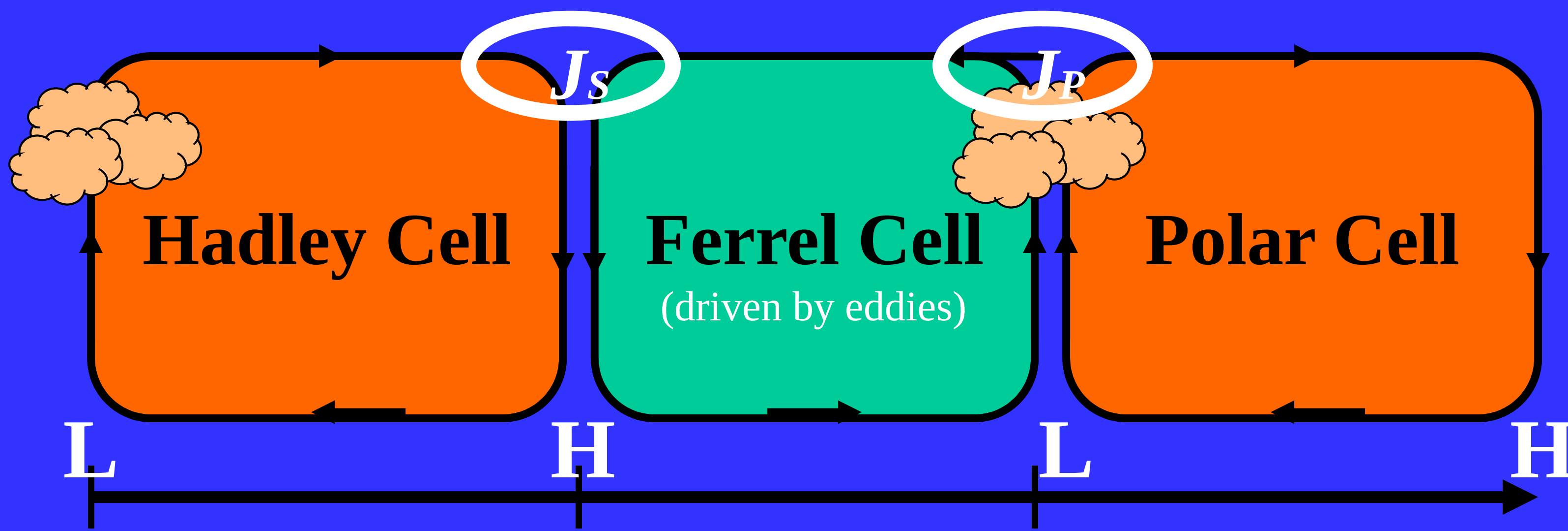
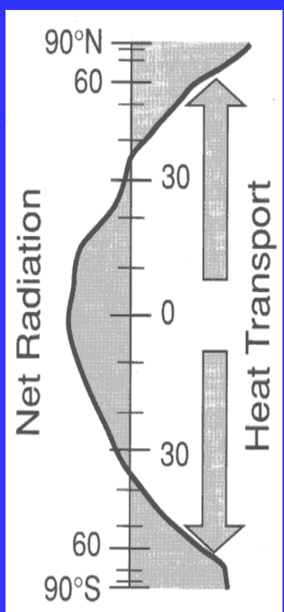
Lecture 9: General Circulation

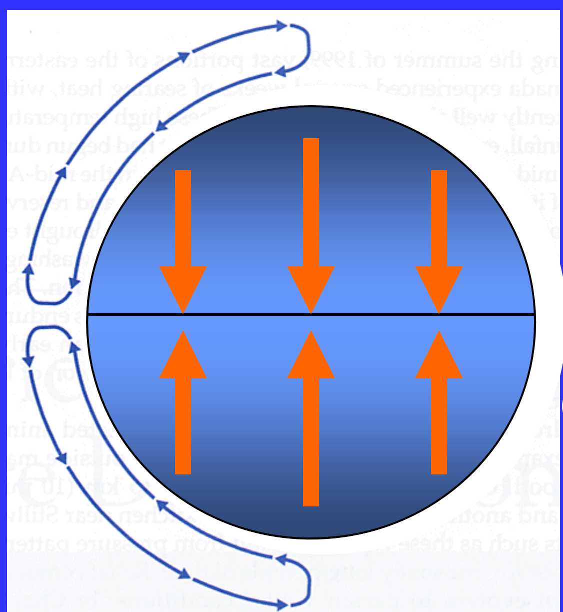


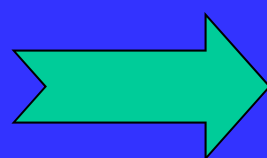
- Three-Cell Circulation in the Atmosphere
- Gyres in the Oceans

Single-Cell Model:
Explains Why There are Tropical Easterlies



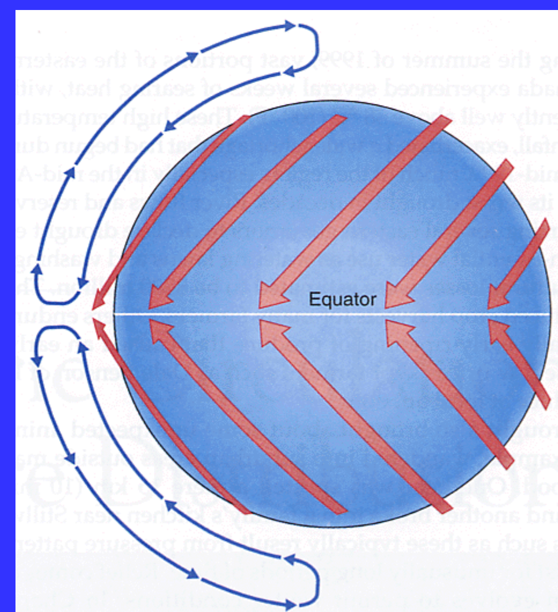
Without Earth Rotation





Coriolis Force

With Earth Rotation



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

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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:

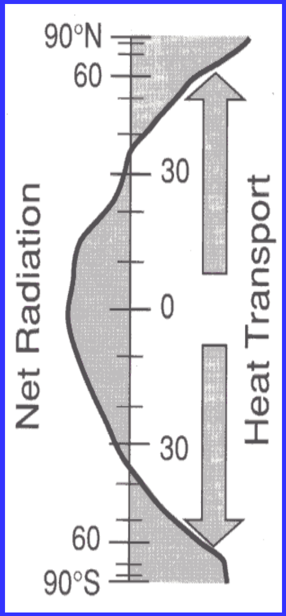
$$(U_0 + u_{Eq}) * a * \text{Cos}(0^\circ) = (U_{60N} + u_{60N}) * a * \text{Cos}(60^\circ)$$

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

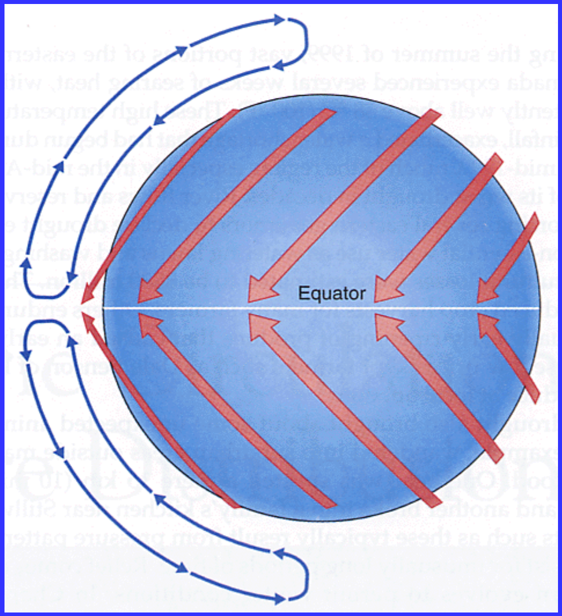
u_{60N} = 687 m/sec !!!!

This high wind speed is not observed!

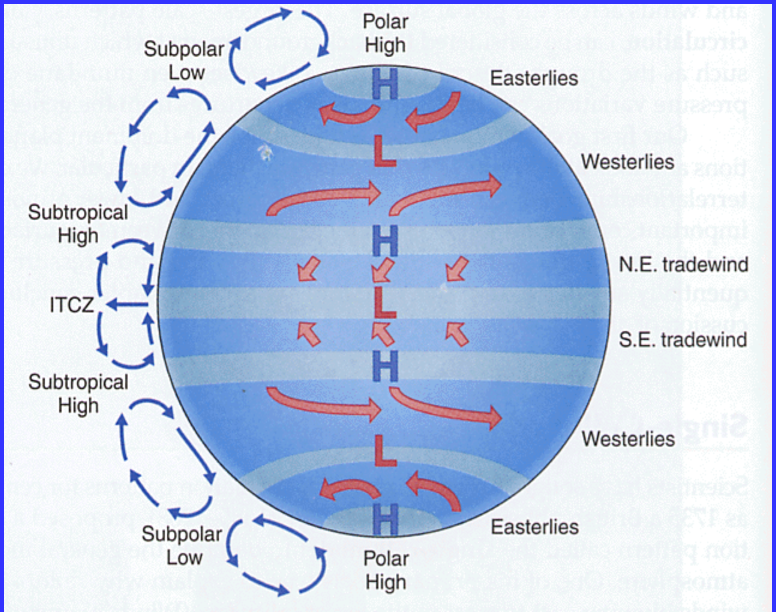
Atmospheric Circulation: Zonal-mean Views



Single-Cell Model

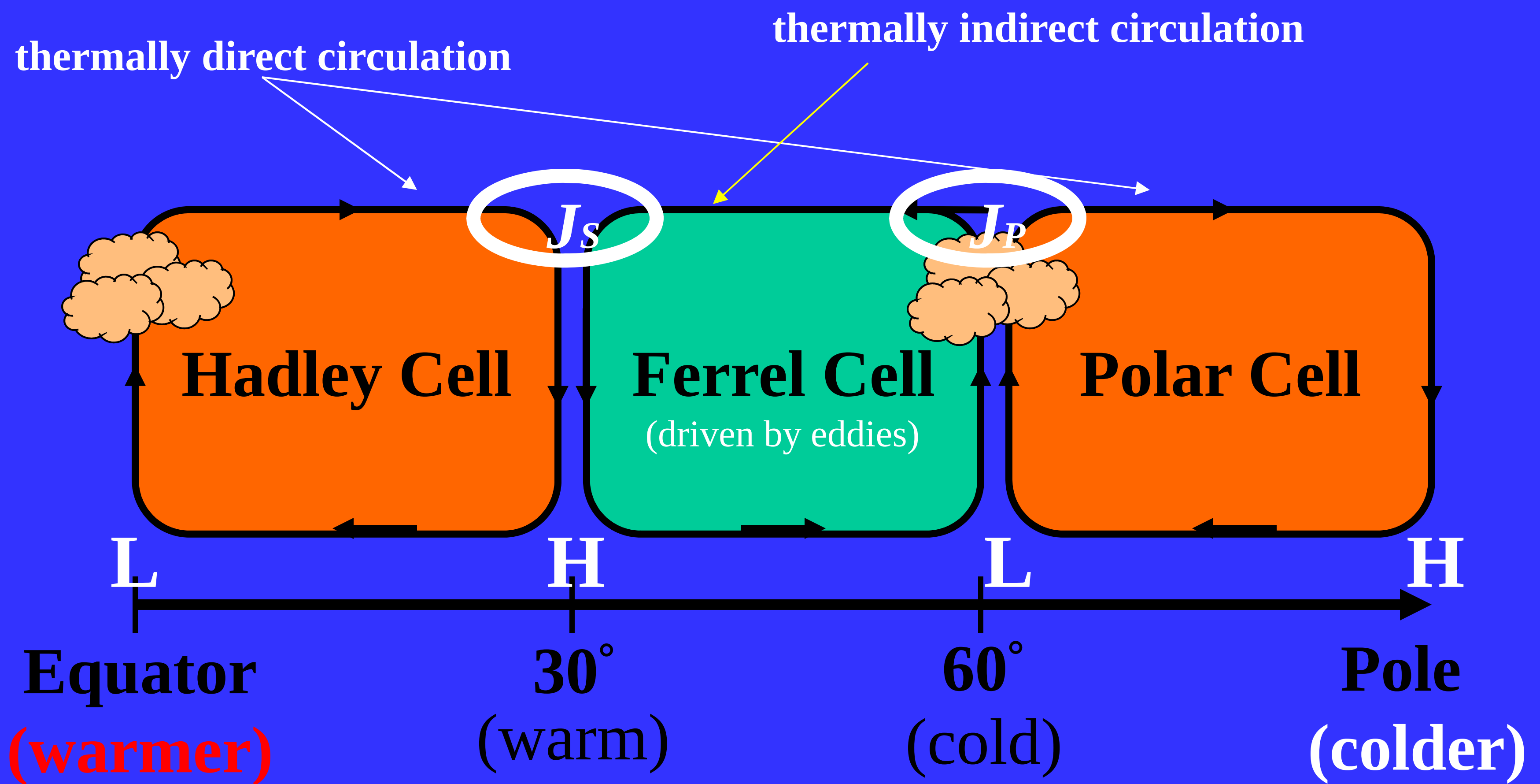


Three-Cell Model

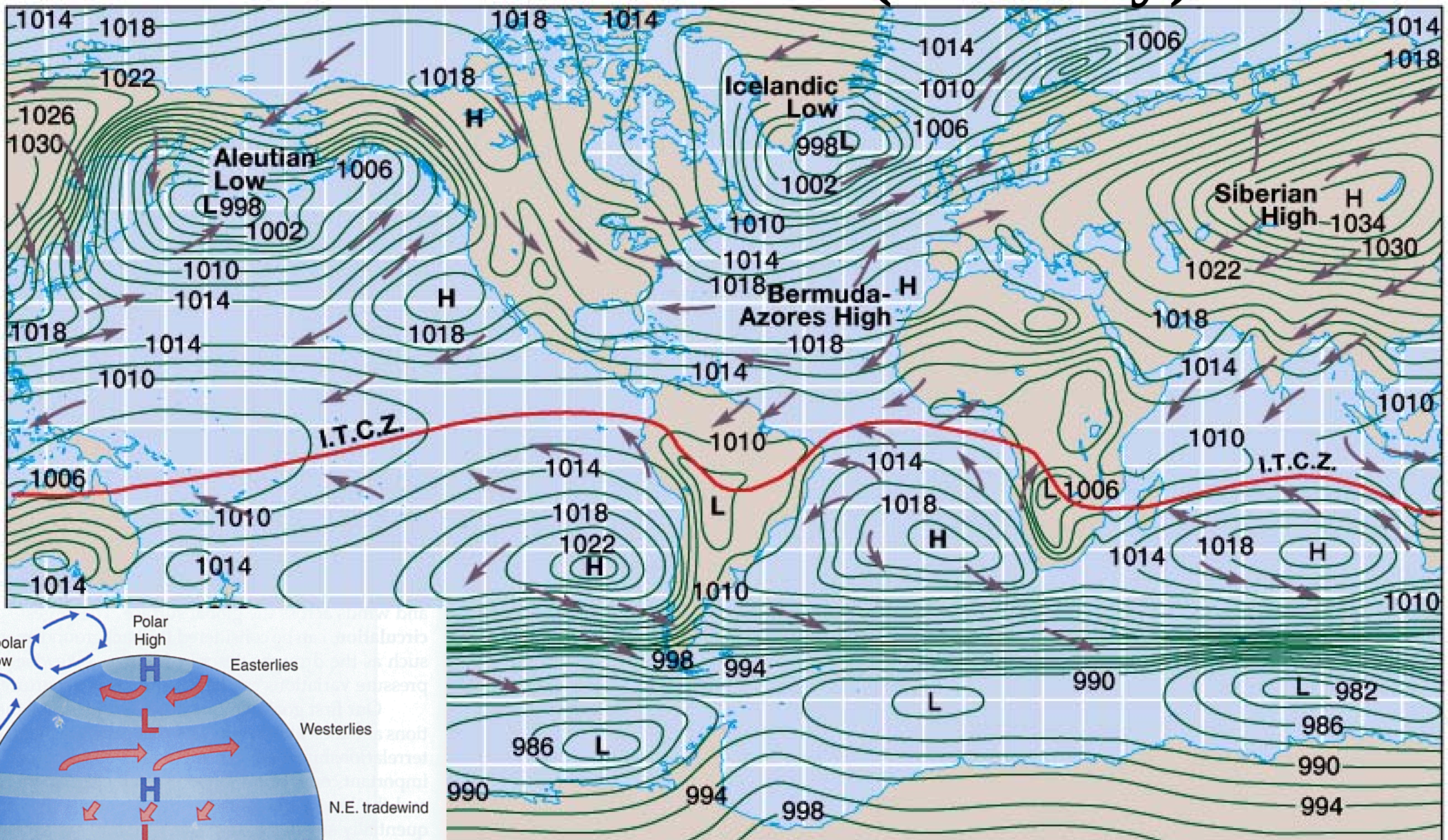


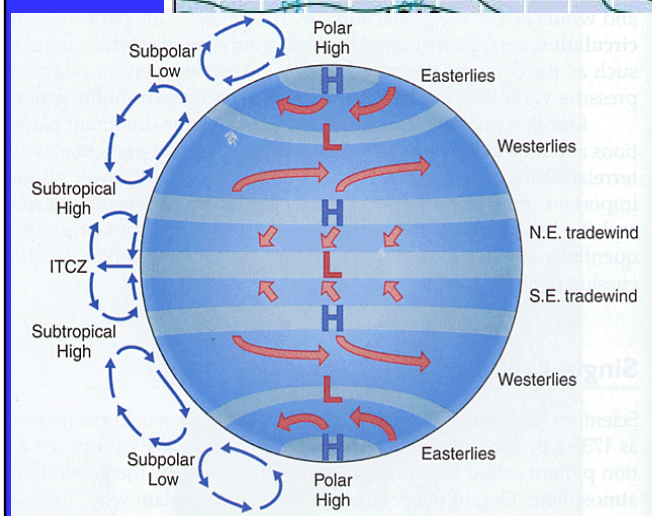
(Figures from *Understanding Weather & Climate* and *The Earth System*)

