Mon Nov 3

Announcements:

- Midterm key on web (see Homeworks and Midterm button)
- Three chapters this week - see reading guide on HW#4
- McCain-Leiberman, election day tomorrow

Where we're going:

- Week 6: present climate
- Week 7: ancient climates, Earth history
- Week 8: recent climates, climate variability
- Weeks 9-11: future climates

Monday and Tuesday:

- Earth as a heat engine
- three big pumps
- atmospheric circulations
- global distribution of temperature and precipitation

Wed: Steve Warren, regional climates

Thurs: water cycle
ocean and solid earth circulations

Friday: lab on reservoirs and cycles?

upcoming talks

MONDAY 3 November

3:30 ATG 310c, Prof Sandy Tudhope, Edinburgh Univ

ENSO: Evidence from living and fossil coral

TUESDAY 4 November

12:30 ATG 310c, Weather discussion

FRIDAY 7 November

3:30 15 OTB (Oceanography Teaching Bldg)

Dr. Brent Helliker, Stanford

"Terrestrial carbon cycle response to climate change"

Physical/Chemical tools	Environmental phenomena

Causes of air motion

- bouyancy
- pressure gradient force
- friction
- Coriolis force

Air circulation

- convergence/divergence (horiz.)
- convection/subsidence (vertical)
- conservation of matter

Phase changes of water

- evaporation/condensation
- latent heat

Ocean vs land heating rate

- conduction
- specific heat capacity
- turbulent mixing
- transmission of light

Global and seasonal distribution of

- temperature
- precipitation

Hadley cell

- Trade Winds
- ITCZ
- subtropical deserts

Land/Ocean circulations

- monsoons
- land and sea breezes

Atmospheric water cycle

Layout of planet Earth

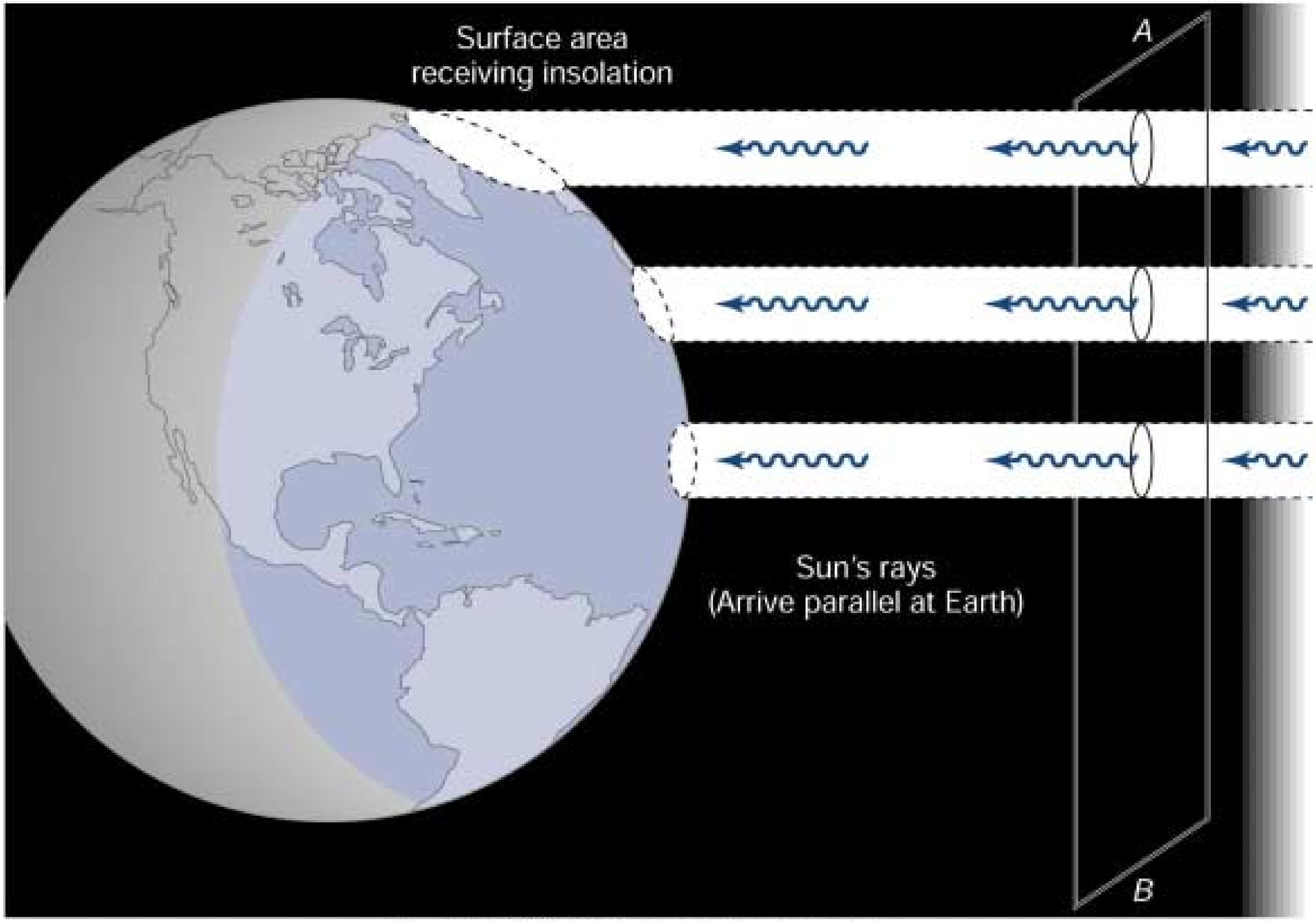
name	latitude range	portion of Earth surface
Tropics	**0 to 30º**	**50%**
Extratropics	**30 to 90º**	**50%**
Subtropics	**~30º**	
Midlatitudes	**30-60º**	**37%**
Polar Regions	**60-90º**	**13%**
Ocean		**70%**
Land		**30%**

Note:

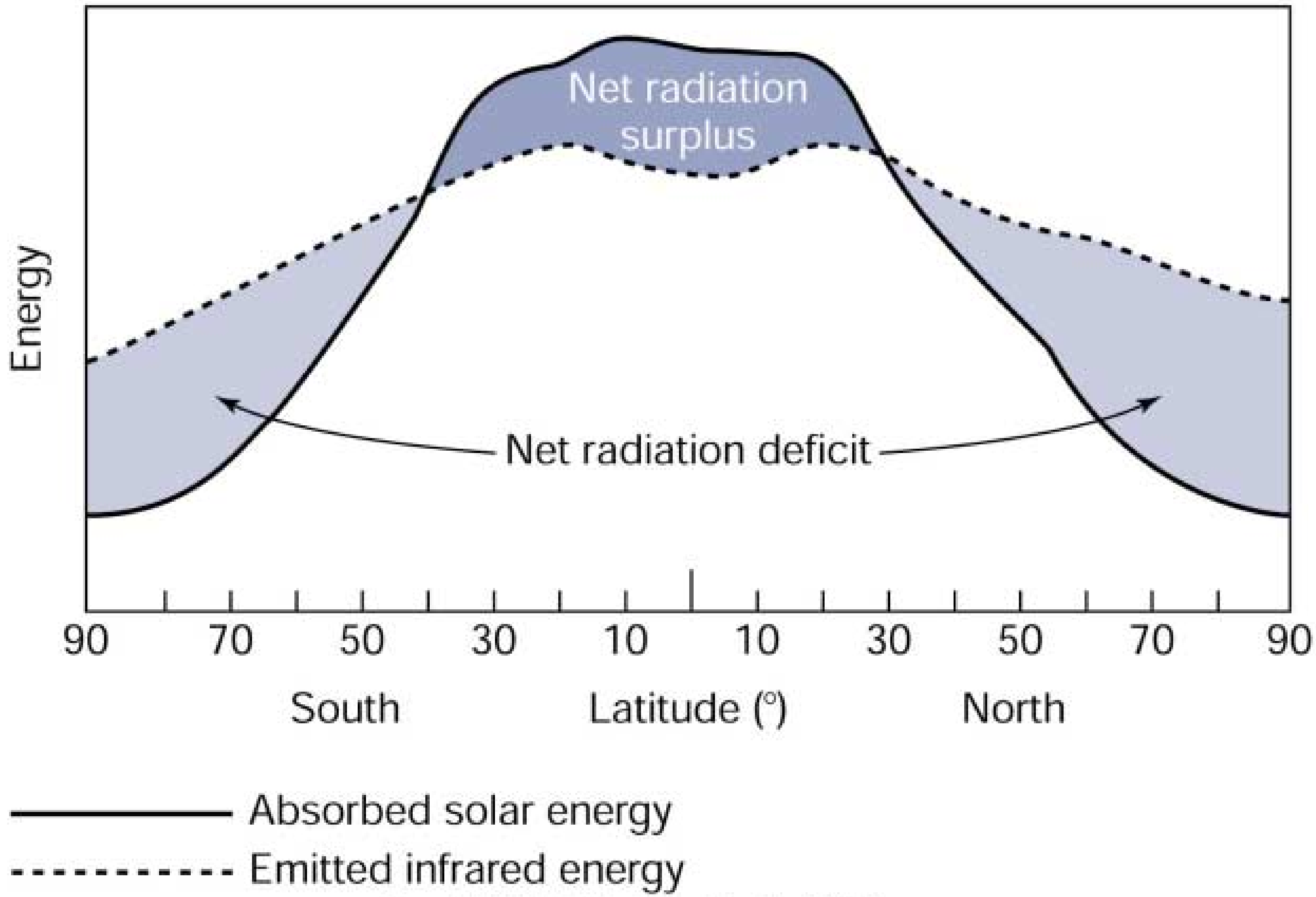
Most of Earth's surface is Tropics and/or Ocean. (These are the major components that a climate model needs to get right.)

Unequal distribution of solar energy with latitude: Fig 04_03

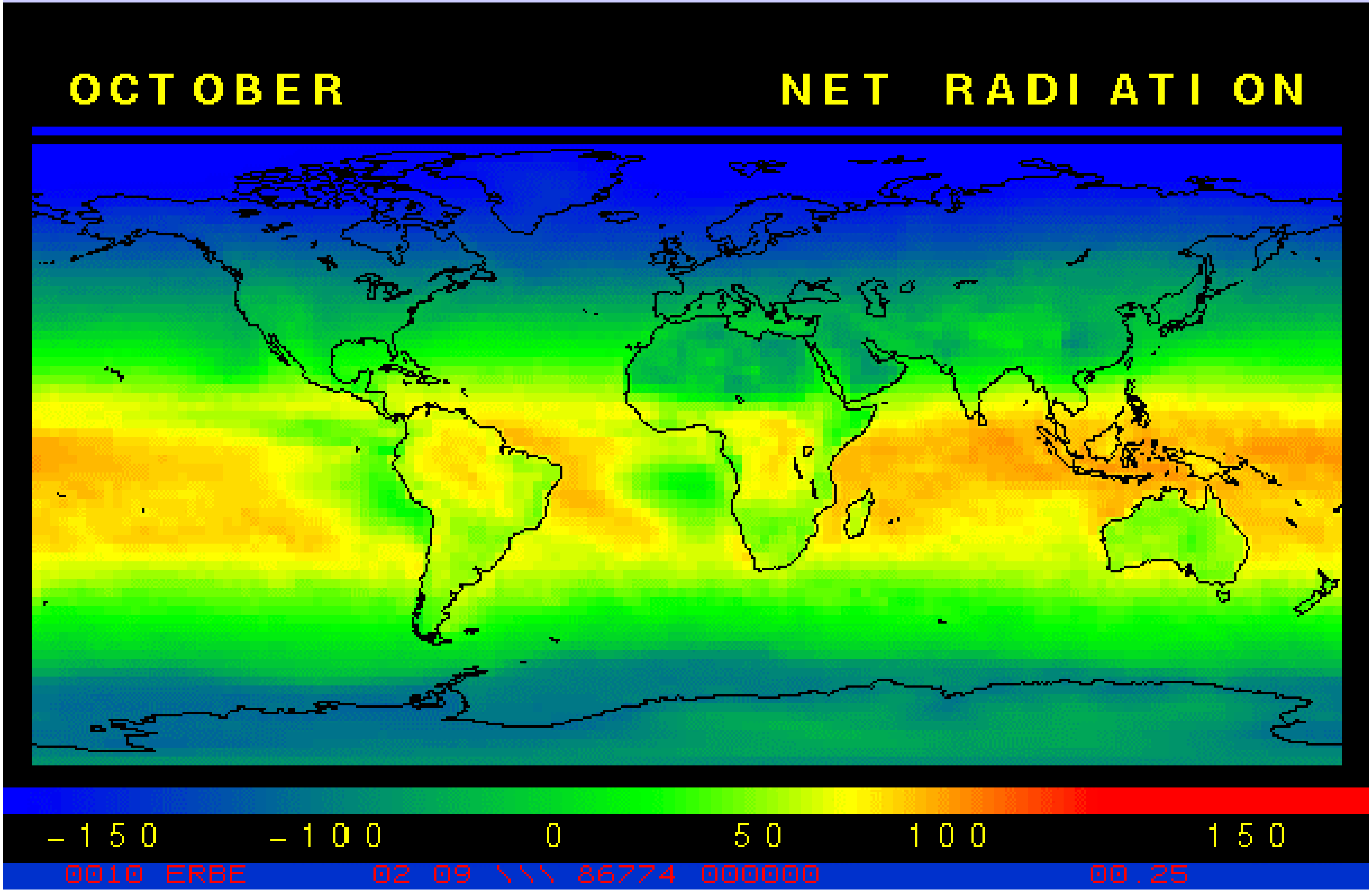
Recall: Flux is energy per unit surface area: W/m2



Net energy as a function of latitude: Fig 04_04

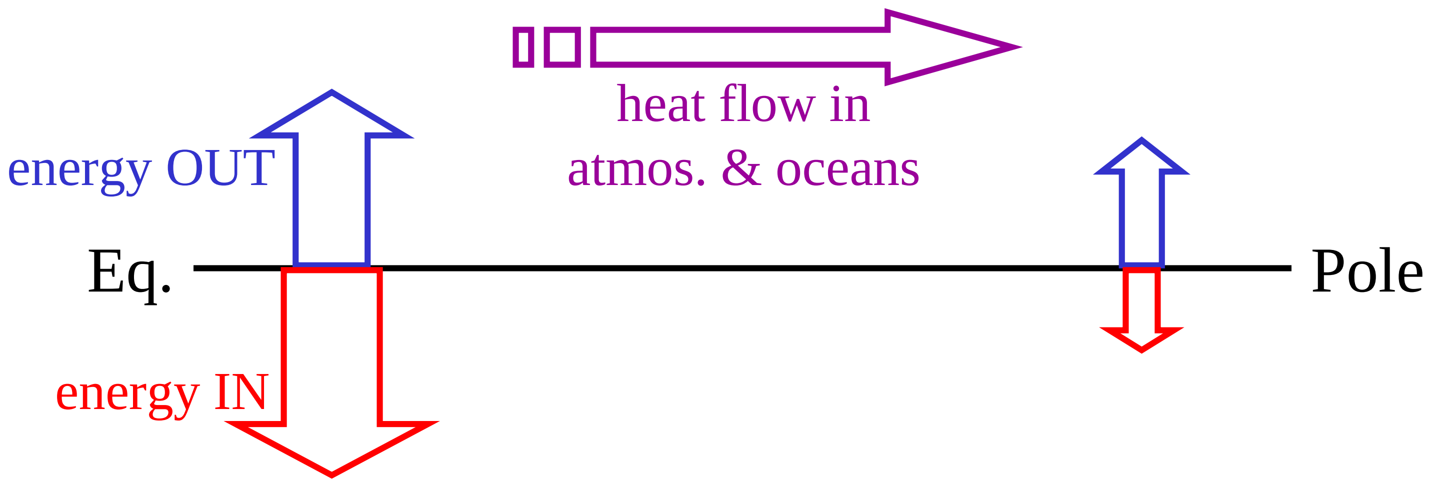


Satellite measurement of net energy: $E_{IN} - E_{OUT}$



data source: Earth Radiation Budget Experiment

Earth as a Heat Engine



With no atmosphere or ocean currents, low latitudes would continue to warm and high latitudes would continue to cool.

