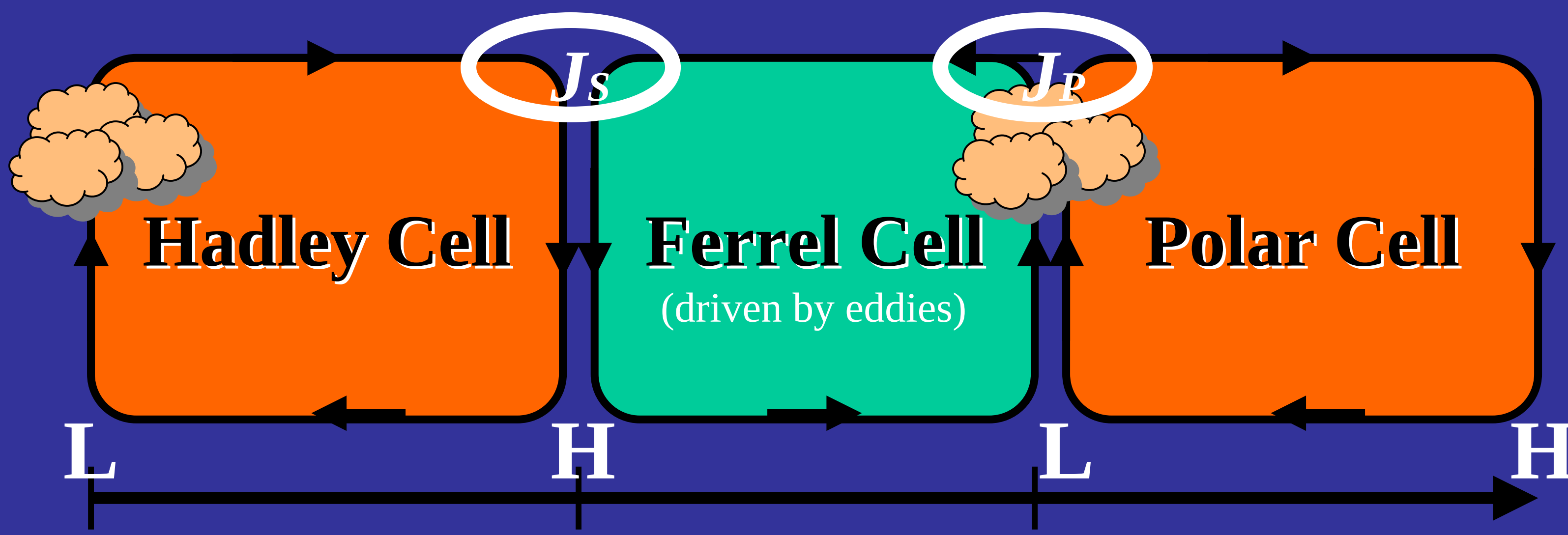
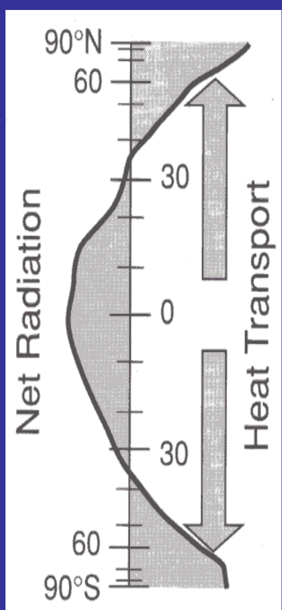
Chapter 8: Atmospheric Circulation and Pressure Distributions

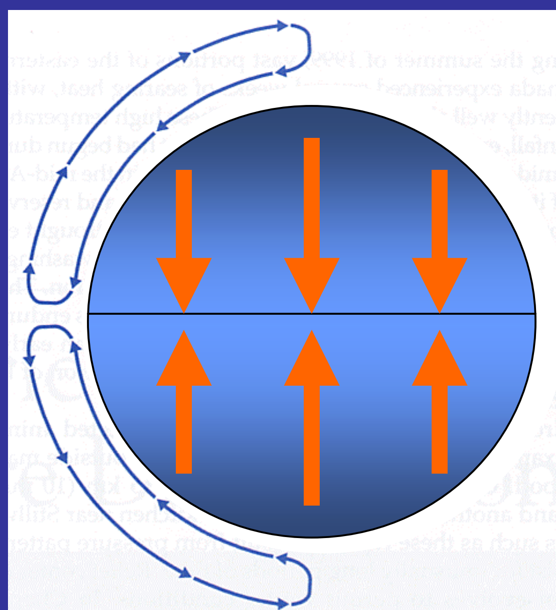


- ❑ General Circulation in the Atmosphere
- ❑ General Circulation in Oceans
- ❑ Air-Sea Interaction: El Nino

Single-Cell Model:
Explains Why There are Tropical Easterlies

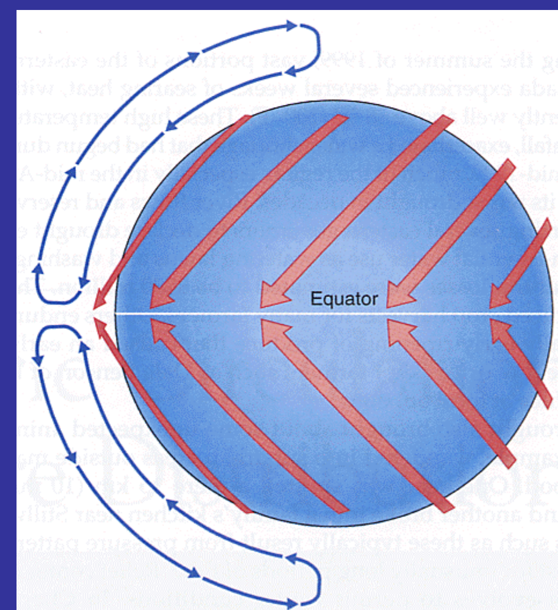
Without Earth Rotation





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:

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

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

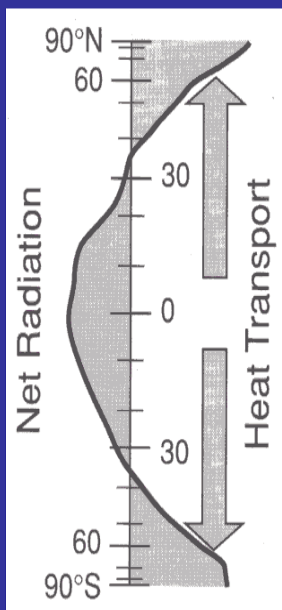
u_{60N} = 687 m/sec !!!!

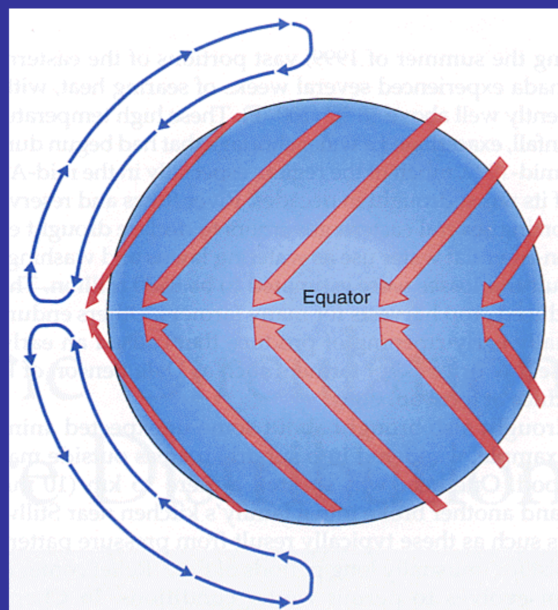
This high wind speed is not observed!

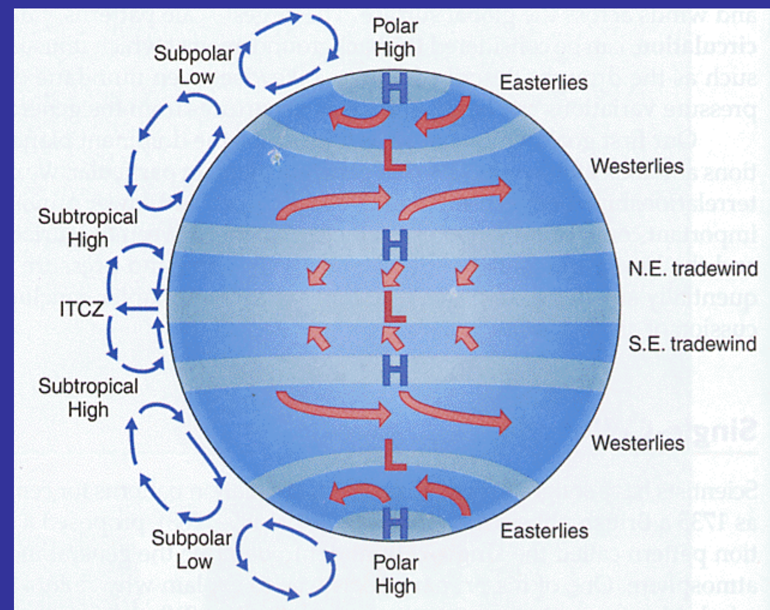
Atmospheric Circulation: Zonal-mean Views

Single-Cell Model

Three-Cell Model

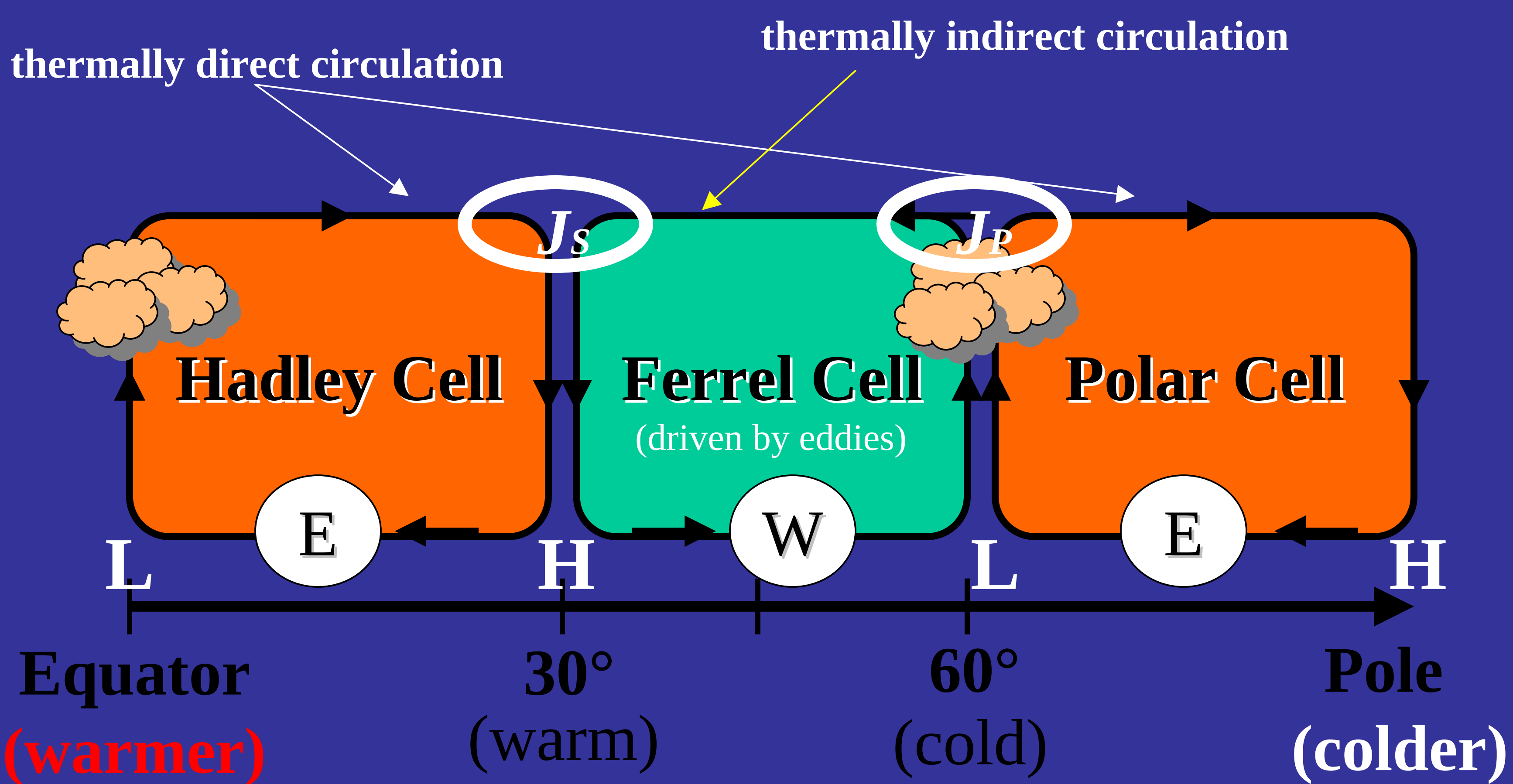






(Figures from *Understanding Weather & Climate* and *The Earth System*)

Properties of the Three Cells



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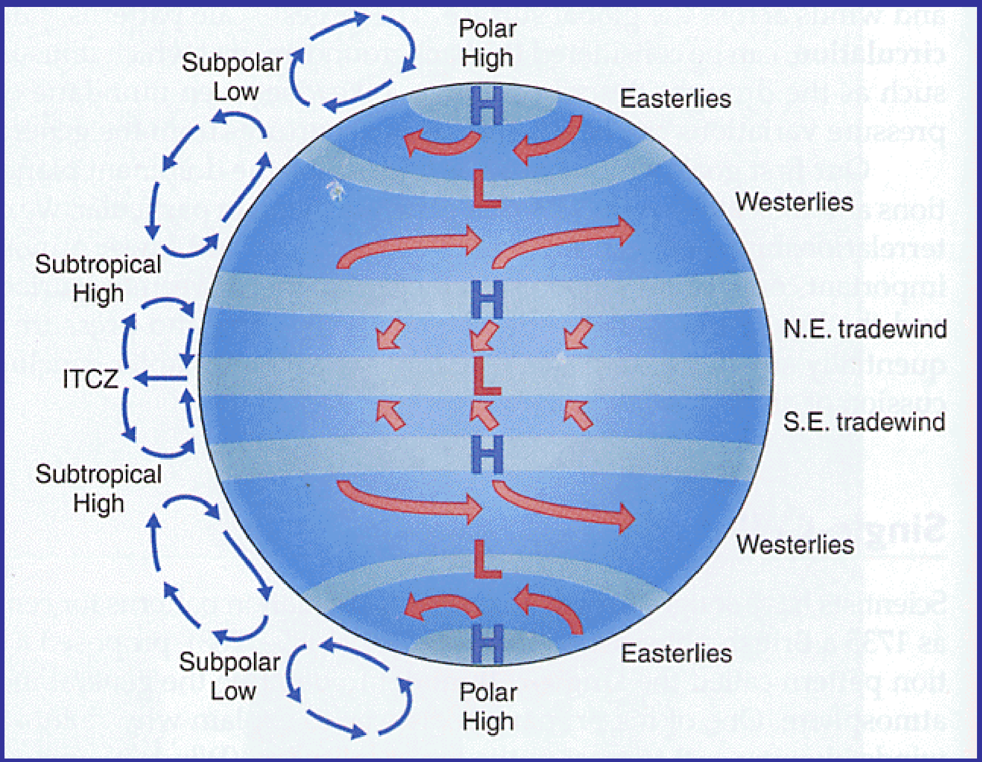
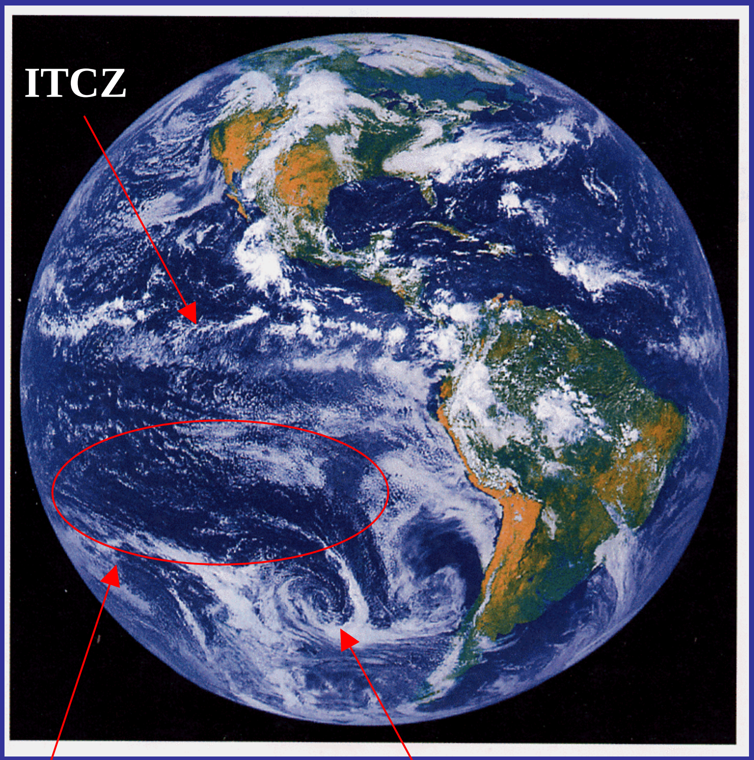
The Three Cells



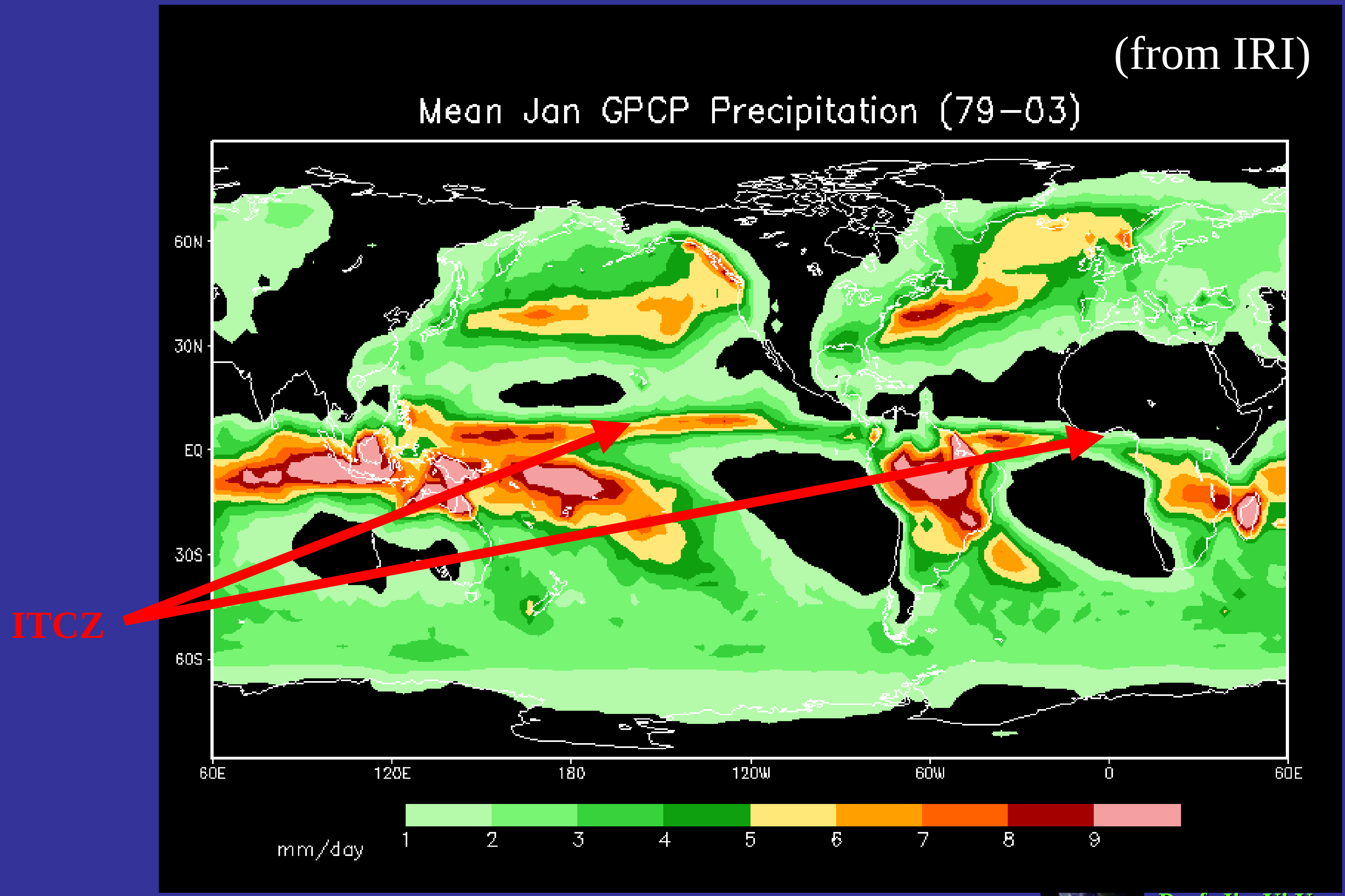


Subtropical High

midlatitude Weather system

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

Precipitation Climatology



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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.