Properties of the Three Cells

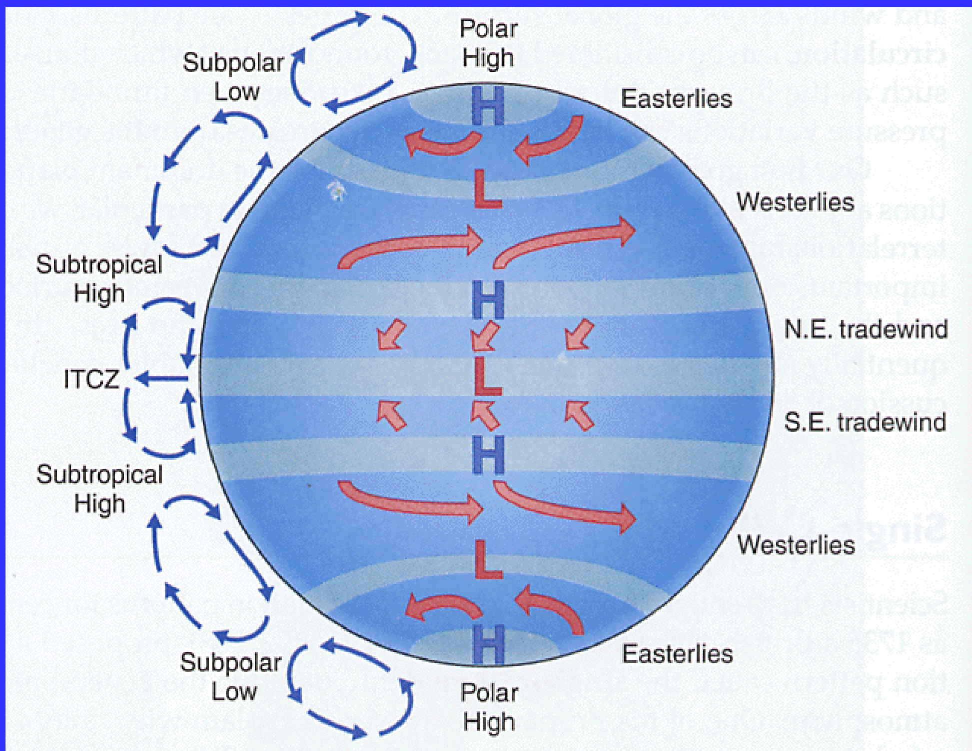


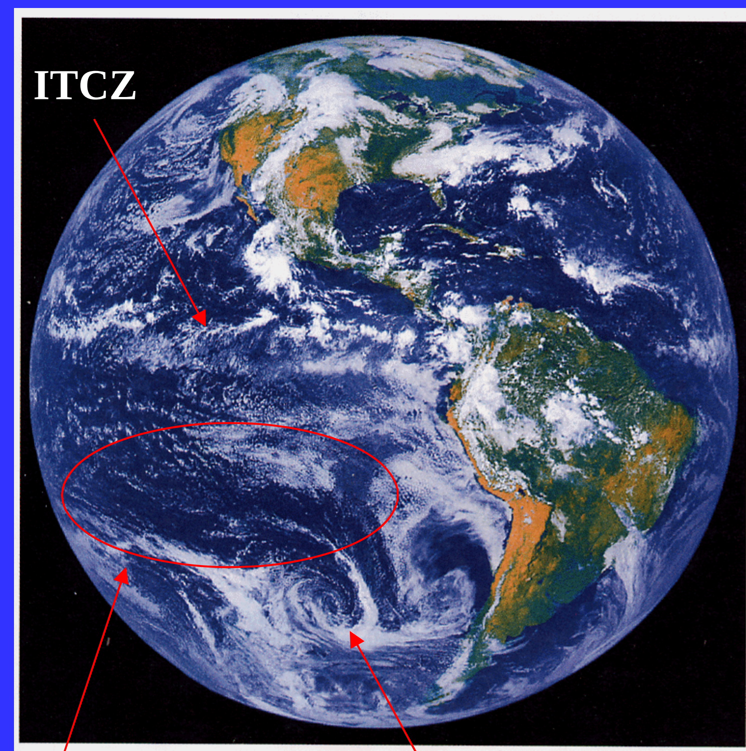
Sea Level Pressure (January)





The Three Cells





Subtropical High

midlatitude Weather system

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

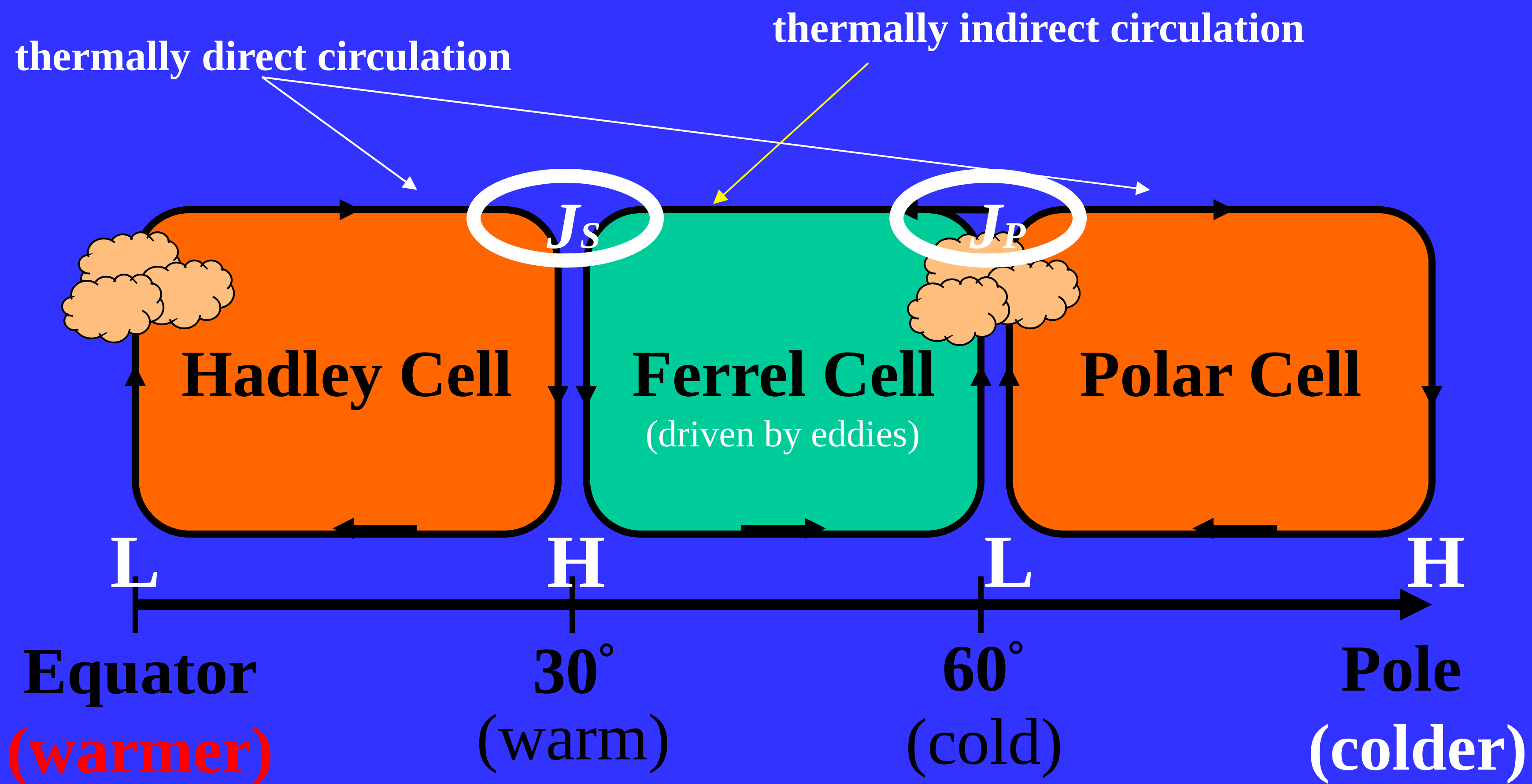
Is the Three-Cell Model Realistic?

- ***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.)

Properties of the Three Cells

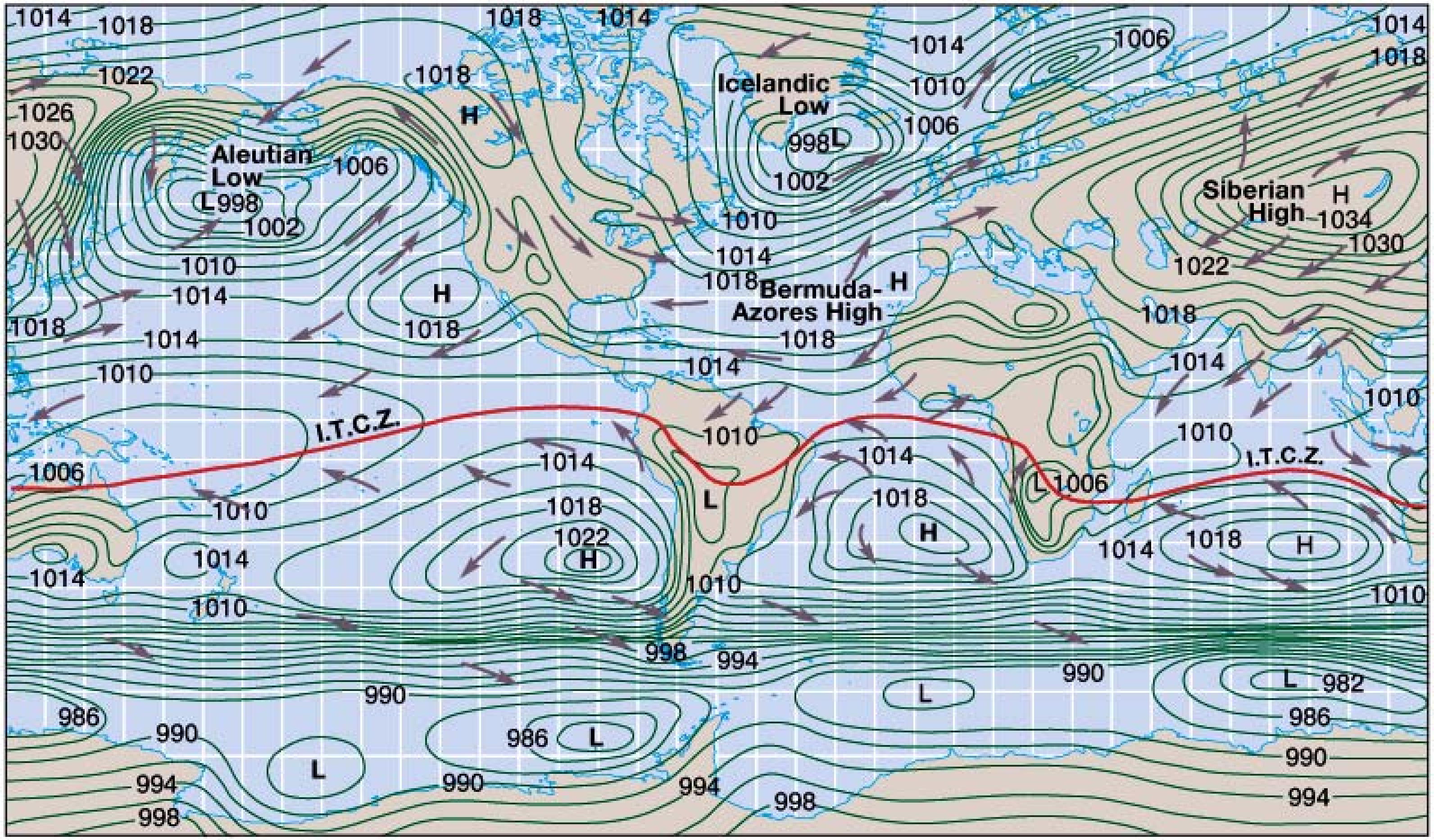


Semi-Permanent Pressure Cells

- **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



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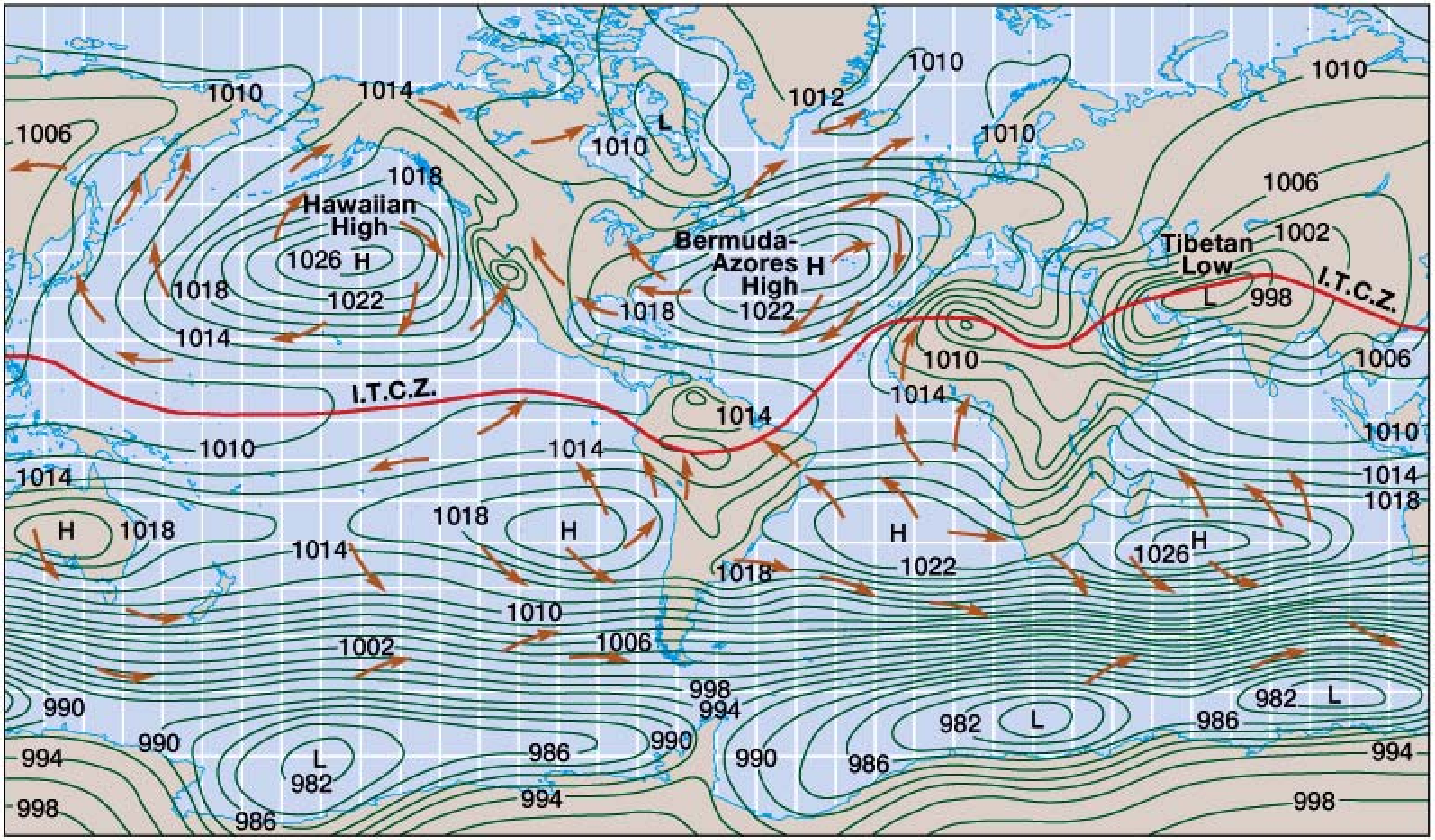
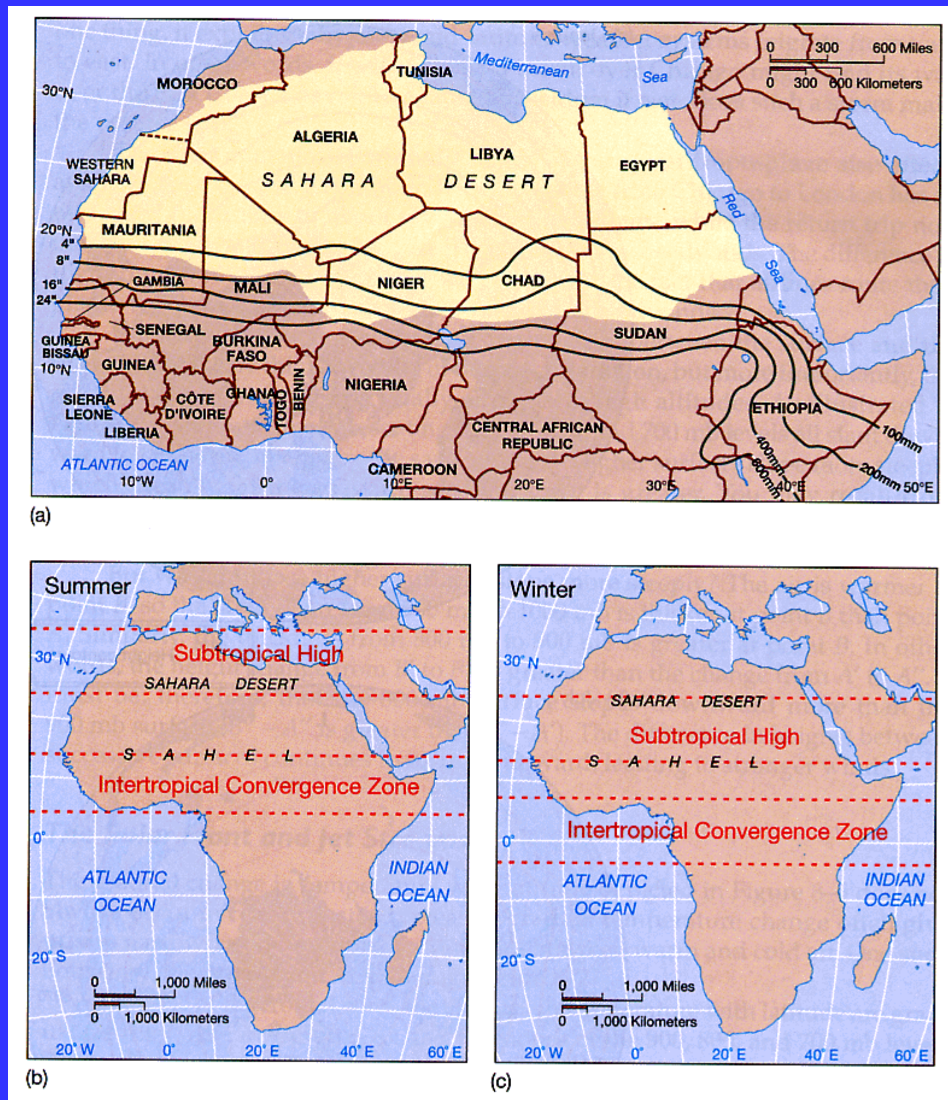
July



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

Sinking Branches and Deserts



(from *Weather & Climate*)