Atmosphere and ocean currents remove heat from Tropics and transport it to high latitudes. (Also from warm to cool regions on smaller scales - e.g. land/sea breezes.)

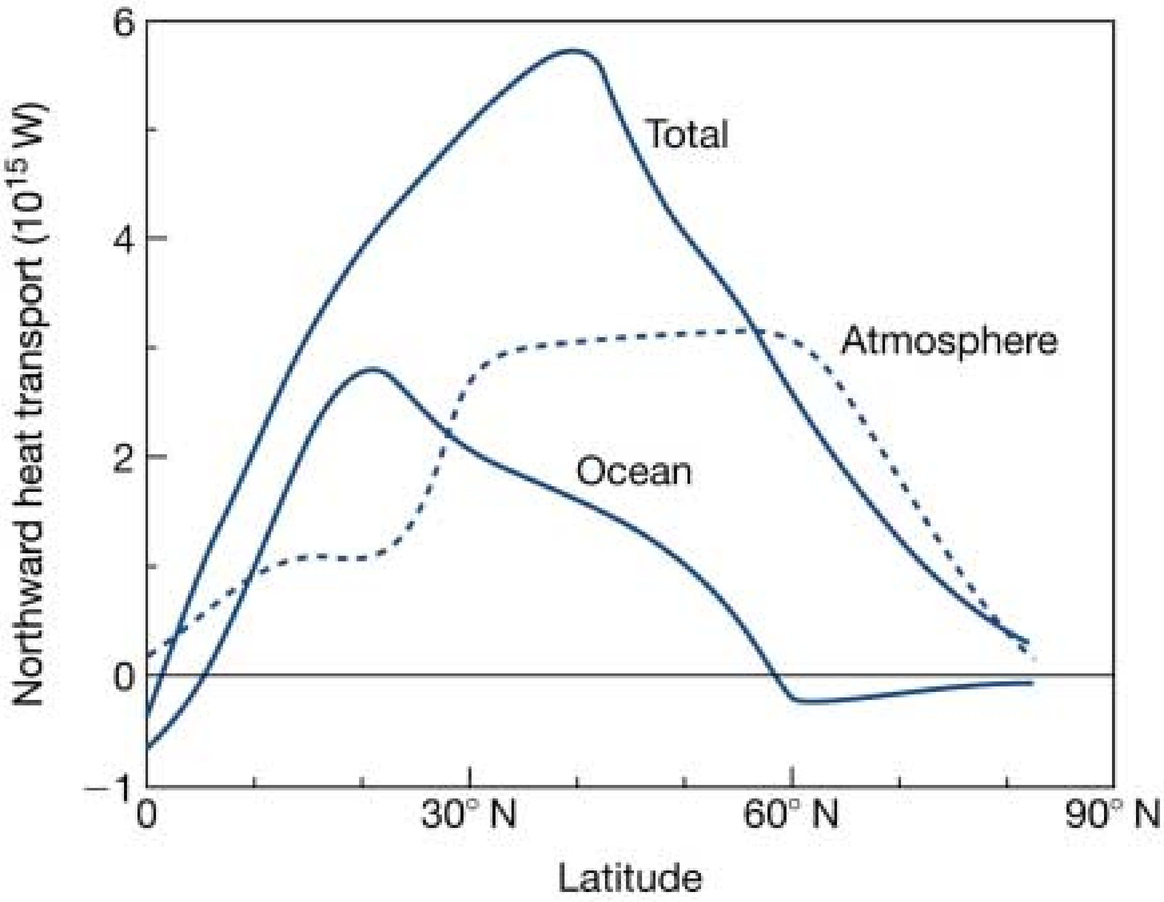
These currents cannot flow in one direction only - air and water would "pile up".

Result is "Circulation"

(warm currents poleward, cool currents equatorward)

Heat transport from low to high latitude: Fig 05_16

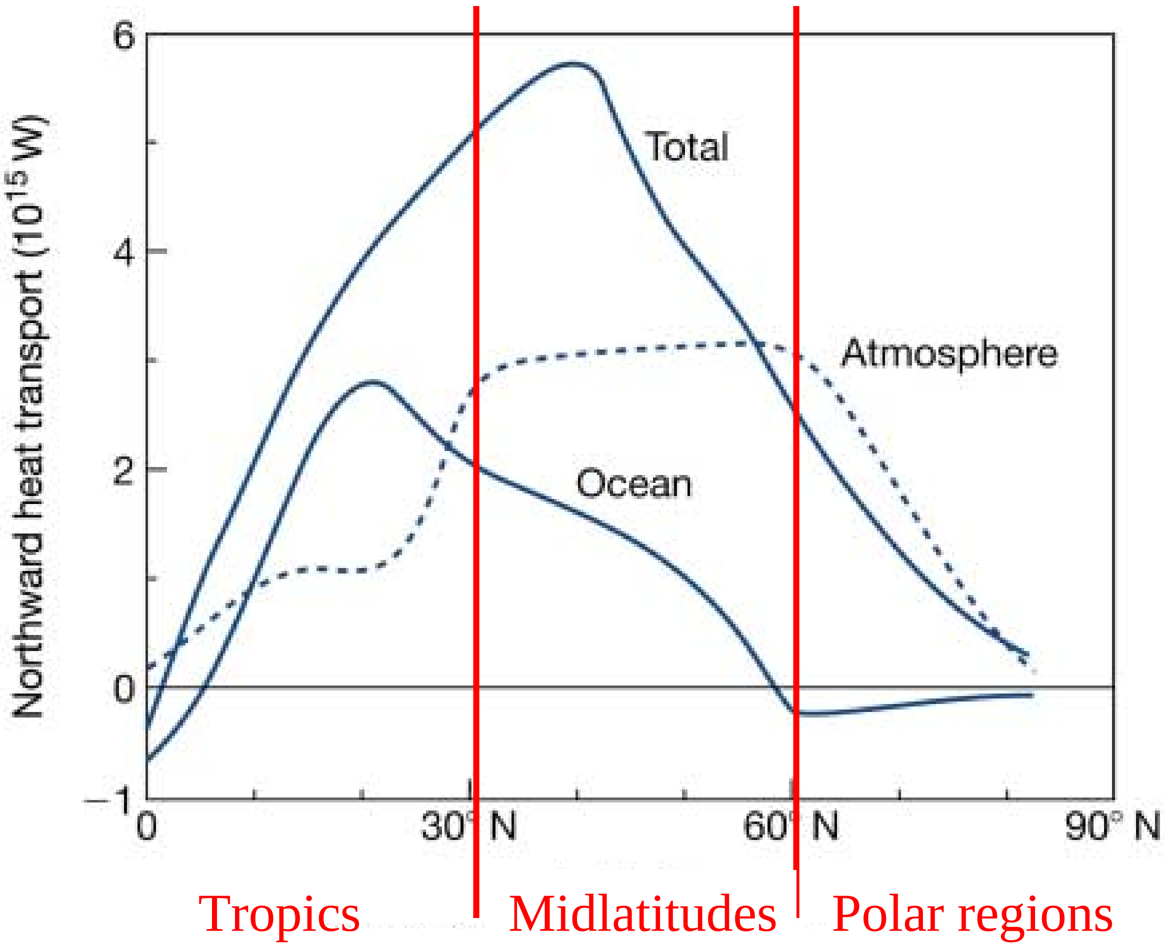
Mechanisms:
(i) general circulation of the atmosphere (actually, troposphere)
(ii) surface ocean currents
Note: These two are intimately connected.



Heat transport from low to high latitude: Fig 05_16

<u>Questions:</u>

1. Where is most heat transferred in the Tropics?
2. Where is most heat transferred in the Midlatitudes?
3. Why does the amount of heat transport decline so rapidly in the Polar Regions



Tropical Circulations

- Move heat from **<u>source</u>** regions to **<u>sink</u>** regions
- Have enormous consequences for regional/seasonal weather
- Three big ones...

Hadley circulation

- encompasses entire Tropics
- moves heat from low latitudes (near Equator) to higher latitudes (near 30º)

Monsoons

- move heat between land and ocean
- regional/seasonal

Walker circulation

- regional (but huge region)
- moves heat from warm Western Pacific to cooler Eastern Pacific
- strengthening and weaking of this is ENSO

Hadley Circulation - 1

buoyancy — rising and falling

(think of rubber ball in water vs rock in water)

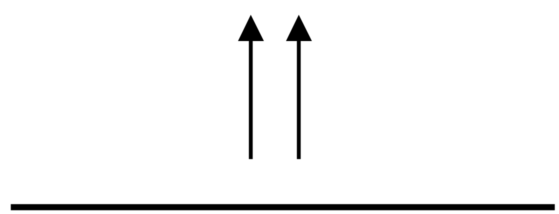
density — mass per unit volume

less dense fluid rises

more dense fluid sinks

gas law — (see p. 60)

warm air is less dense



Eq.

Hadley Circulation - 2

pressure gradient force

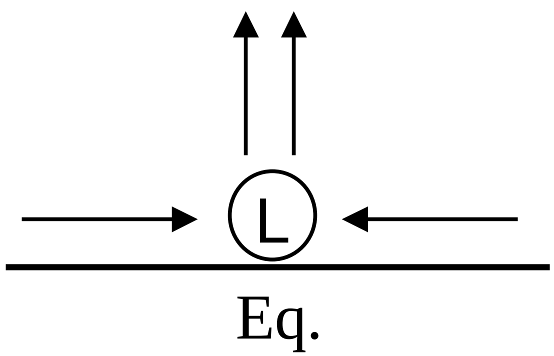
"gradient" refers to high and low pressure regions

cause of horizontal air motions

induces air to flow from high pressure to low pressure

actual air motion is modified by:

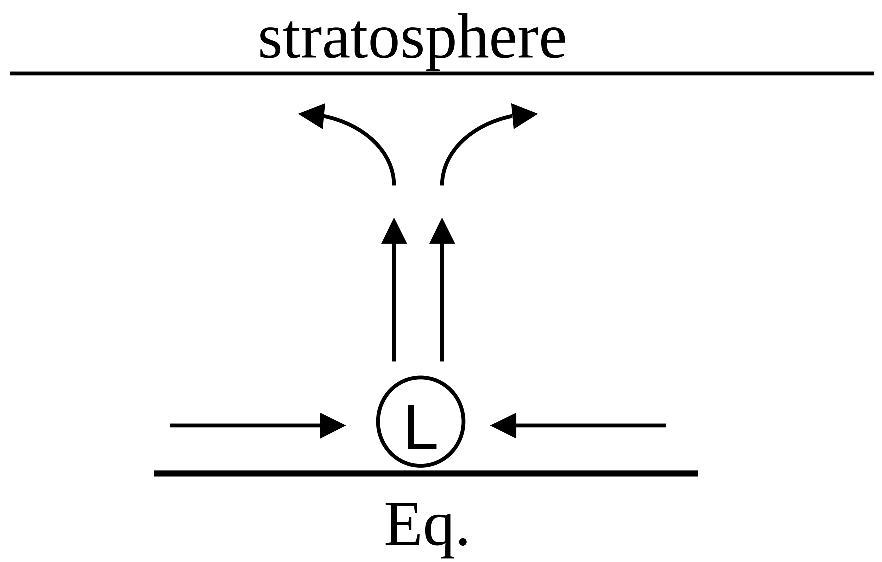
- friction
- Earth rotation (Coriolis force)



Hadley Circulation - 3

stratosphere

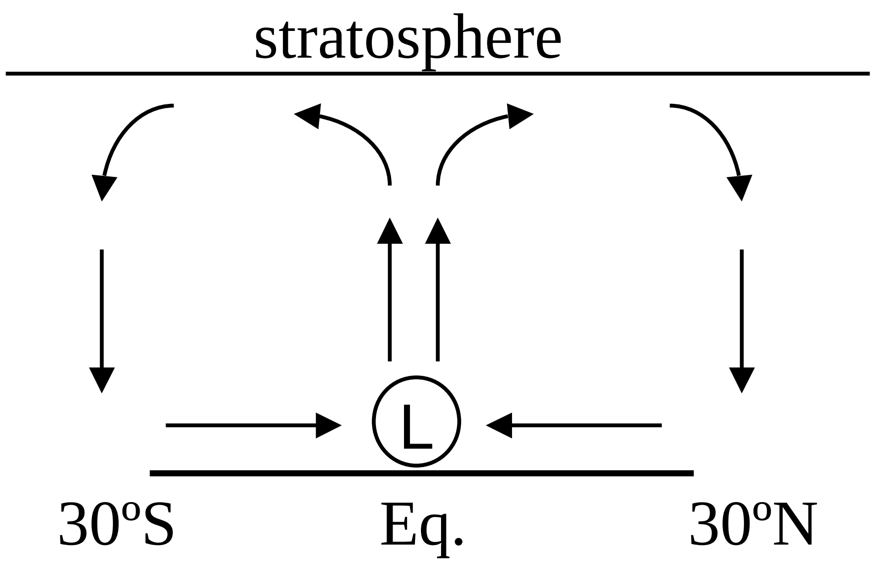
- very stable region
- vertical motion is inhibited
- acts as a lid