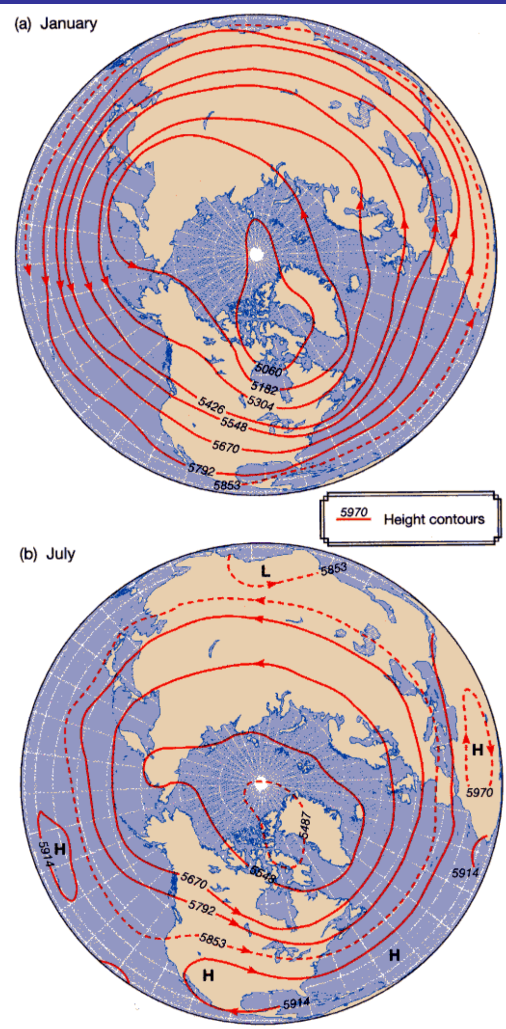
Is the Three-Cell Model Realistic?

- ***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.)

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).

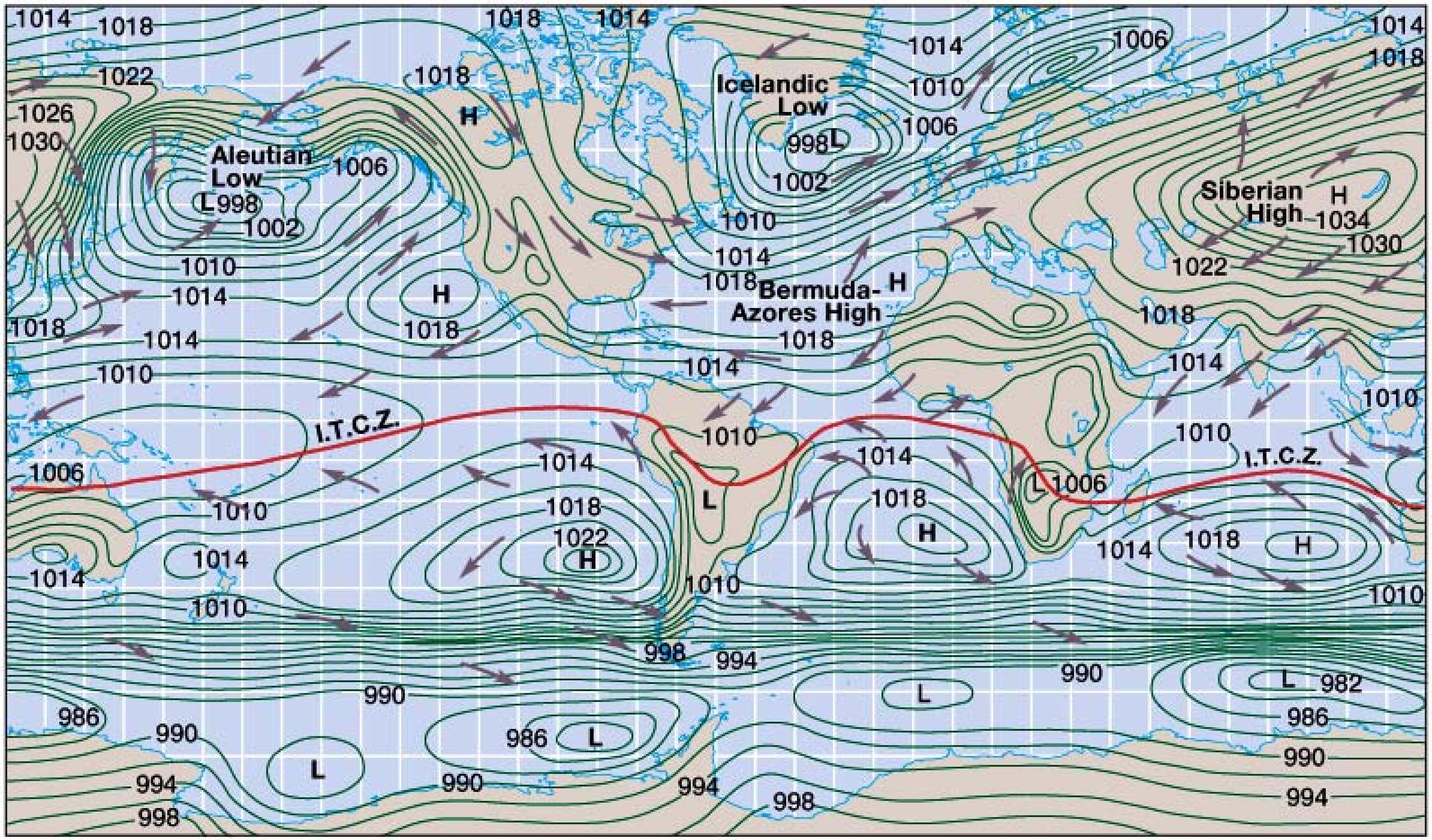
Bottom Line

- Pressure and winds associated with Hadley cells are close approximations of real world conditions
- Ferrel and Polar cells do not approximate the real world as well
- Surface winds poleward of about 30^{o} do not show the persistence of the trade winds, however, long-term averages do show a prevalence indicative of the westerlies and polar easterlies
- For upper air motions, the three-cell model is unrepresentative
- The Ferrel cell implies easterlies in the upper atmosphere where westerlies dominate
- Overturning implied by the model is false
- The model does give a good, simplistic approximation of an earth system devoid of continents and topographic irregularities

Semi-Permanent Pressure Cells

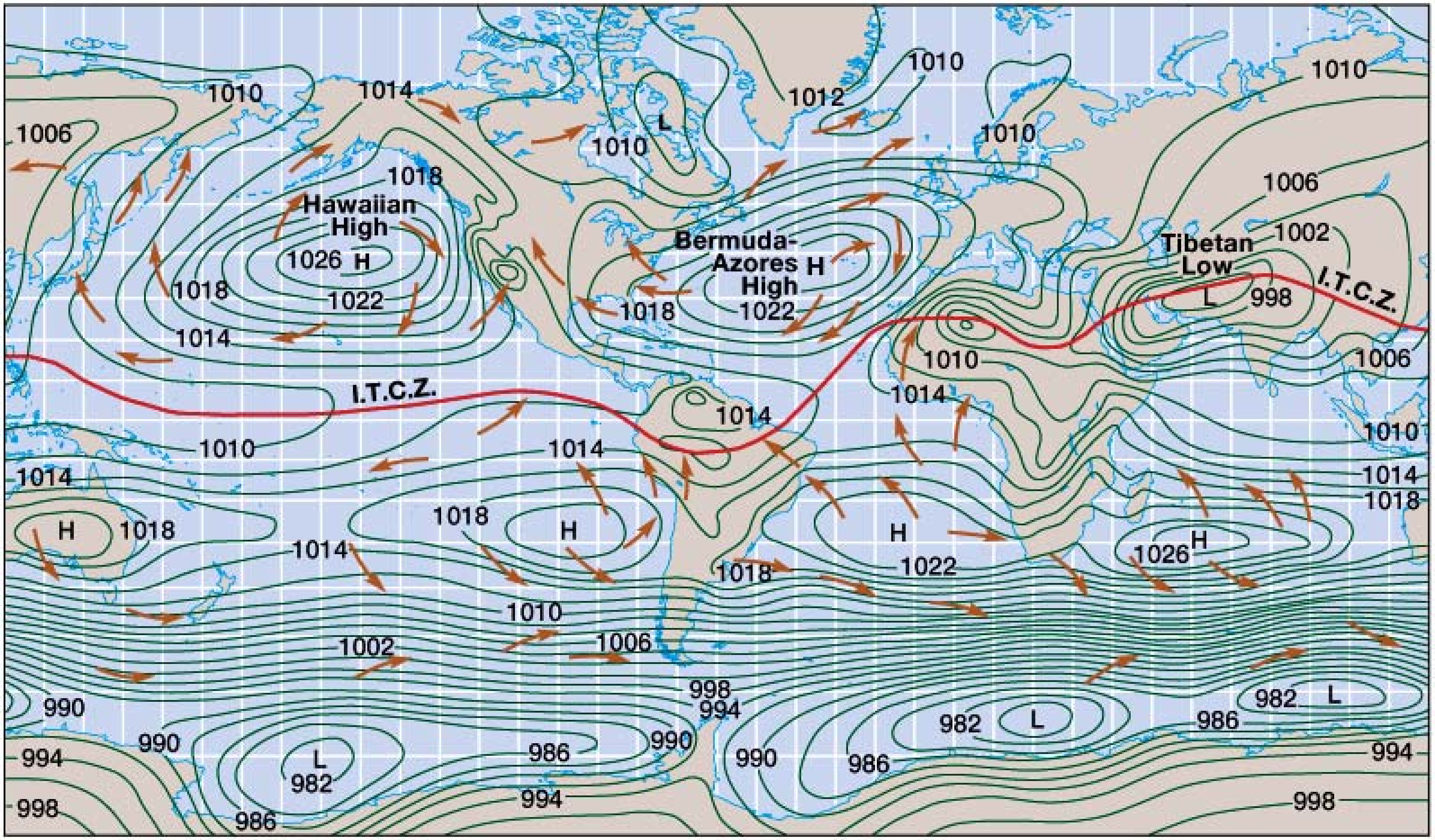
- **The Aleutian, Icelandic, and Tibetan lows**
  - The oceanic (continental) lows achieve maximum strength during winter (summer) months
  - The summertime Tibetan low is important to the east-Asia monsoon
- **Siberian, Hawaiian, and Bermuda-Azores highs**
  - The oceanic (continental) highs achieve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

January



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

July



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

Global Distribution of Deserts

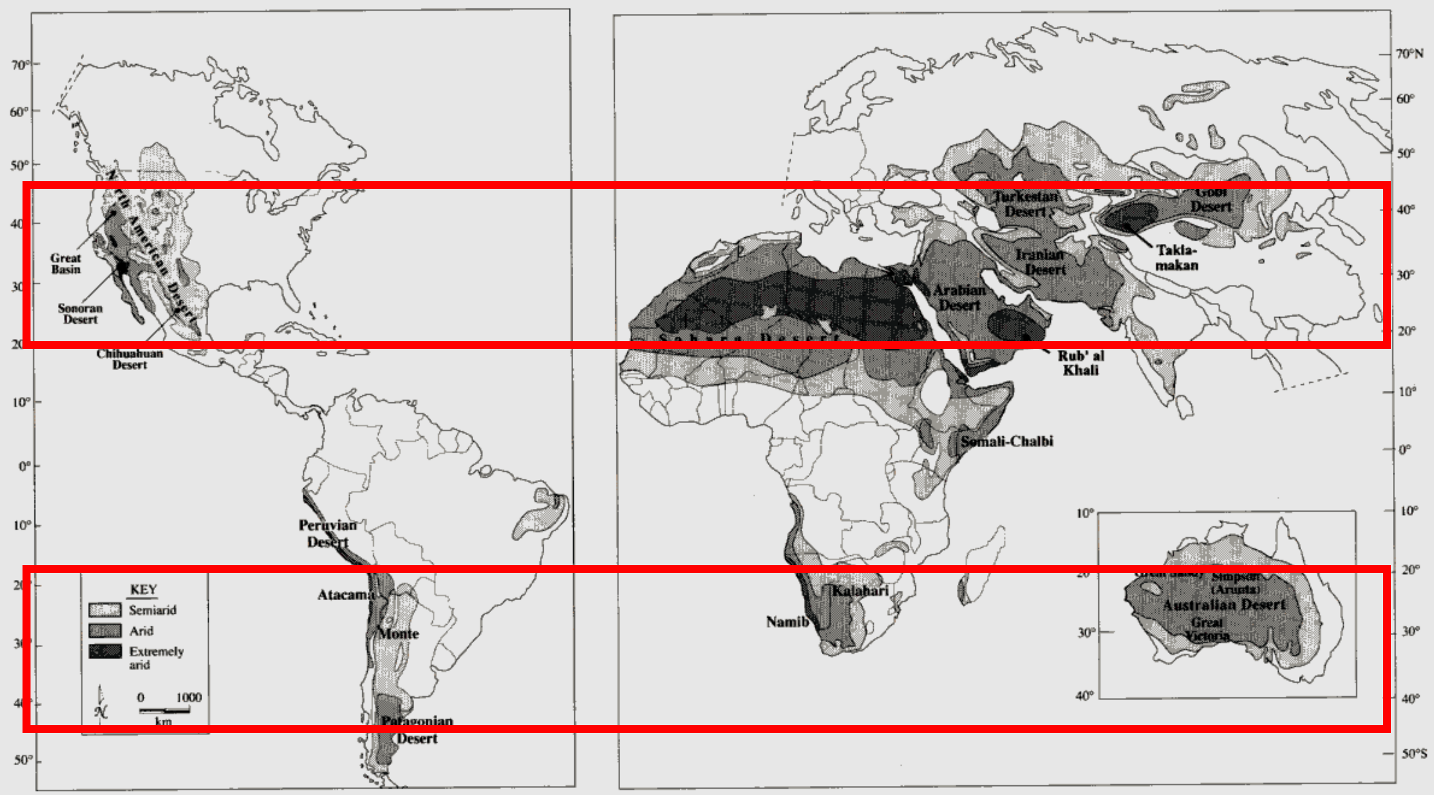
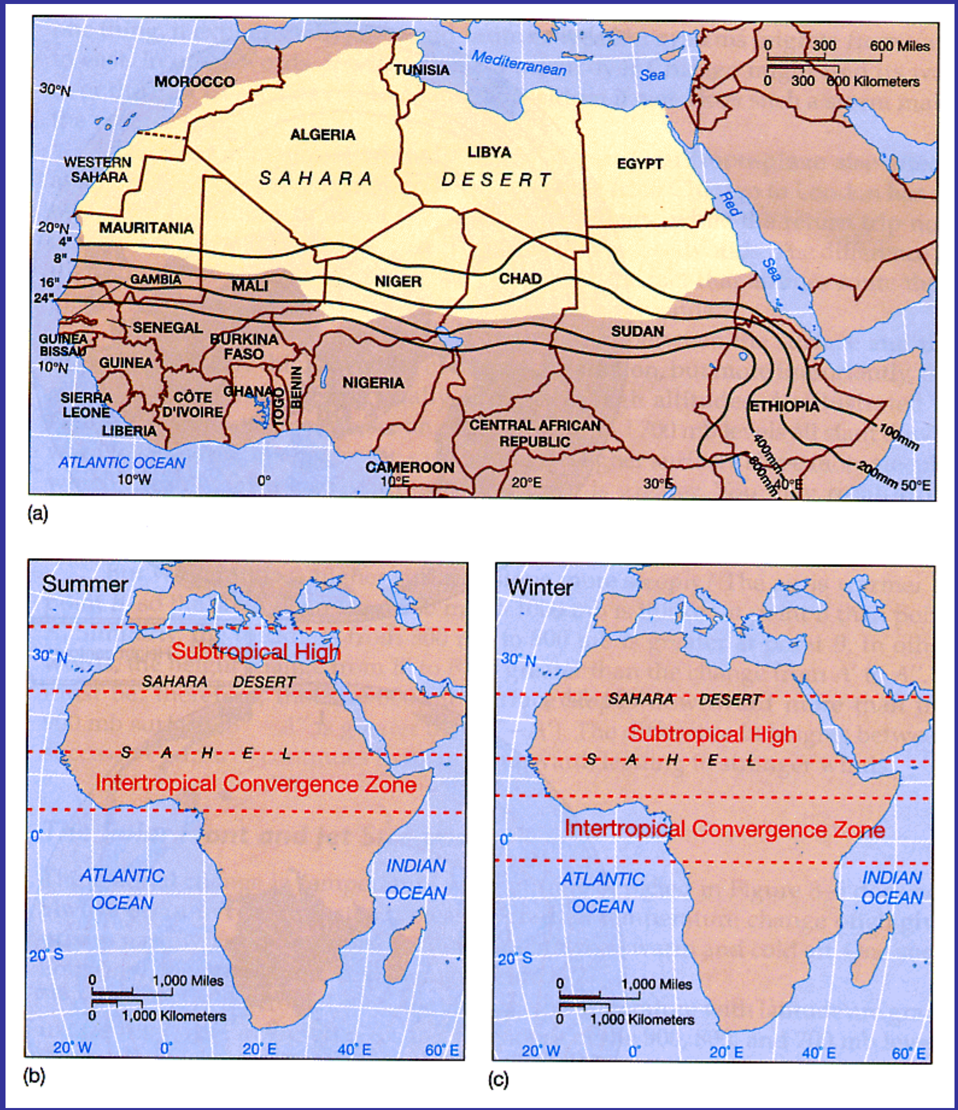


Fig. 6.21 Map showing arid lands around the world. Meigs classification taken from *Mosaic* magazine (Vol. 8, Jan/Feb 1977). [See McGinnies *et al.*, eds., (1968). Permission granted by the Office of Arid Lands Studies.]

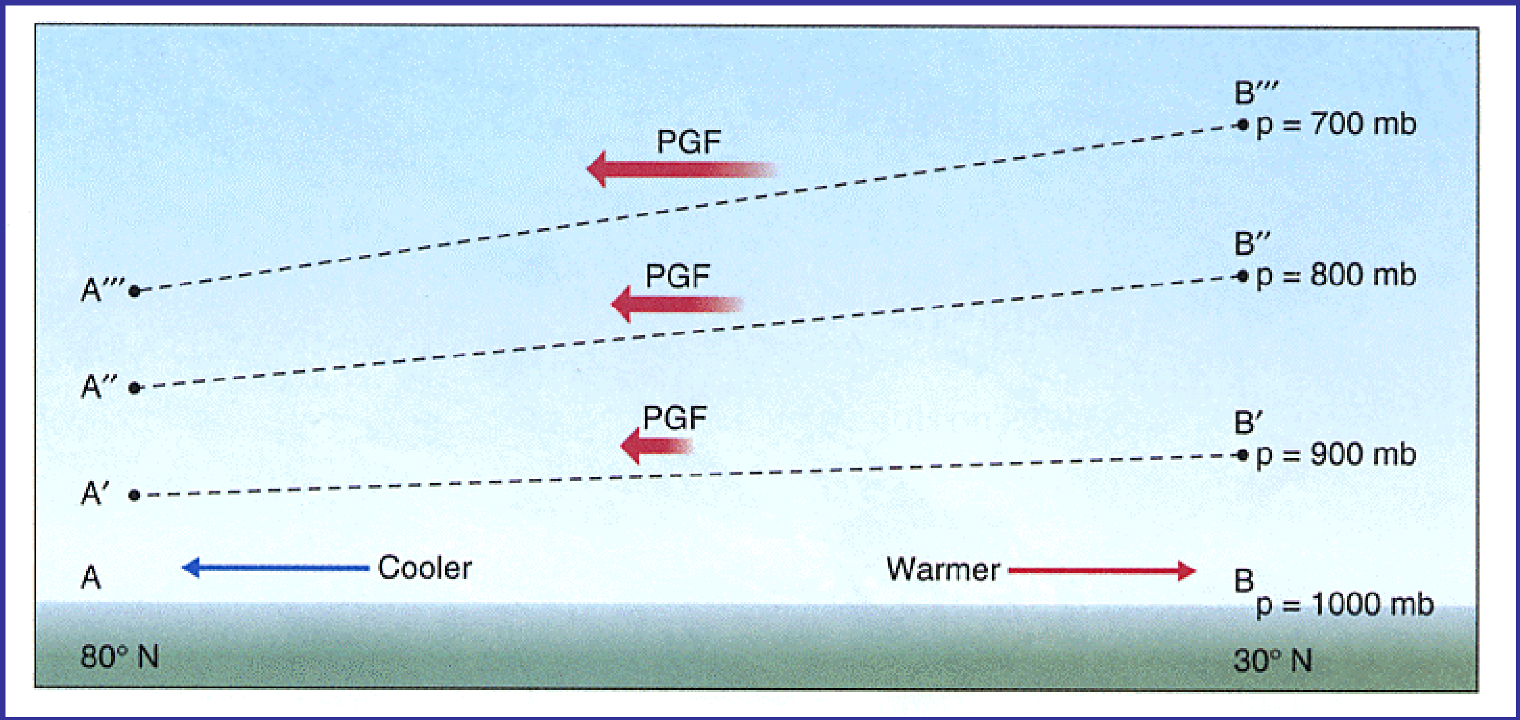
(from *Global Physical Climatology*)

Sinking Branches and Deserts



(from *Weather & Climate*)

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).