Global Distribution of Deserts

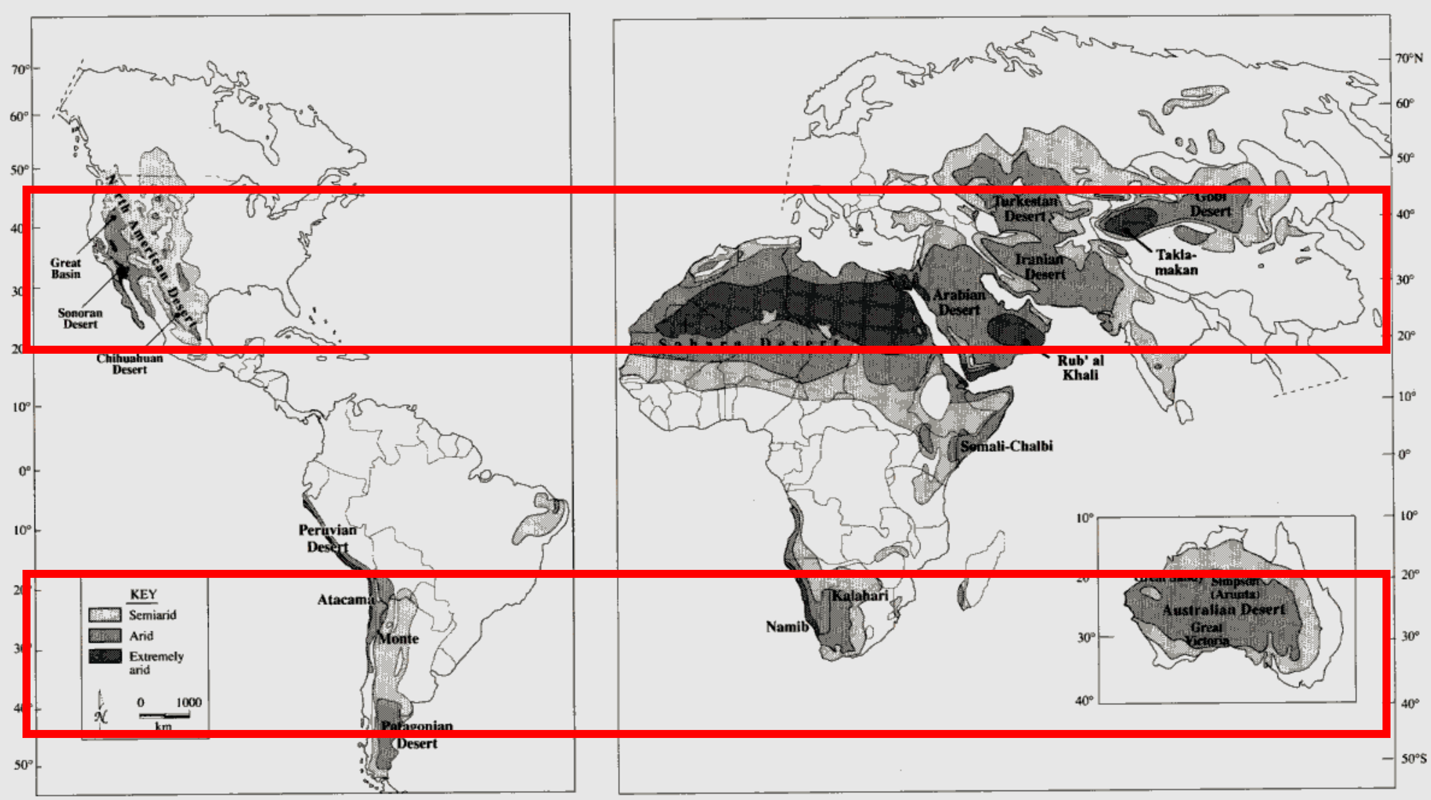


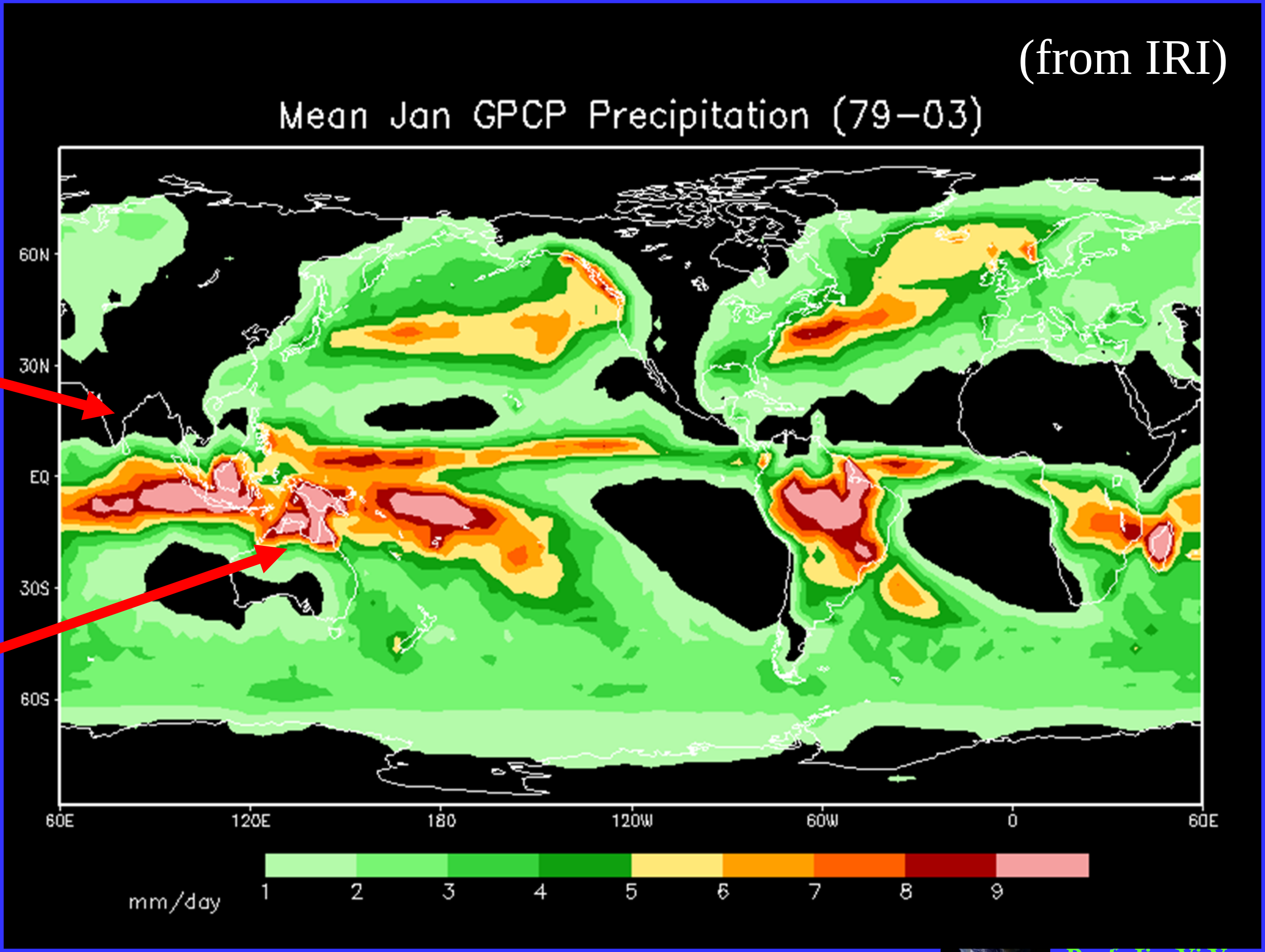
Fig. 6.21 Map showing arid lands around the world. Meigs classification taken from *Mosaic* magazine (Vol. 8, Jan/Feb 1977). [See McGinnies *et al.*, eds., (1968). Permission granted by the Office of Arid Lands Studies.]

(from *Global Physical Climatology*)

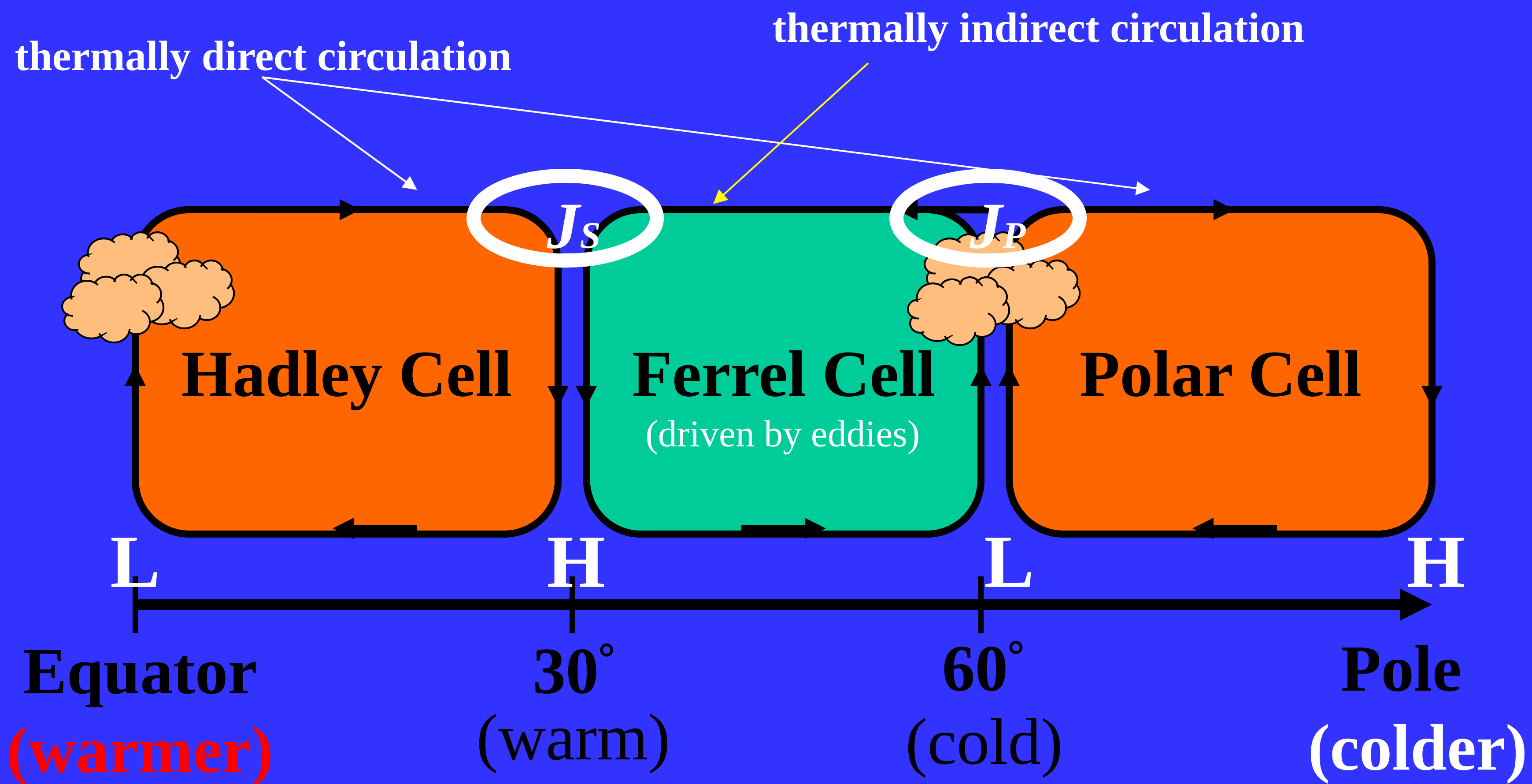
Seasonal Cycle of Rainfall

Indian Monsoon

Australian Monsoon



Properties of the Three Cells



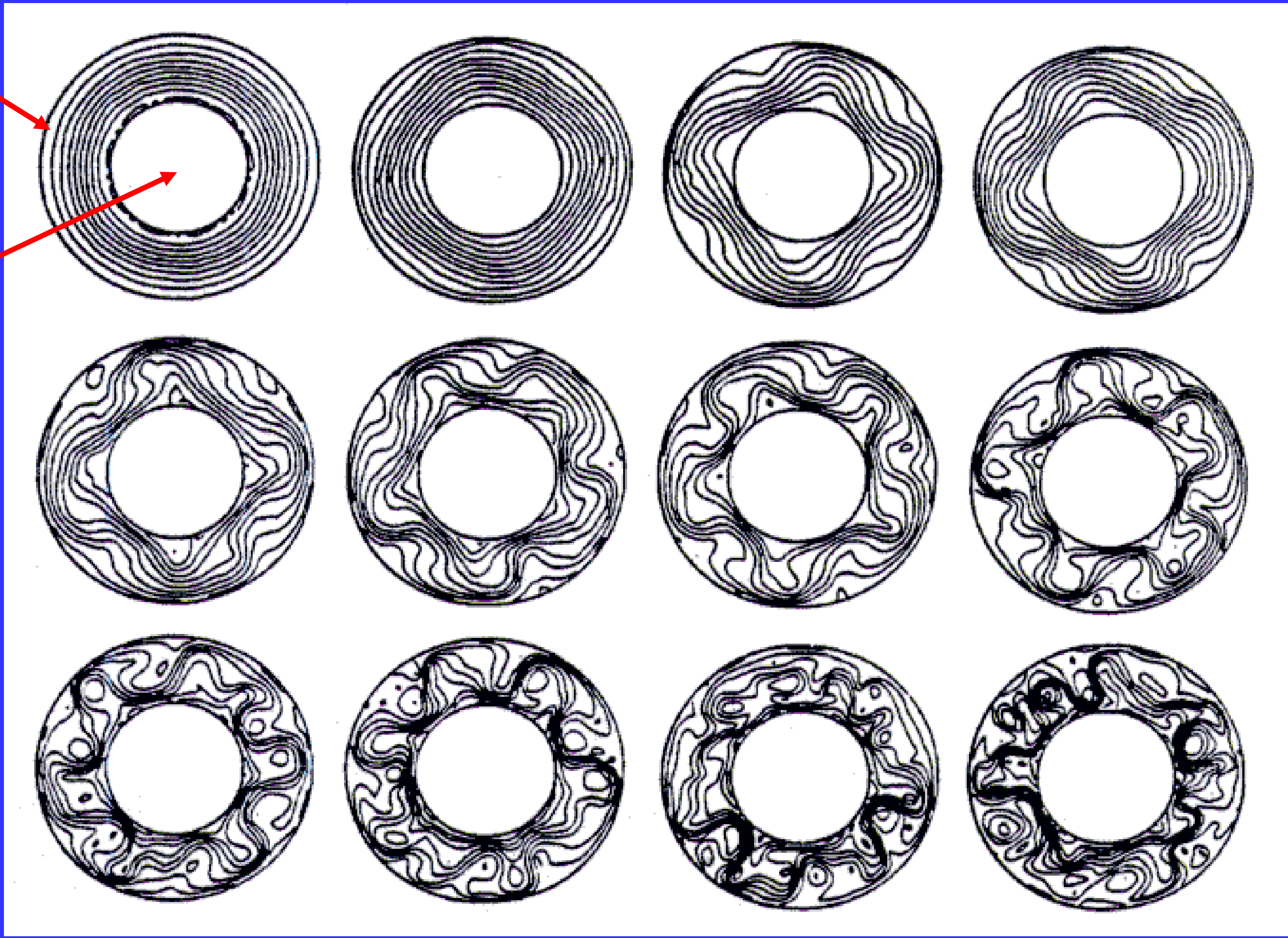
Parameters Determining Mid-latitude Weather

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

Rotating Annulus Experiment

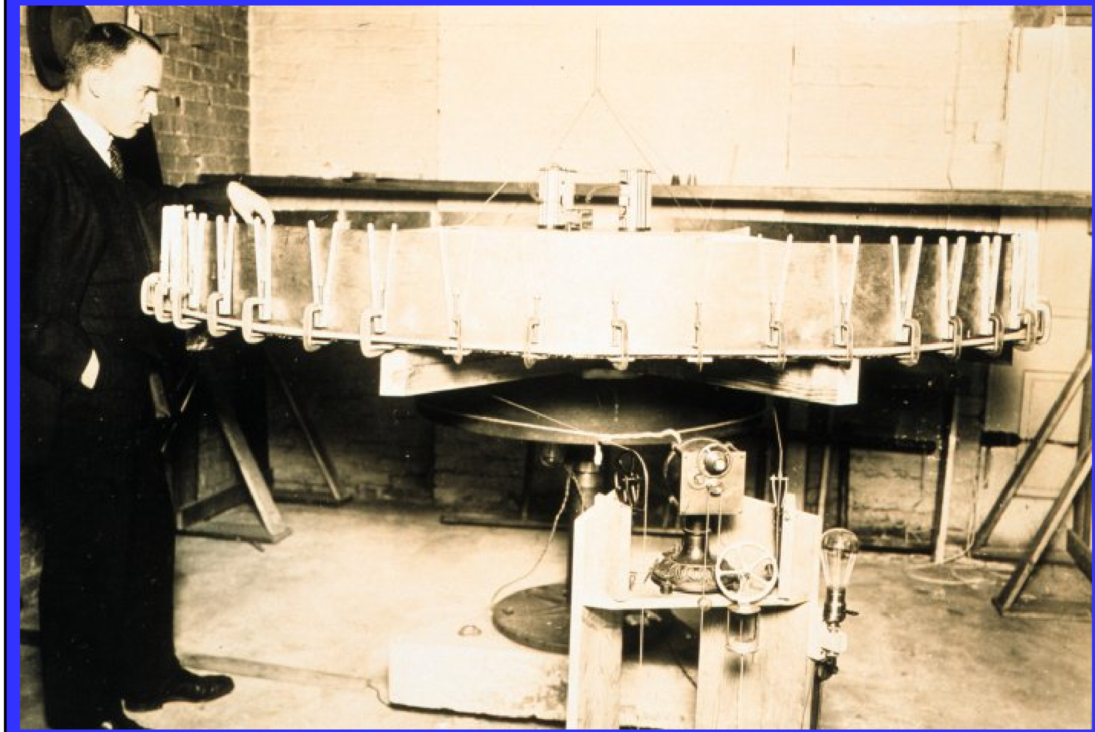
Cooling Outside

Heating Inside



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

New Understanding of Cyclone after WWII



Carl Gustav Rossby (1898-1957)

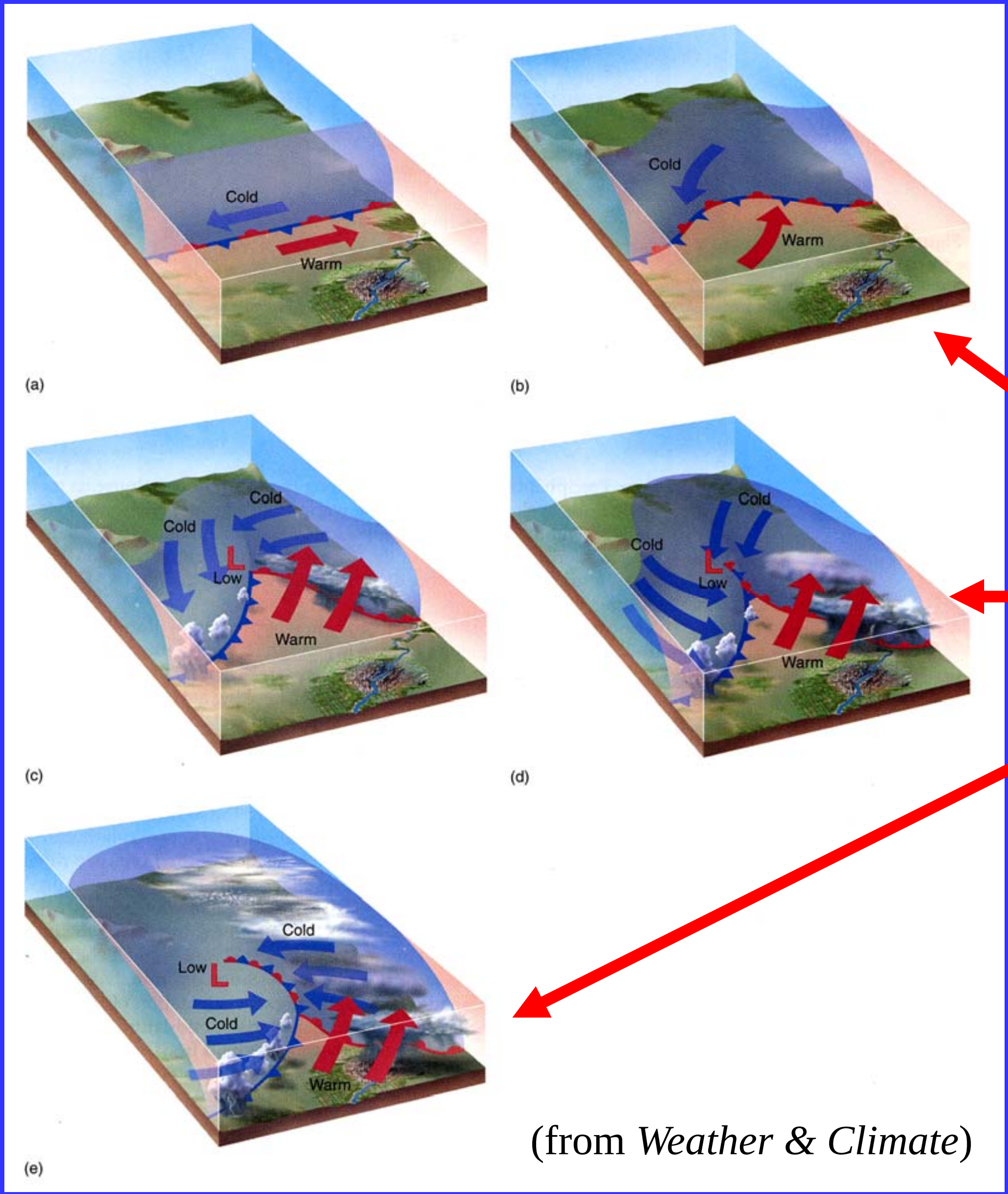
- Carl Rossby mathematically expressed relationships between mid-latitude cyclones and the upper air during WWII.
- Mid-latitude cyclones are a large-scale waves (now called Rossby waves) that grow from the "baroclinic" instabiloity associated with the north-south temperature differences in middle latitudes.

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.

