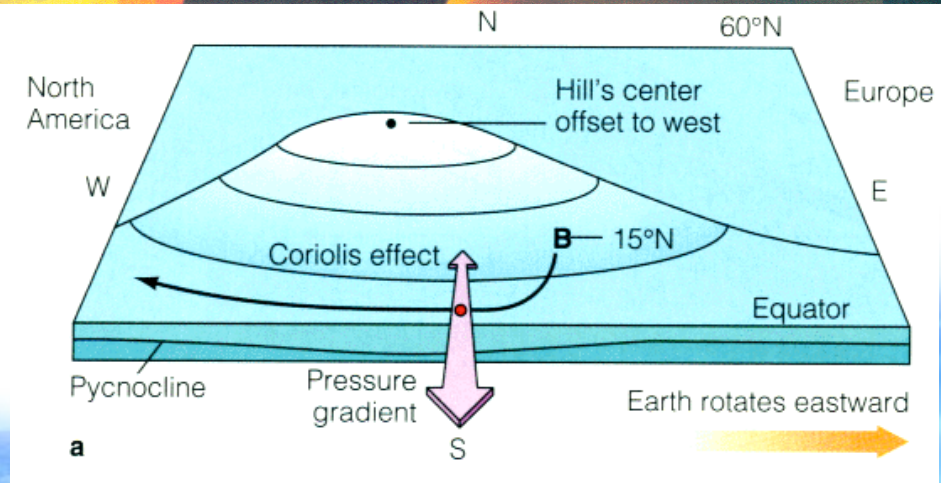
Ekman Transport



Step 3: Geostrophic Current (Pressure Gradient Force + Coriolis Force)



**NASA-TOPEX
Observations of
Sea-Level Height**



Thermohaline Circulation

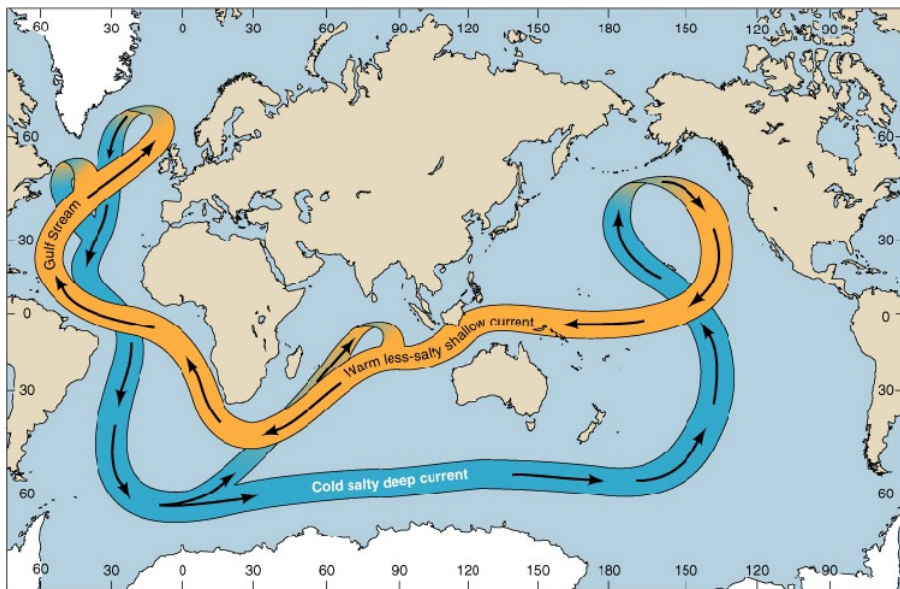
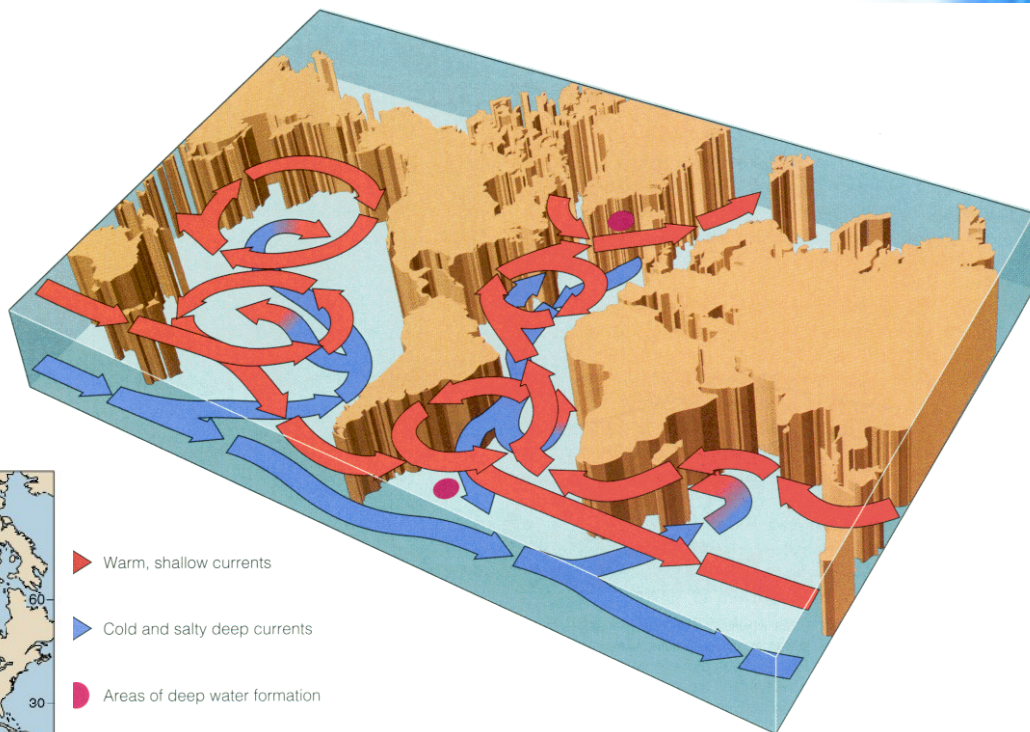
- Thermo → Temperature
- Haline → salinity

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.



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 thermohaline circulation
 - ➔ The rate of global warming in the atmosphere will increase.