Subtropical and Polar Jet Streams

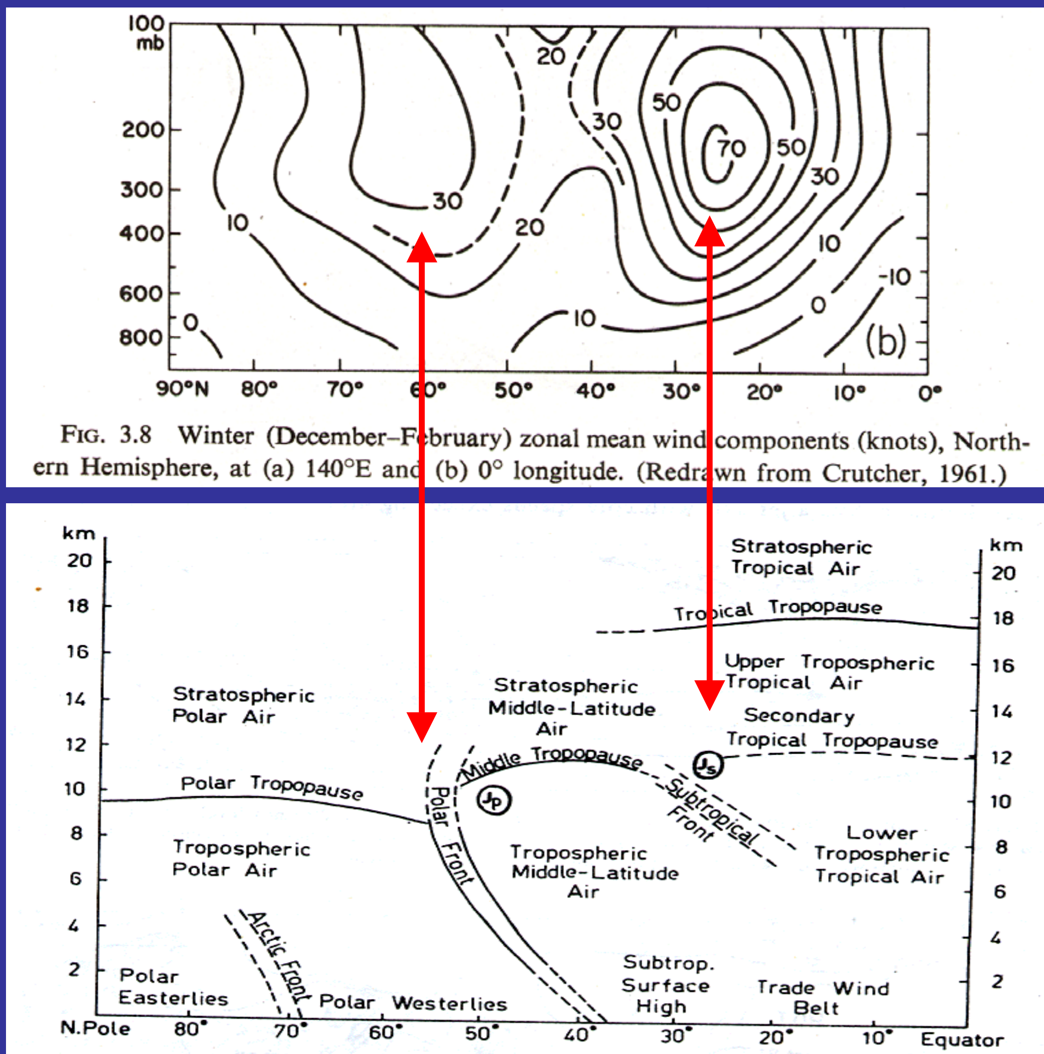


FIG. 3.8 Winter (December–February) zonal mean wind components (knots), Northern Hemisphere, at (a) 140°E and (b) 0° longitude. (Redrawn from Crutcher, 1961.)

(from *Atmospheric Circulation Systems*)

❑ Subtropical Jet

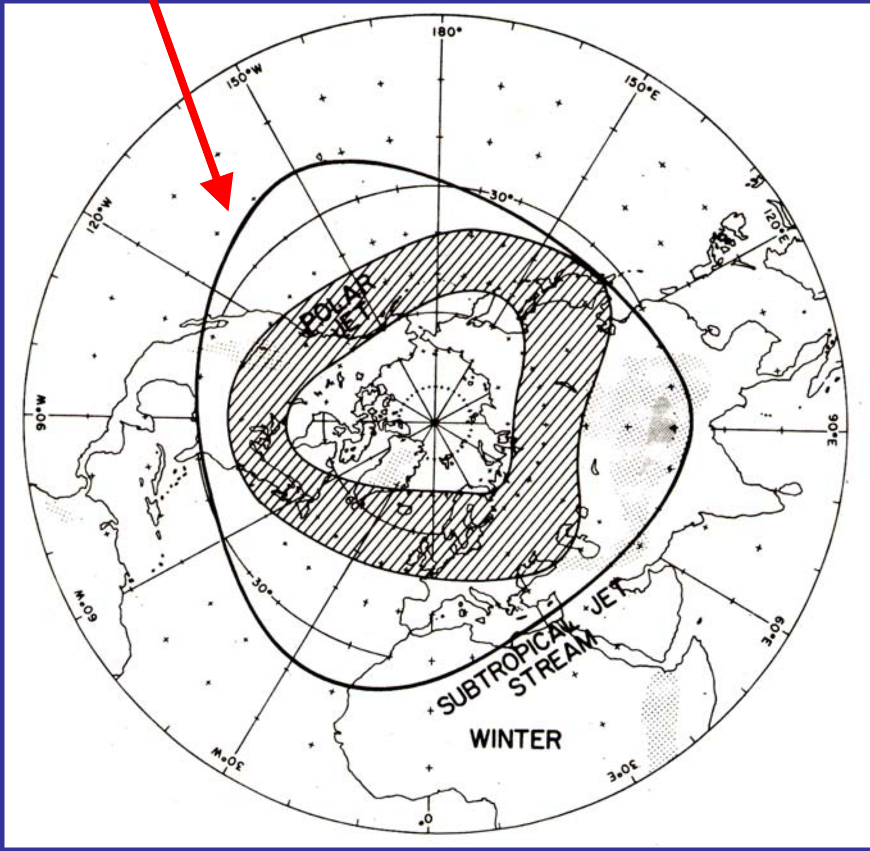
Located at the higher-latitude end of the Hadley Cell. The jet obtain its maximum wind speed (westerly) due the conservation of angular momentum.

❑ Polar Jet

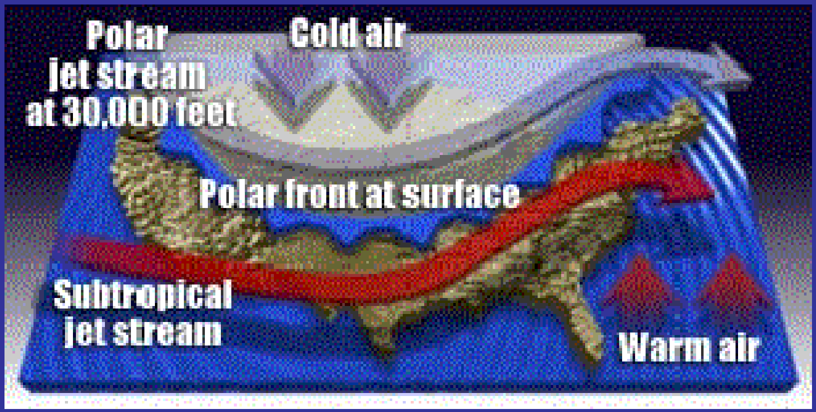
Located at the thermal boundary between the tropical warm air and the polar cold air. The jet obtain its maximum wind speed (westerly) due the latitudinal thermal gradient (thermal wind relation).

Jet Streams Near the Western US

Pineapple Express



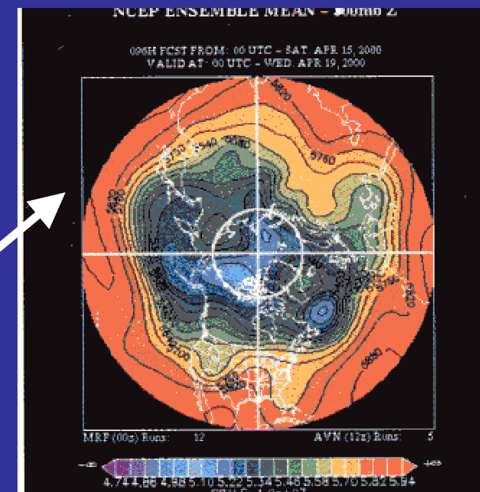
(from *Riehl (1962), Palmen and Newton (1969)*)

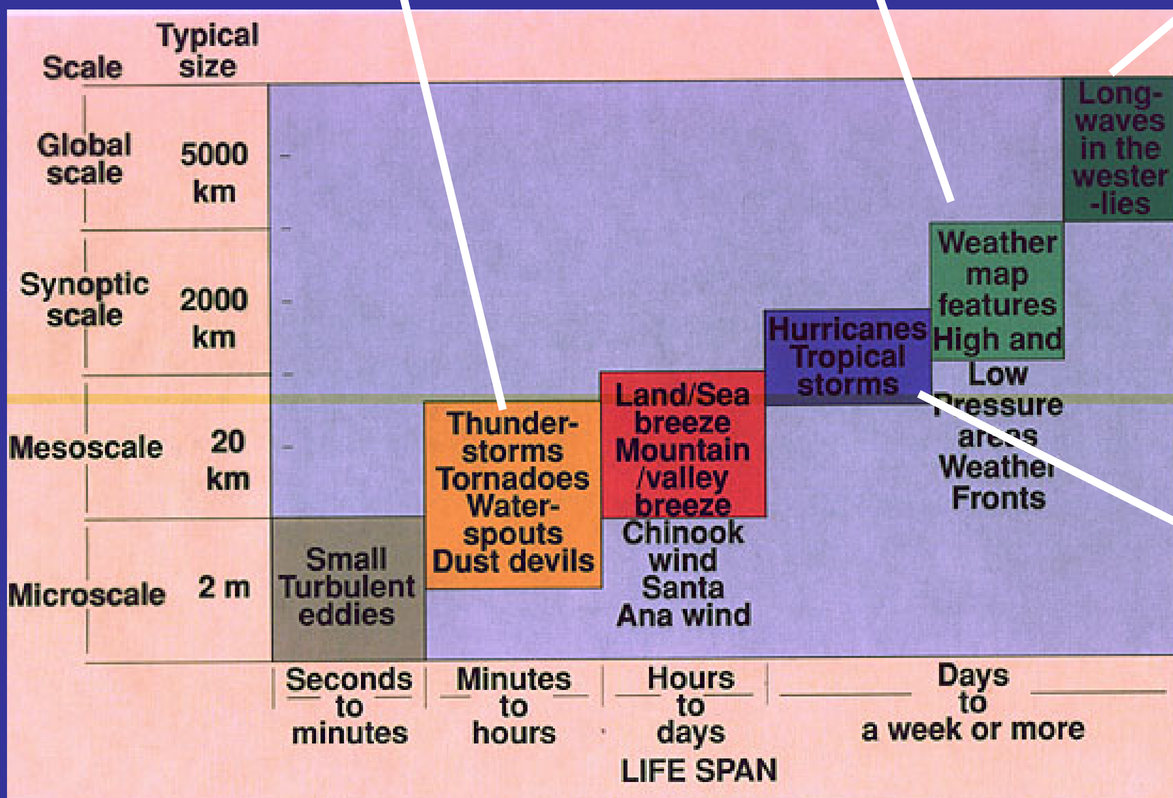


❑ Both the polar and subtropical jet streams can affect weather and climate in the western US (such as California).

❑ El Nino can affect western US climate by changing the locations and strengths of these two jet streams.

Scales of Motions in the Atmosphere





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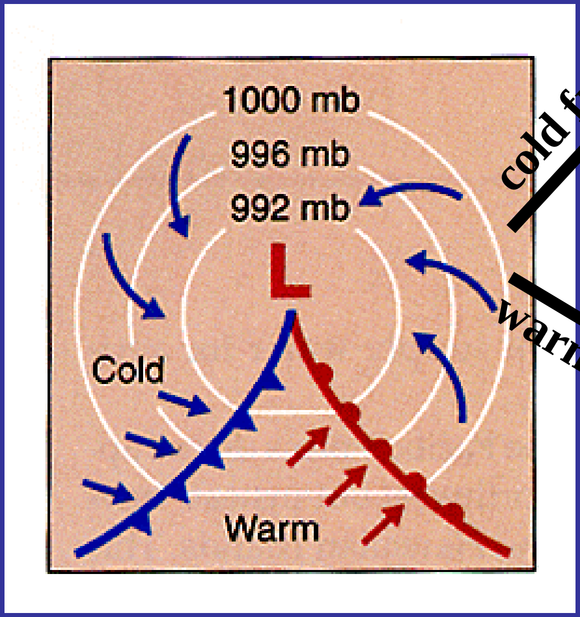
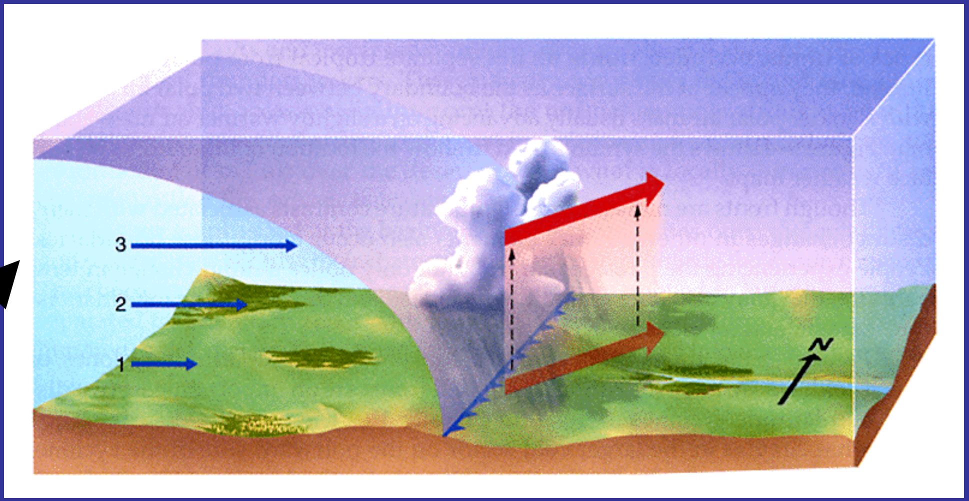
Cold and Warm Fronts

Mid-Latitude Cyclone

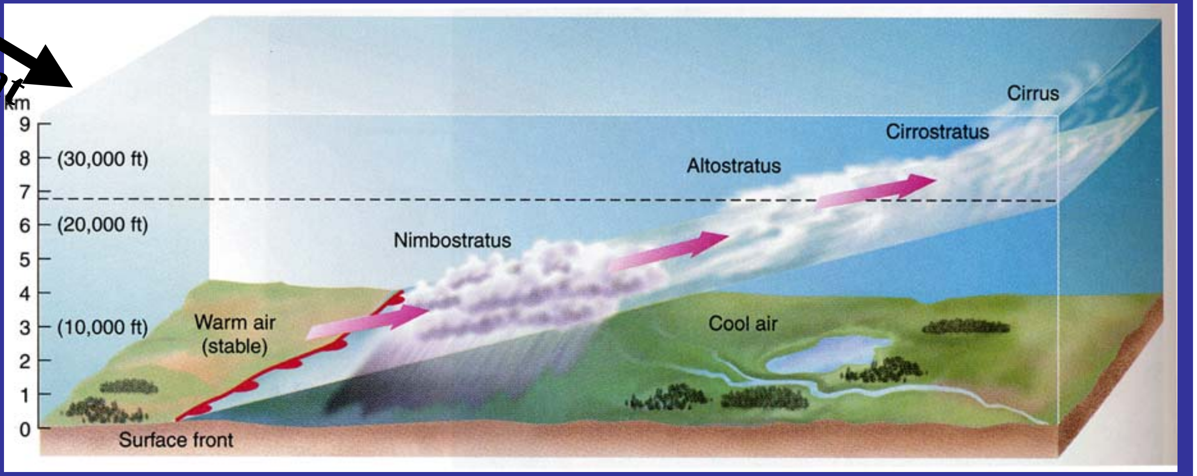


(From *Weather & Climate*)

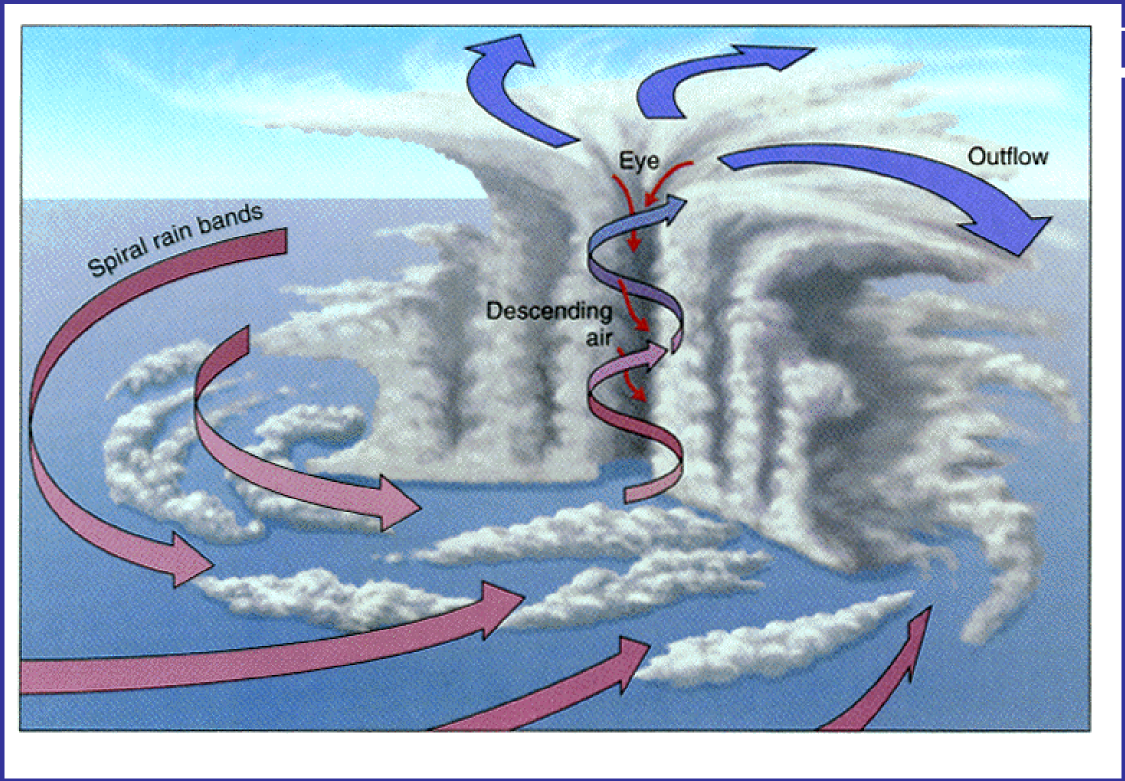
cold front



warm front



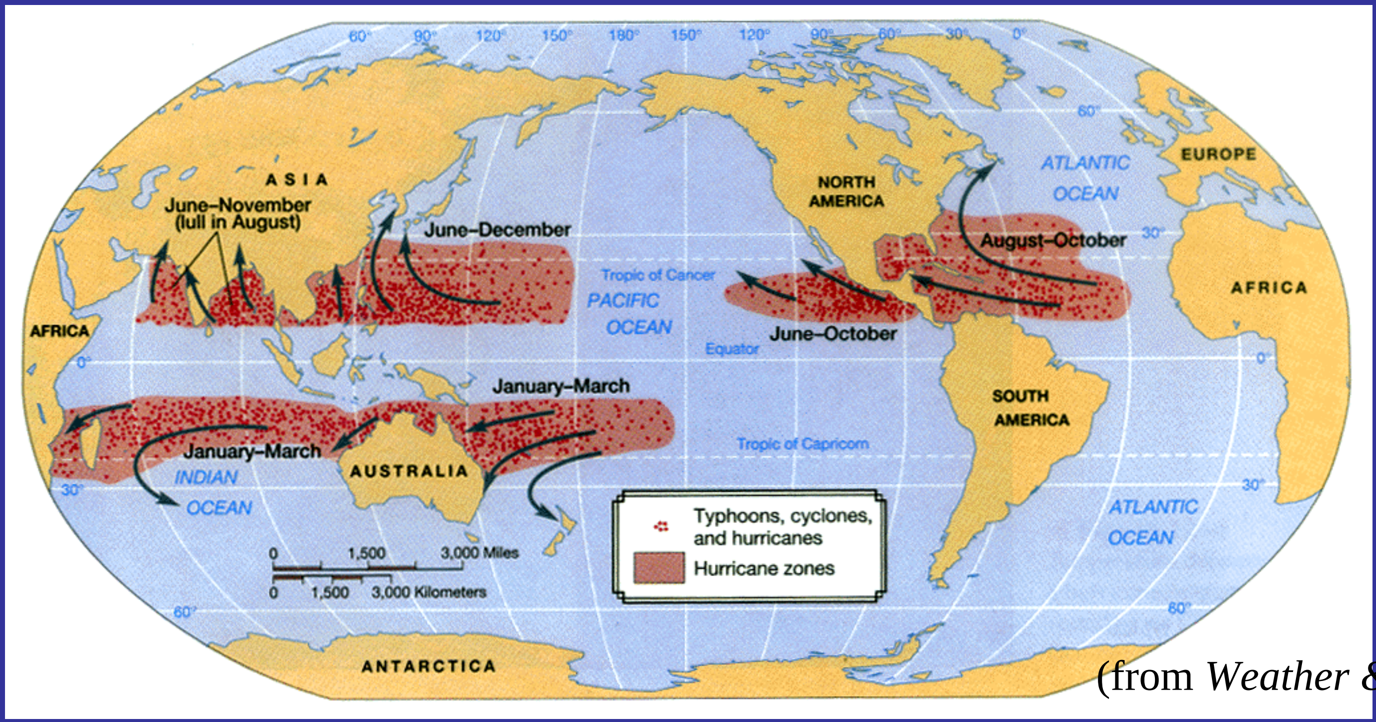
Tropical Hurricane



(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…

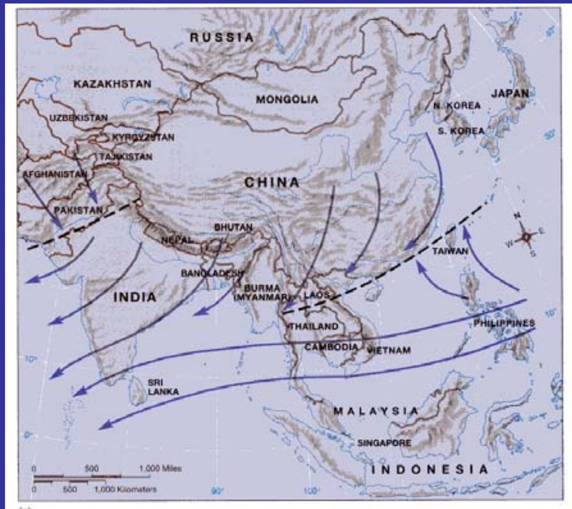


(from *Weather & Climate*)

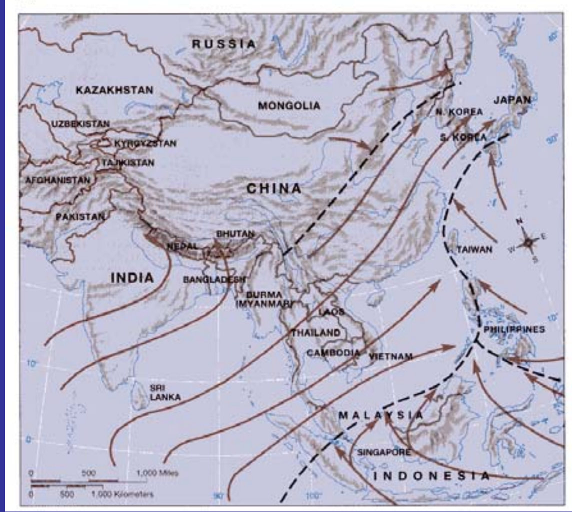
- ***Hurricanes:*** extreme tropical storms over Atlantic and eastern Pacific Oceans.
- ***Typhoons:*** extreme tropical storms over western Pacific Ocean.
- ***Cyclones:*** extreme tropical storms over Indian Ocean and Australia.