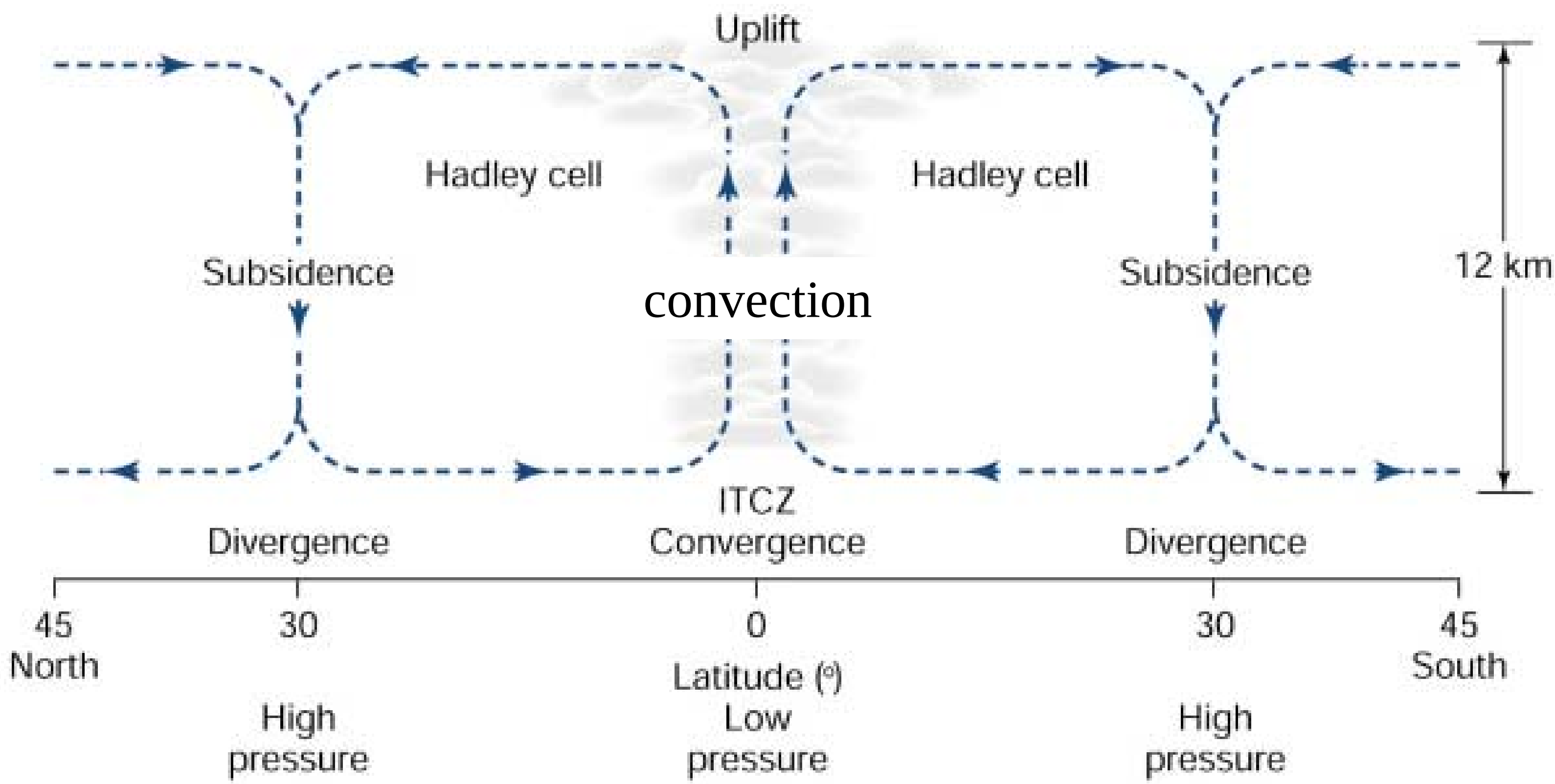
Hadley Circulation - 4

conservation of matter ... >>>>> **CIRCULATION**

The Hadley Circulation



Hadley Circulation - Fig 04_03



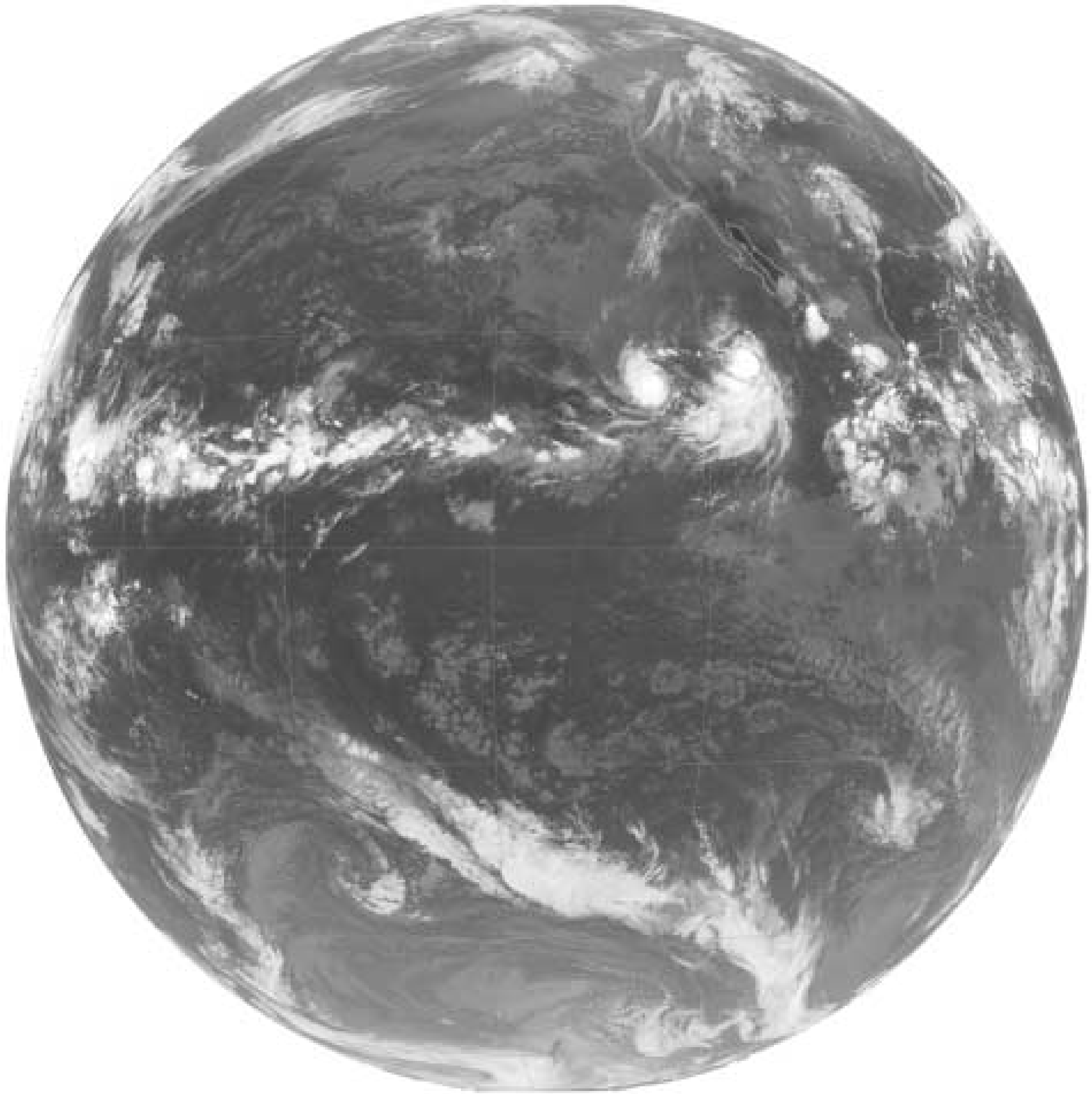
<u>Horizontal motions</u>

convergence: coming together
divergence: spreading apart

<u>Vertical motions</u>

convection: rising air
subsidence: sinking air

IR satellite image ITCZ: Fig 04_07



Tues Nov 4

Upcoming talks:

TUESDAY 4 November

12:30 ATG 310c, Weather discussion

FRIDAY 7 November

3:30 15 OTB (Oceanography Teaching Bldg)

Dr. Brent Helliker, Stanford

"Terrestrial carbon cycle response to climate change"

Yesterday:

- Hadley cell - major circulation and good example of a circulation

Today:

- Tropical circulations wrap-up
- Land/ocean contrasts
- Water cycle (if time)

Wed: Steve Warren, regional climates in Tropics (in-class: questions)

Thurs: water cycle
ocean and solid earth circulations

Friday: lab on reservoirs and cycles?

Outline

Tropical circulations (focus on Hadley)

- Convection: precipitation and heat transfer
- Subsidence: clear skies, deserts
- Convergence: surface winds
- Seasonal variations due to orbital parameters

Extra-tropical circulations

Land/ocean contrasts

- physical basis
- effects on wide range of time- and space-scales

Water cycle

- main components and processes
- Box Models and Residence Time

Goals

- understand distribution of climates around the world
- understand the challenges of "climate modeling"

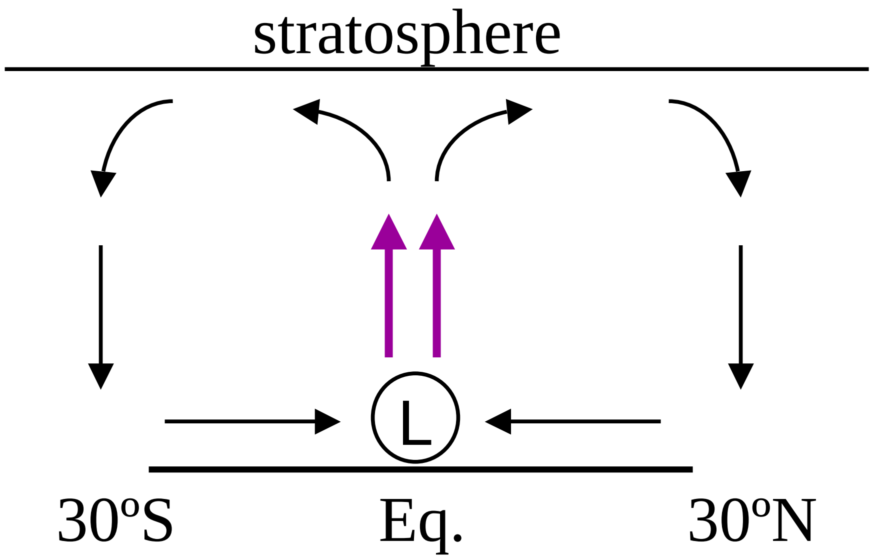
George Hadley (1685-1768)

English physicist and meteorologist. Proposed theory planetary-scale circulation cells in a 1735 paper,

"Concerning the Cause of the General Trade Winds"

Speaking of news...

Hadley Circulation - convection



Convection

- evaporation at surface
- phase change (liquid > gas)
- requires tremendous energy
- energy carried up as latent heat

specific heat of water: 2 J/g/ºC

"It takes 2 Joules of energy to heat 1 gram of water by 1ºC."

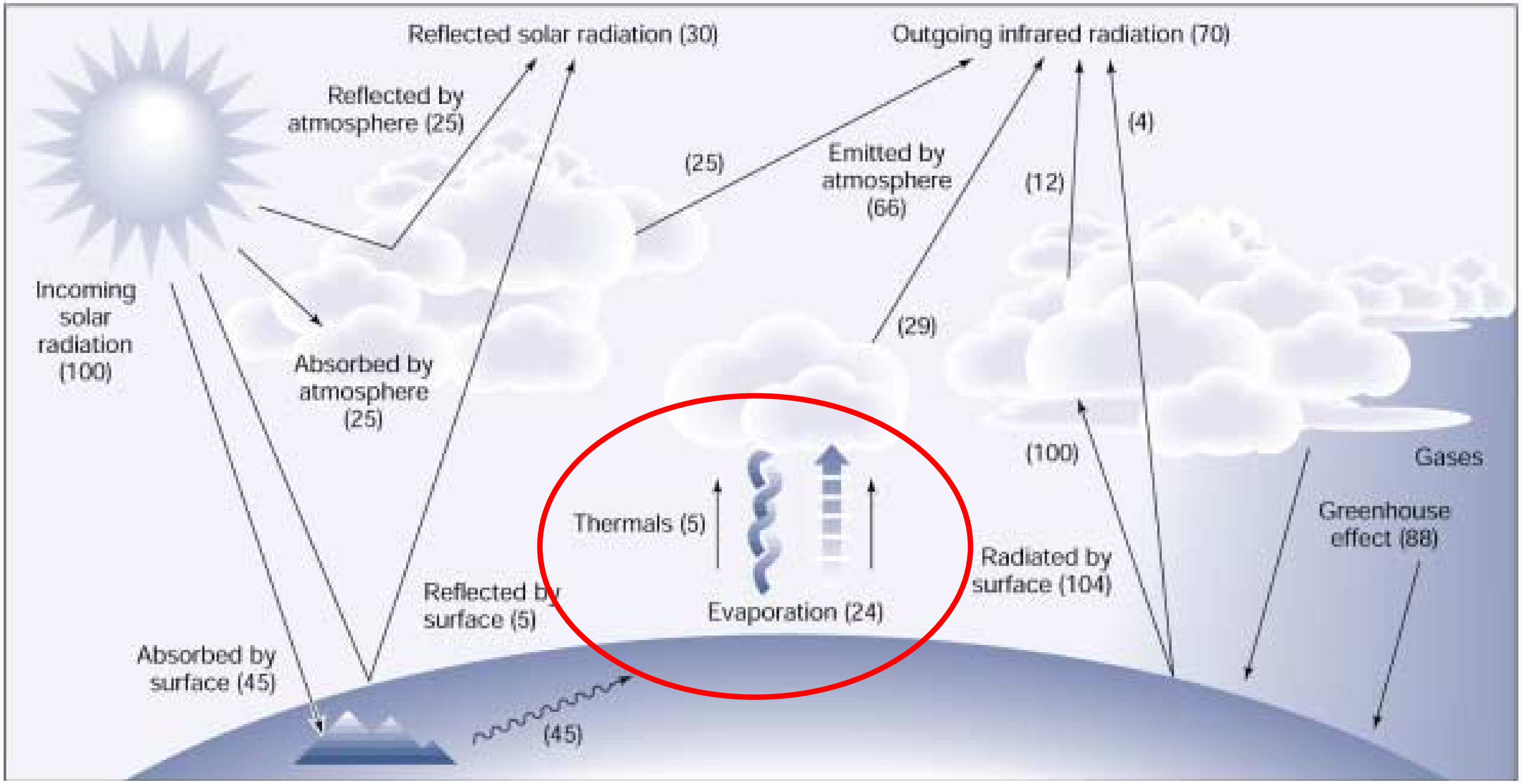
latent heat of water: 2500 J/g

"It takes 2500 Joules of energy to evaporate 1 gram of water."

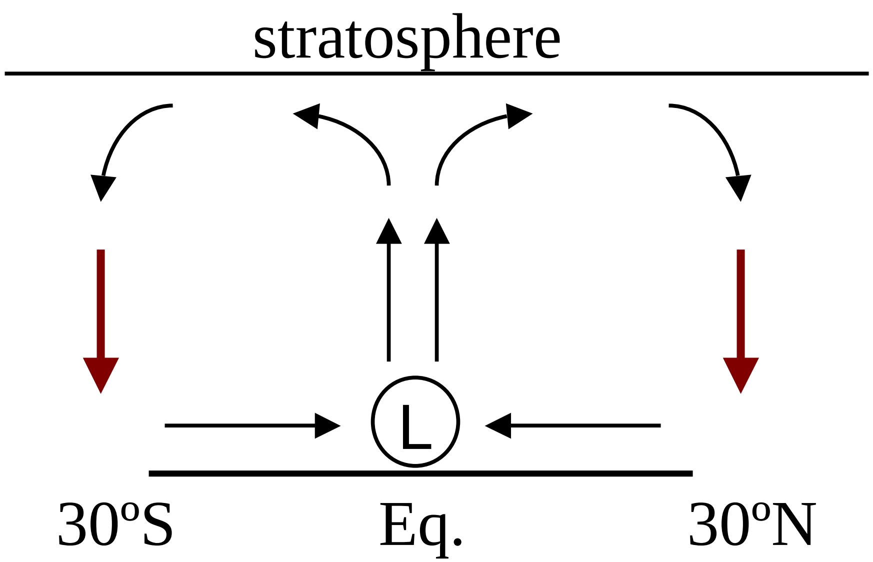
- rising air expands and cools (see gas law, p. 60)
- this causes water to condense when RH=100% (saturation)
- clouds form
- latent heat is released, causing the cloudy air to warm
- becomes less dense and more buoyant
- rises even faster >> towering cumulonimbus (thunderstorms)

Convection and the energy budget

Huge amounts of energy (and moisture) are transported into the atmosphere by convection.