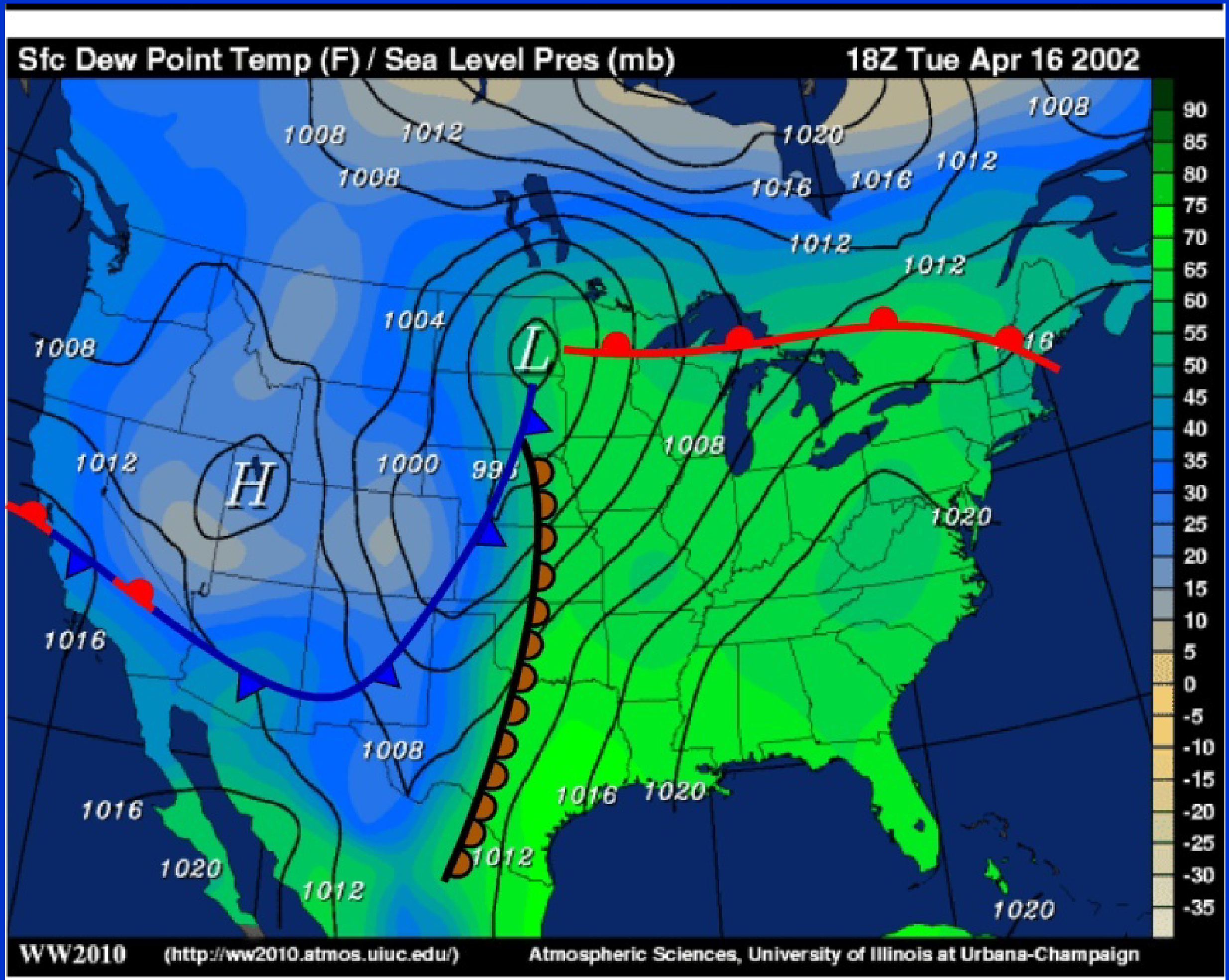
Life Cycle of Mid-Latitude Cyclone



(from *Weather & Climate*)

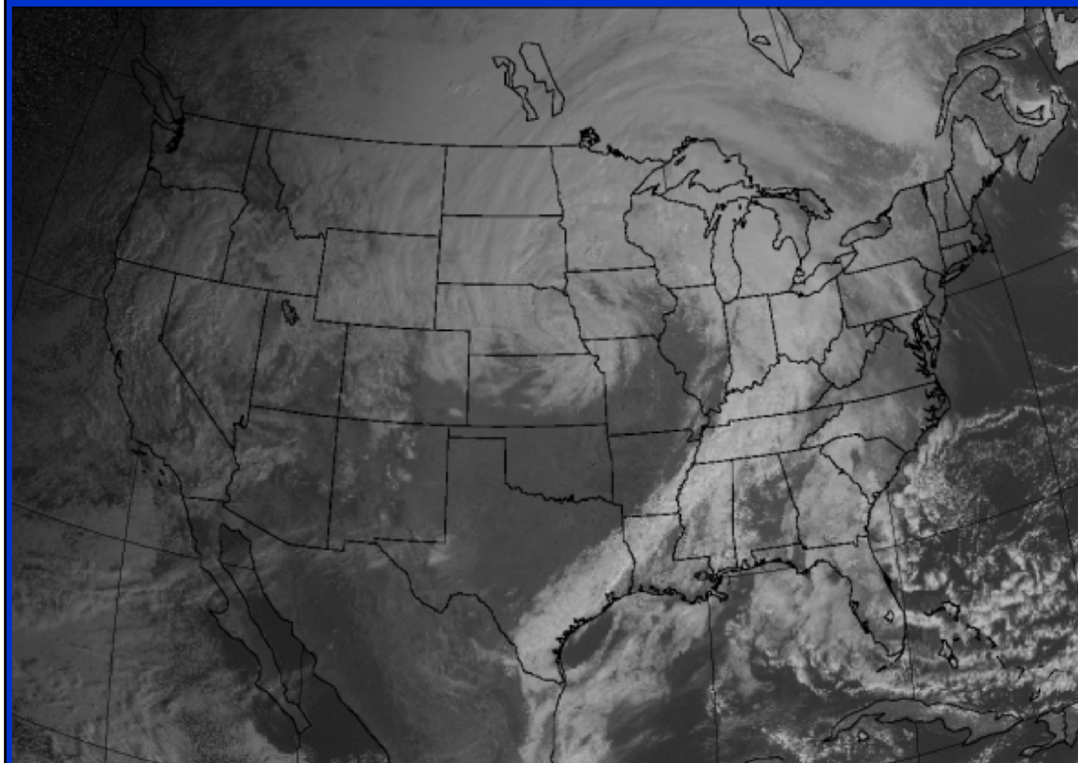
- Cyclogenesis
- Mature Cyclone
- Occlusion

Winter Cyclones: East of the Rocky Mountain



Courtesy of the Department of Atmospheric Sciences
University of Illinois at Urbana-Champaign

Extratropical Cyclones

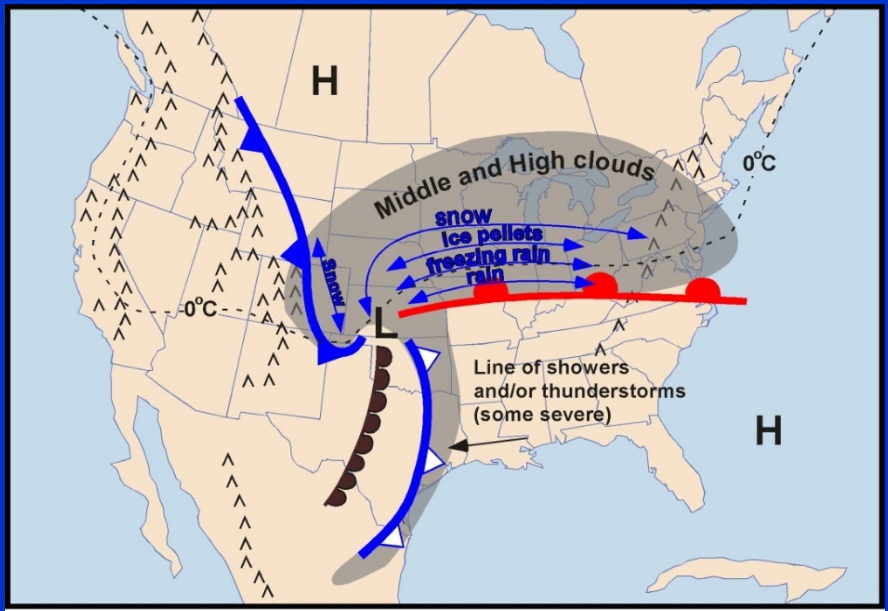


Courtesy of the Department of Atmospheric Sciences
University of Illinois at Urbana-Champaign

Visible satellite image of an extratropical cyclone covering the central United States

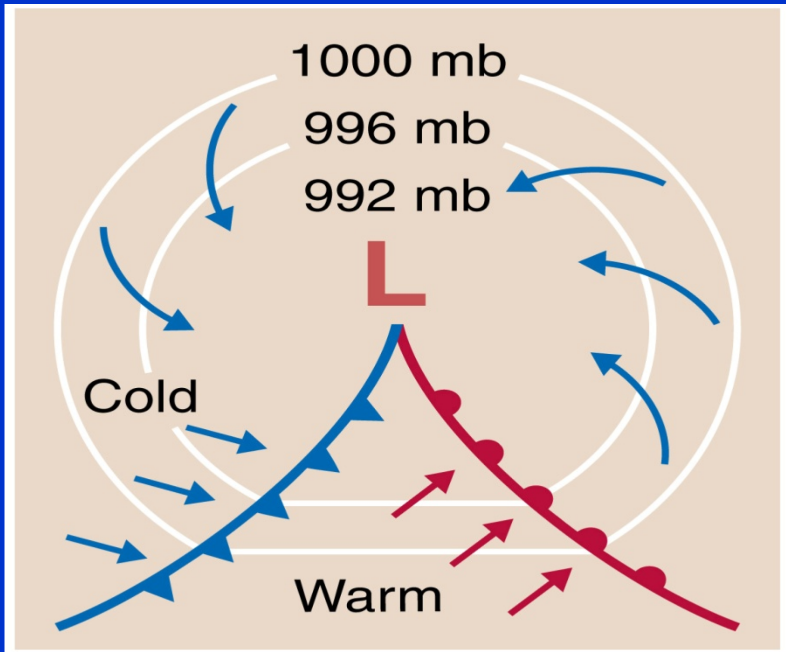
- Extratropical cyclones are large swirling storm systems that form along the jetstream between 30 and 70 latitude.
- The entire life cycle of an extratropical cyclone can span several days to well over a week.
- The storm covers areas ranging from several hundred to thousand miles across.

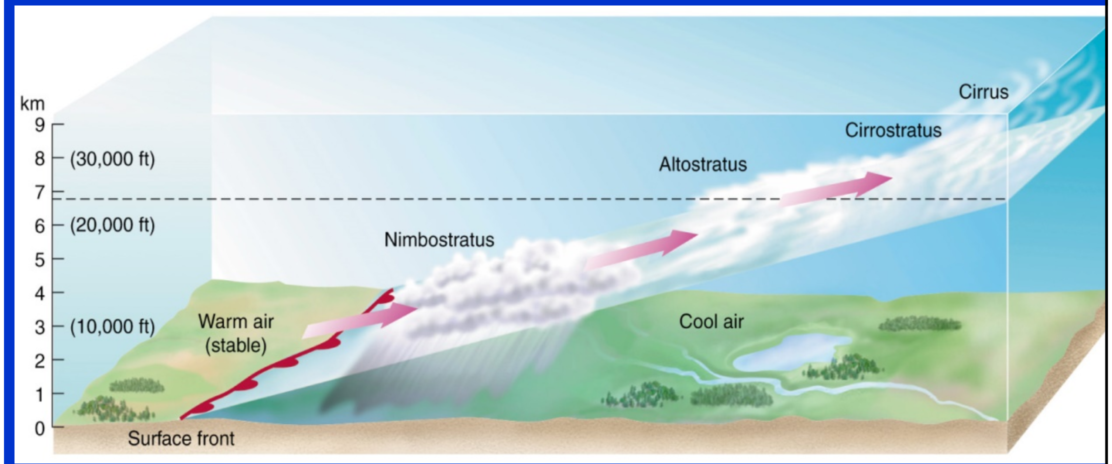
Summary of Early Weather

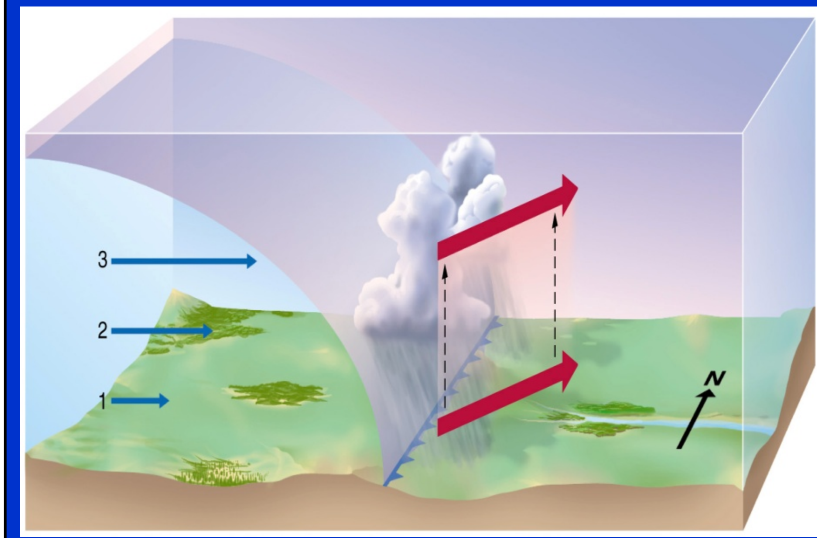


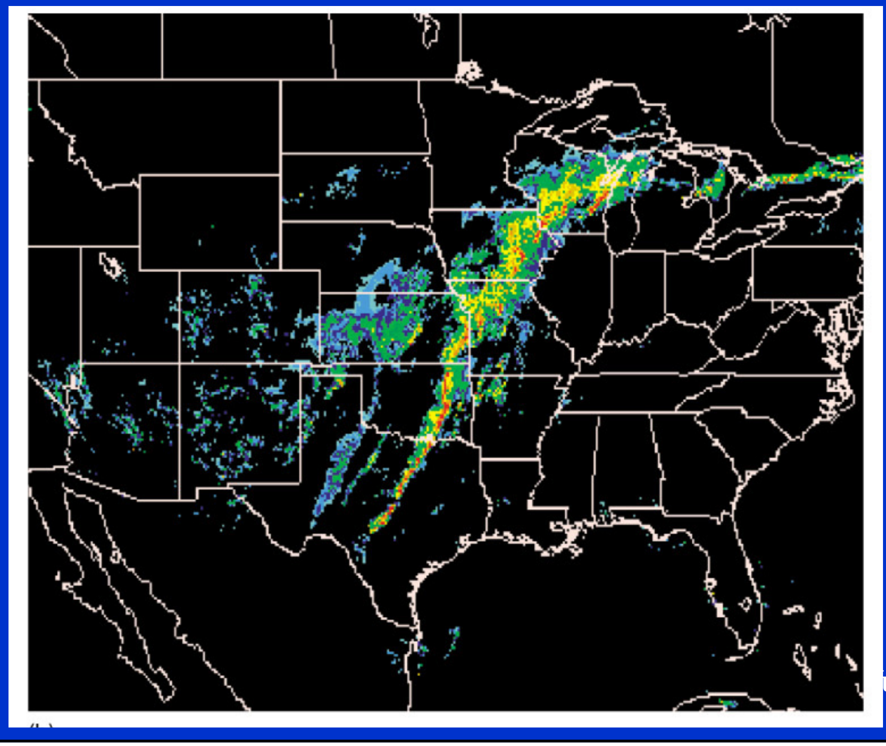
- ***East of the Cyclone***: widespread clouds and precipitations to the north of the warm front in the forms of rain, freezing rain, and/or snow.
- ***South of the Cyclone***: a line of showers or thunderstorms forms along the leading eastern-most boundary, which could be the upper-level front, dry line, or a cold front.
- These two precipitation centers (east and south) form a "Comma" cloud.
- ***Northwest of the Cyclone***: Snow forms along the up-slope side of the Rockies.

Extratropical Cyclone / Winter Storm

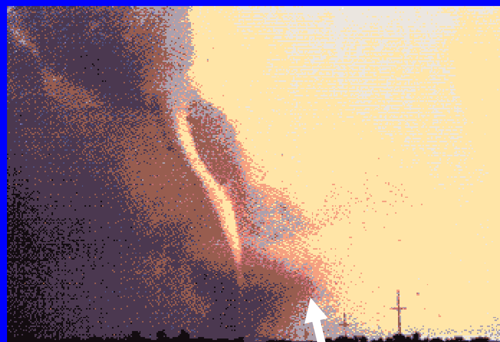


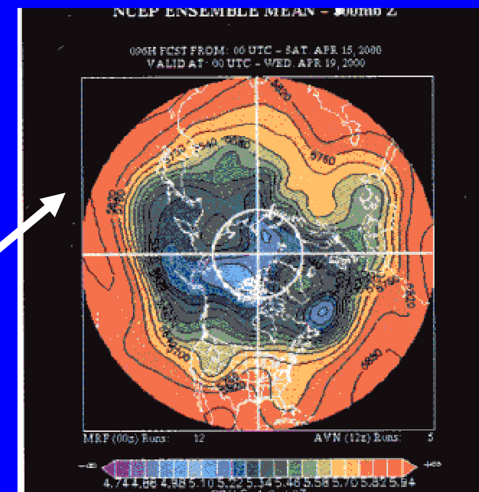


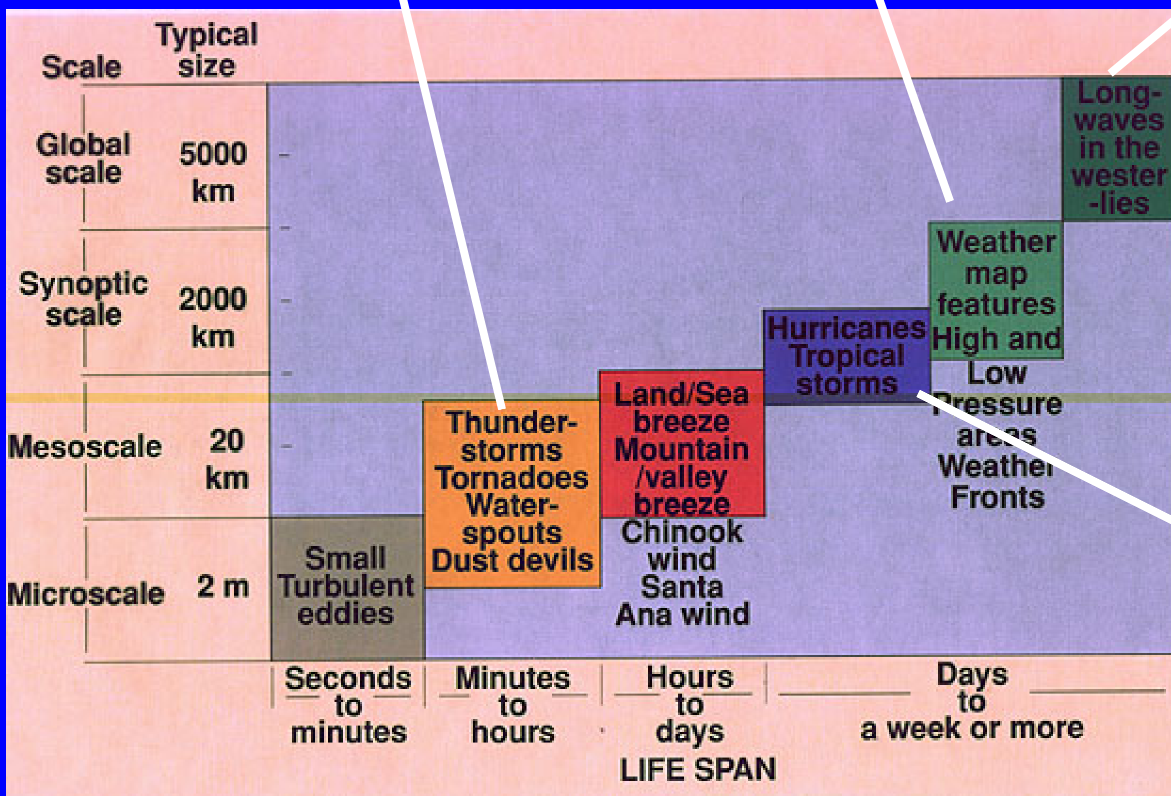




Scales of Motions in the Atmosphere







(from Meteorology Today by C. Donald Ahrens © 1994 West Publishing Company)