Monsoon: Another Sea/Land-Related Circulation of the Atmosphere

Winter



Summer



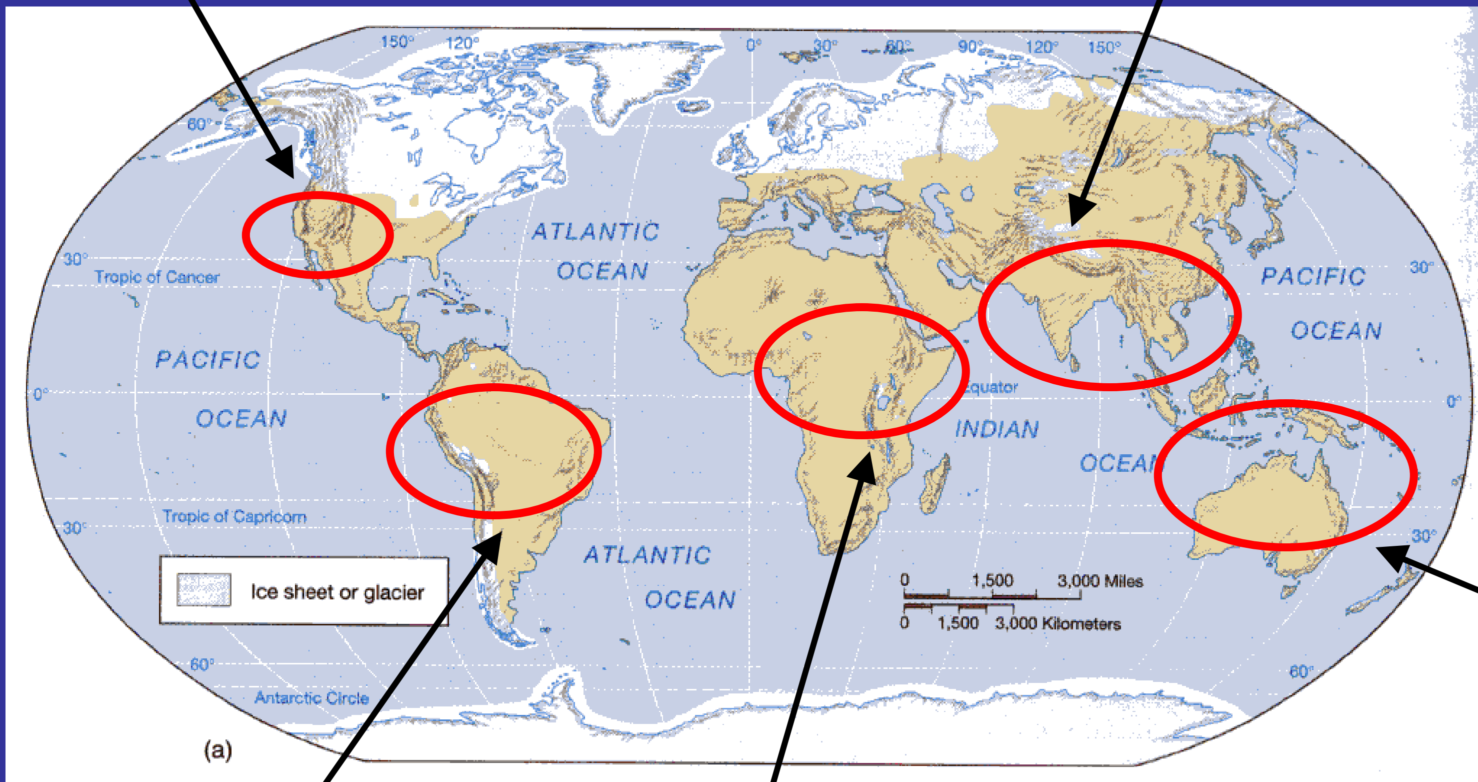
- ❑ Monsoon is a climate feature that is characterized by the ***seasonal reversal in surface winds***.
- ❑ The very different heat capacity of land and ocean surface is the key mechanism that produces monsoons.
- ❑ During summer seasons, land surface heats up faster than the ocean. Low pressure center 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.

(figures from *Weather & Climate*)

How Many Monsoons Worldwide?

North America Monsoon

Asian Monsoon



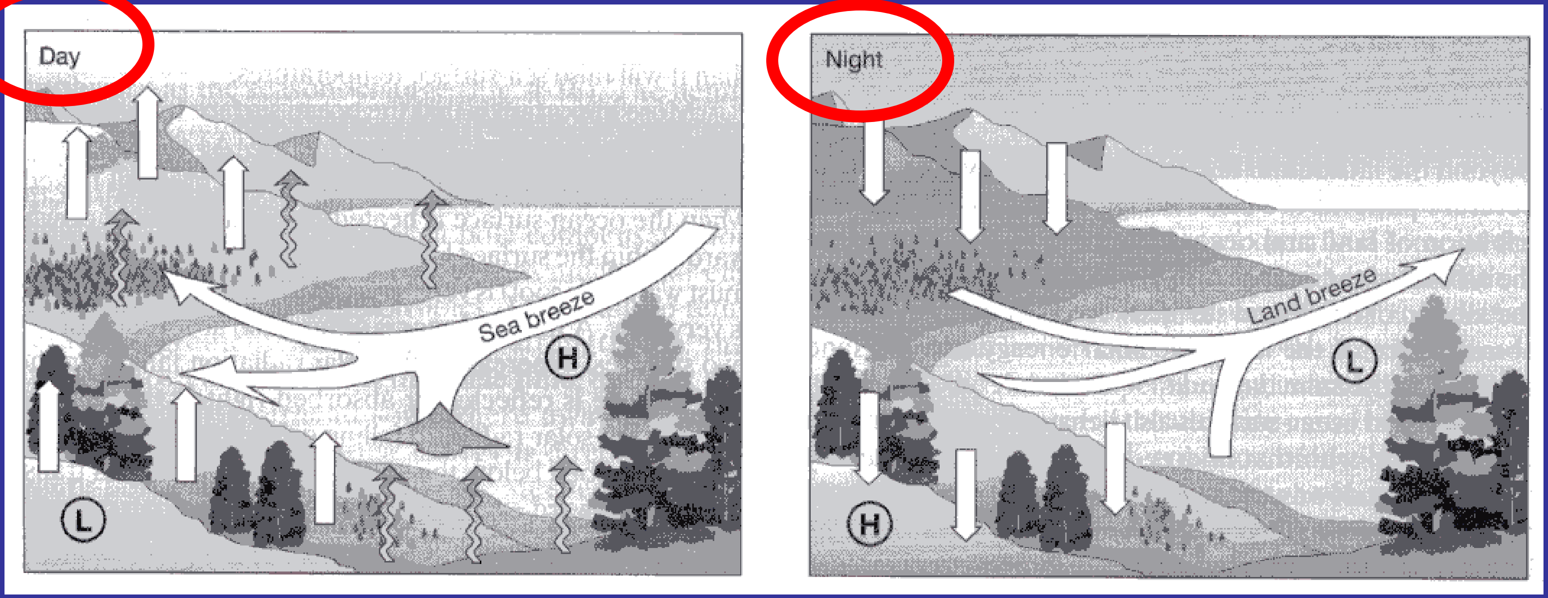
Australian Monsoon

South America Monsoon

East Africa Monsoon

(figure from *Weather & Climate*)

Sea/Land Breeze

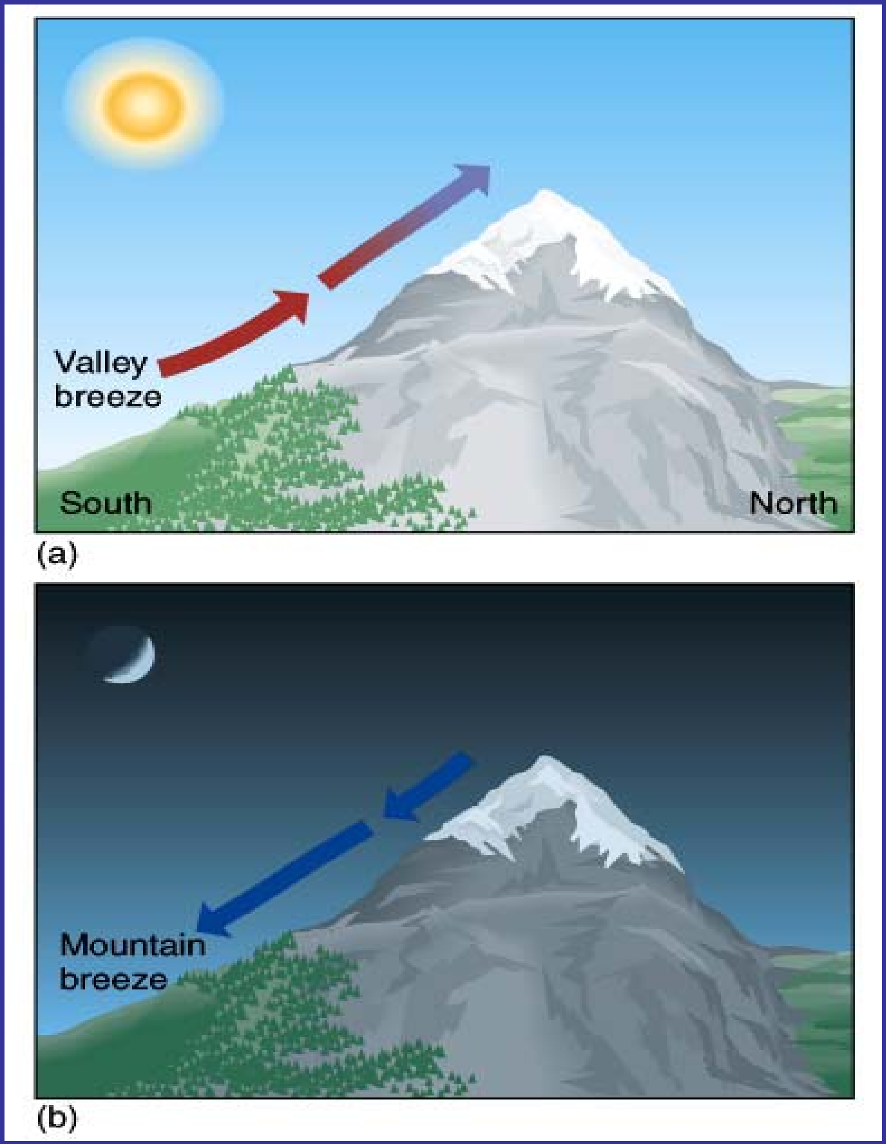


❑ Sea/land breeze is also produced by the different heat capacity of land and ocean surface, similar to the monsoon phenomenon.

❑ 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*)

Valley and Mountain Breeze



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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

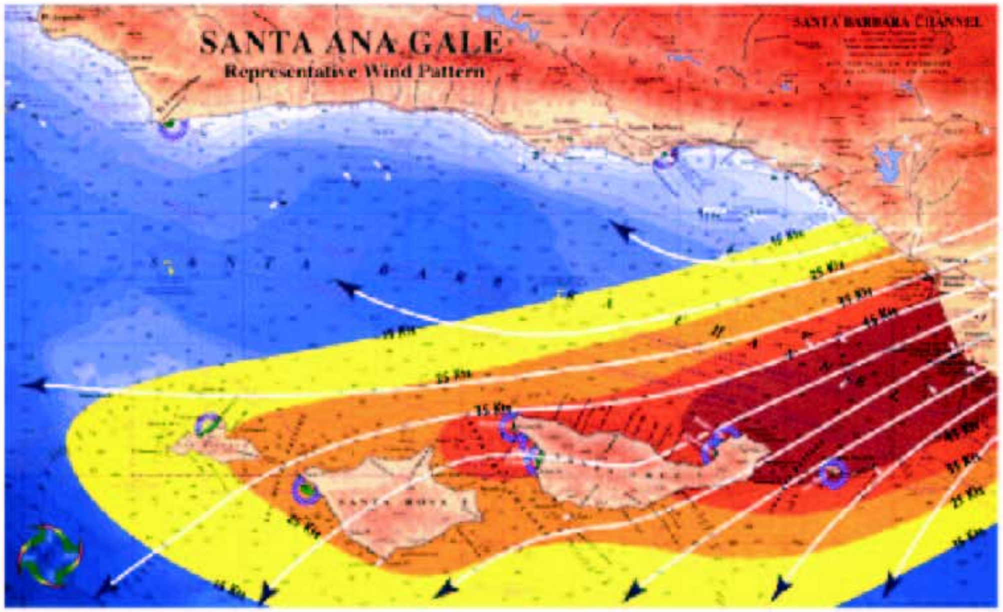
Strong warm and dry winds blow over the southern California from the Great Basin, with speeds exceed 25 knots (46 km/hr).

Generation Mechanism

(from NASA's Observatorium website)

Santa Ana Wind

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).

Basic Ocean Structures

Warm up by sunlight!

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

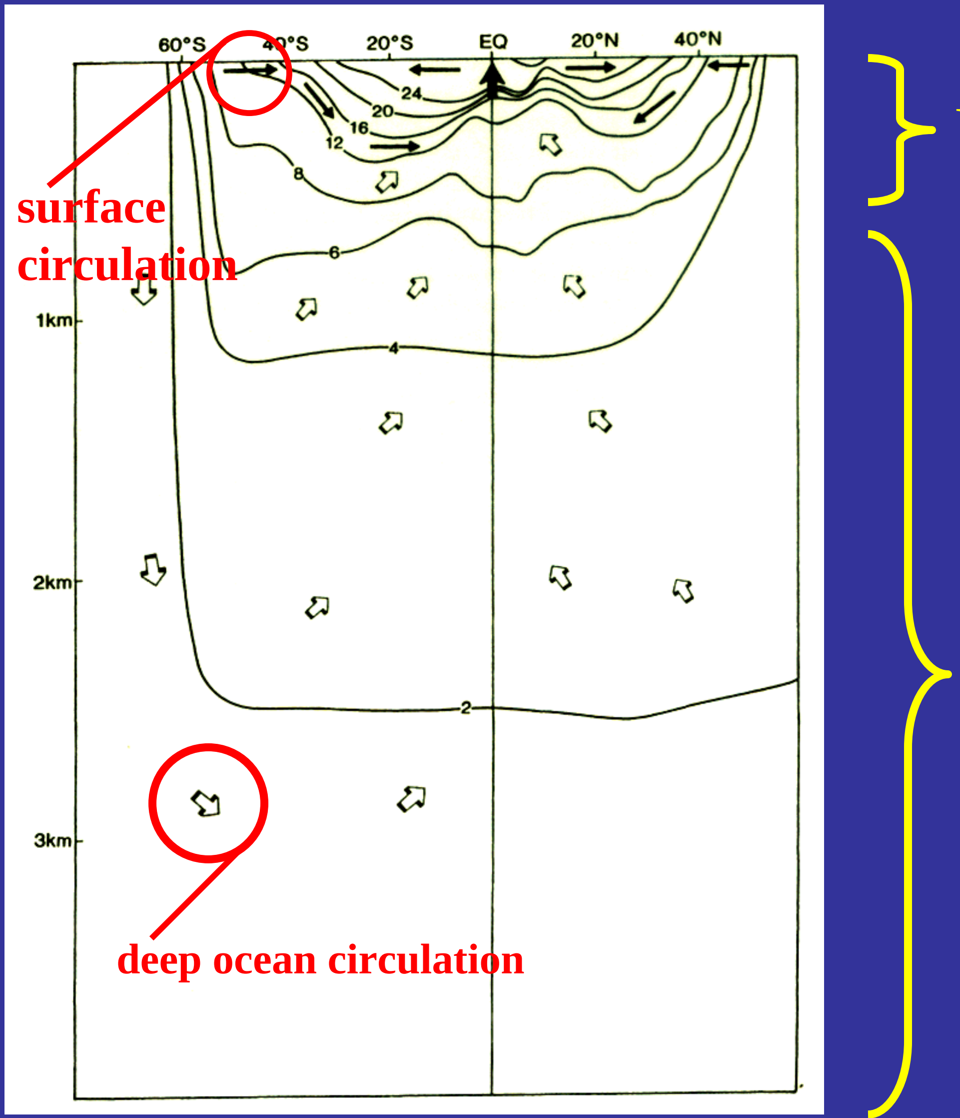
  Shallow, warm upper layer where light is abundant and where most marine life can be found.

- **Deep Ocean**

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

No sunlight!

Basic Ocean Current Systems



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

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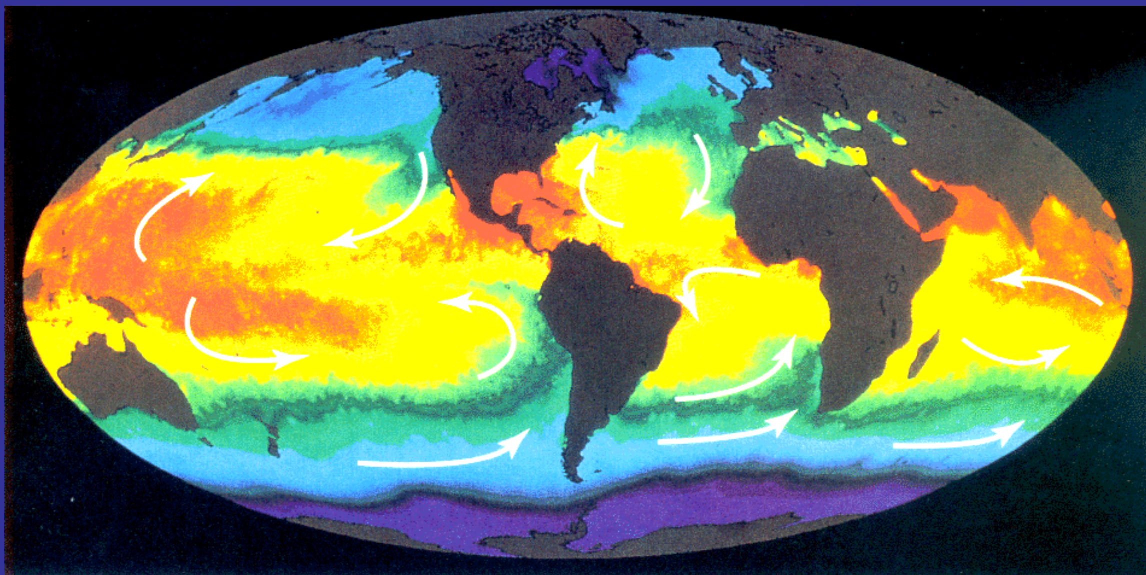
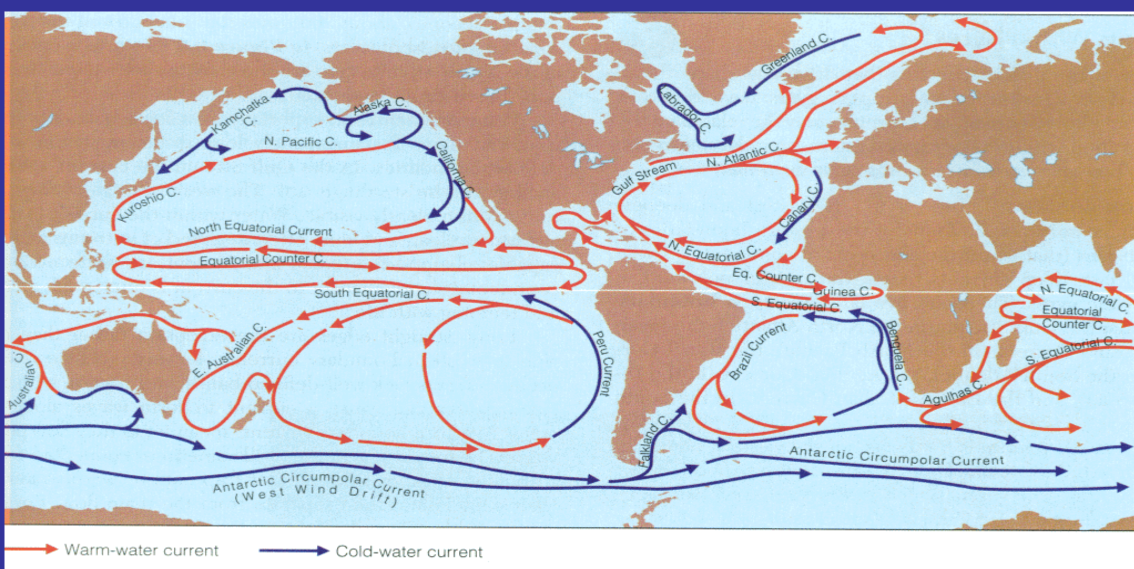
Six Great Current Circuits in the World Ocean





- ❑ **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)