Hadley Circulation - subsidence



Subsidence

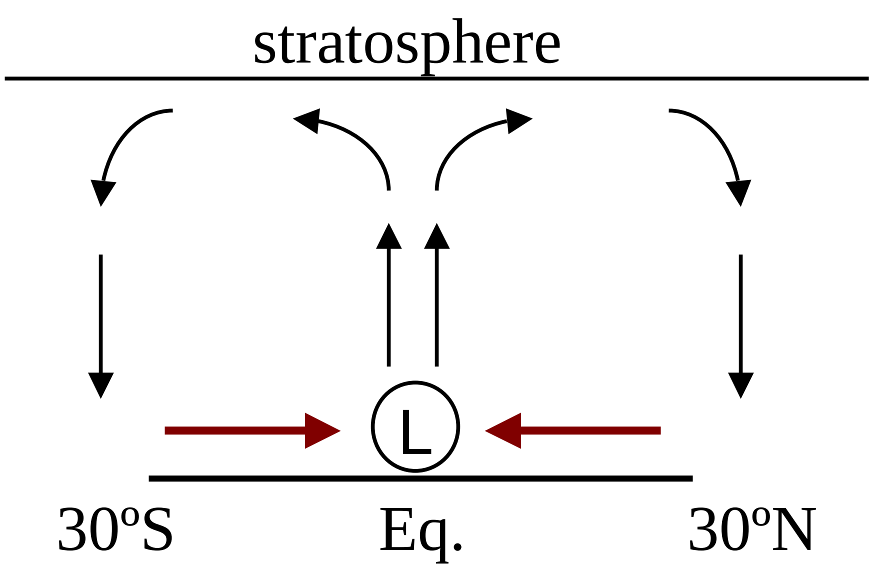
- sinking air compresses and warms
- this suppresses cloud formation
- absence of rain - deserts

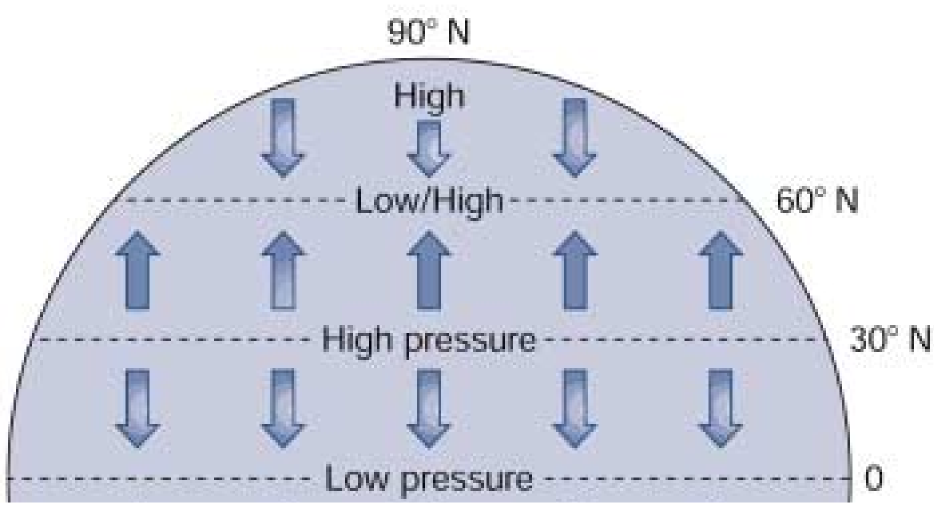
(a) Sonoran

Hadley Circulation - convergence

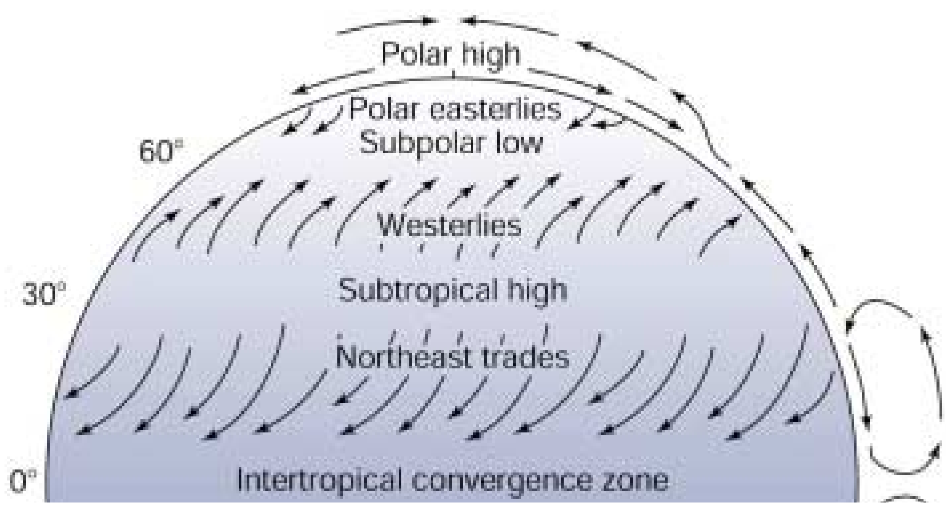
Low-level Convergence

- air forced upwards: "ITCZ"
  (Inter-Tropical Convergence Zone)
- horizontal motion modified by
  - friction
  - Earth's rotation (Coriolis Force)
- Coriolis: wind (or ocean current)
  veers right in N Hemi.