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Extratropical Cyclones in North America

Cyclones preferentially form in five locations in North America:

(1) East of the Rocky Mountains

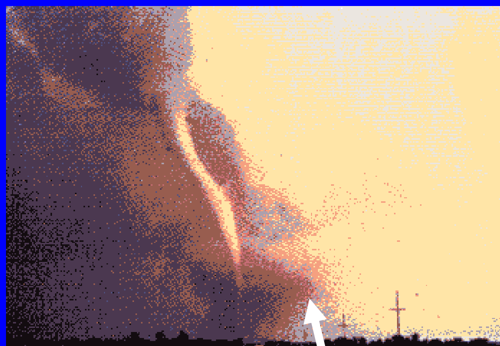
(2) East of Canadian Rockies

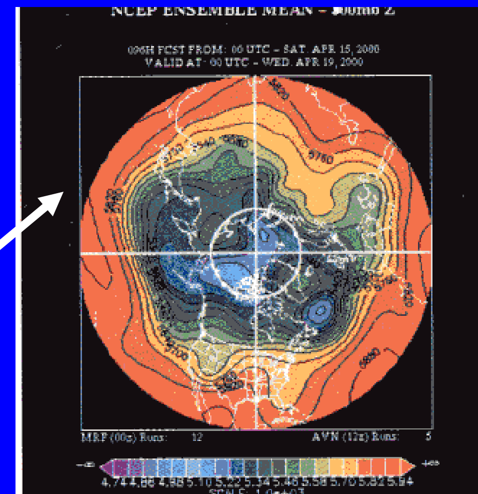
(3) Gulf Coast of the US

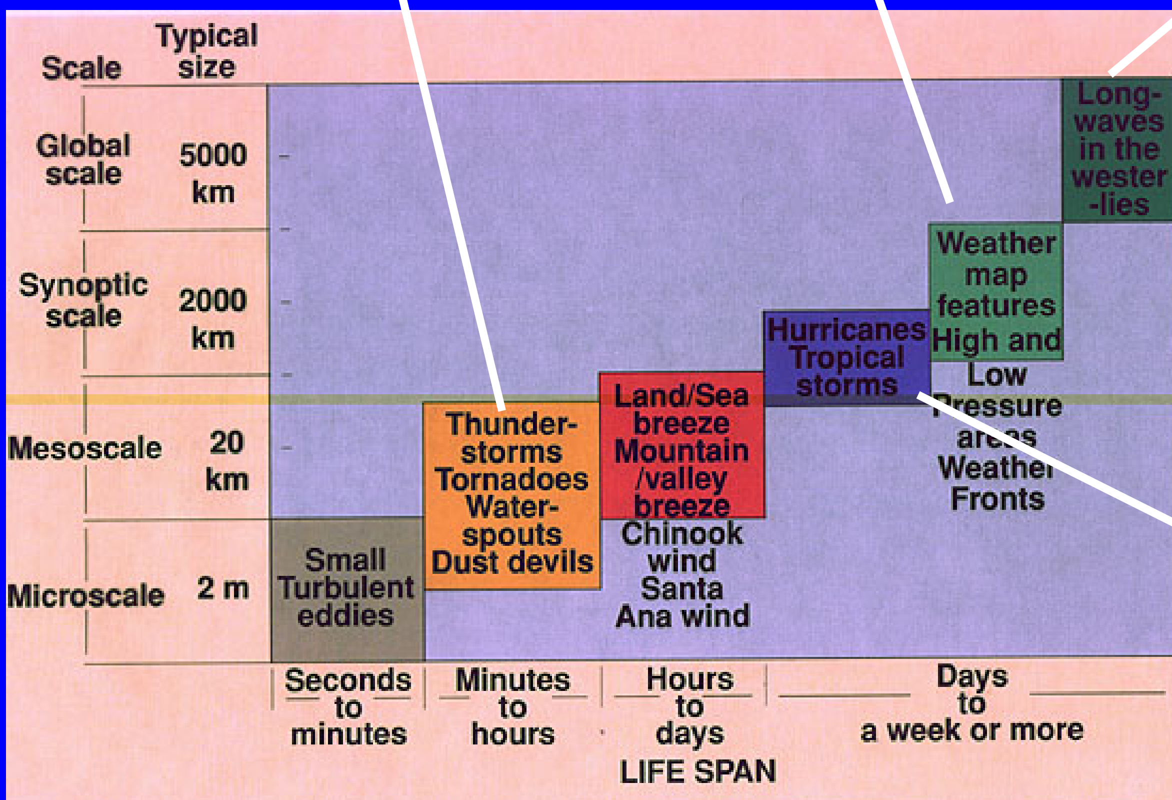
(4) East Coast of the US

(5) Bering Sea & Gulf of Alaska

Scales of Motions in the Atmosphere







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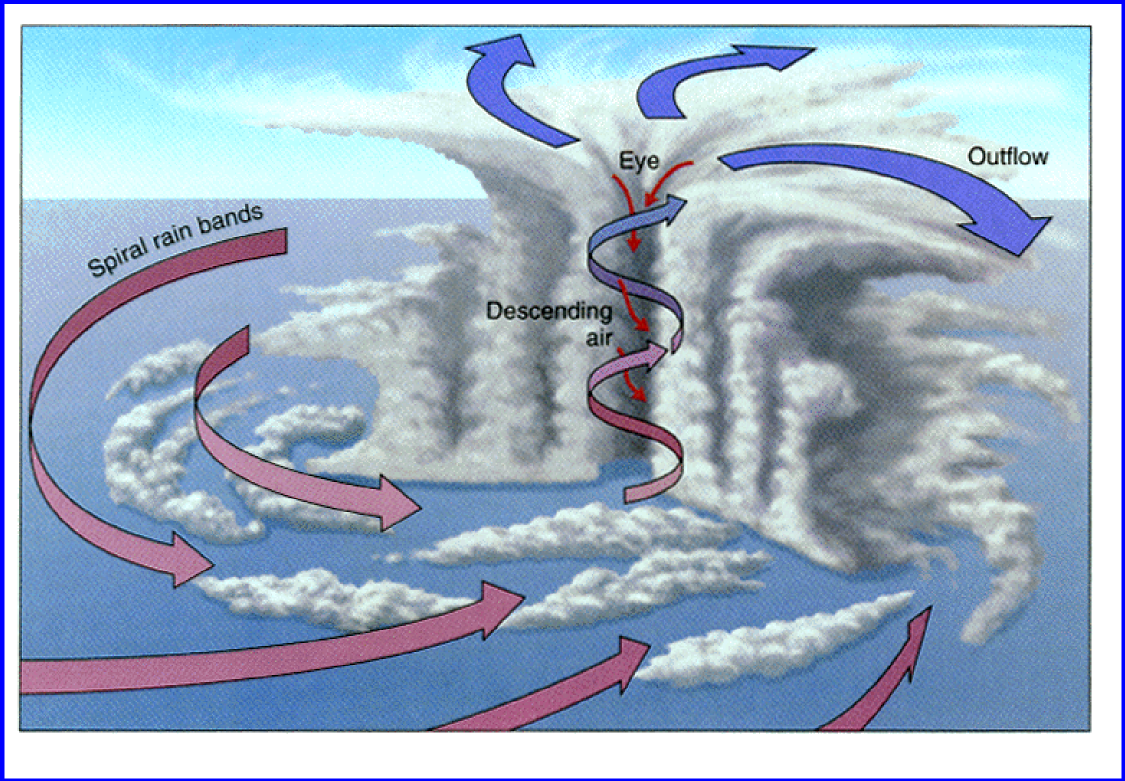
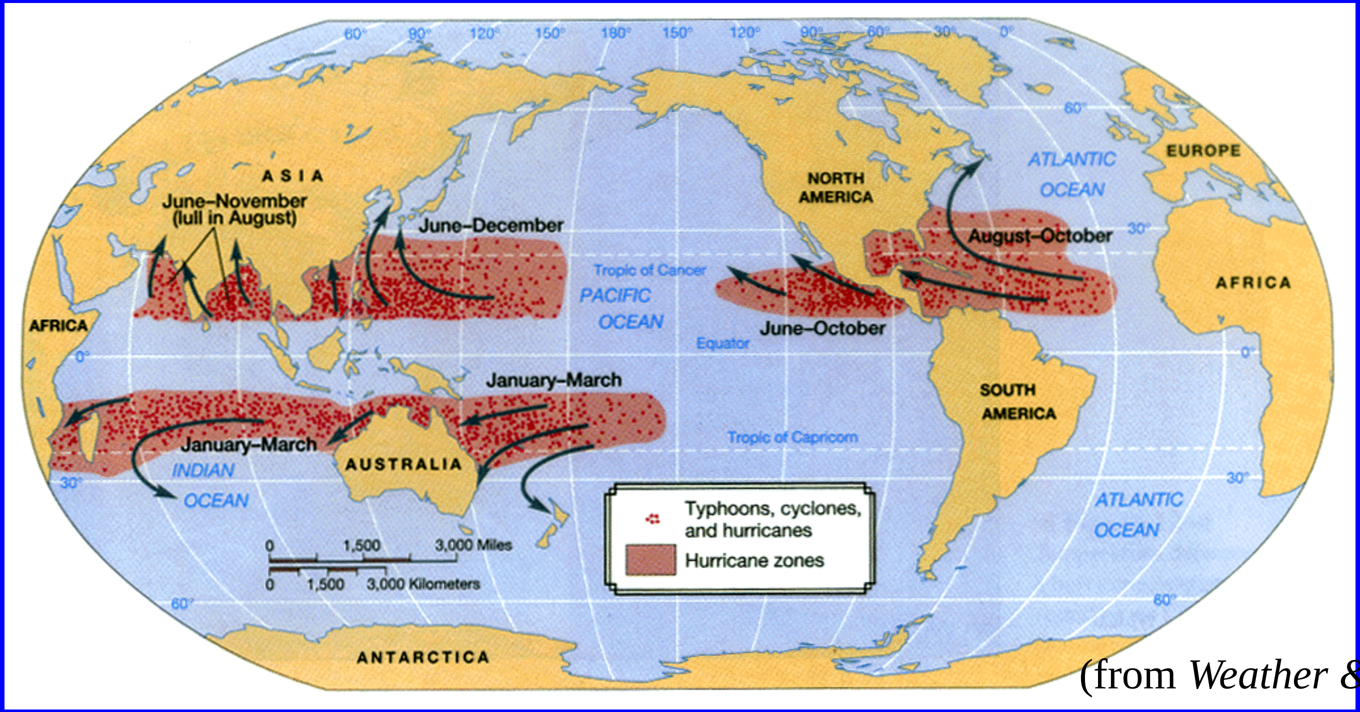
Tropical Hurricane



(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.

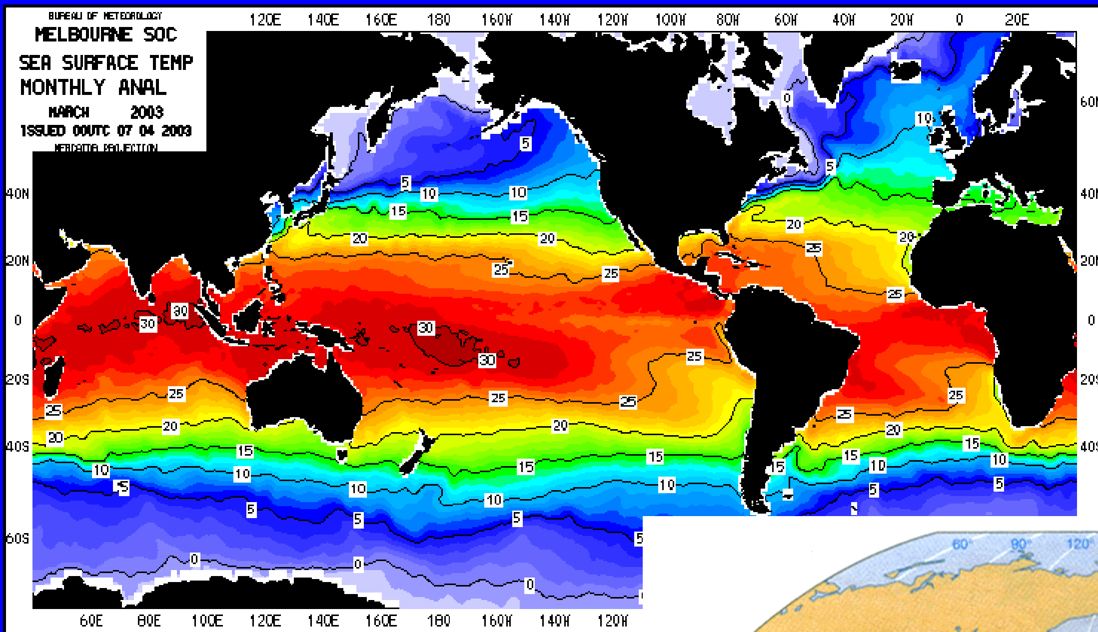
Naming Convention

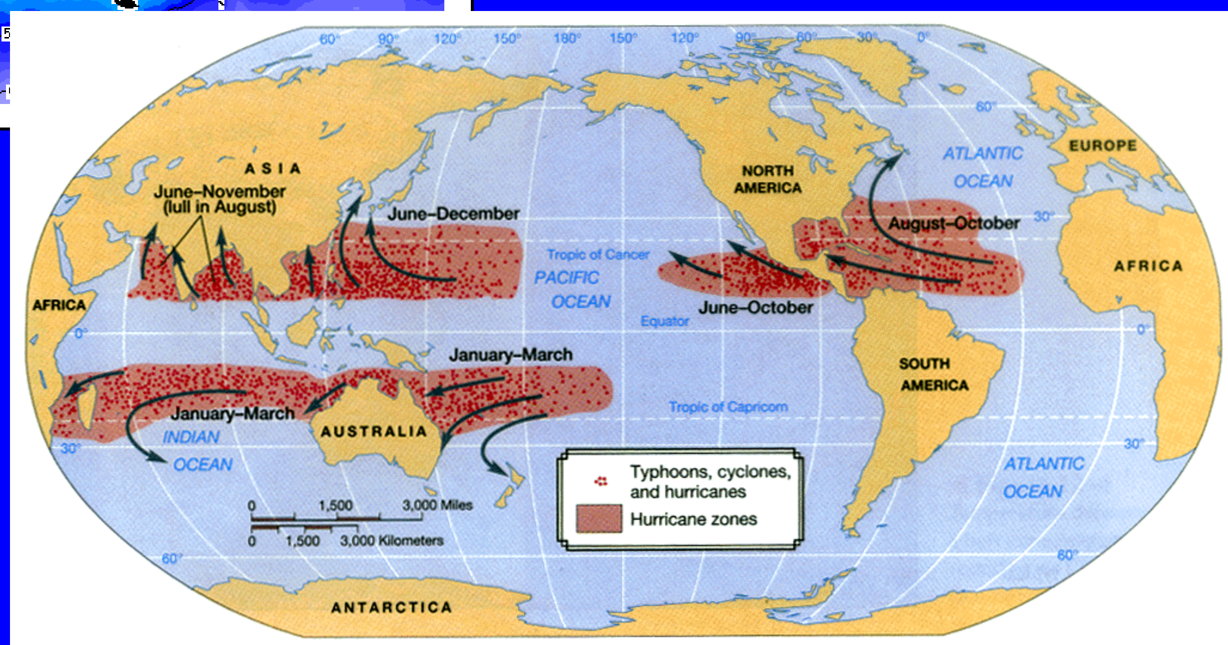


(from *Weather & Climate*)

- ***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.

Ocean Temperature And Hurricane



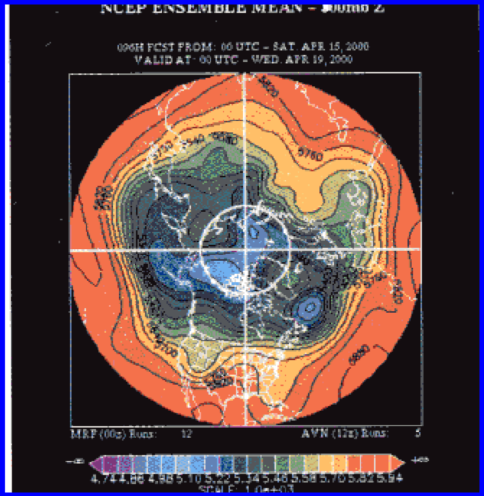


- Hurricanes form over large pools of warm water.

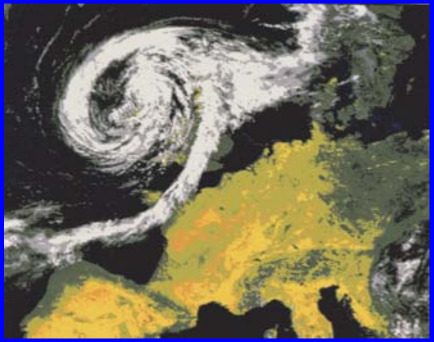
Which one is the tropical cyclone?