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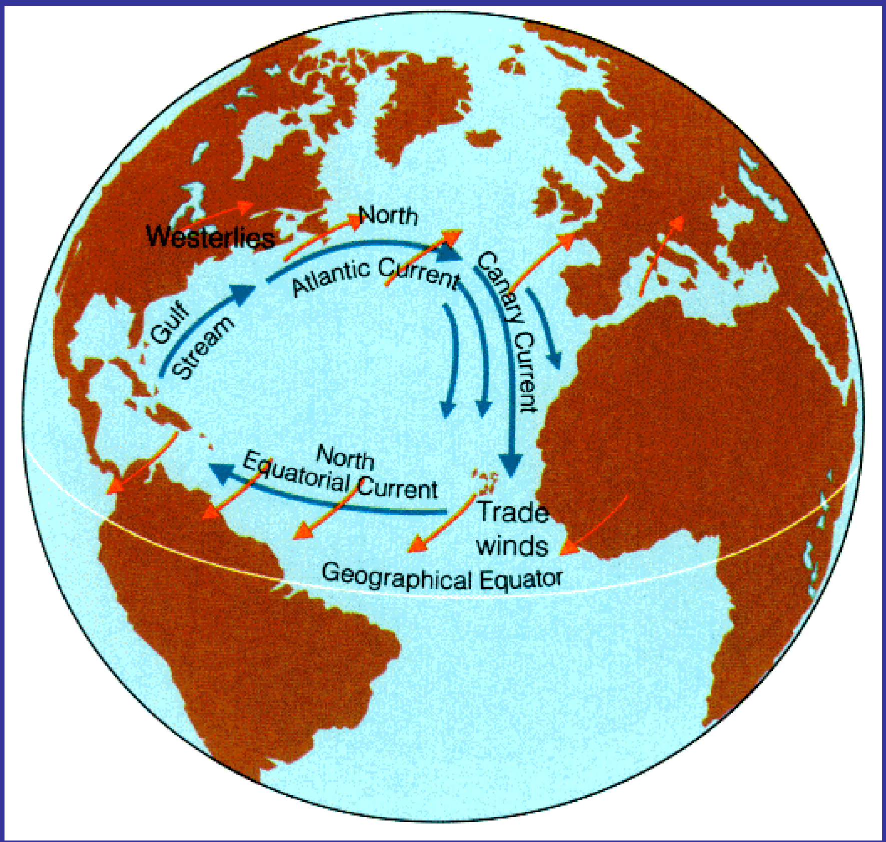
Characteristics of the Gyres

(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)

- **Trade Wind-Driven Current**

  North Equatorial Current
  South Equatorial Current

- **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)

- **Westerly-Driven Current**

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

Step 1: Surface Winds

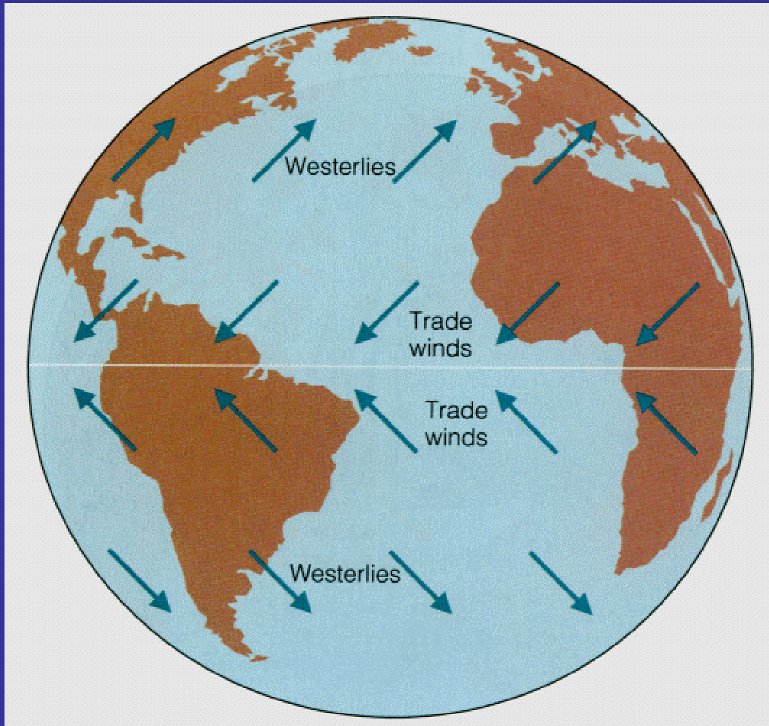


Figure 9.1 Winds, driven by uneven solar heating and Earth's spin, drive the movement of the ocean's surface currents. The prime movers are the powerful westerlies and the persistent trade winds (easterlies).

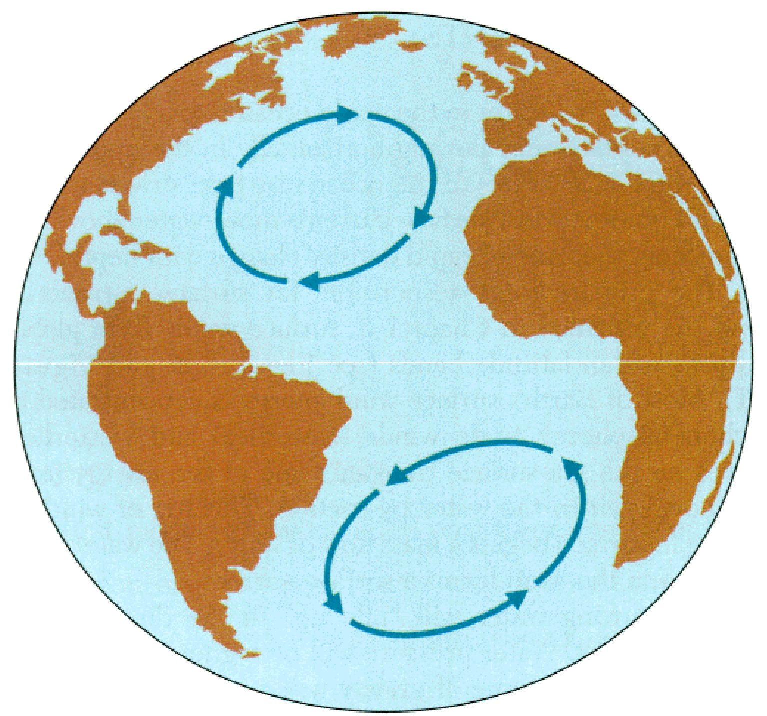
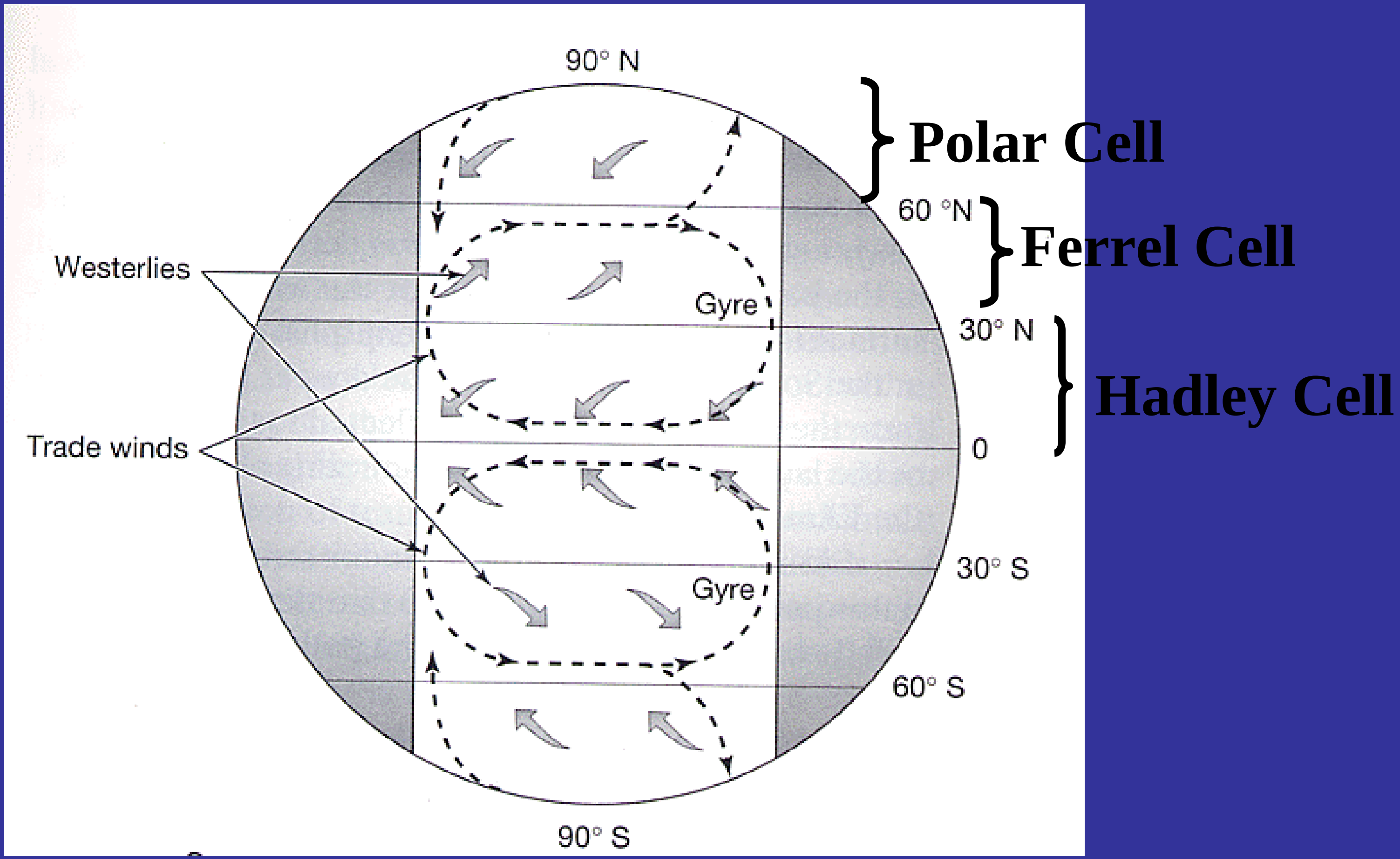


Figure 9.2 A combination of four forces—surface winds, the sun's heat, the Coriolis effect, and gravity—circulates the ocean surface clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, forming gyres.

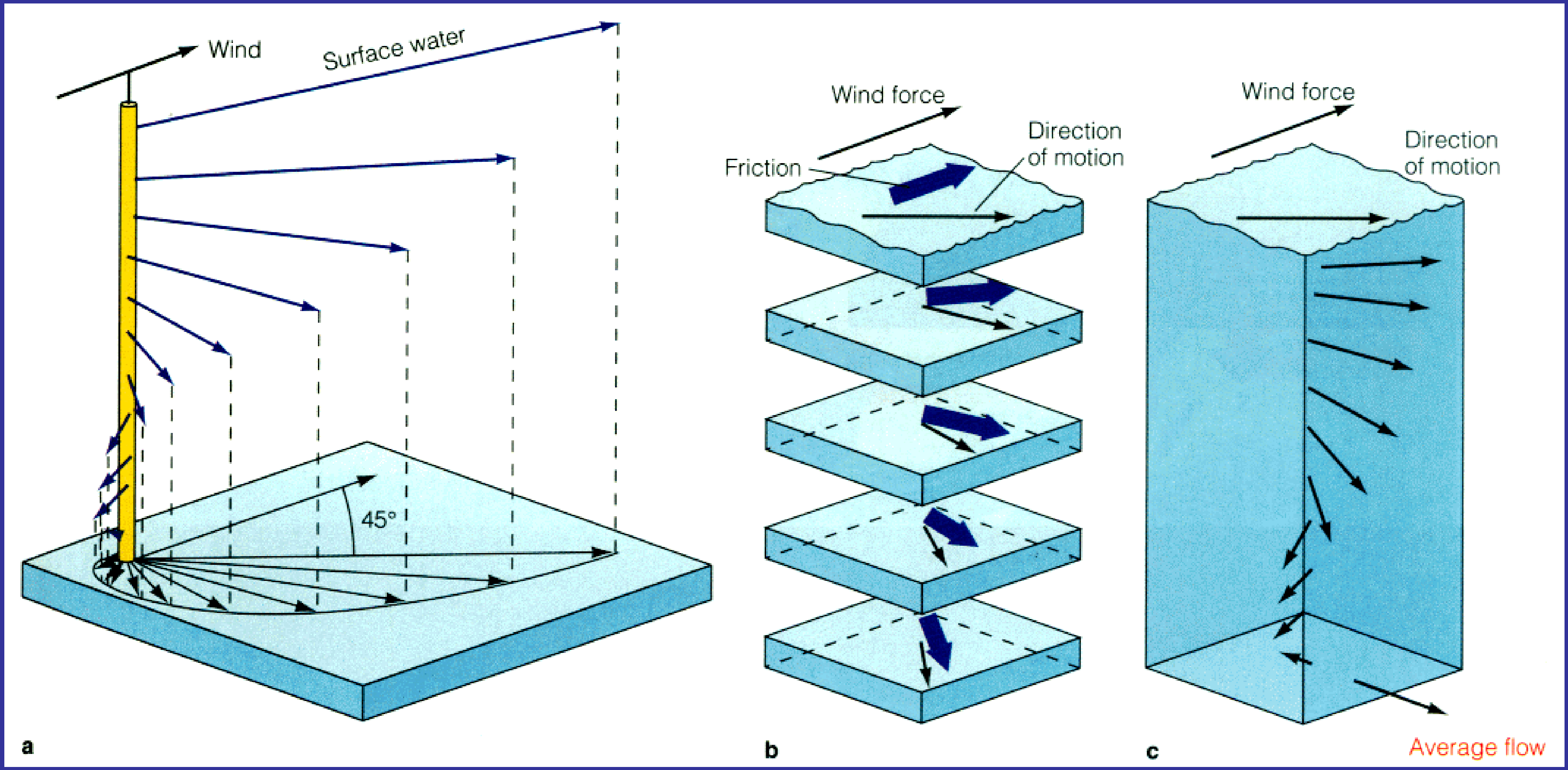
(Figure from *Oceanography* by Tom Garrison)

Winds and Surface Currents



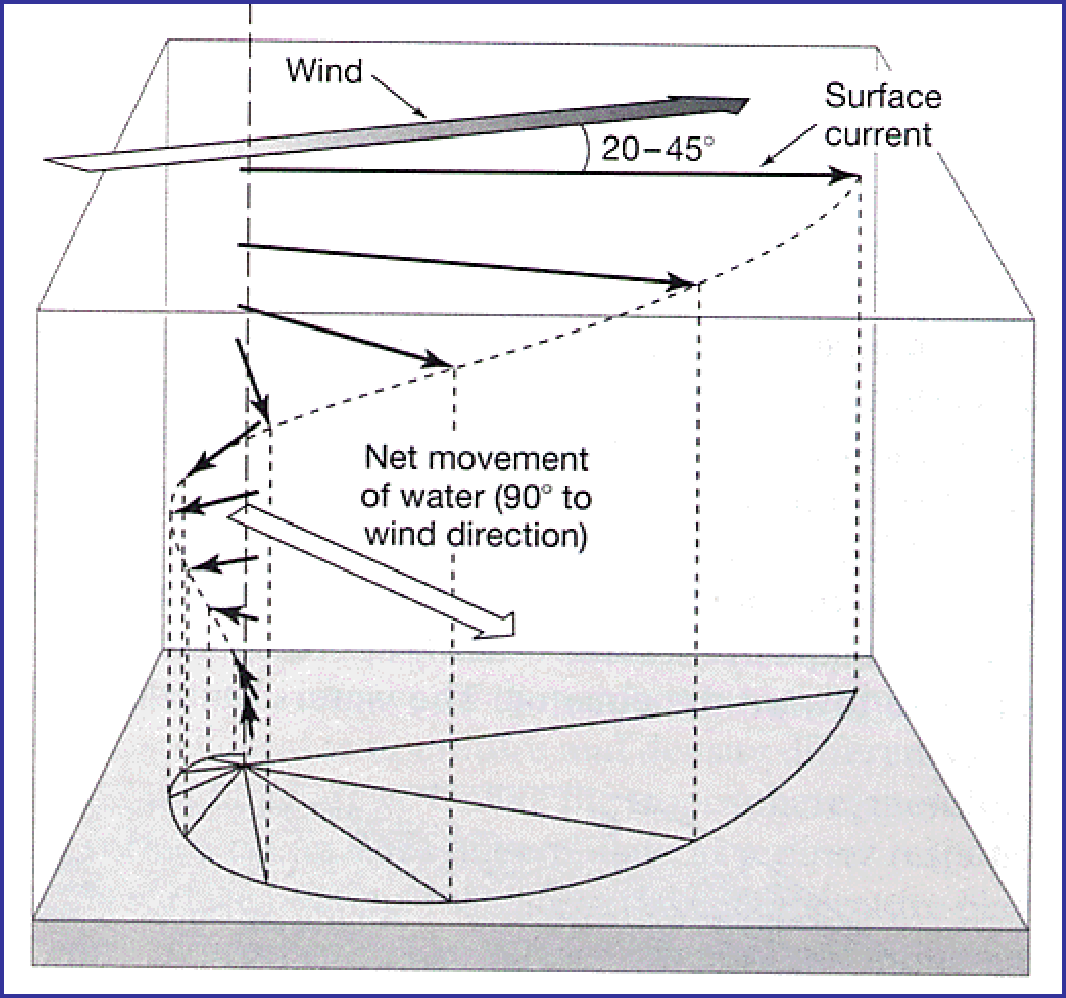
(Figure from *The Earth System*)

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



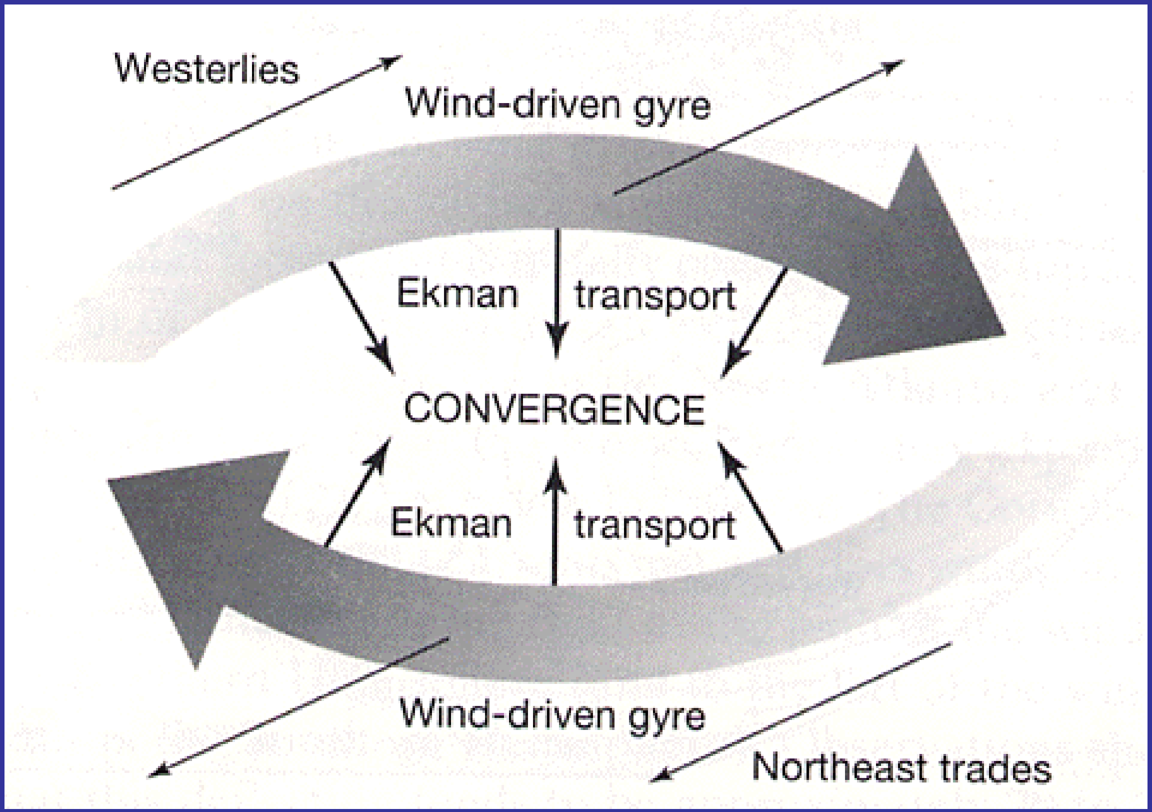
(Figure from *Oceanography* by Tom Garrison)

Ekman Spiral – A Result of Coriolis Force



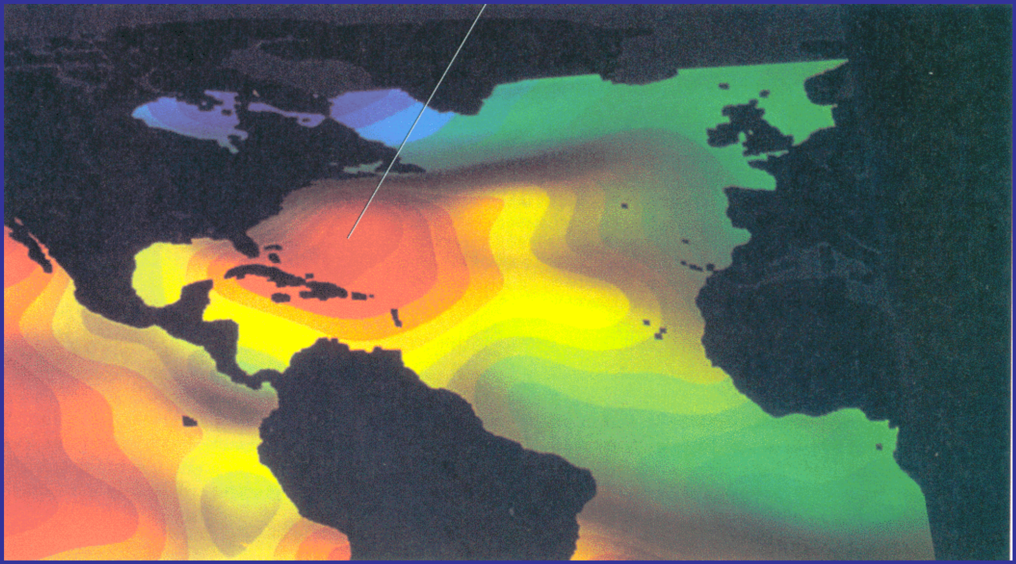
(Figure from *The Earth System*)