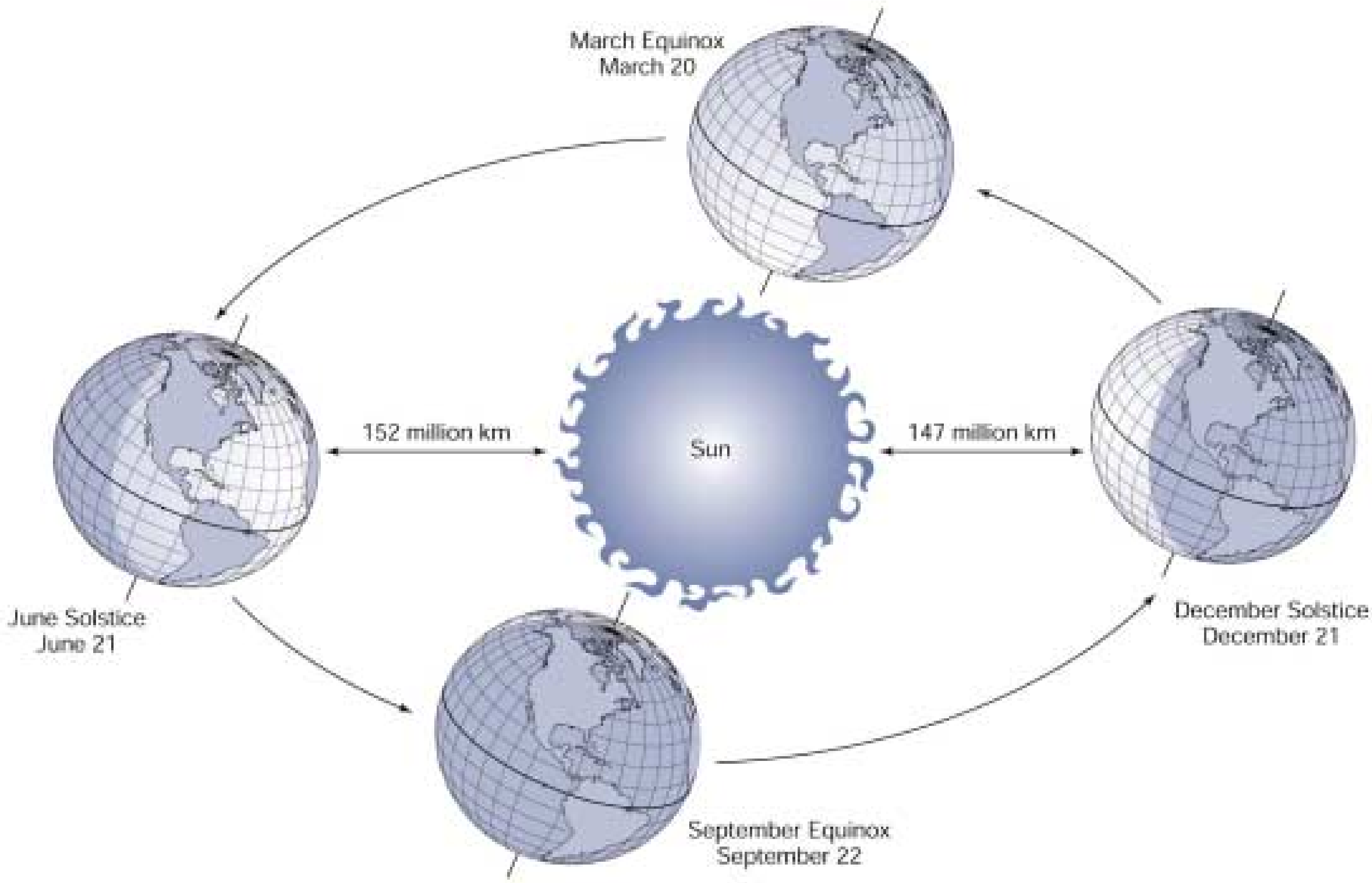
non-rotating planet



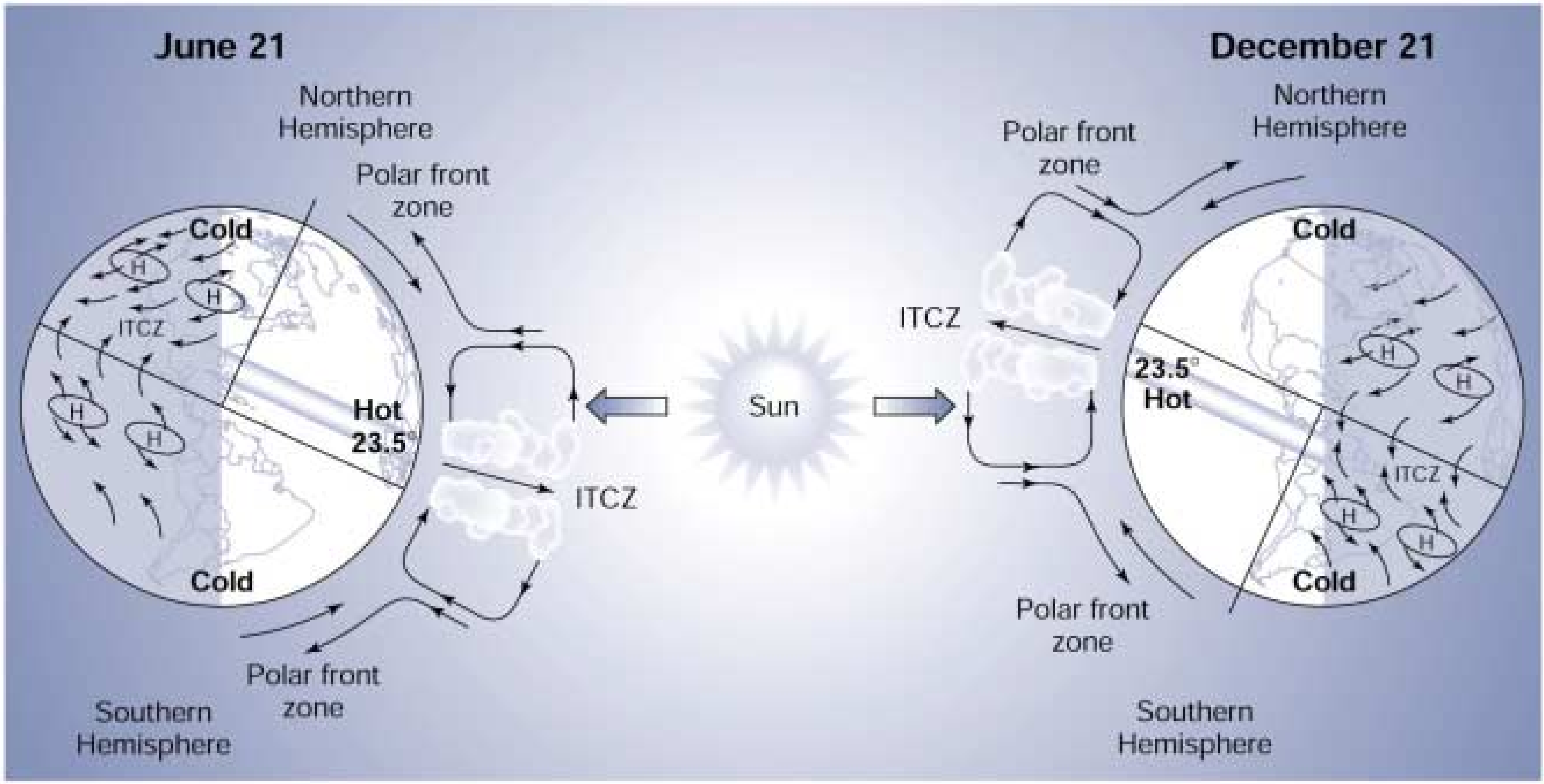
Earth

Orbital parameters and seasons: Fig 4-15

obliquity: tilt of Earth's axis with respect to orbital plane



Hadley - seasonal movement: Fig 04_16

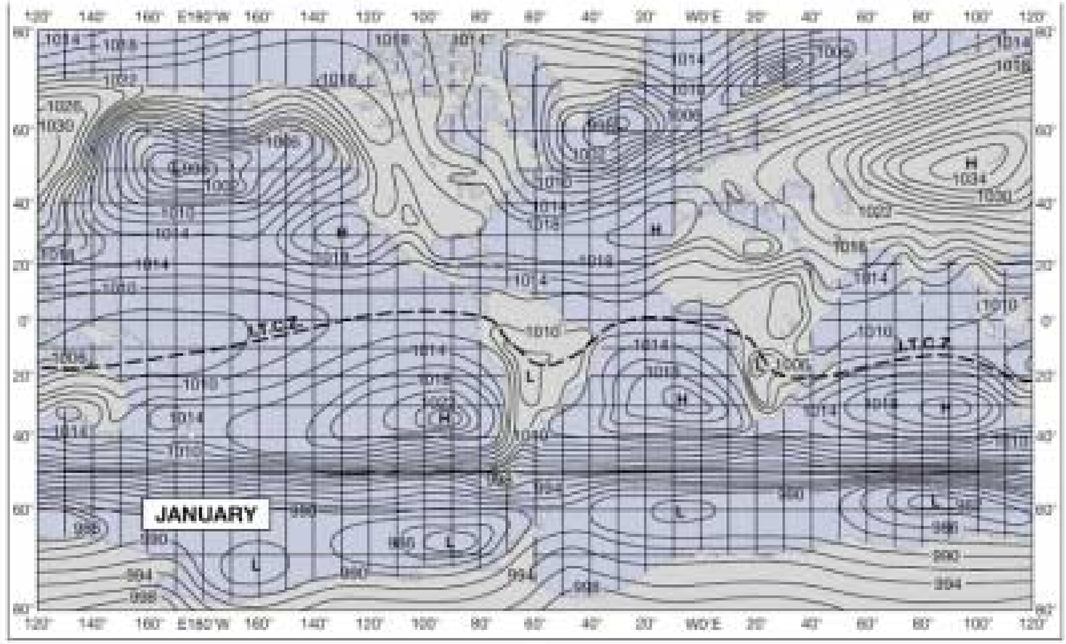


June/July: ITCZ north, wet season in N Hemi Tropics

Dec/Jan: ITCZ south, wet season in S Hemi Tropics

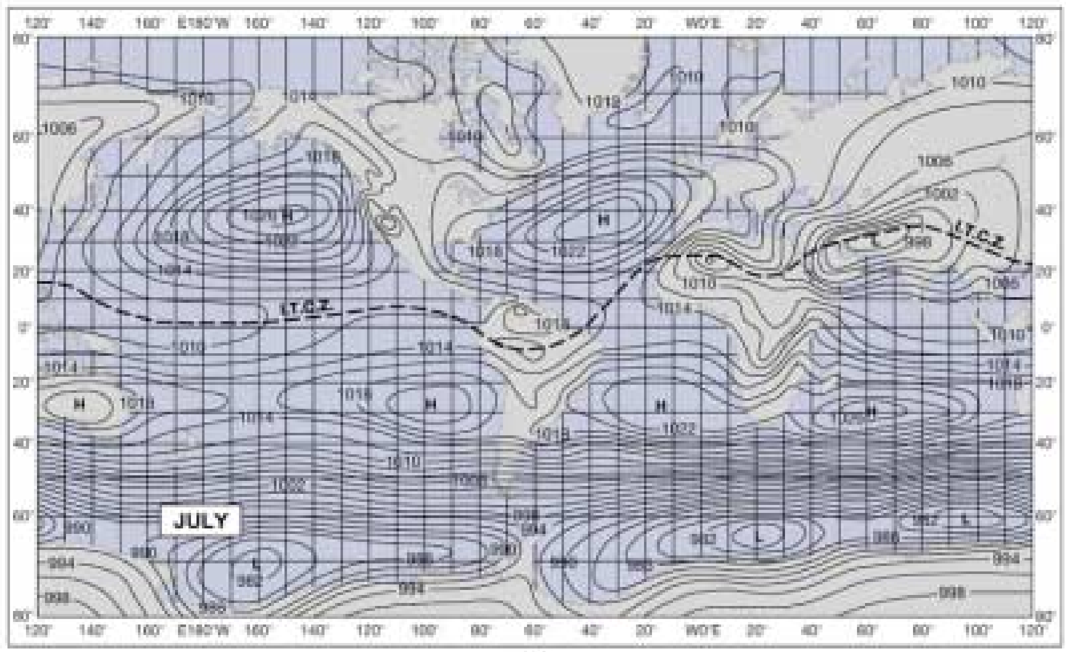
Seasonal
surface pressure
Fig 4-18

Dec/Jan: ITCZ south, wet season in S Hemi Tropics



(a)

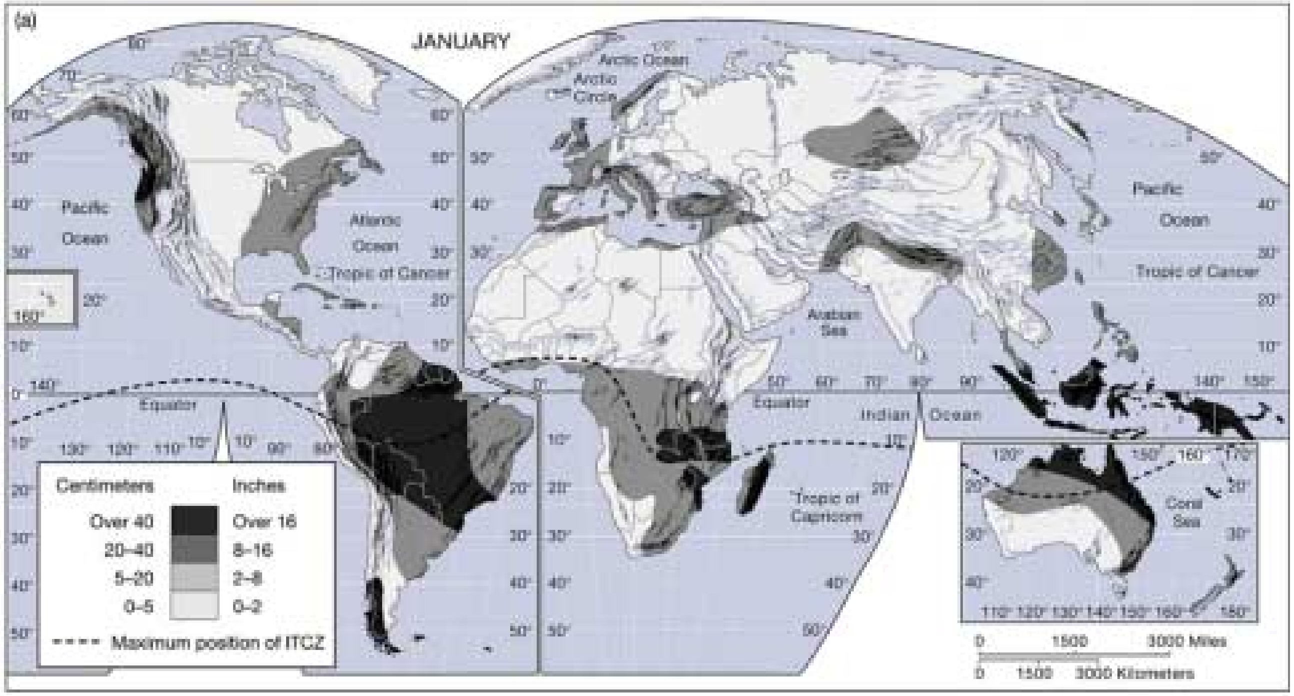
June/July: ITCZ north, wet season in N Hemi Tropics



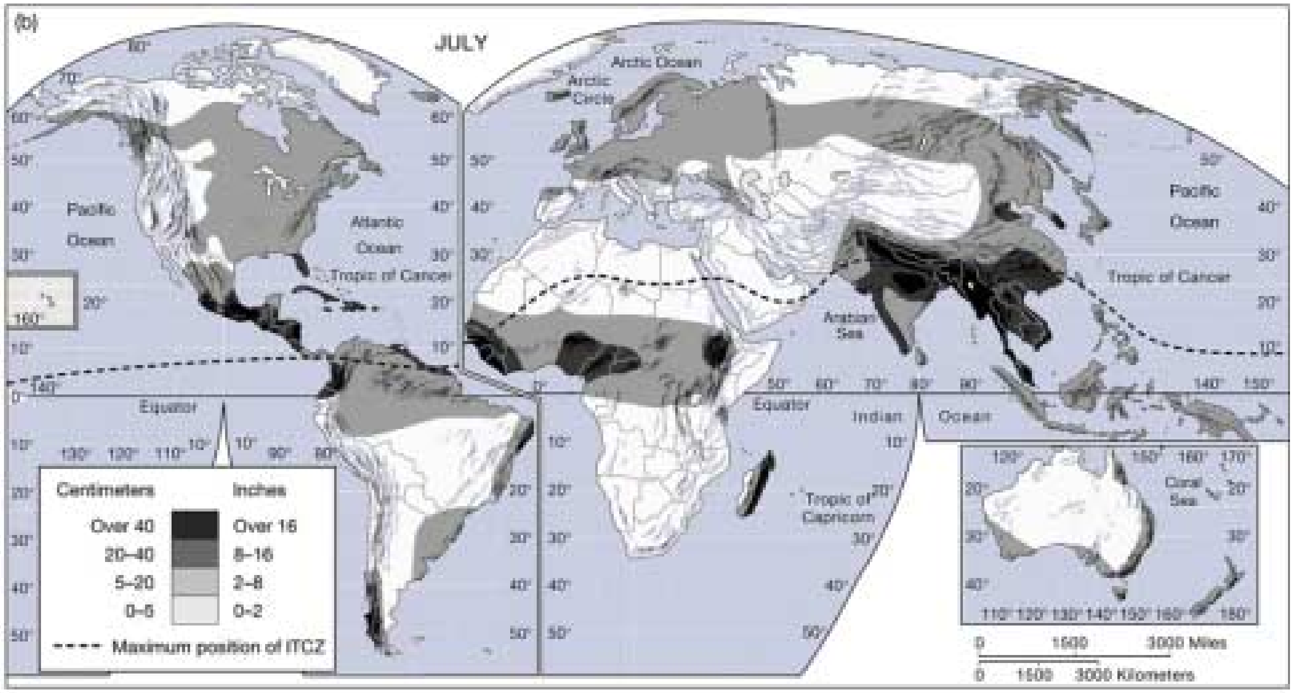
(b)

Seasonal Precipitation

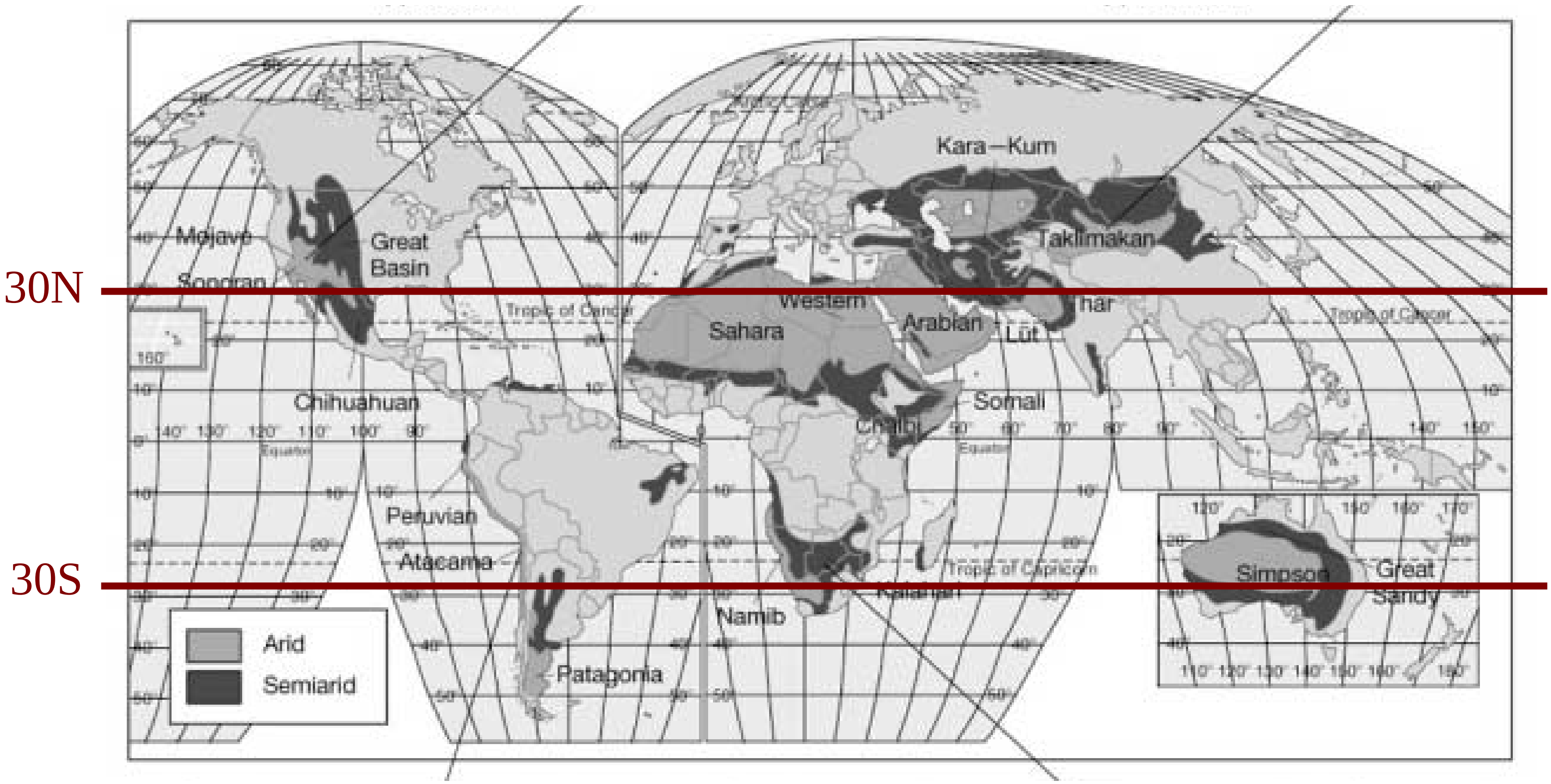
Dec/Jan: ITCZ south, wet season in S Hemi Tropics



June/July: ITCZ north, wet season in N Hemi Tropics



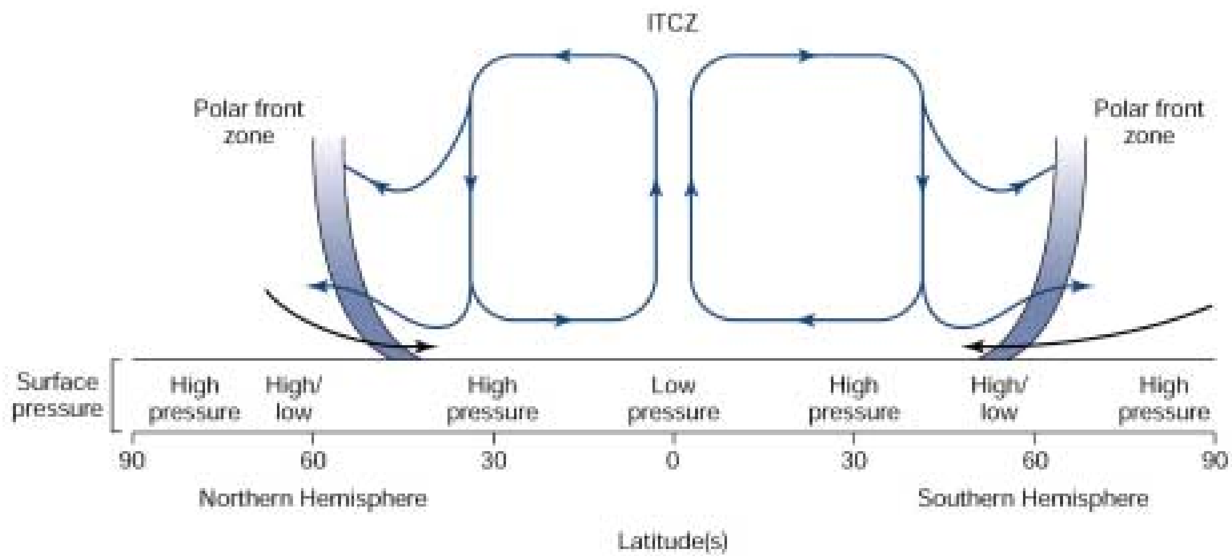
Deserts: Fig 04_24



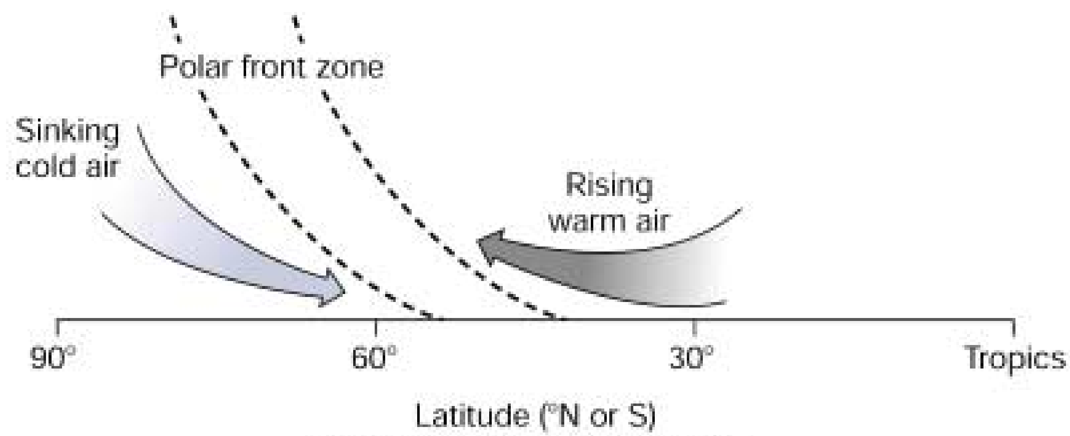
<u>Causes:</u> - descending arms of the Hadley cell (roughly +/- 30º)
- continental interiors (far from water source)
- leeward (downwind) slopes of mountains
- west coasts with cold ocean (fog and low cloud but no rain)