(A)

(C)

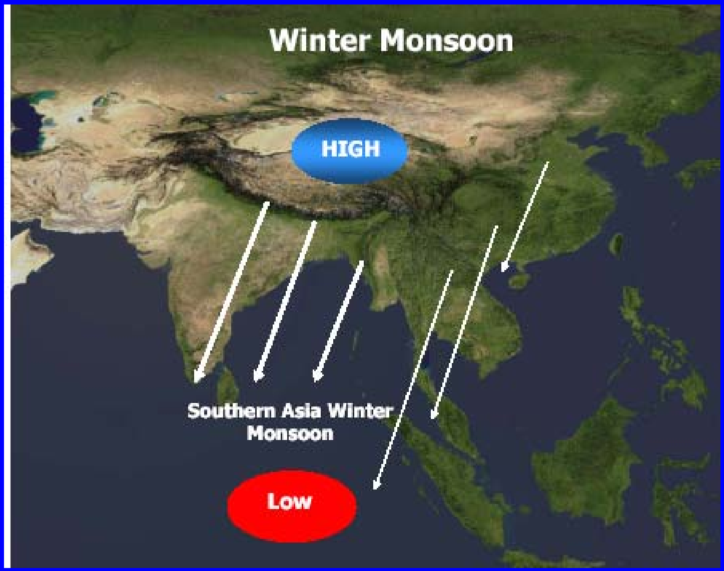


(B)

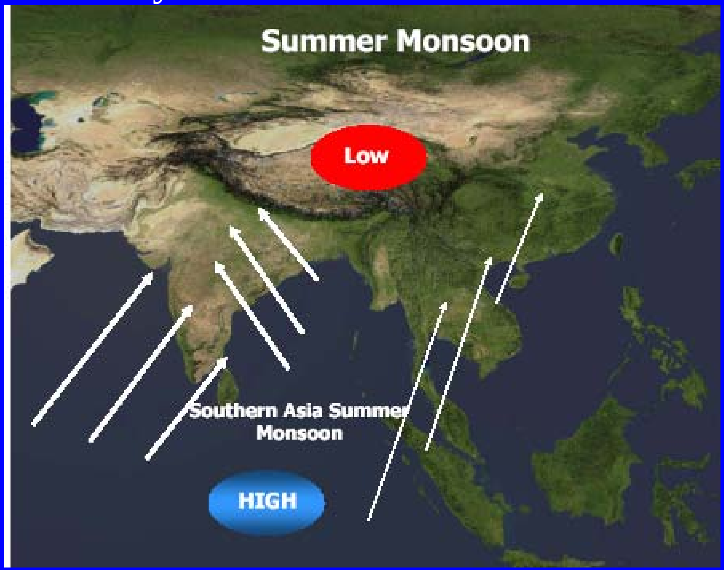


(D)

Monsoon: Sea/Land-Related Circulation



Courtesy of Kevin G. Cannariato

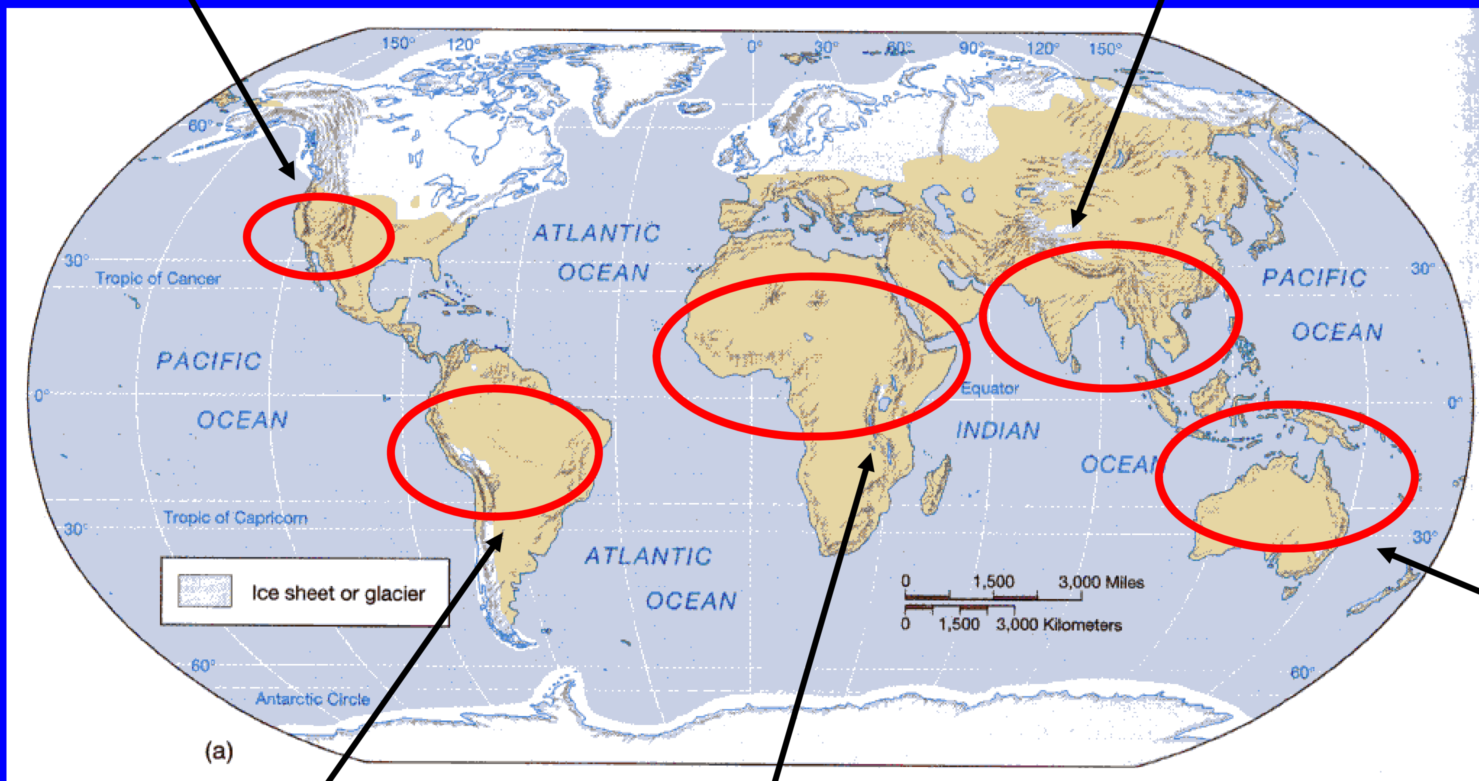


- ❑ Monsoon (Arabic "season")
- ❑ Monsoon is a climate feature that is characterized by the ***seasonal reversal in surface winds***.
- ❑ The very different heat capacity of land and ocean surface is the key mechanism that produces monsoons.
- ❑ During summer seasons, land surface heats up faster than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



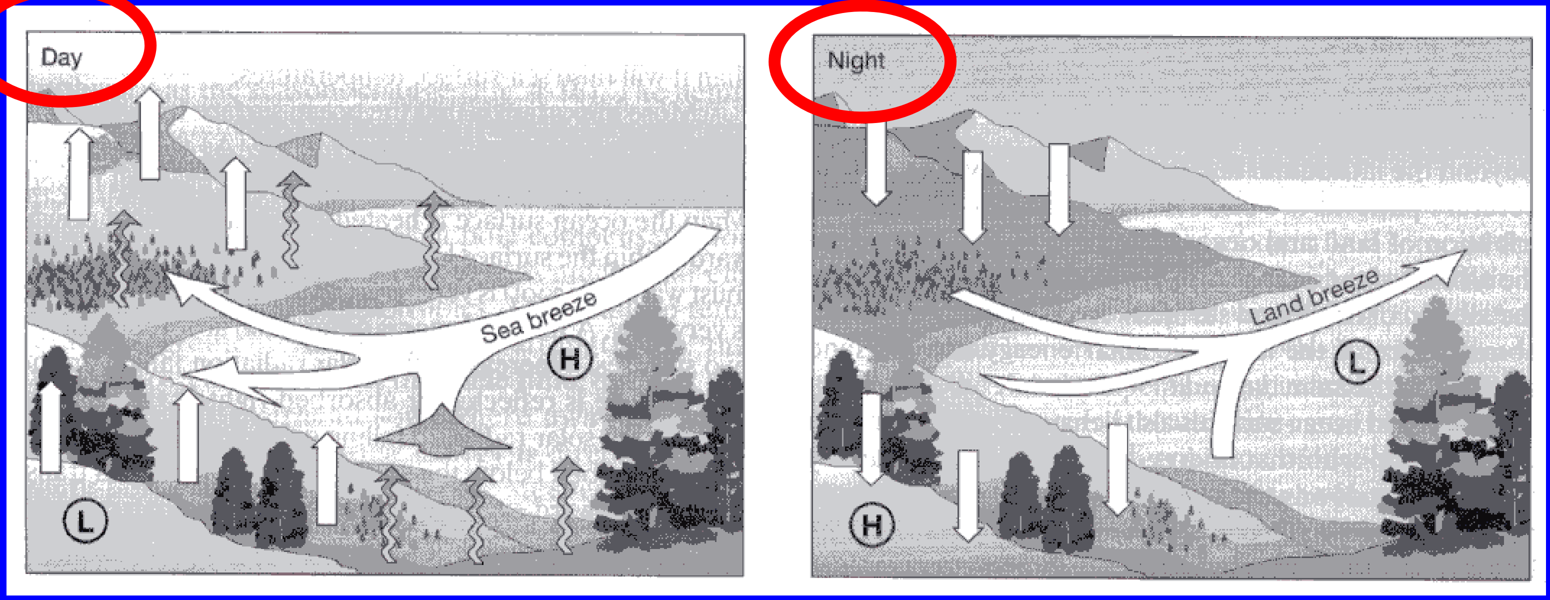
Australian Monsoon

South America Monsoon

Africa Monsoon

(figure from *Weather & Climate*)

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*)

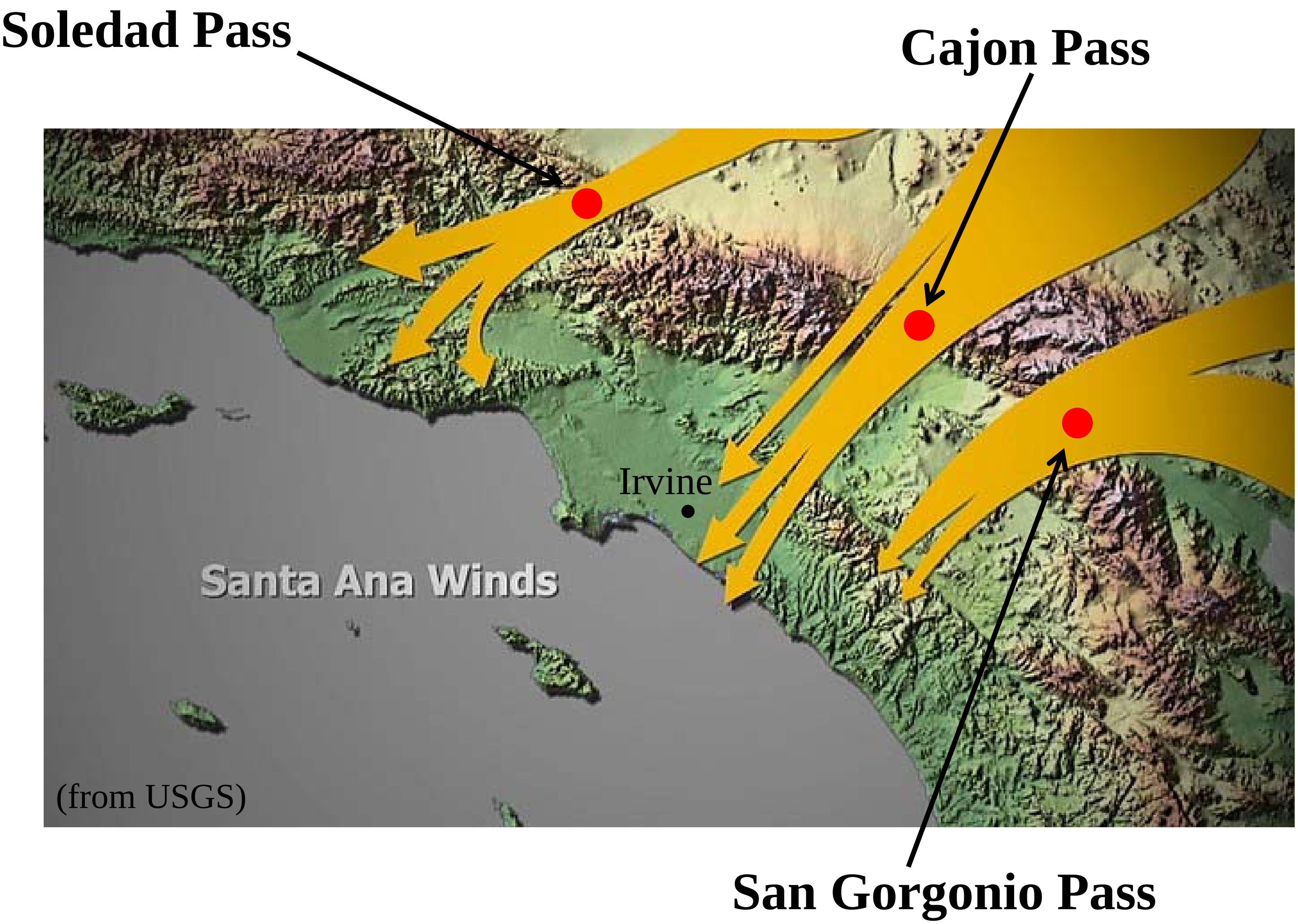
Santa Ana Wind

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).

Where do the winds enter California?

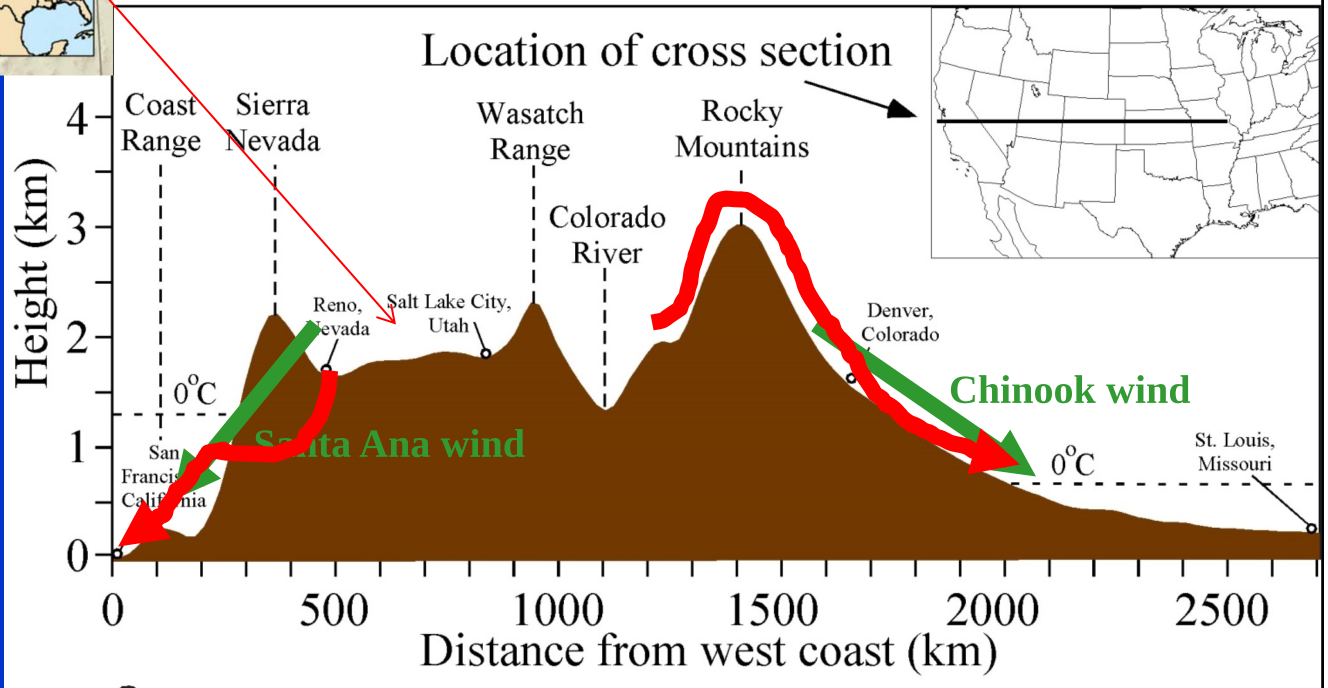


Generation Mechanism

(from NASA's Observatorium website)

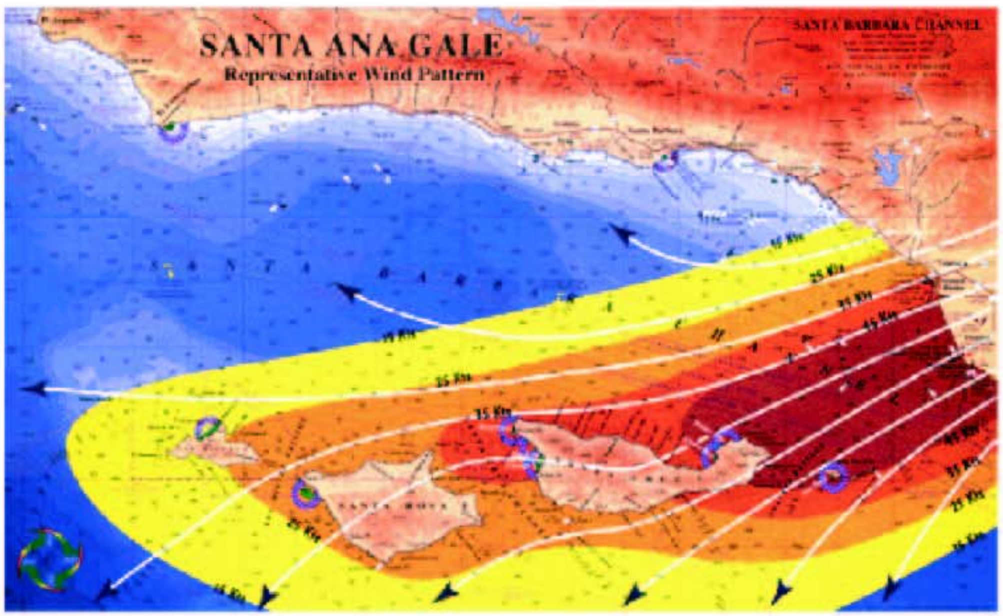
Great Basin

OREGON
IDAHO
WYOMING
Boise
Snake River Plain
Columbia Plateau
Cascade Range
Rocky Mts.
Great Basin
Sierra Nevada
Humboldt
Great Salt Lake
Salt Lake City
Ogden
Provo
Wasatch Range
Reno
Carson City
Sacramento
San Francisco
NEVADA
UTAH
Colorado Plateau
ARIZONA
CALIFORNIA
Las Vegas
Mojave Desert
Los Angeles
San Diego
Mexicali
Salton Sea
MEXICO
(from Wikipedia)



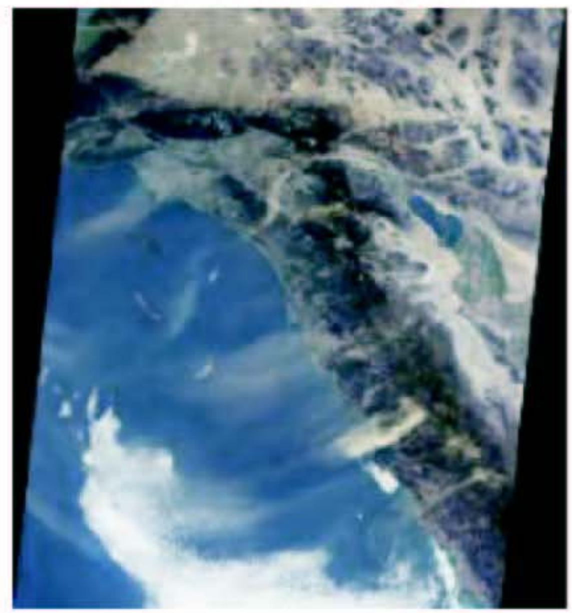
Location of cross section
Coast Range
Sierra Nevada
Wasatch Range
Rocky Mountains
Colorado River
Reno, Nevada
Salt Lake City, Utah
Denver, Colorado
St. Louis, Missouri
0°C
Santa Ana wind
Chinook wind
Height (km)
Distance from west coast (km)
0
500
1000
1500
2000
2500
1
2
3
4

Santa Ana Wind



Santa Ana Guide ©1999 Channel Crossings Press

Santa Ana winds on February 9, 2002
NASA MISR observation



Diurnal and Seasonal Variations

Diurnal variation:

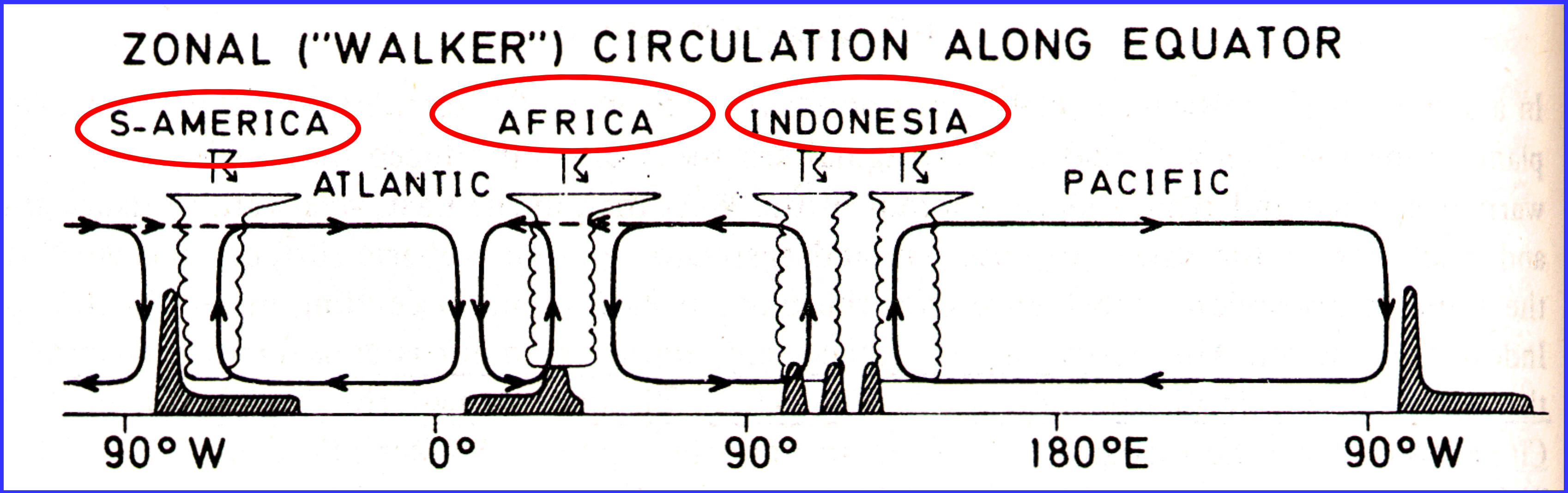
Stronger Santa Ana wind at night and weaker Santa Ana wind on the day.