Ekman Transport

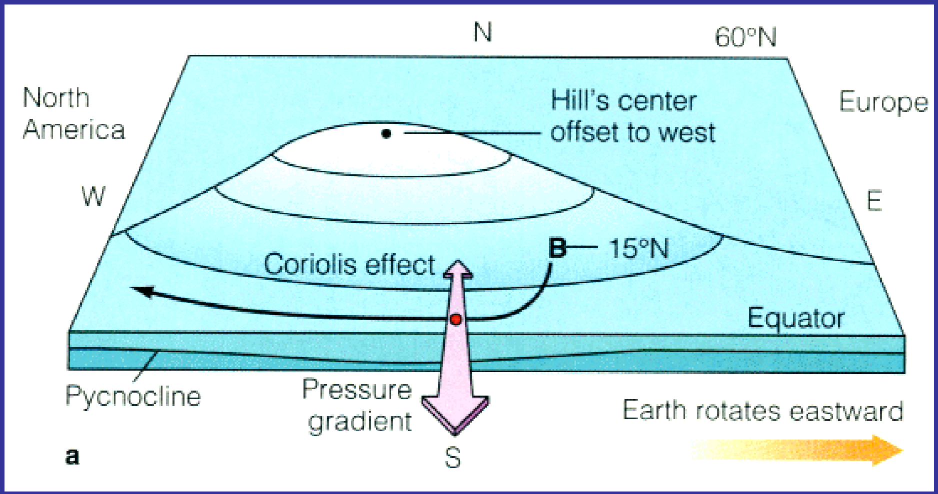


(Figure from *The Earth System*)

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



NASA-TOPEX Observations of Sea-Level Hight



(from *Oceanography* by Tom Garrison)

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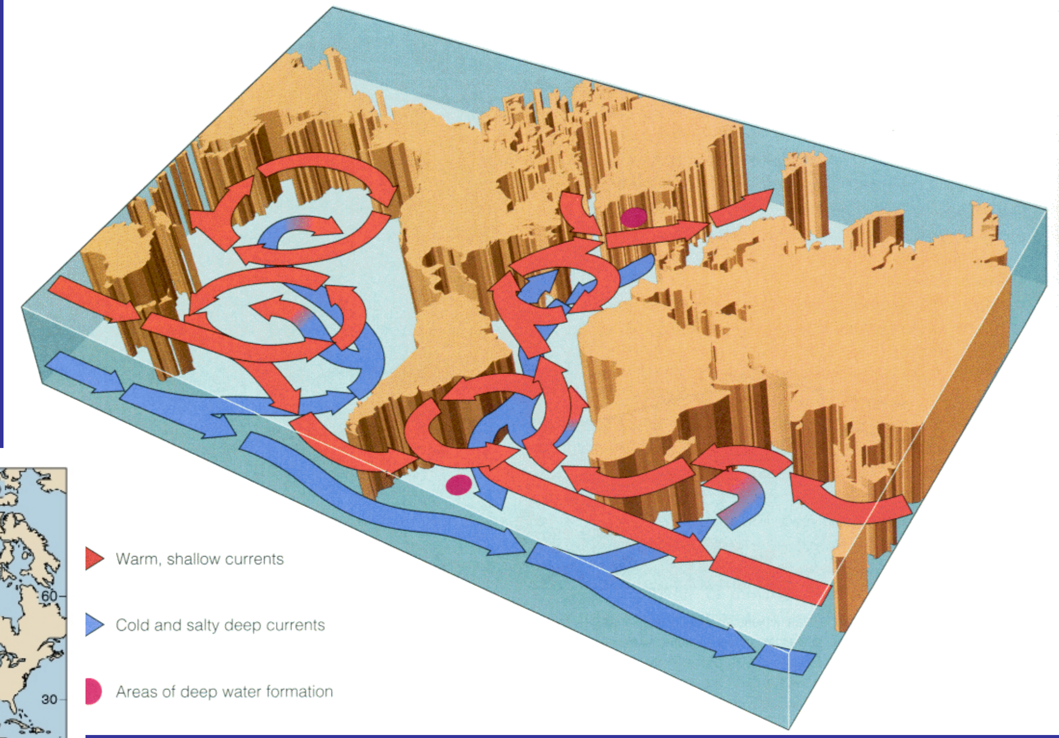
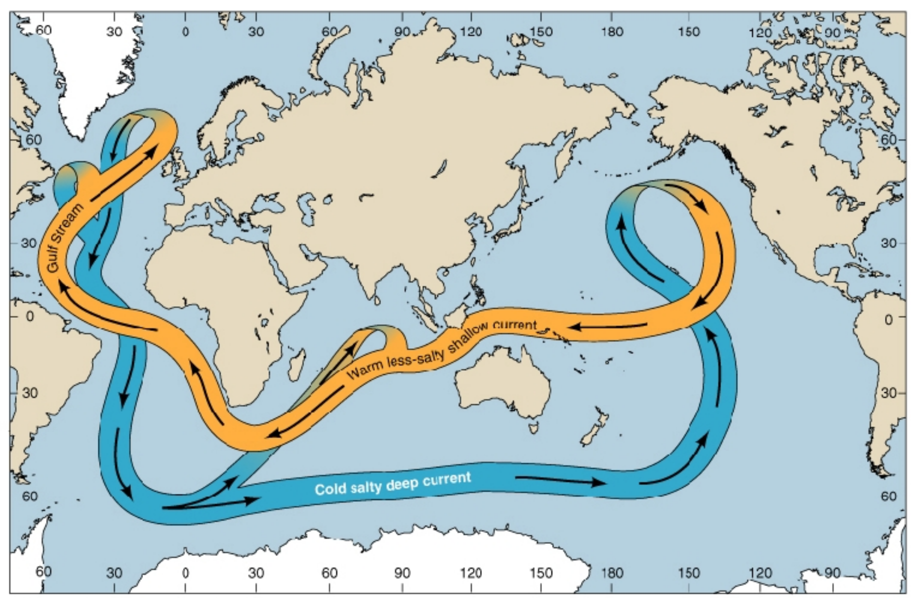
Thermohaline Conveyor Belt

❑ 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)

Thermohaline Circulation

- Thermo → temperature
- Haline → salinity

Density-Driven Circulation

Cold and salty waters go down

Warm and fresh waters go up

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.

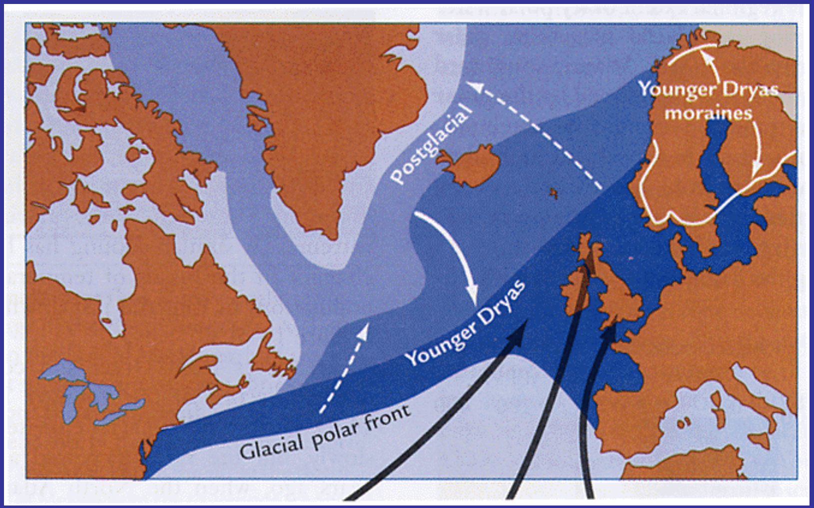
- ***If the warming is fast***

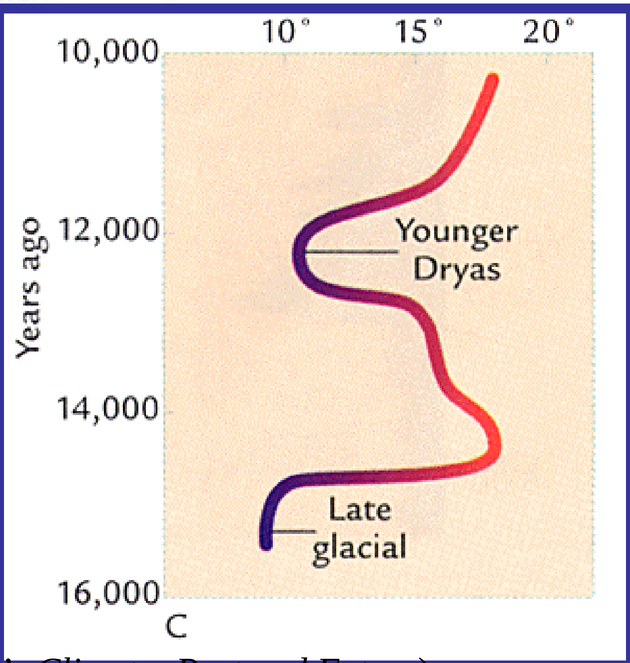
  Surface ocean becomes so warm (low water density)

→ No more thermohalione circulation

→ The rate of global warming in the atmosphere will increase.

Mid-Deglacial Cooling: The Younger Dryas

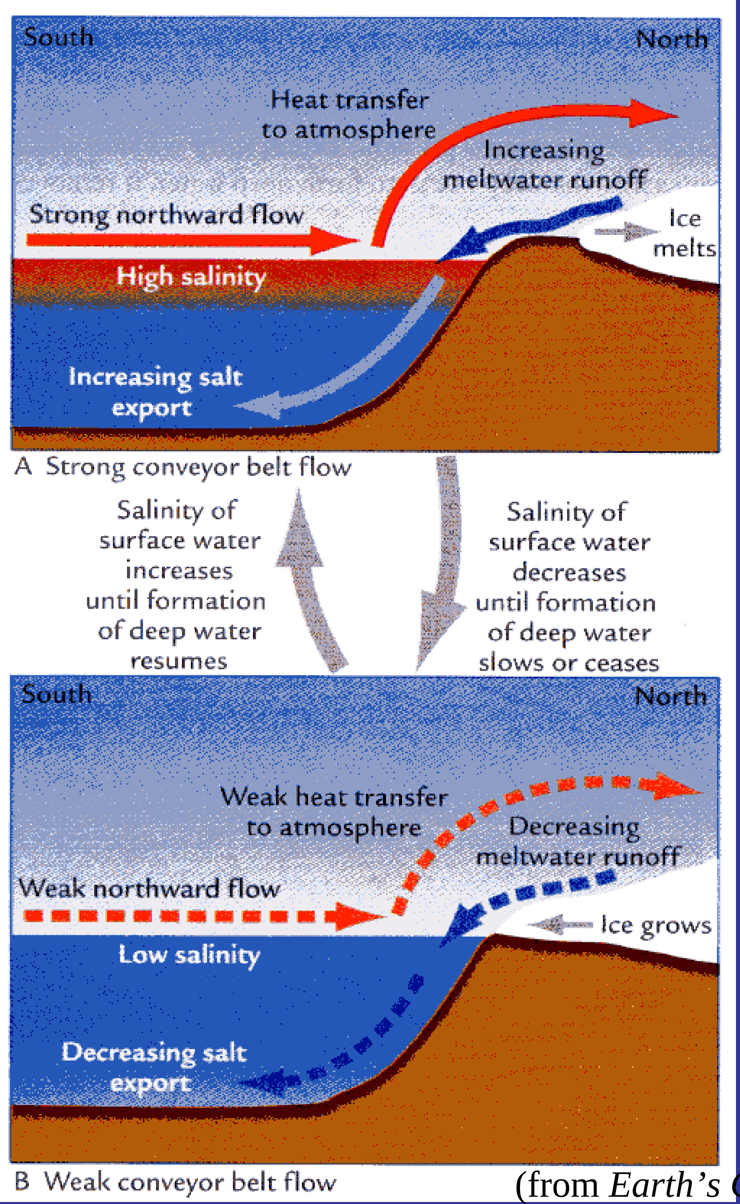




(from *Earth's Climate: Past and Future*)

- The mid-deglacial pause in ice melting was accompanied by a brief climate osscilation in records near the subpolar North Atlantic Ocean.
- Temperature in this region has warmed part of the way toward interglacial levels, but this reversal brought back almost full glacial cold.
- Because an Arctic plant called "Dryas" arrived during this episode, this mid-deglacial cooling is called "the Younger Dryas" event.

Interactions Within Climate System

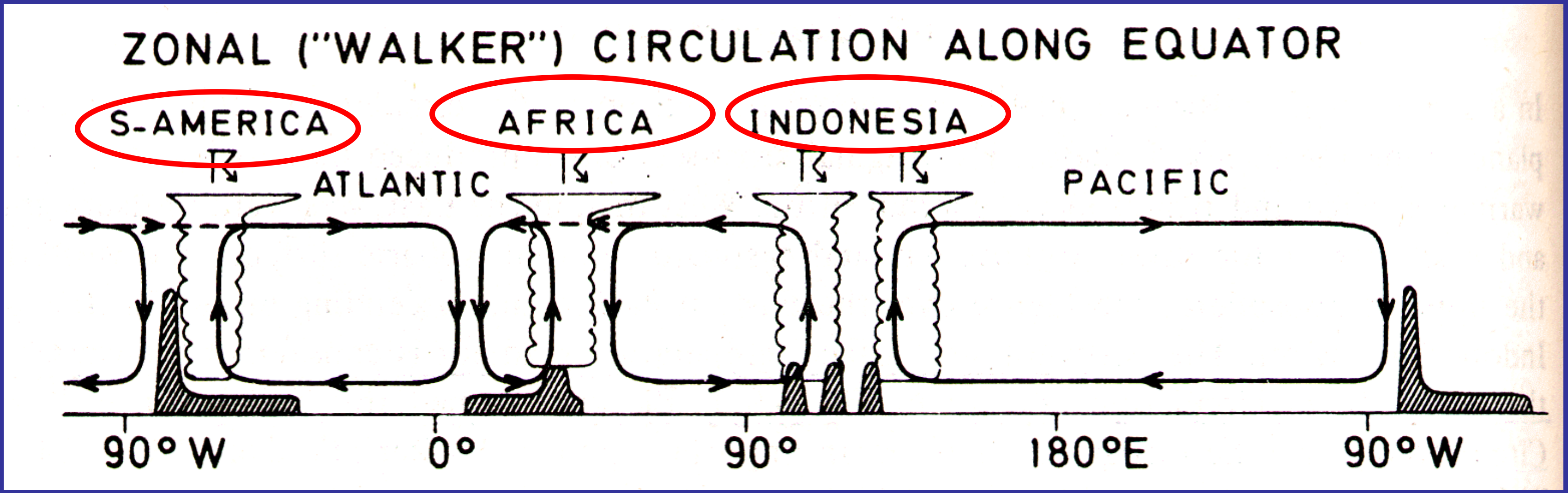


(from *Earth's Climate: Past and Future*)

- This hypothesis argues that millennial oscillations were produced by the internal interactions among various components of the climate system.
- One most likely internal interaction is the one associated with the deep-water formation in the North Atlantic.
- Millennial oscillations can be produced from changes in northward flow of warm, salty surface water along the conveyor belt.
- Stronger conveyor flow releases heat that melts ice and lowers the salinity of the North Atlantic, eventually slowing or stopping the formation of deep water.
- Weaker flow then causes salinity to rise, completing the cycle.

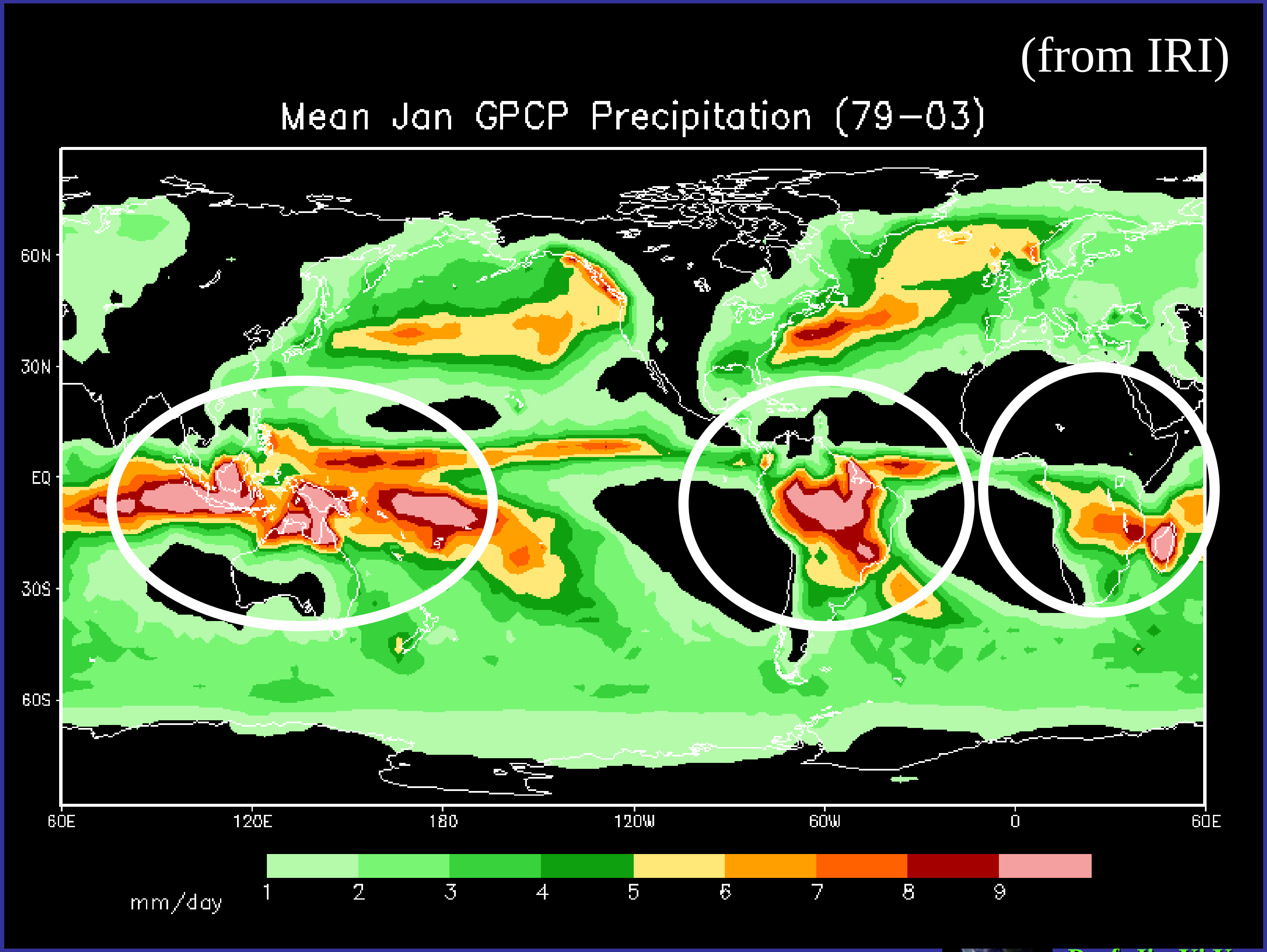
East-West Circulation

(from *Flohn (1971)*)



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

Precipitation Climatology



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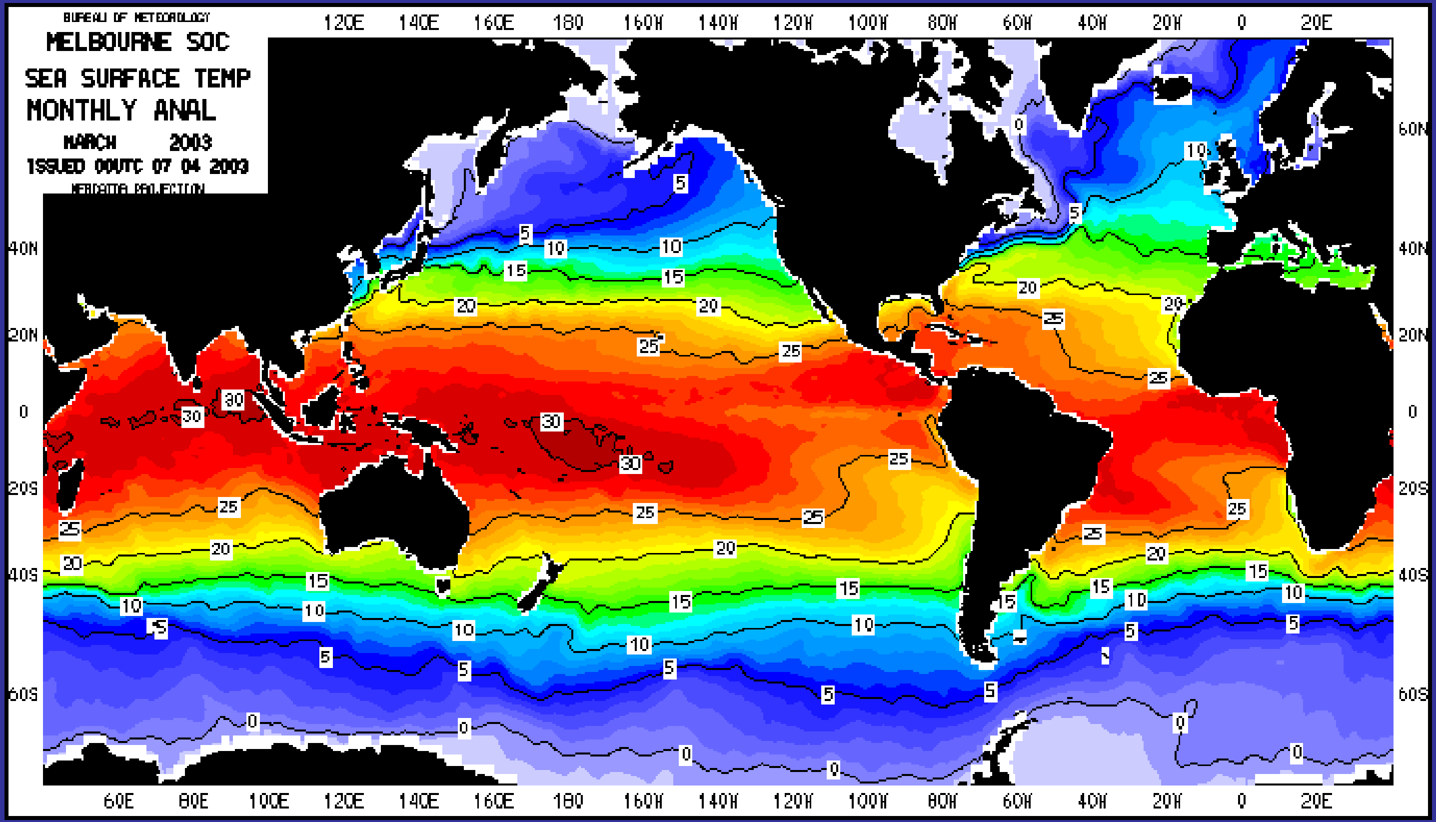
Walker Circulation and Ocean Temperature