Tropics vs extratopics, vertical profile, Fig 04_06

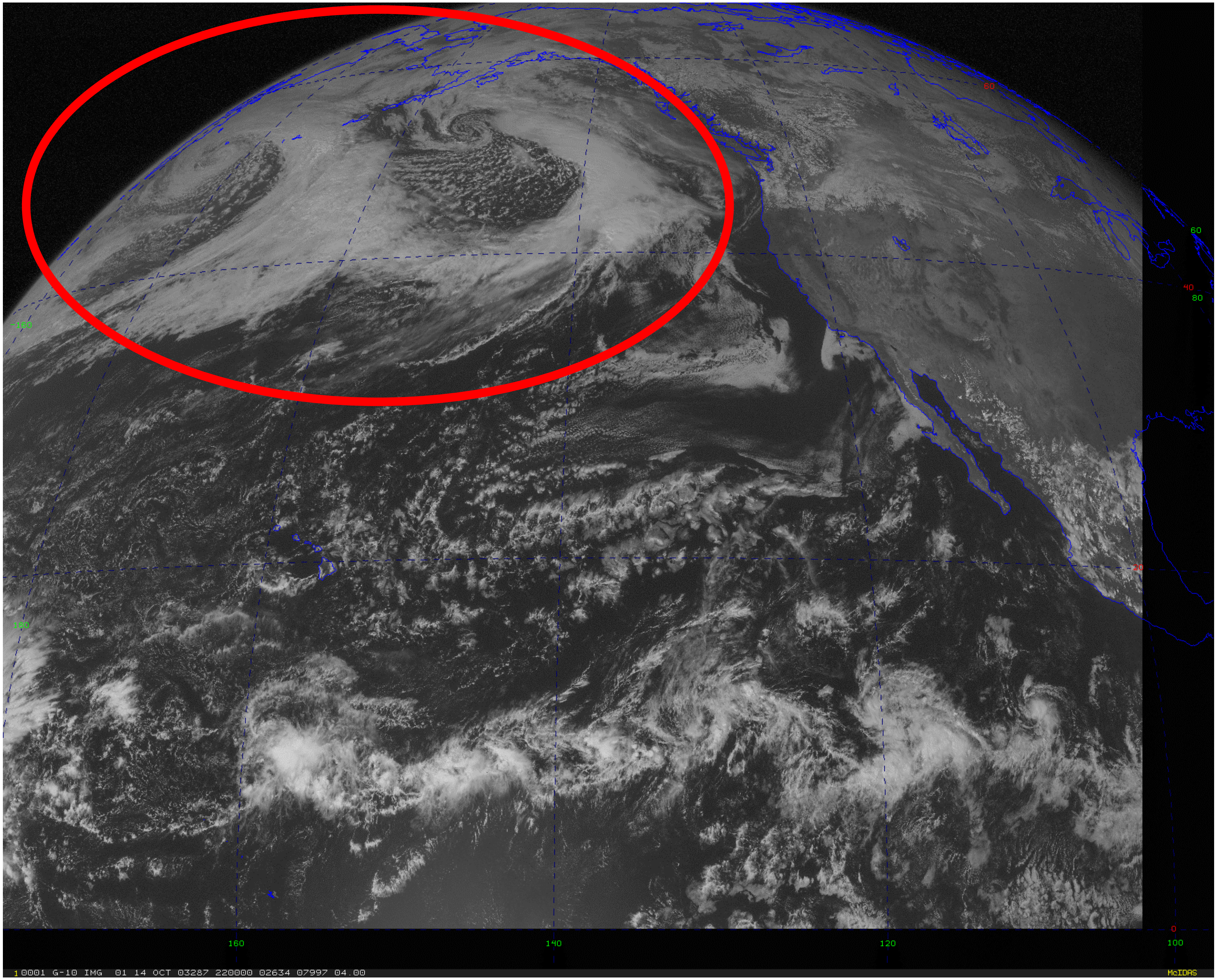
<u>Tropics:</u>
- surface heating drives convection



<u>Extra-Tropics</u>:
- colliding air masses drives convection
- warm air rises over cold (density effect)
- massive heat transport in atmosphere



Extra-Tropical Cyclones (frontal systems)



Land/ocean contrasts

Ocean surfaces change temperature far more slowly than land surfaces.

WHY???

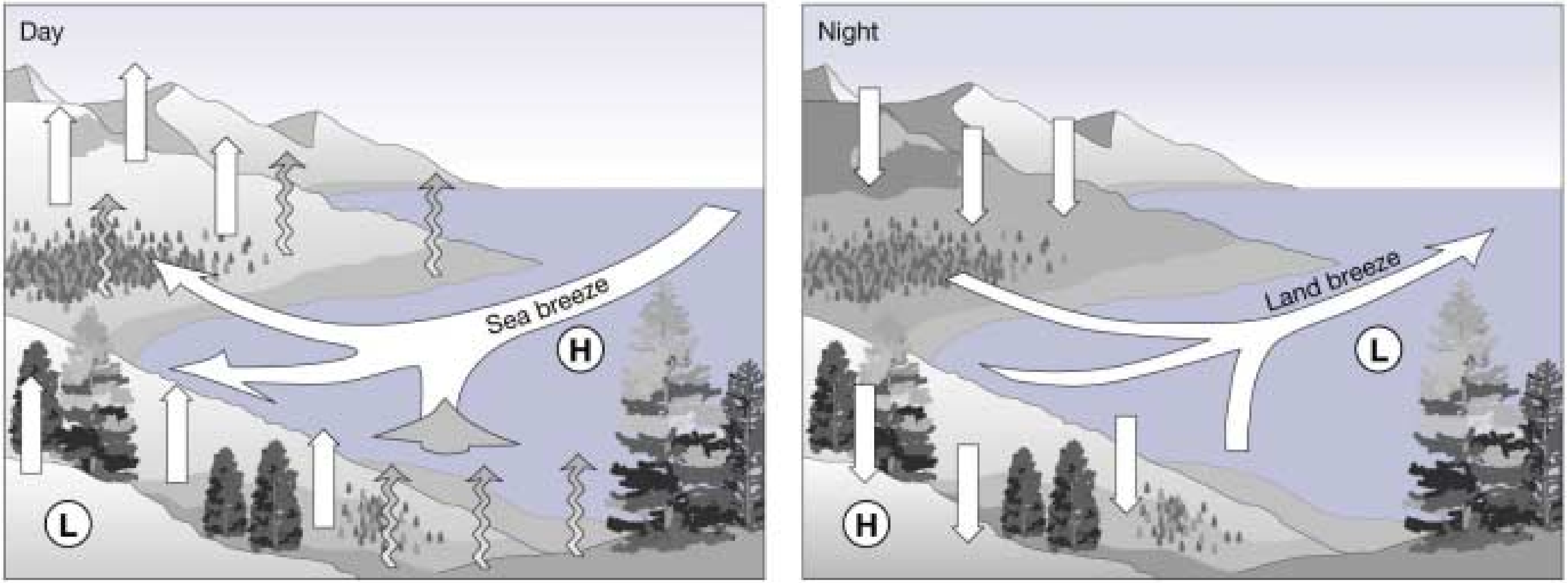
Four reasons:

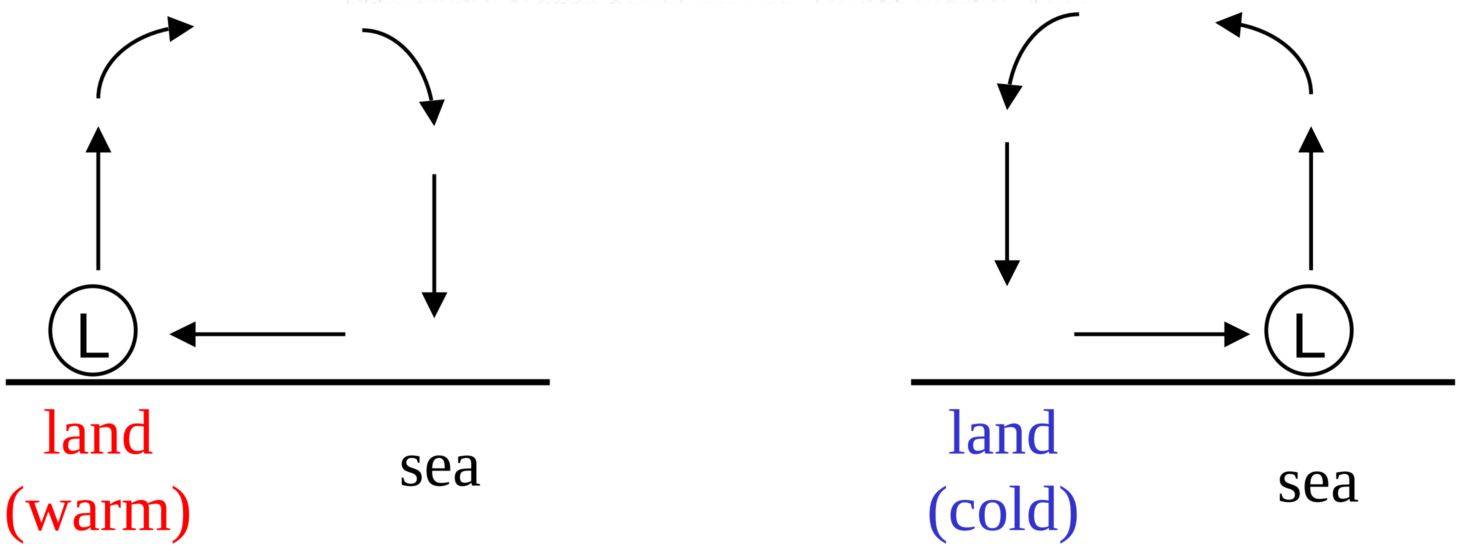
- thermal conductivity is higher for water
  heat is transferred downward (away from surface) more efficiently in water
- specific heat capacity is higher for water
  takes more heat to change temperature of water
- transmission of solar energy to greater depth in water
  energy penetrates many meters in water vs a few mm
- turbulent transfer of heat (absent for land)
  surface water is mixed downward, transferring heat away from the surface

Which is most important???

Turbulent mixing. To warm (or cool) the ocean surface, you have to warm a layer ~100 m thick vs only a few mm for the land.

Diurnal effect: sea/land breeze (Fig 04-17)





Seasonal effect: "Find the continents game"

Contour lines show seasonal temperature range (like Fig 4-1c of text)

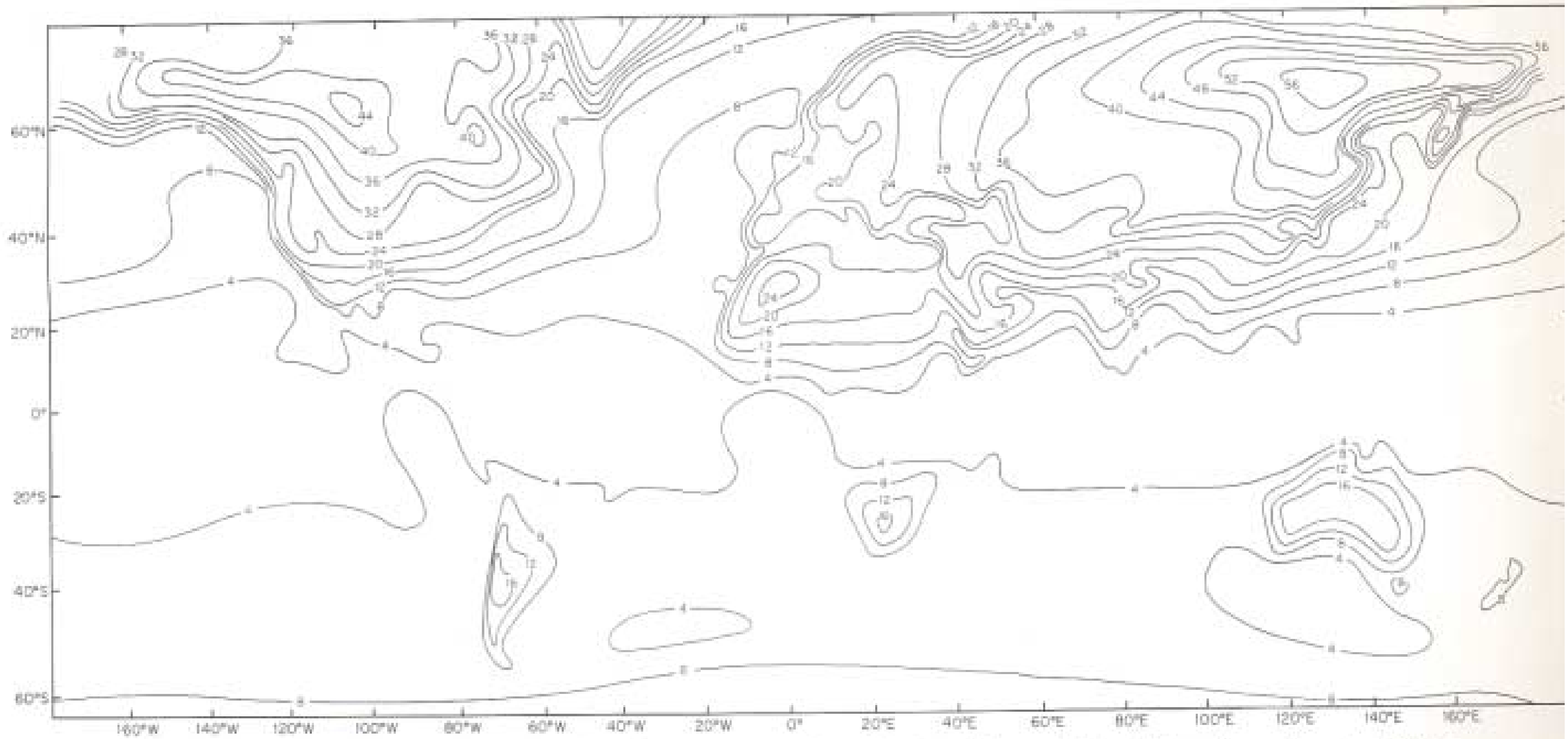
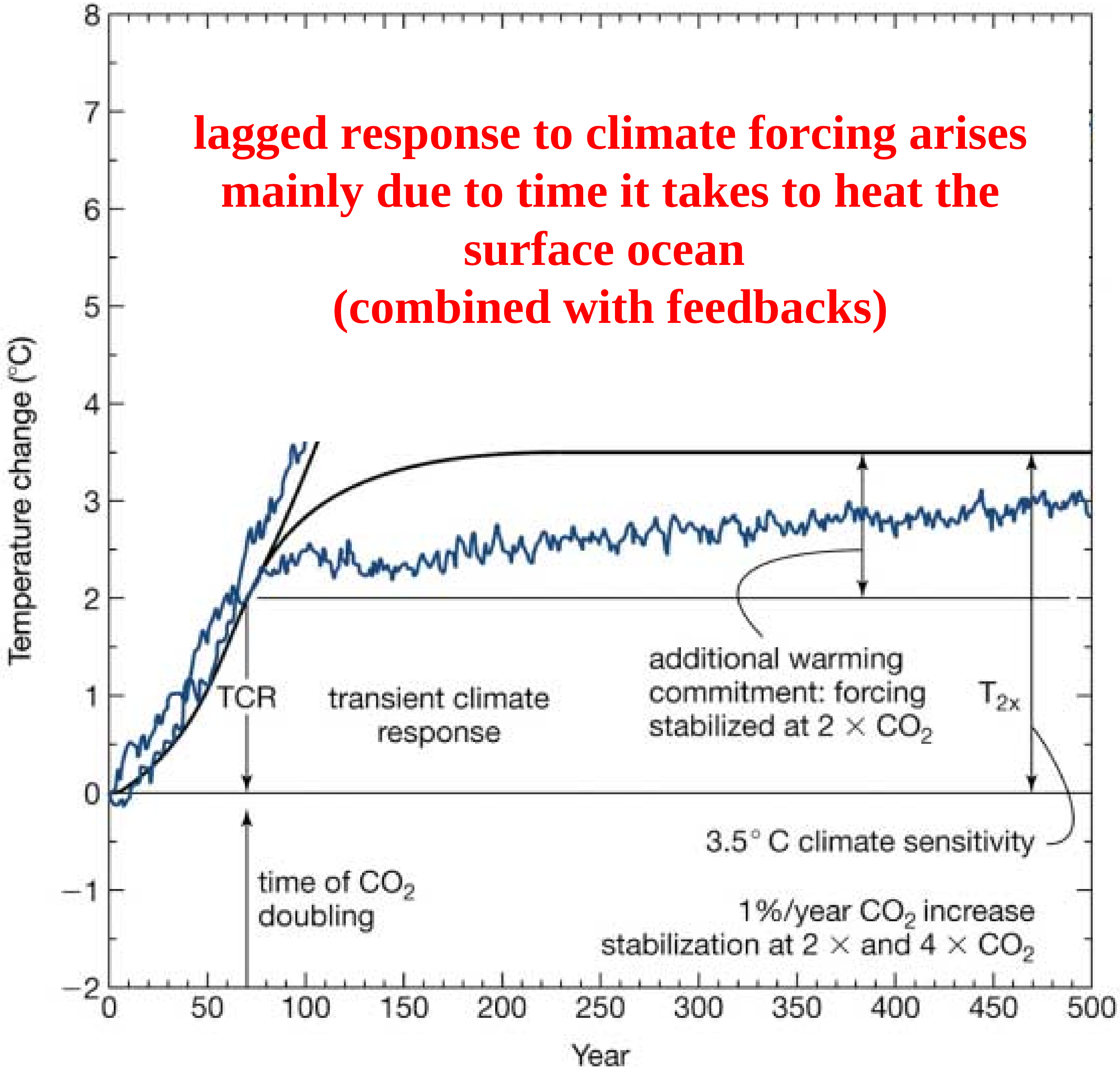