Seasonal Variation:

Occurs most frequently in winter (November to March).

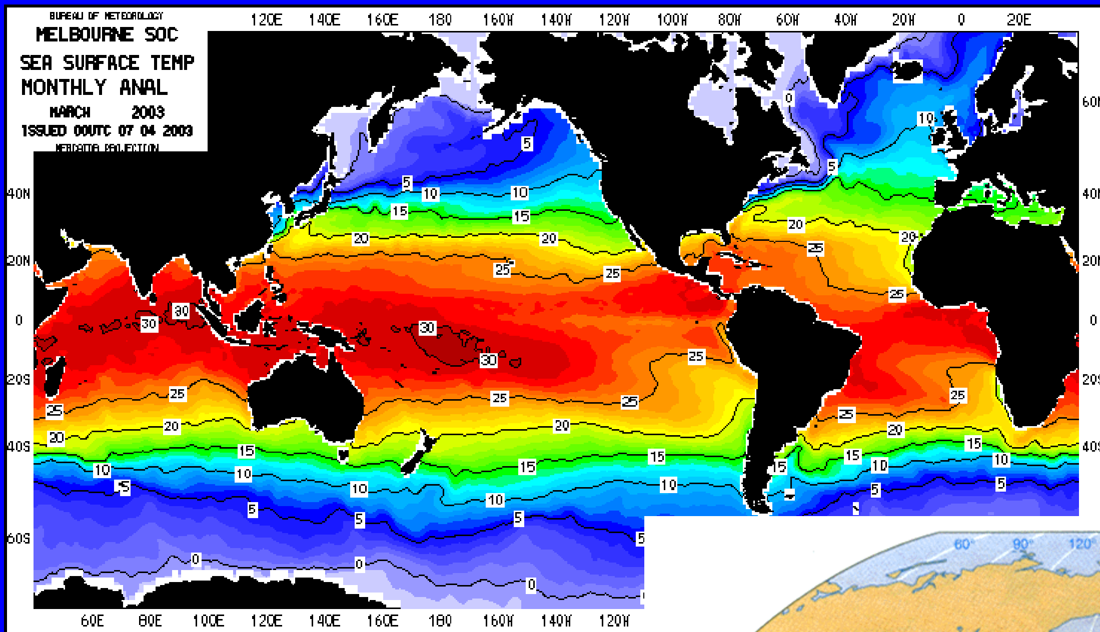
East-West Circulation

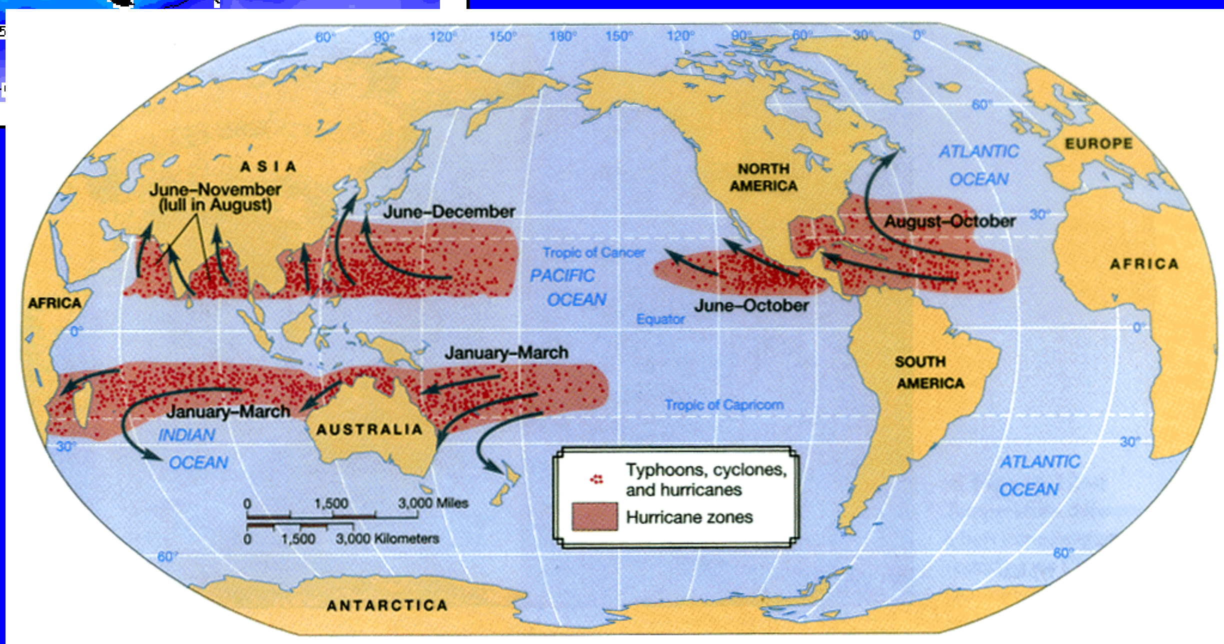
(from *Flohn (1971)*)



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

Ocean Temperature And Hurricane

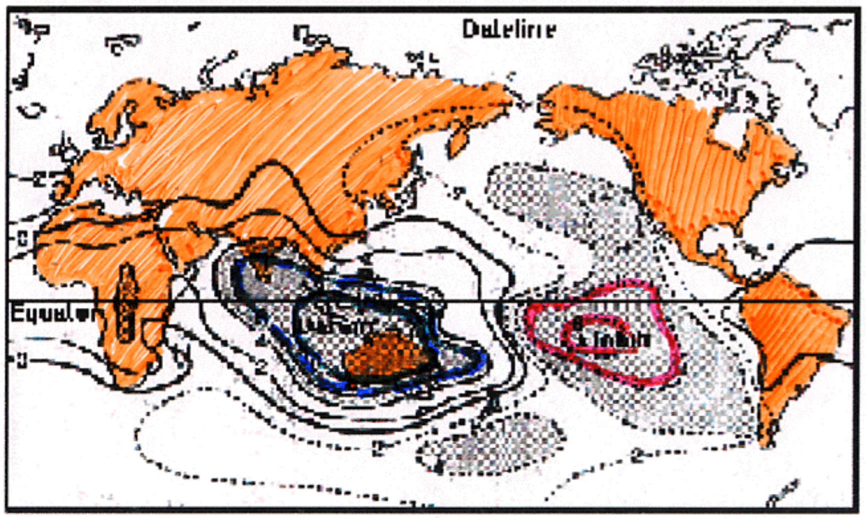




- ❑ **Hurricanes form over large pools of warm water.**

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.

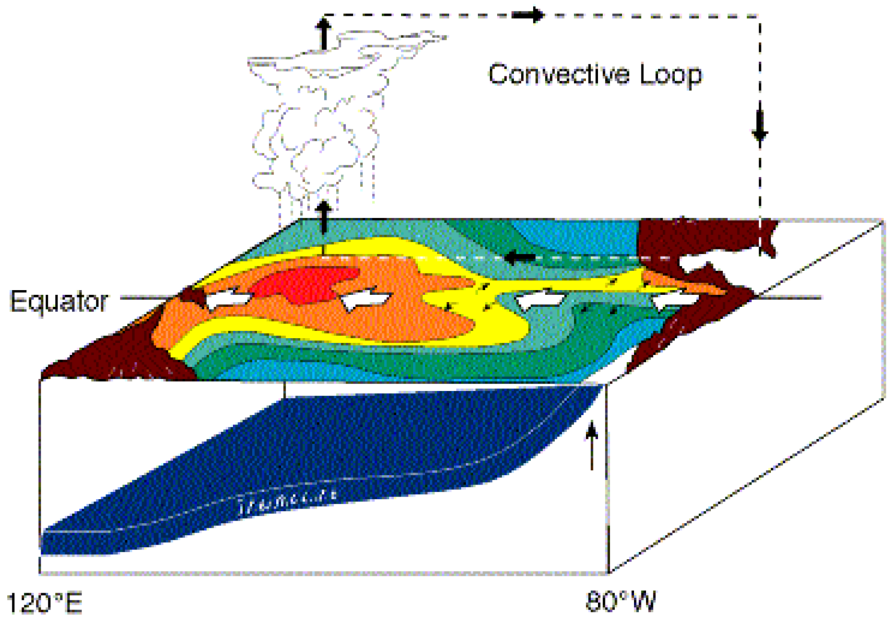


(from Rasmusson 1984)

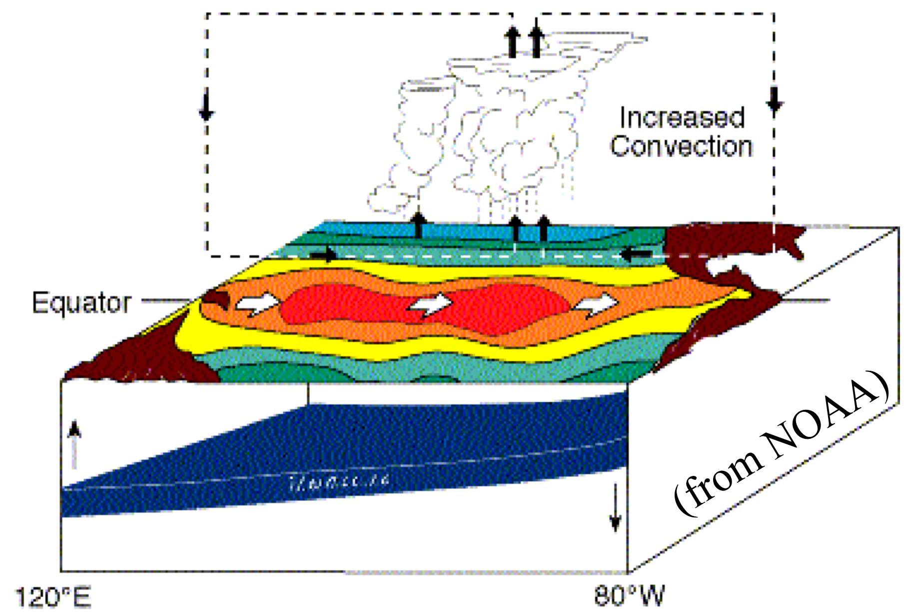
Sir Gilbert Walker

El Nino-Southern Oscillation

Normal Condition

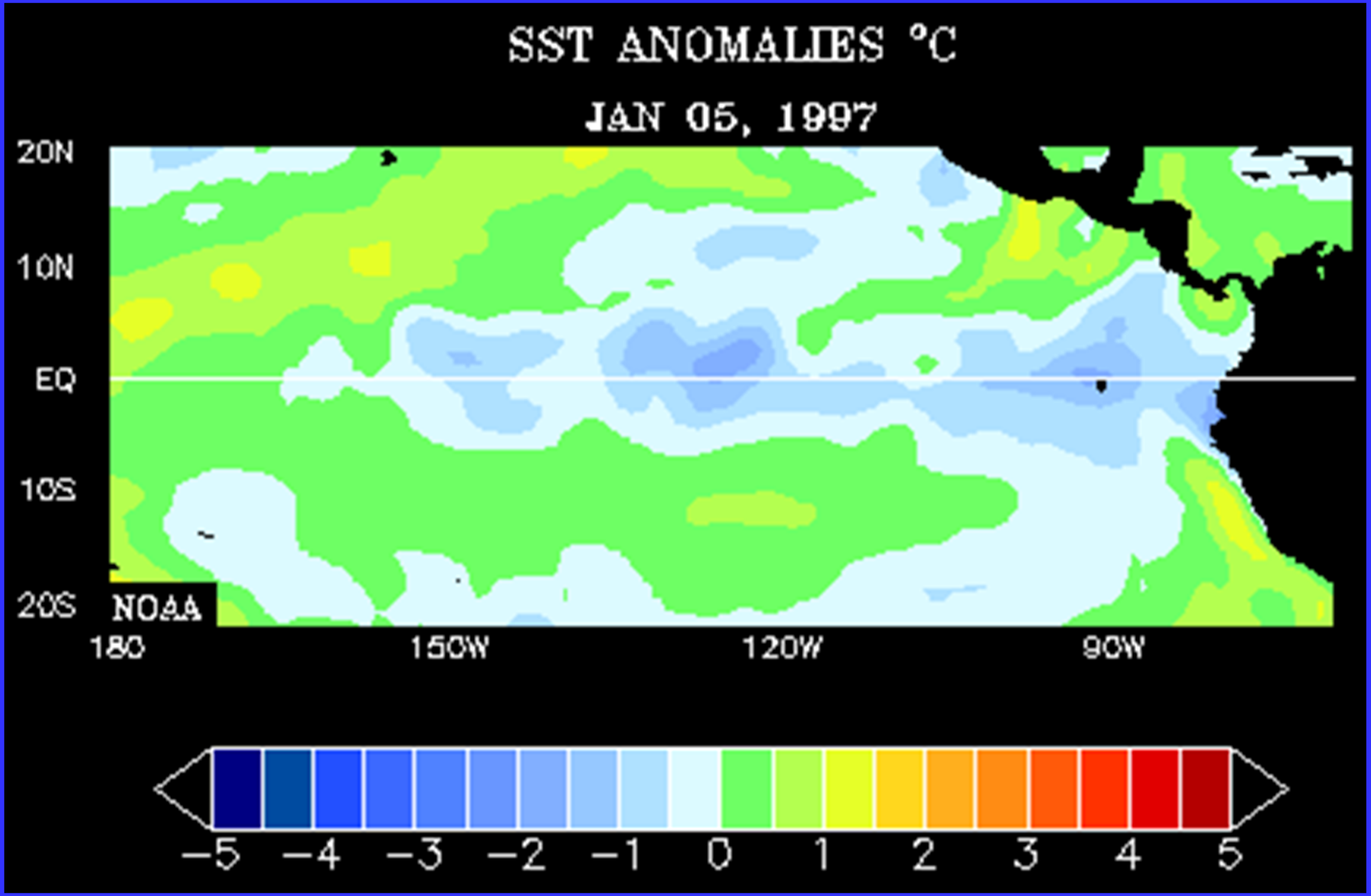


ENSO Condition



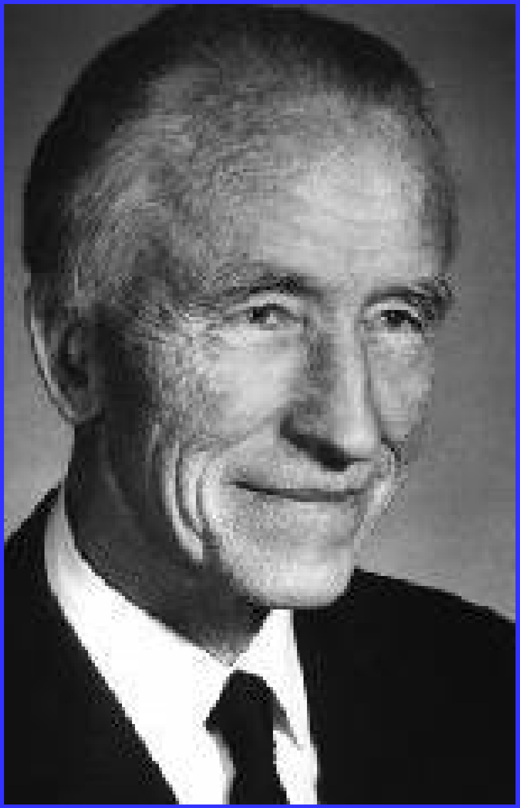
ENSO is a ***basin-wide*** coupled ocean-atmosphere phenomenon that involves equatorial ***thermocline variations***.

1997-98 El Nino



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

Hurricanes occur in ____________

(a) polar regions (b) mid-latitudes (c) tropics

Monsoons occur in ______________

(a) polar regions (b) mid-latitudes (c) tropics

Winter storms occur in ____________

(a) mid-latitudes (b) tropics

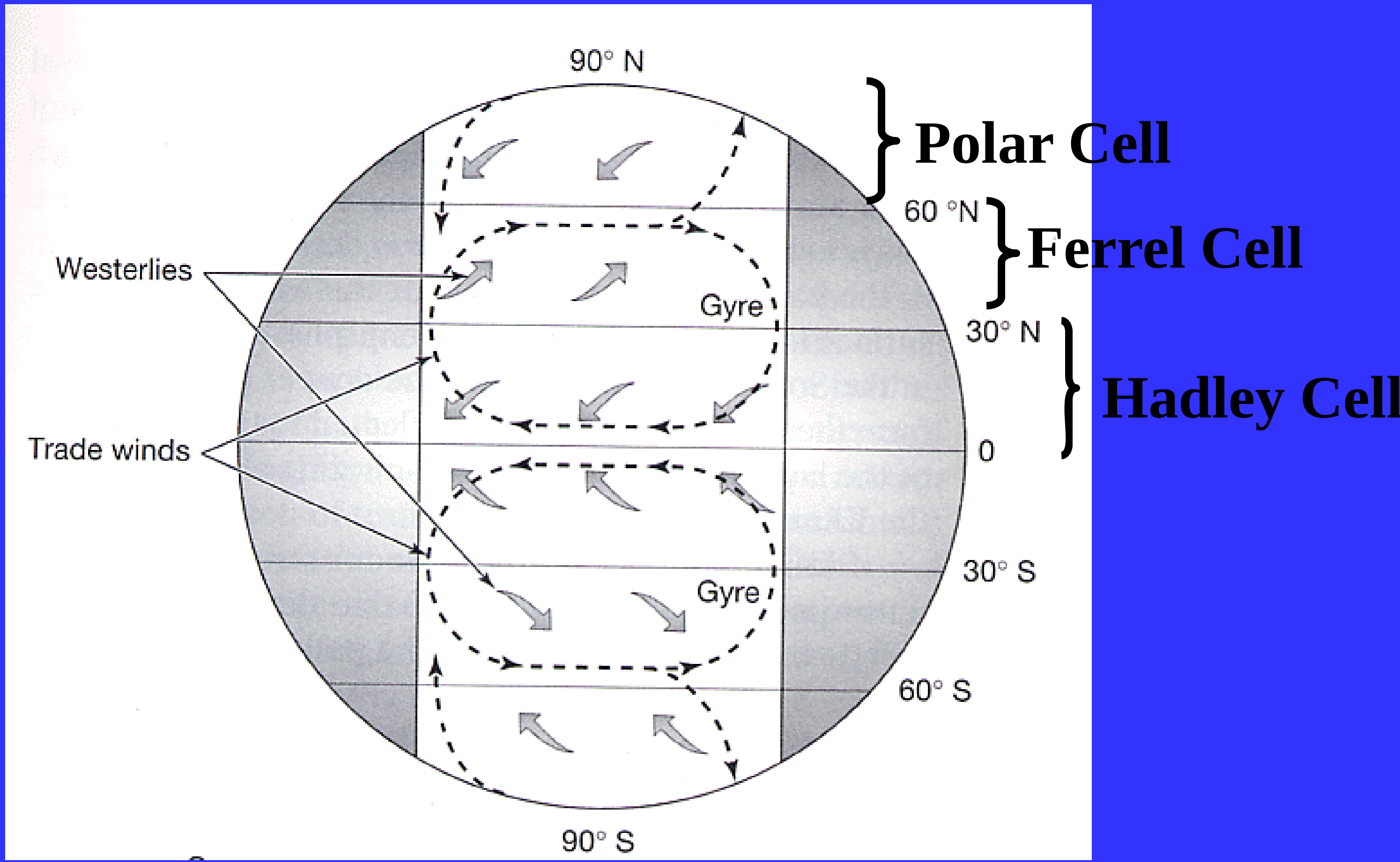
Sea-land breezes occur in ______________

(a) polar regions (b) mid-latitudes (c) tropics

Walker circulations locate in ____________

(a) polar regions (b) mid-latitudes (c) tropics

Winds and Surface Currents



(Figure from *The Earth System*)

ESS15
Prof. Jin-Yi Yu

Basic Ocean Structures

Warm up by sunlight!