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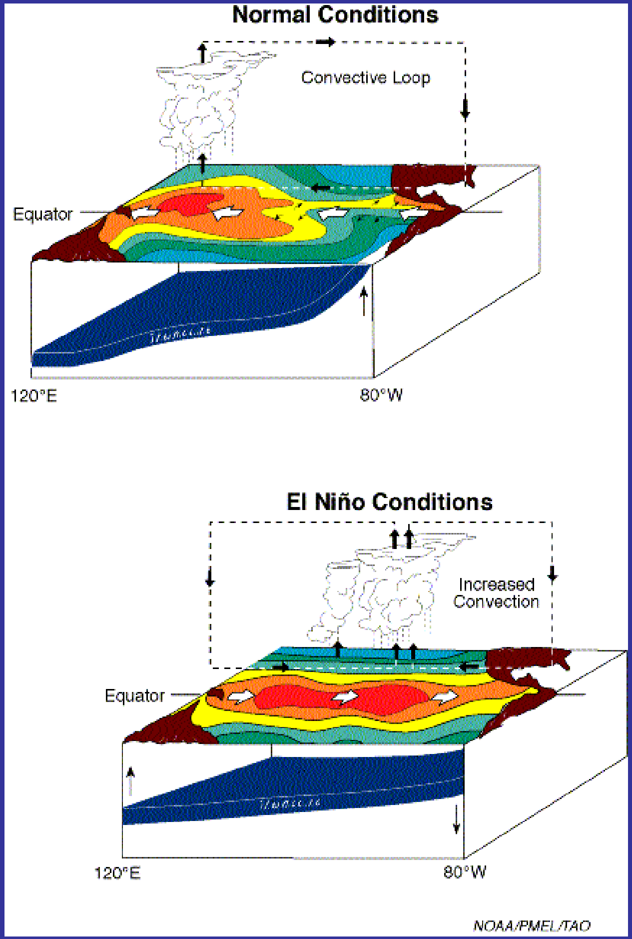
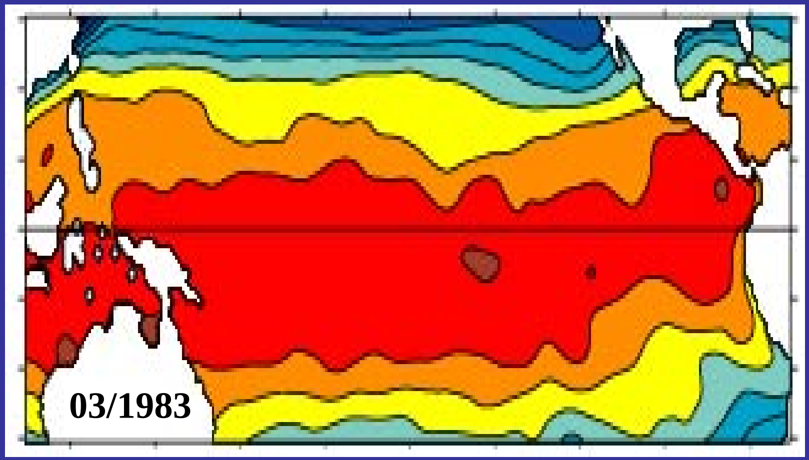
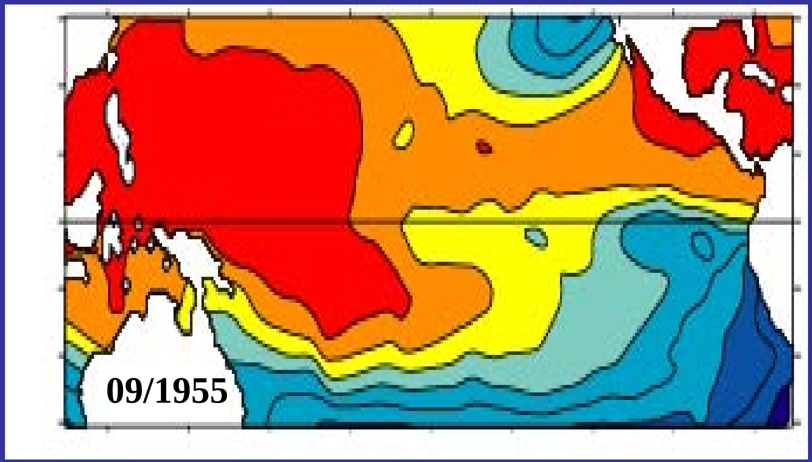
Walker Circulation and Ocean



El Nino

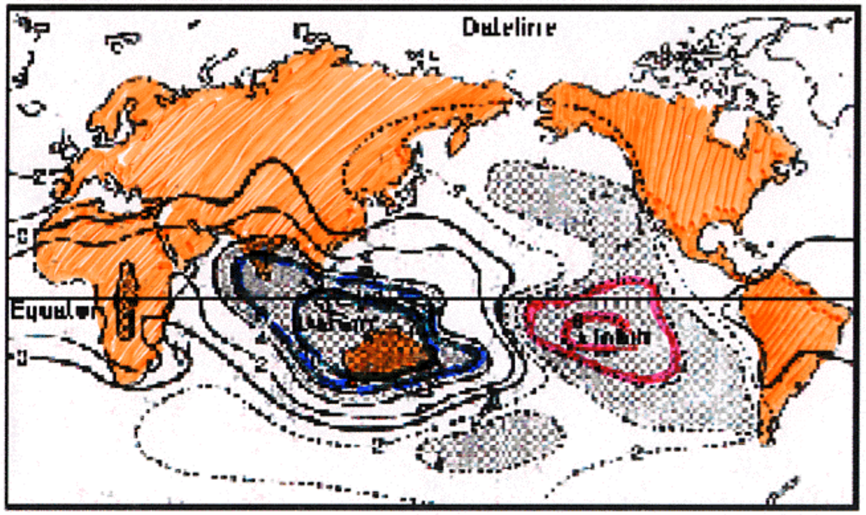


La Nina



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

History of El Niño

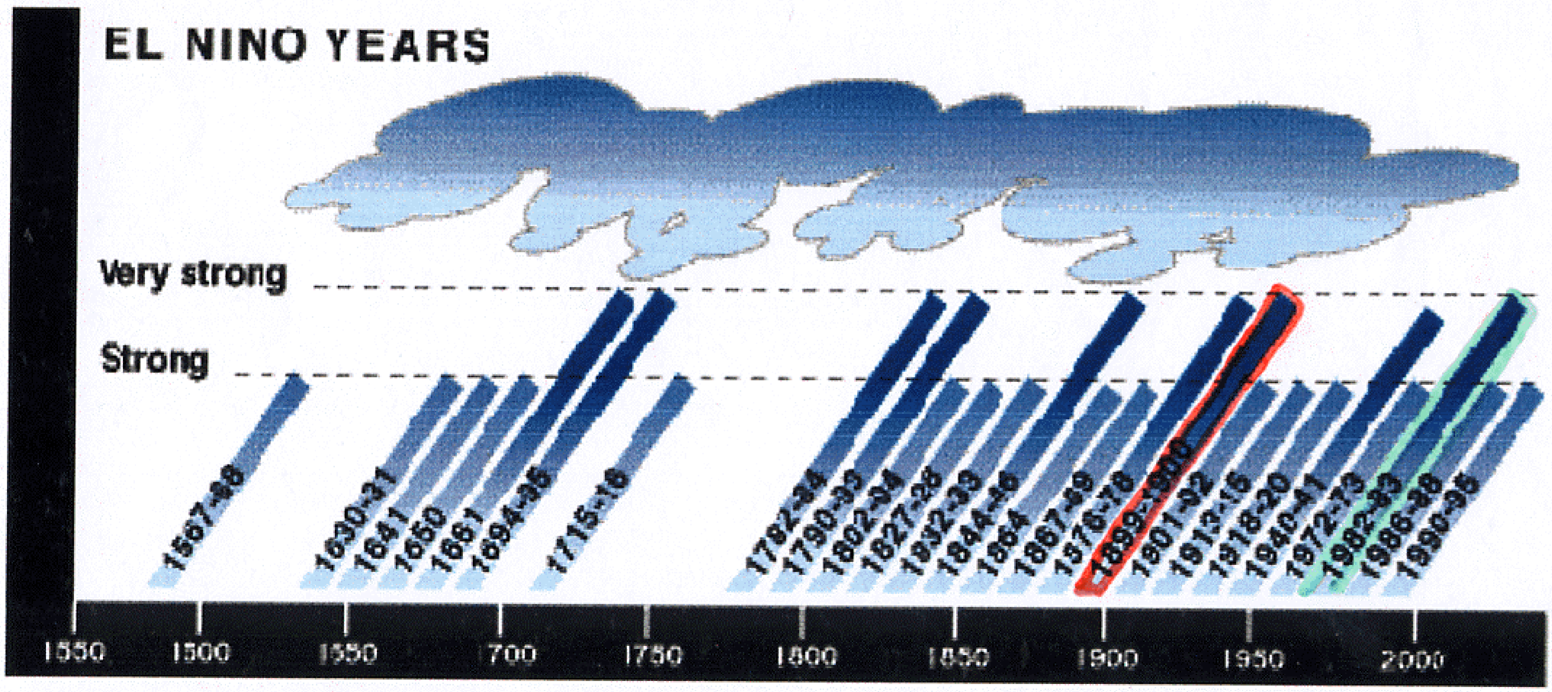
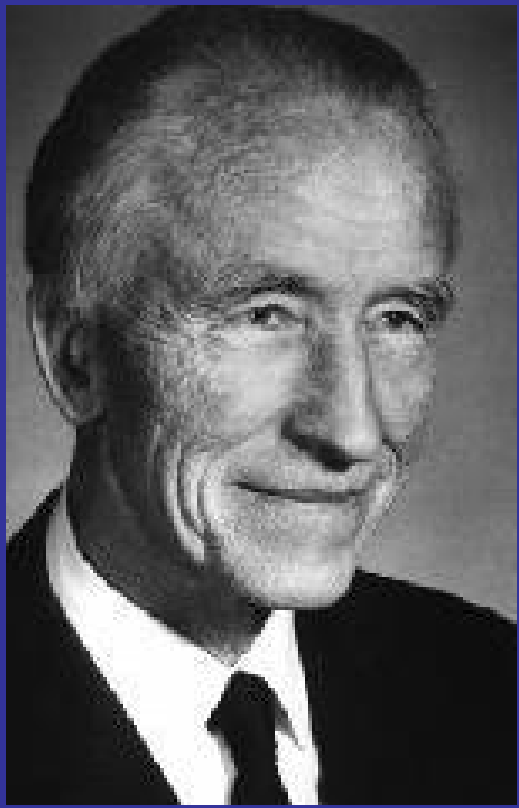


Table from Environmental News Network

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

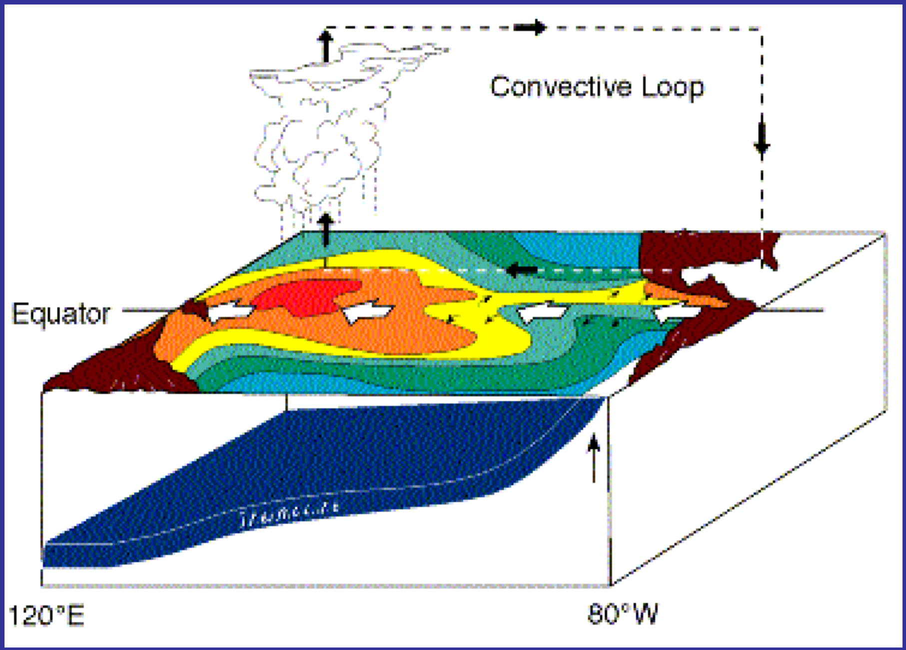
Polar Front Theory

Vilhelm Bjerknes (1862-1951)

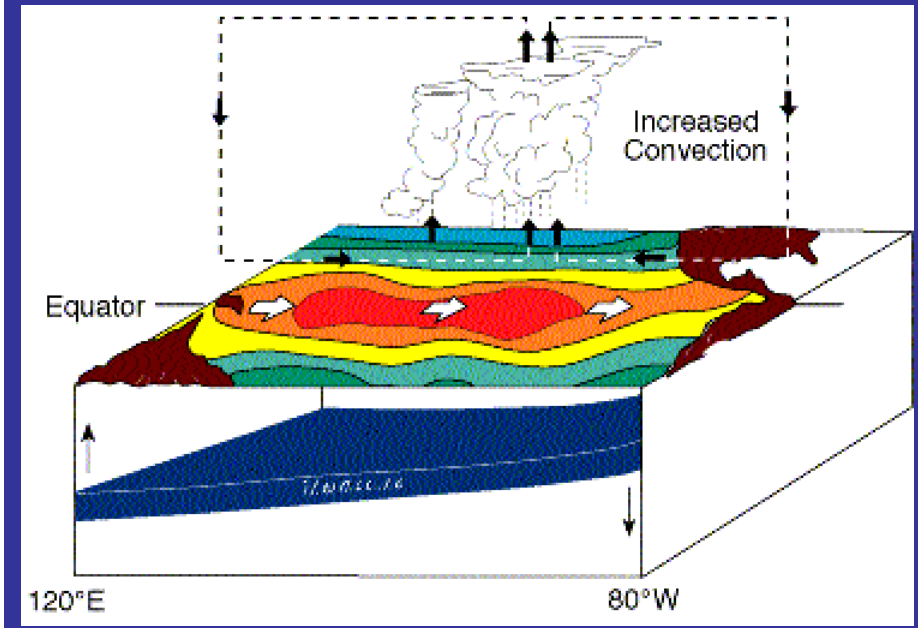
- ***Bjerknes,*** the founder of the Bergen school of meteorology, developed polar front theory during WWI to describe the formation, growth, and dissipation of mid-latitude cyclones.

Coupled Atmosphere-Ocean System

Normal Condition

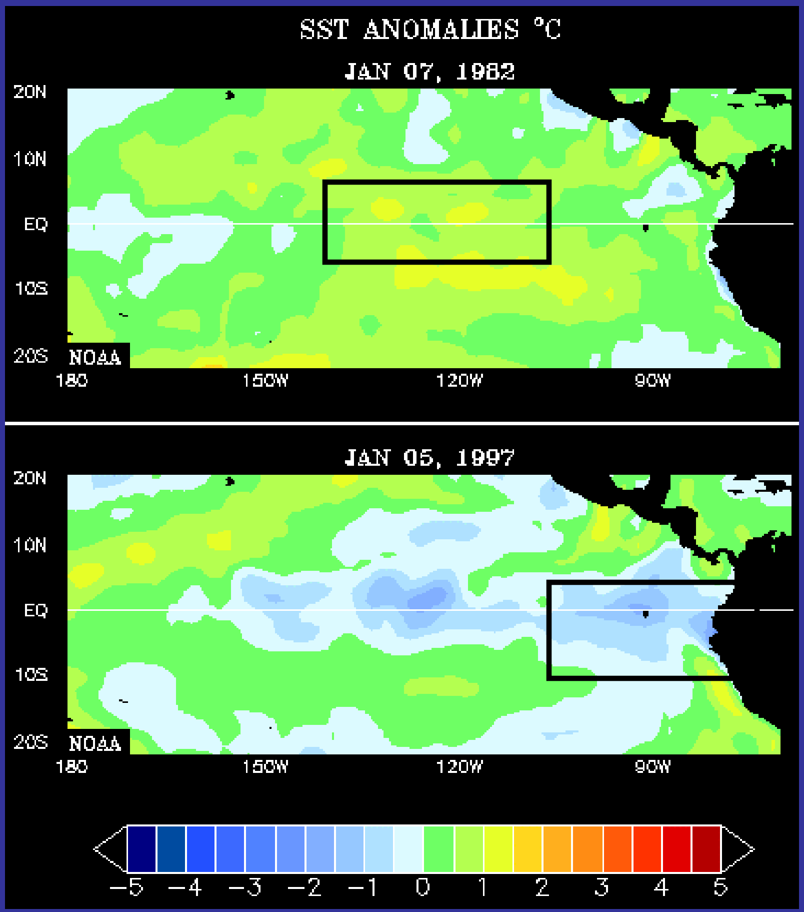


El Nino Condition



(from NOAA)

a birds-eye view of 2 of the largest
El Niño events of last century:



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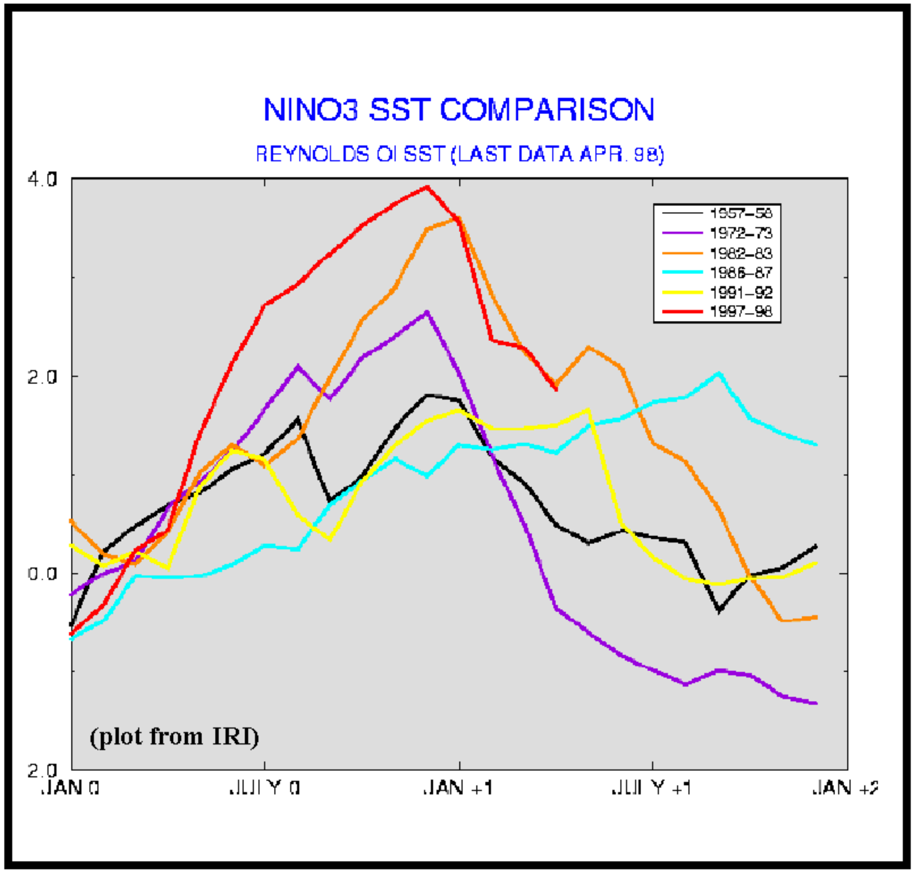
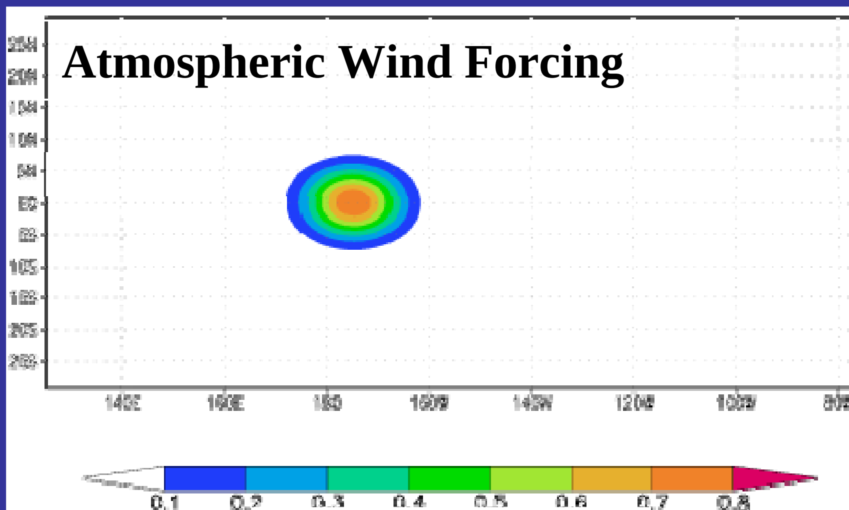
ENSO's Phase-Lock to the Annual Cycle

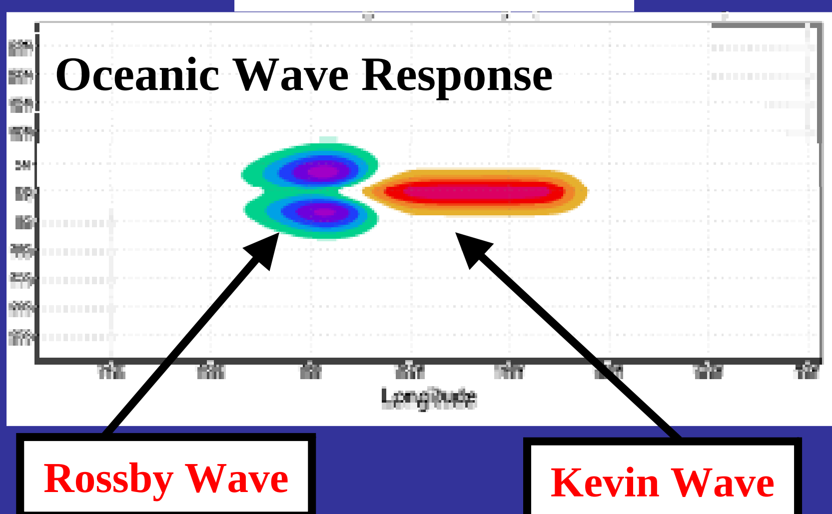


- Composition analyses have shown that ENSO events tend to onset, grow, and decay at certain seasons of the year (Rasmusson and Carpenter 1982).