Fig. 7.20 The "Find the Continents" game! Annual range in temperature at the earth's surface, in degrees Celsius. (Adapted from a figure by A. S. Monin and P. P. Shirshov which appeared in Report No. 16, *GARP Publications Series*, World Meteorological Organization—International Council Scientific Unions, p. 203.)

compare: Tropics vs Extratropics

Land vs Ocean

Decade-to-Century-Scale Effect



Land/Ocean Contrasts - Summary

Illustration of a "coupled system":

The oceans have an enormously stabilizing effect on atmospheric temperature.

This arises primarily because of turbulent mixing of the ocean surface layer.

This turbulent mixing (as we will see in Chap 6) is caused by atmospheric winds.

Thurs Nov 6

Upcoming talks:

FRIDAY 7 November

3:30 15 OTB (Oceanography Teaching Bldg)

Dr. Brent Helliker, Stanford

"Terrestrial carbon cycle response to climate change"

Today:

- Some clarifications
- Water cycle / Residence Time
- Surface Ocean currents
- Deep ocean circulation ("Thermo-Haline Circulation" or THC)
- Solid Earth circulation (plate tectonics, Wilson cycle)

Friday: lab demos on reservoirs, cycles, Coriolis, clouds, etc

>>> LOCATION: ATG 116 (Machine Shop) <<<

Land/ocean contrasts

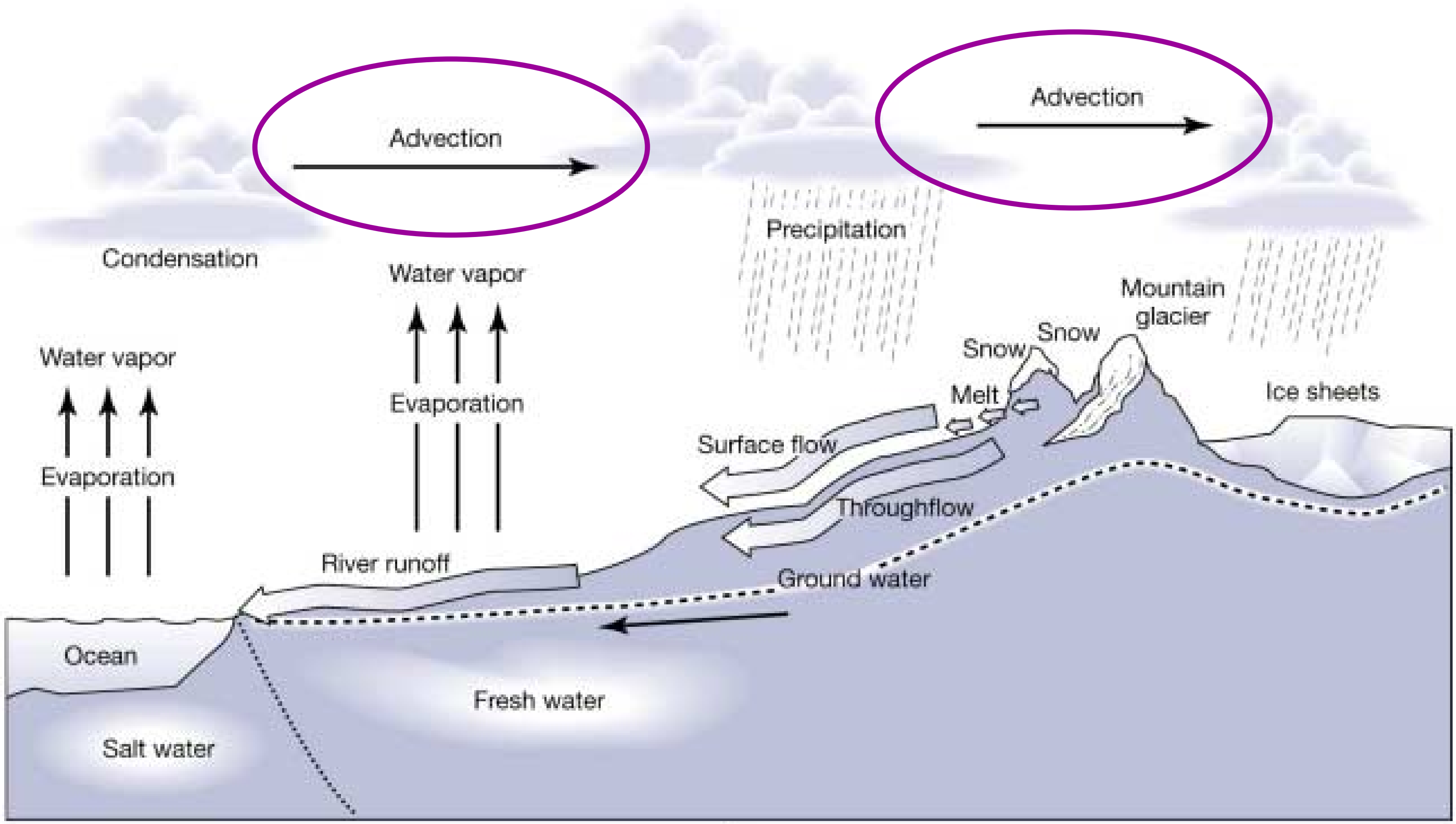
Four reasons why ocean changes temperature more slowly than land

- thermal conductivity is higher for water
  heat is transferred downward (away from surface) more efficiently in water
- specific heat capacity is higher for water
  takes more heat to change temperature of water
- transmission of solar energy to greater depth in water
  energy penetrates many meters in water vs a few mm
- turbulent transfer of heat (absent for land)
  surface water is mixed downward, transferring heat away from the surface

Most important?

Turbulent mixing. To warm (or cool) the ocean surface, you have to warm a layer ~100 m thick vs only a few mm for the land.

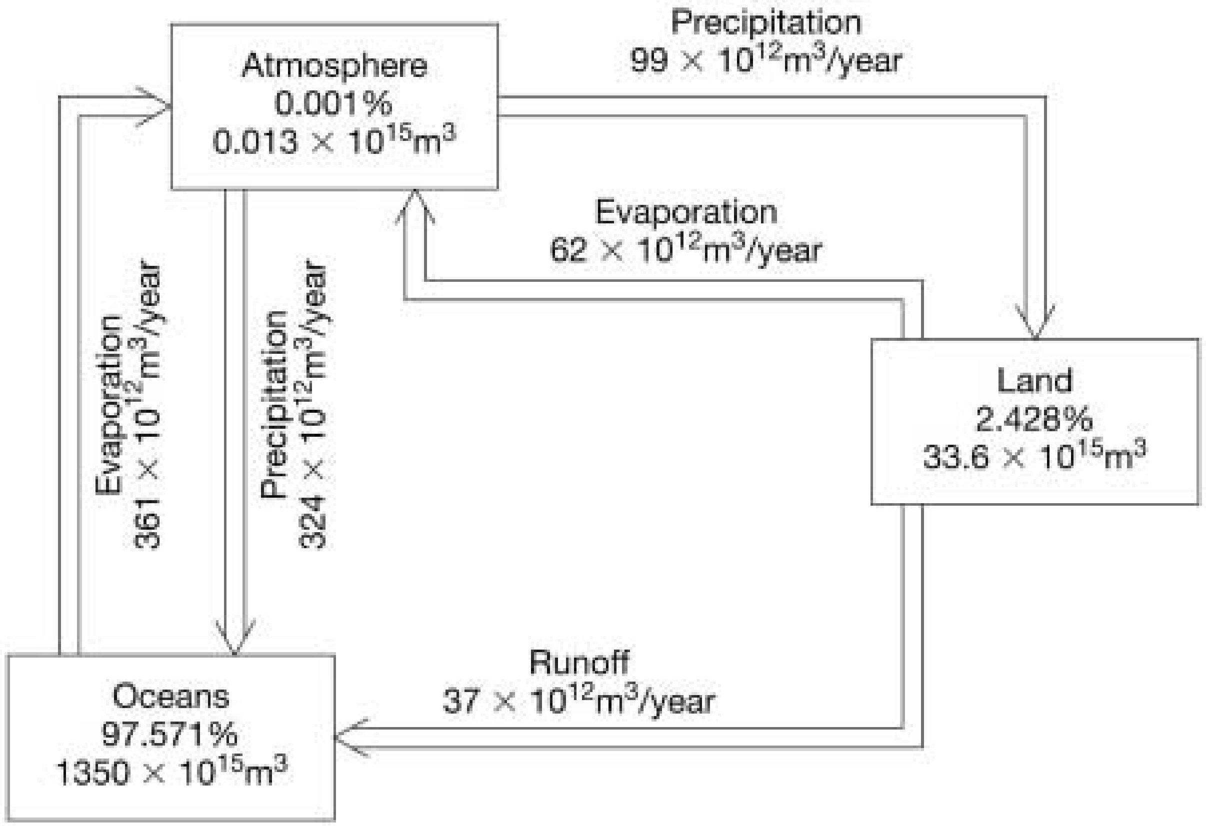
Water Cycle Picture: Fig 4-22a



(a)

advection: Horizontal transport by atmospheric winds. Can apply to a substance, energy, or a property like temperature.

"Box Model" of the Water Cycle: Fig 4-22b



reservoir: Specified location in which some material substance is found. (One "box" in a "box model" representation of a system.)
burden: The total amount of material within a given reservoir.
source (sink): The rate at which material is added to (removed from) a reservoir.
residence time: The average amount of time material spends within a reservoir.

Residence Time (or Lifetime)

Residence Time: The average amount of time material spends within a reservoir.

Standard method of calculation:

$$\text{Residence Time} = \frac{\text{Burden}}{\text{Sink}}$$

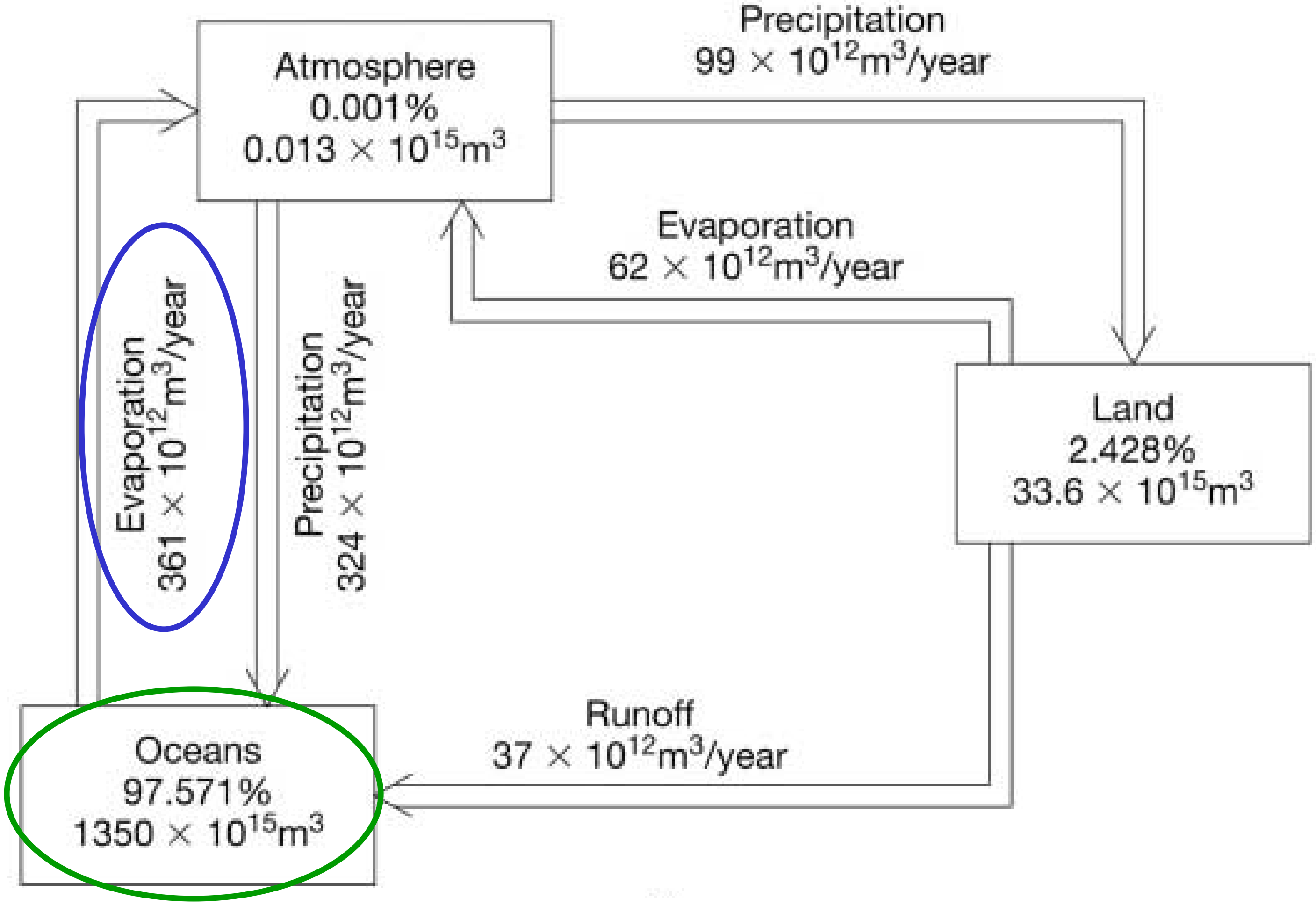
This simple formula provides a powerful means of evaluating the time scale for change in a system.