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

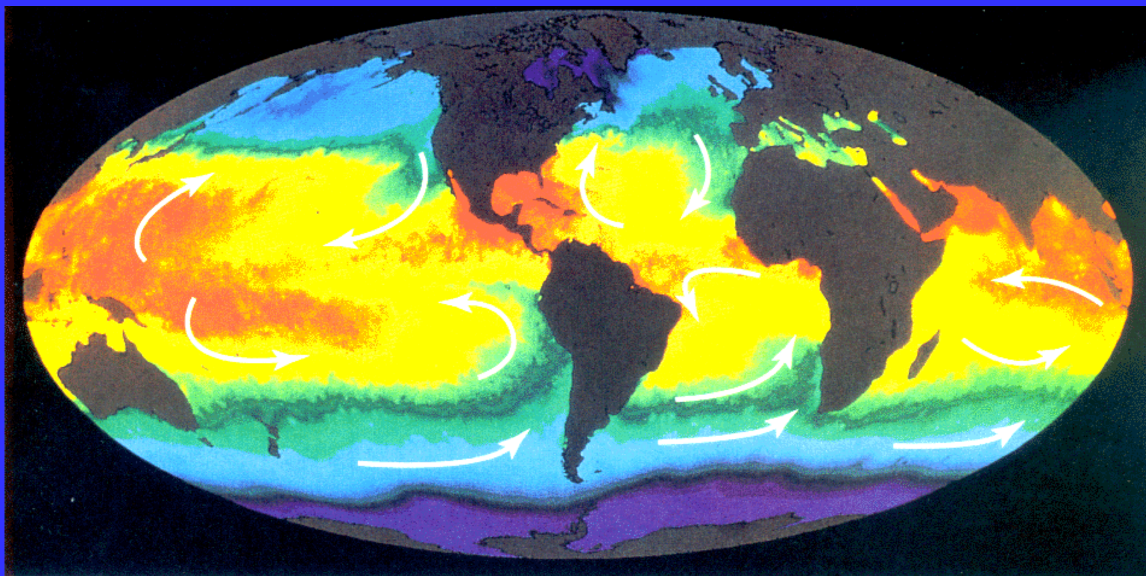
  Shallow, warm upper layer where light is abundant and where most marine life can be found.

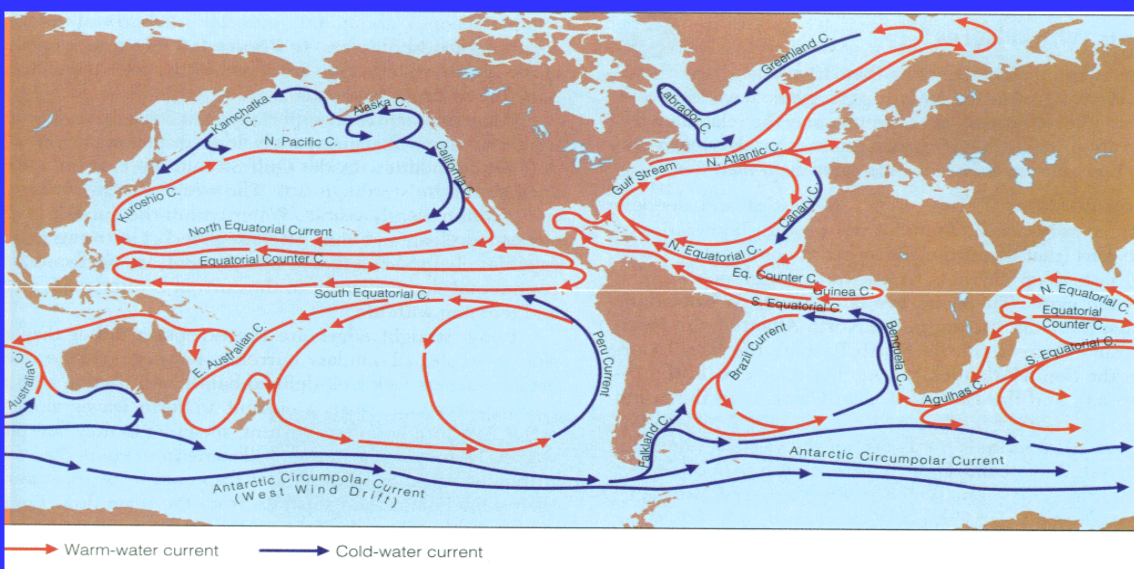
- **Deep Ocean**

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

No sunlight!

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:**

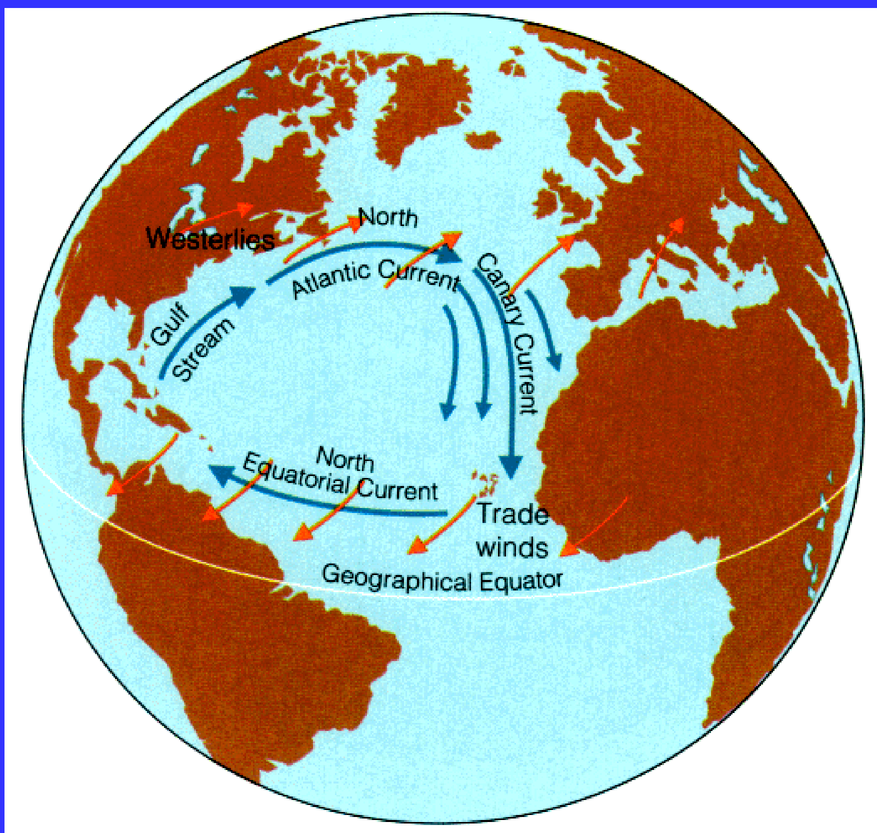
Antarctic Circumpolr Current

(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)

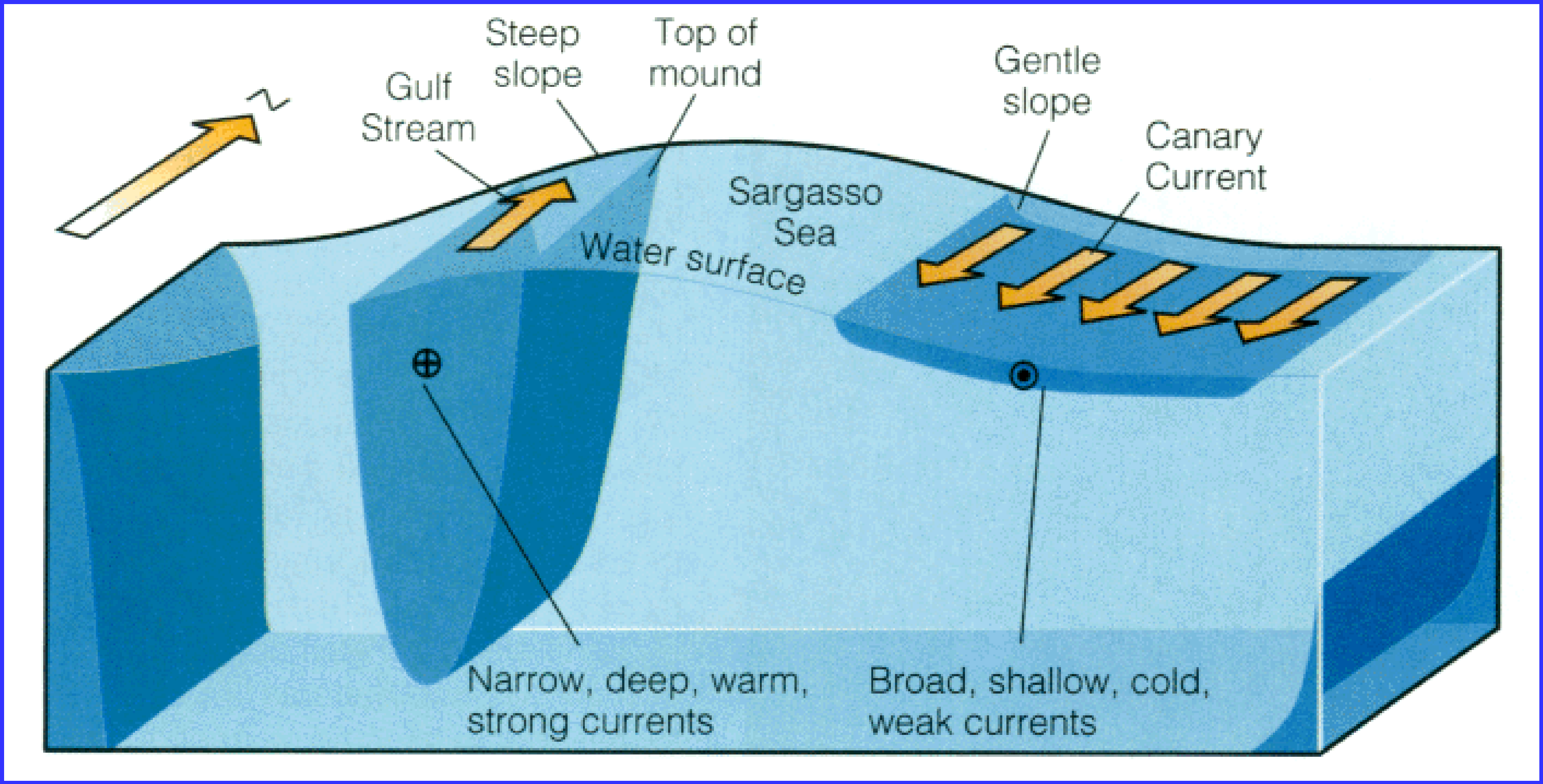
Trade wind-driven current

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

Boundary Currents



(Figure from *Oceanography* by Tom Garrison)

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)

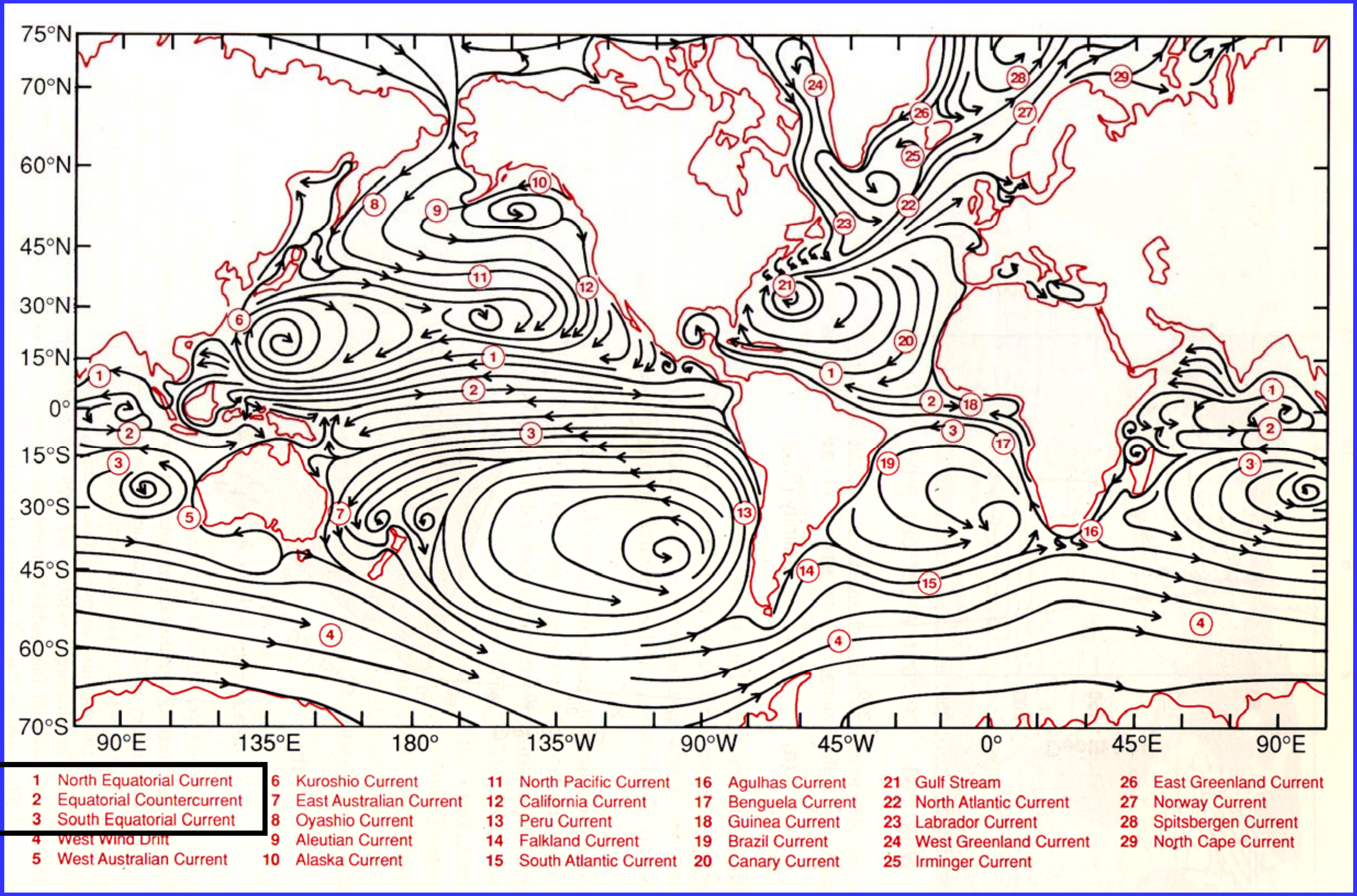
- **Trade Wind-Driven Current**

  North Equatorial Current
  South Equatorial Current

- **Westerly-Driven Current**

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

Global Surface Currents



(from *Climate System Modeling*)

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Thermohaline Circulation

- Thermo → temperature
- Haline → salinity

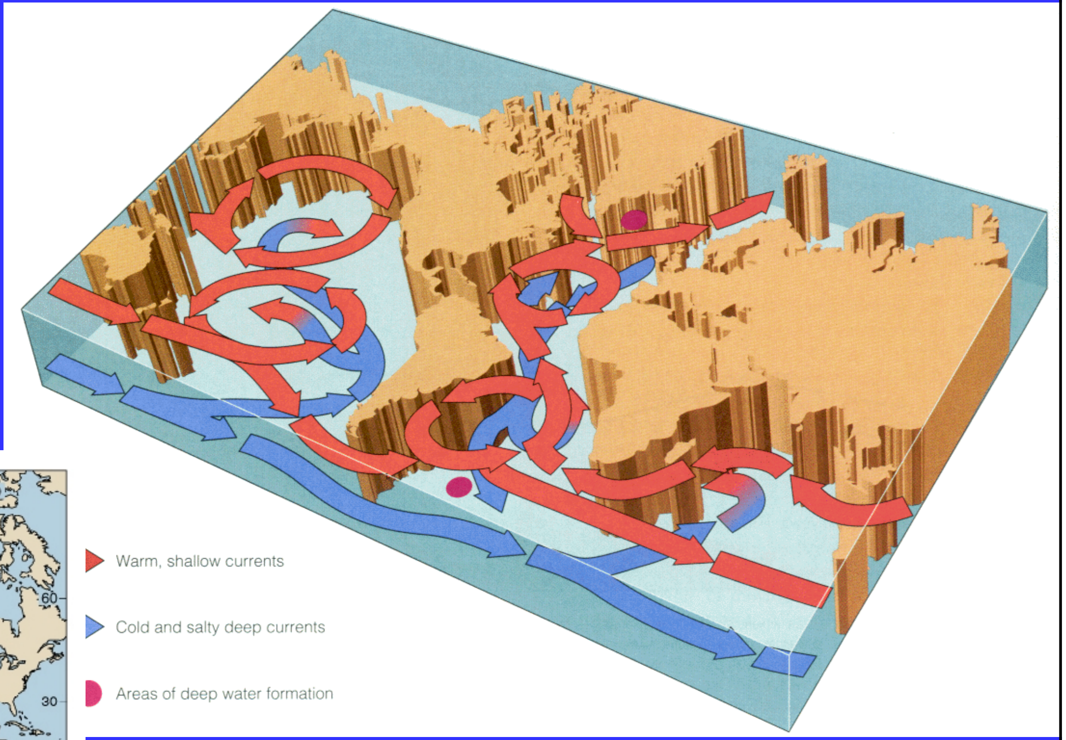
Density-Driven Circulation

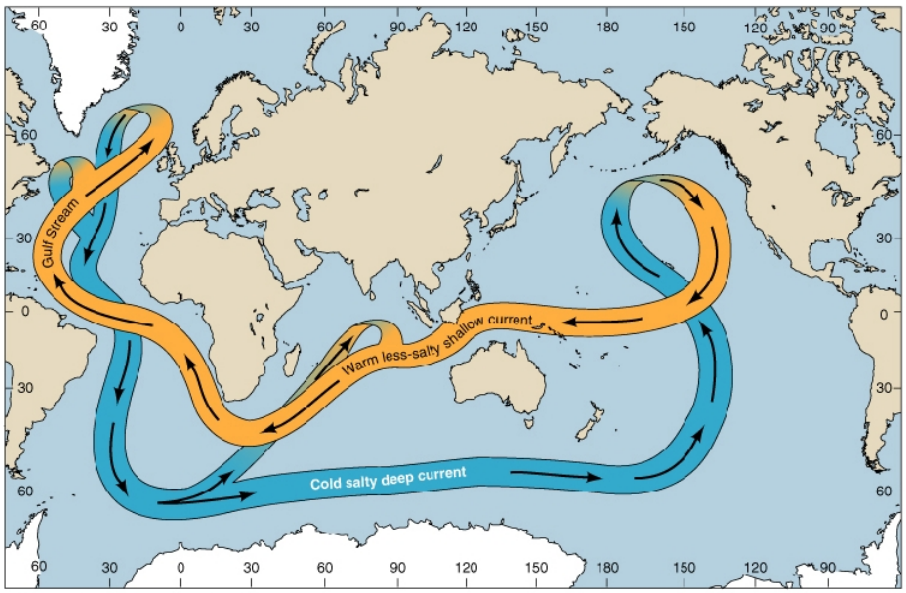
Cold and salty waters go down

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)

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.