Delayed Oscillator: Wind Forcing

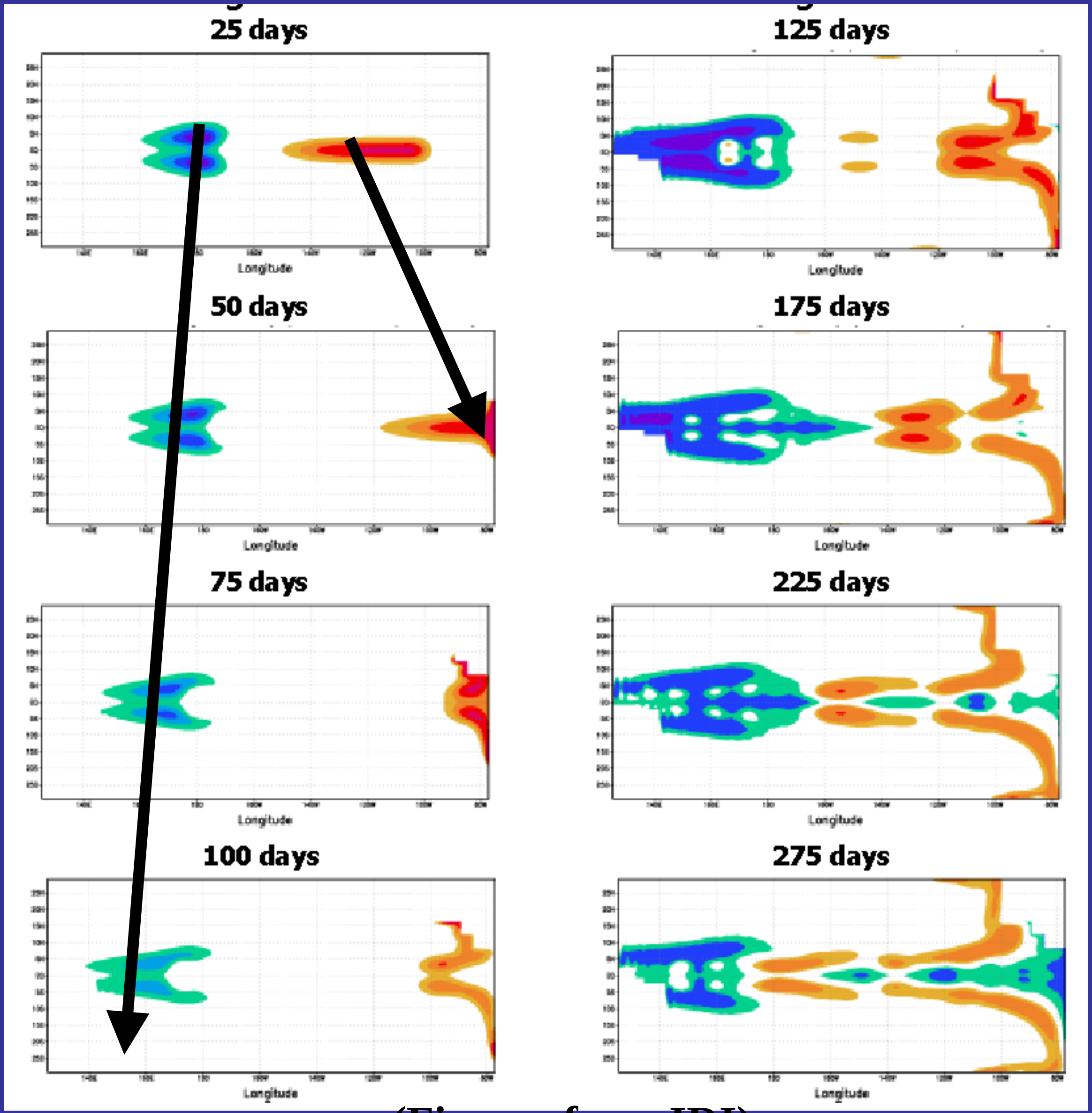


(Figures from IRI)



- The delayed oscillator suggested that oceanic Rossby and Kevin waves forced by atmospheric wind stress in the central Pacific provide the phase-transition mechanism (I.e. memory) for the ENSO cycle.
- The propagation and reflection of waves, together with local air-sea coupling, determine the period of the cycle.

Wave Propagation and Reflection



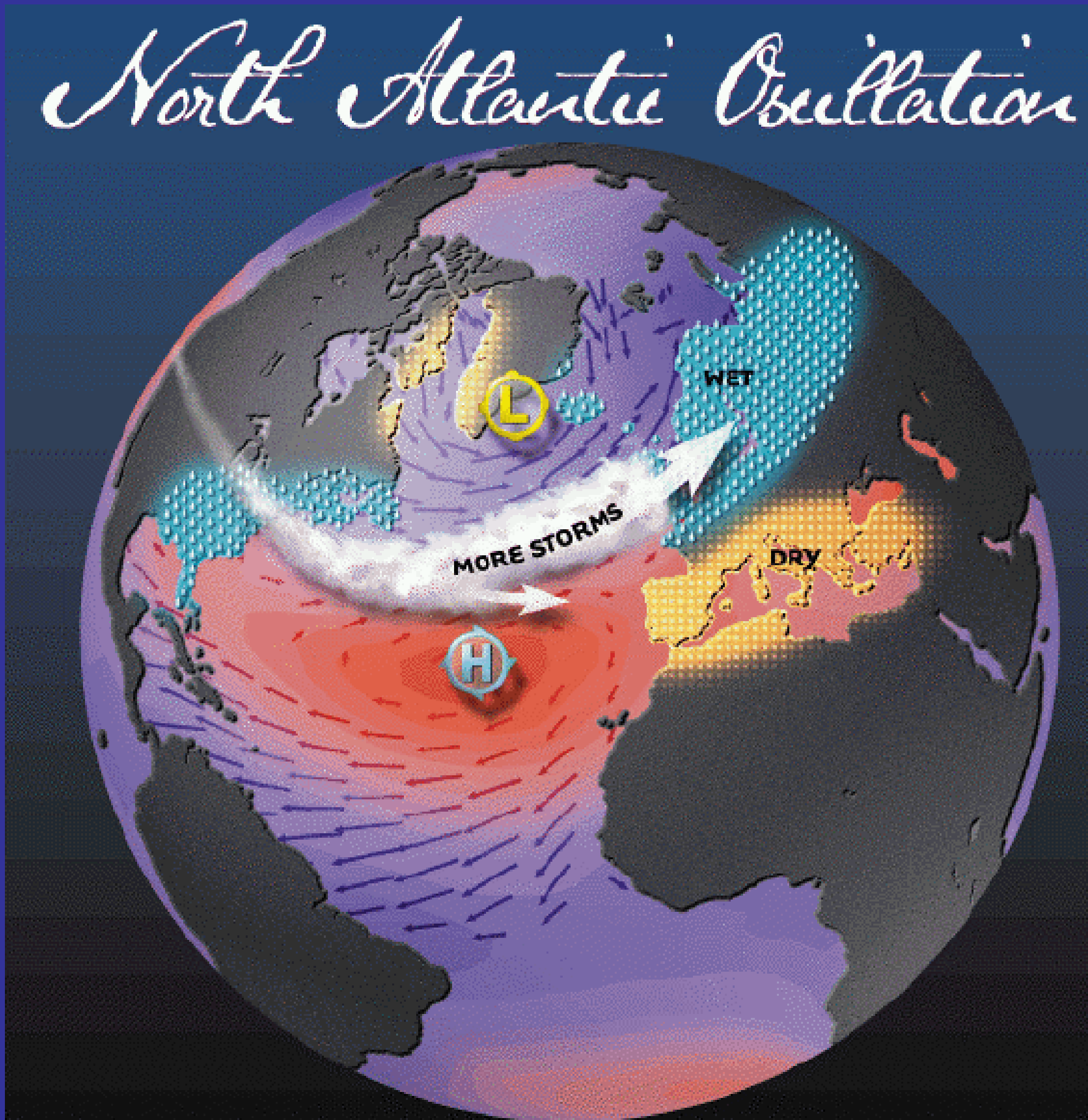
(Figures from IRI)

- It takes Kevin wave (phase speed = 2.9 m/s) about 70 days to cross the Pacific basin (17,760km).
- It takes Rossby wave about 200 days (phase speed = 0.93 m/s) to cross the Pacific basin.

Why Only Pacific Has ENSO?

- Based on the delayed oscillator theory of ENSO, the ocean basin has to be big enough to produce the “delayed” from ocean wave propagation and reflection.
- It can be shown that only the Pacific Ocean is “big” (wide) enough to produce such delayed for the ENSO cycle.
- It is generally believed that the Atlantic Ocean may produce ENSO-like oscillation if external forcing are applied to the Atlantic Ocean.
- The Indian Ocean is considered too small to produce ENSO.

North Atlantic Oscillation

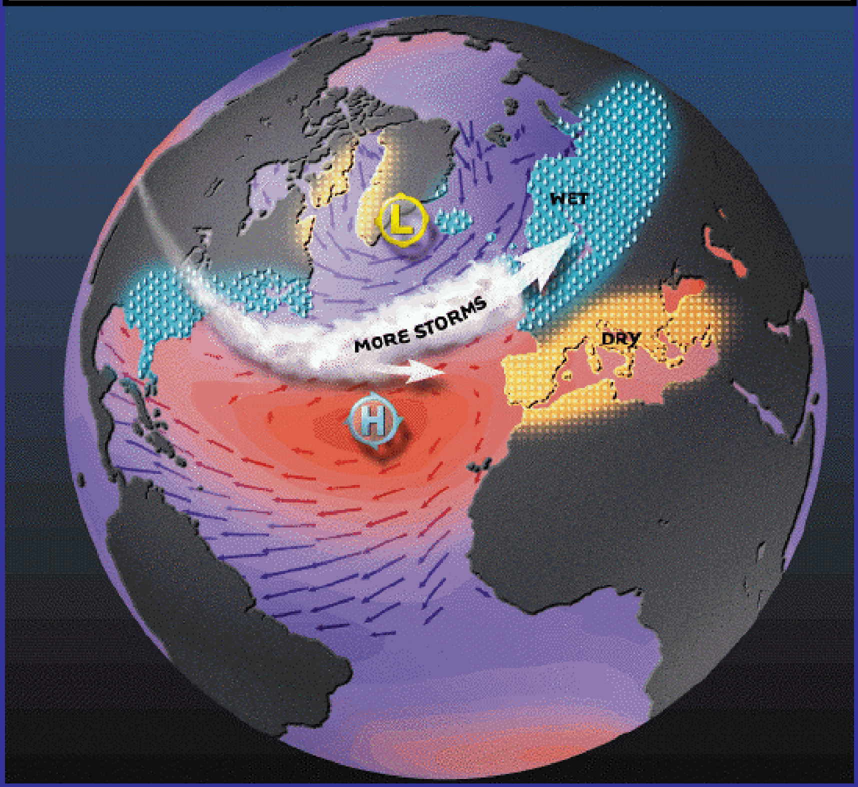


(from http://www.ldeo.columbia.edu/res/pi/NAO/)

- The NAO is the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe and much into Northern Asia.
- The NAO is a large scale seesaw in atmospheric mass between the subtropical high and the polar low.
- The corresponding index varies from year to year, but also exhibits a tendency to remain in one phase for intervals lasting several years.

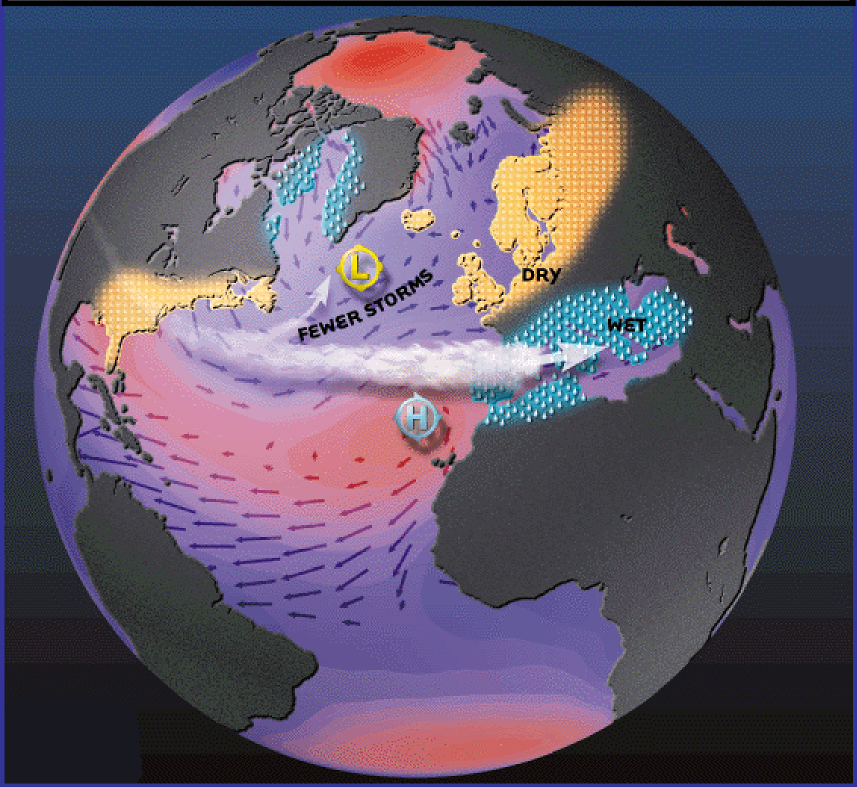
Positive and Negative Phases of NAO

Positive Phase



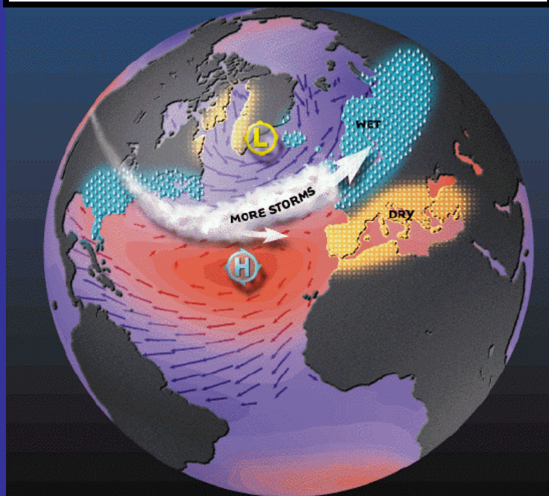
❑ **A stronger and more northward storm track.**

Negative Phase



❑ **A weaker and more zonal storm track.**

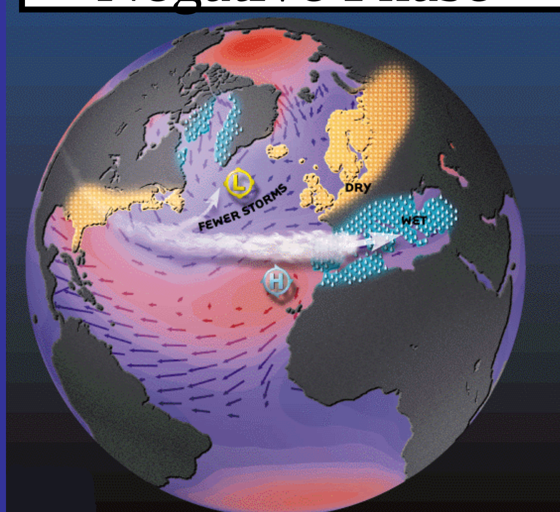
Positive Phase



Positive NAO Index

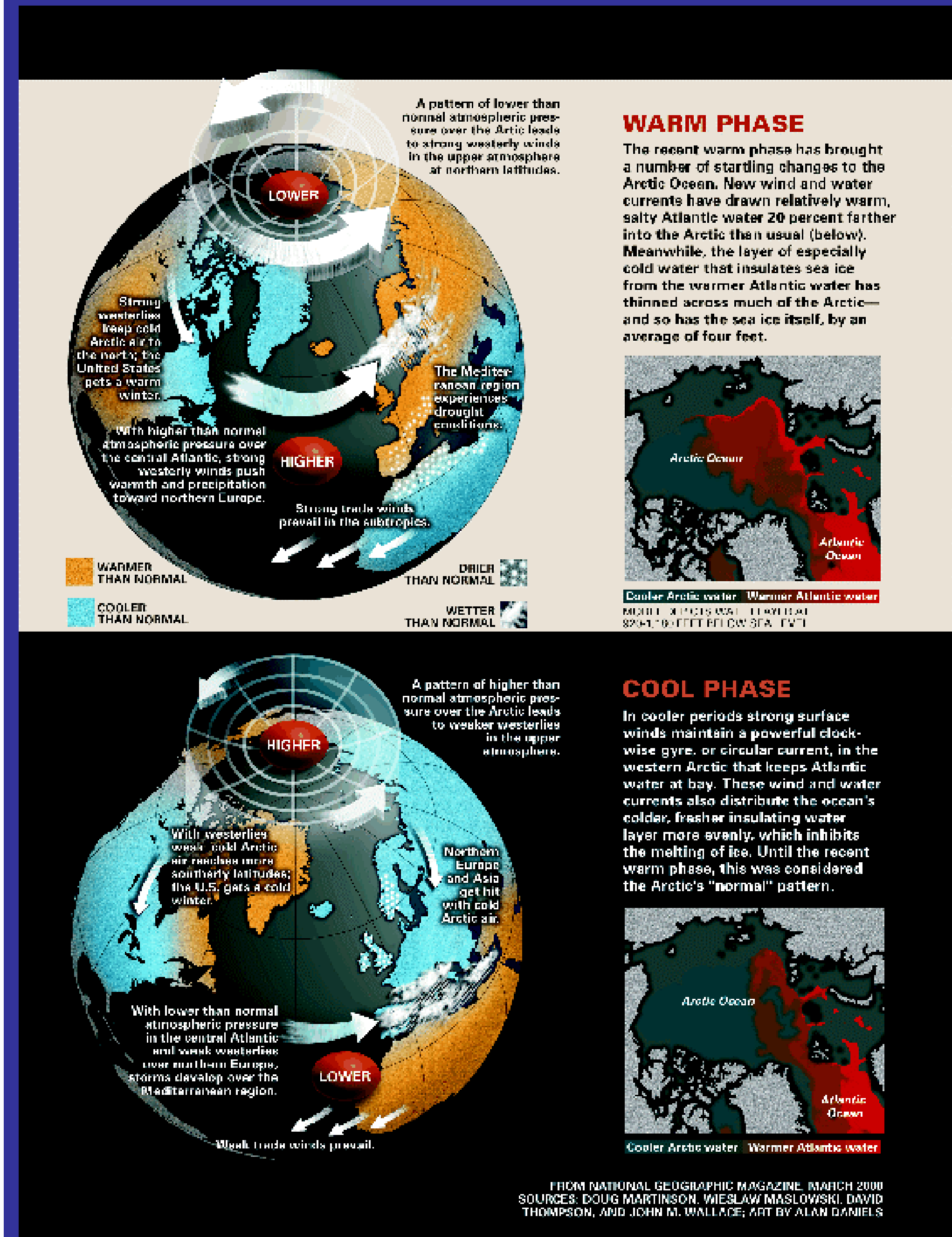
- Stronger subtropical high and a deeper than normal Icelandic low.
- More and stronger winter storms crossing the Atlantic Ocean on a more northerly track.
- Warm and wet winters in Europe and in cold and dry winters in northern Canada and Greenland
- The eastern US experiences mild and wet winter conditions

Negative Phase



Negative NAO Index

- Weak subtropical high and weak Icelandic low.
- Fewer and weaker winter storms crossing on a more west-east zonal pathway.
- Moist air into the Mediterranean and cold air to northern Europe
- US east coast experiences more cold air outbreaks and hence snowy weather conditions.
- Greenland, however, will have milder winter temperatures



North Atlantic Oscillation
= Arctic Oscillation
= Annular Mode