We will use it extensively in discussing the carbon cycle and global warming.

On HW #4, you are asked to calculate the residence time of water in the atmosphere.

What is the Residence Time of water in the ocean?

Residence Time
= Burden / Sink



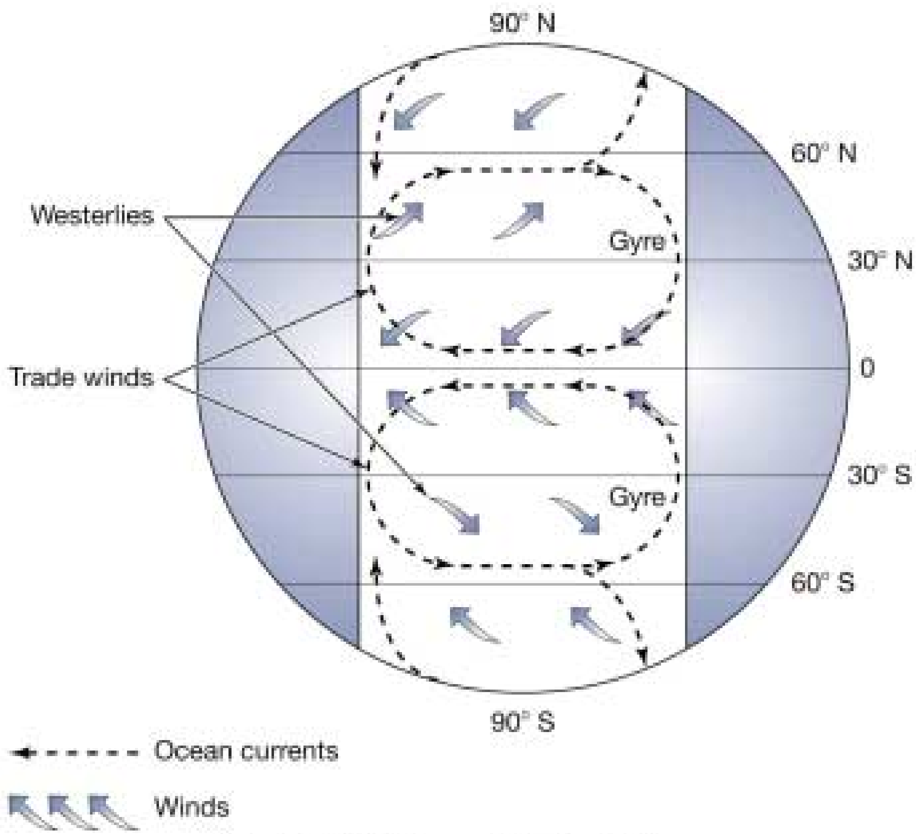
Burden = 1350e15 m^3
Sink (due to evaporation)
= 361e12 m^3/yr

$$RT = \frac{1350\text{e}15 \text{ m}^3}{361\text{e}12 \text{ m}^3/\text{yr}} = \frac{1350\text{e}3 \text{ yr}}{361}$$

= 3.7e3 yr = 3700 yr

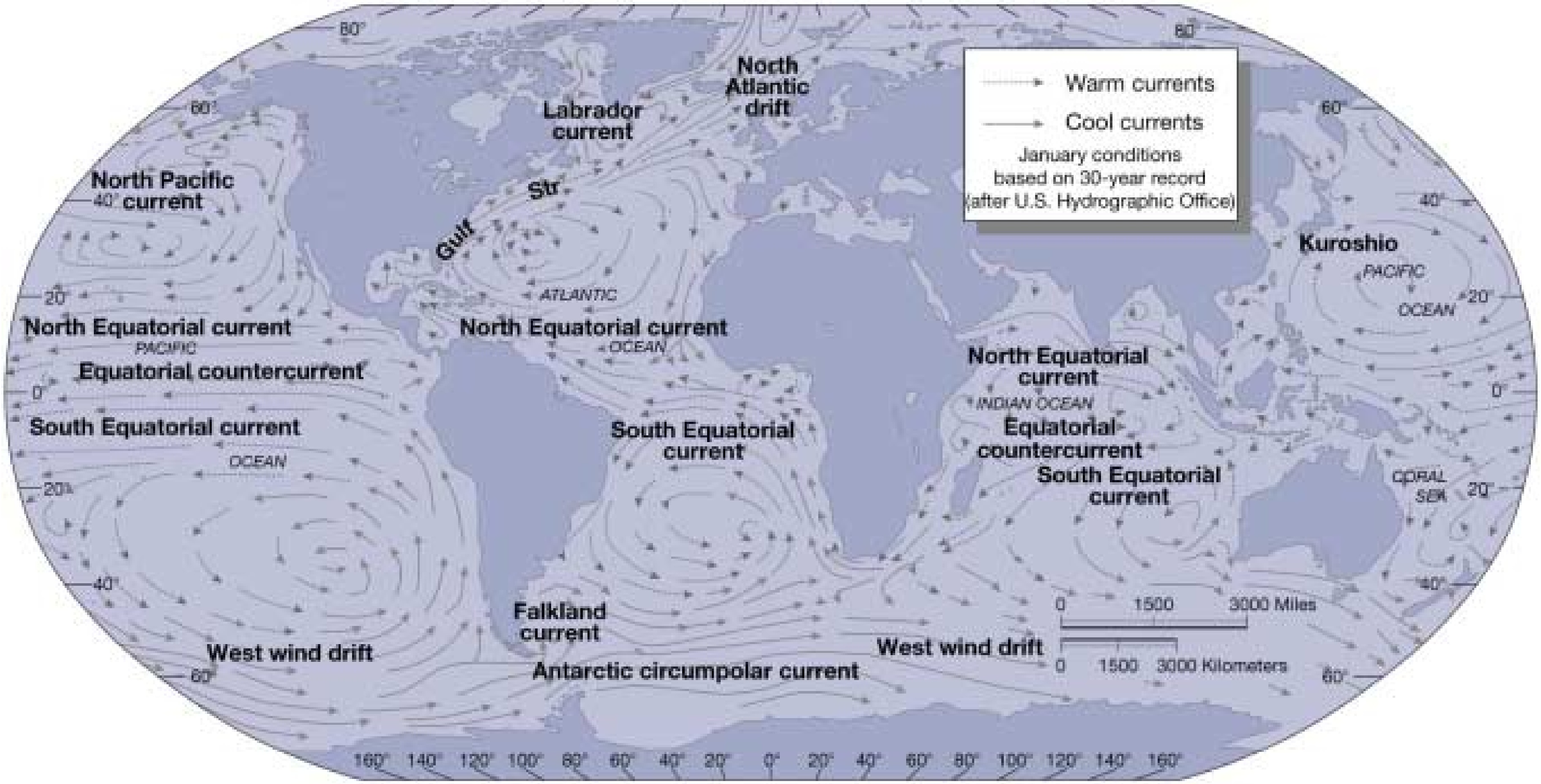
Surface Ocean Currents: Fig 5-2

- wind-driven
- circulating "gyres" in each ocean basin



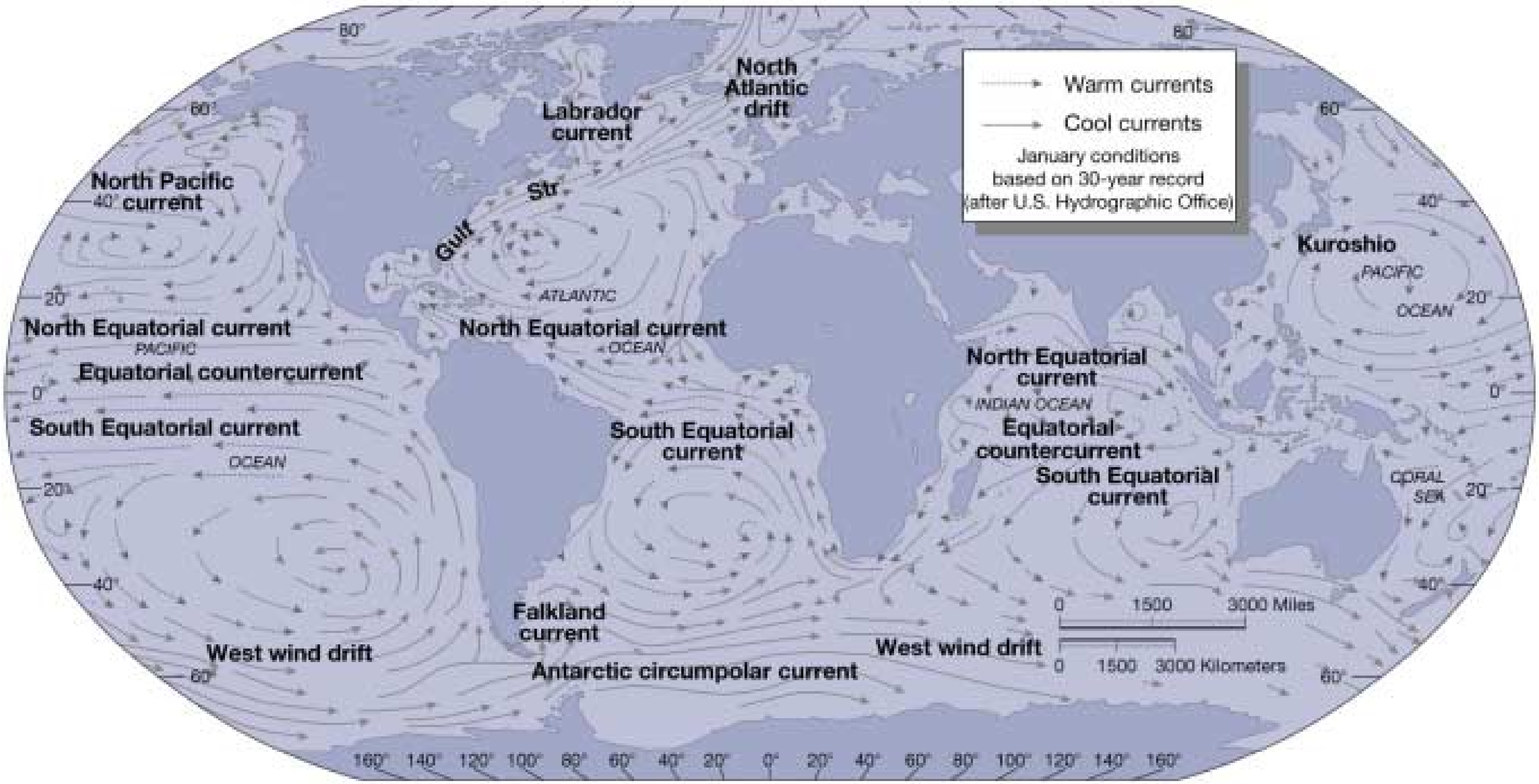
Surface Ocean Currents: Fig 5-3

- warm and cold currents along continents influence regional climates
  - e.g. cold currents on Western margins enhance desert
- transport heat poleward.... HOW?



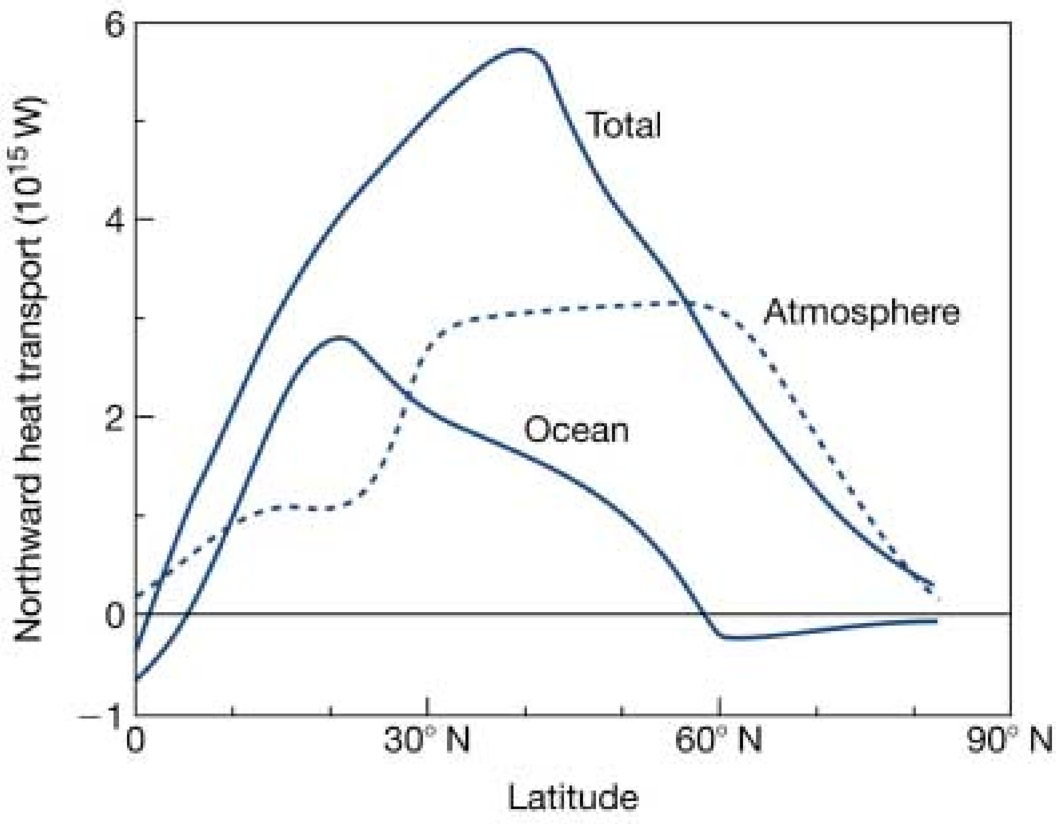
Surface Ocean Currents: Fig 5-3

- driven by wind, specifically, by friction of air moving over water
- causes turbulent, vertical mixing of upper ocean
- well-mixed surface layer is ~100 m thick.   HOW MANY ATMOSPHERES?



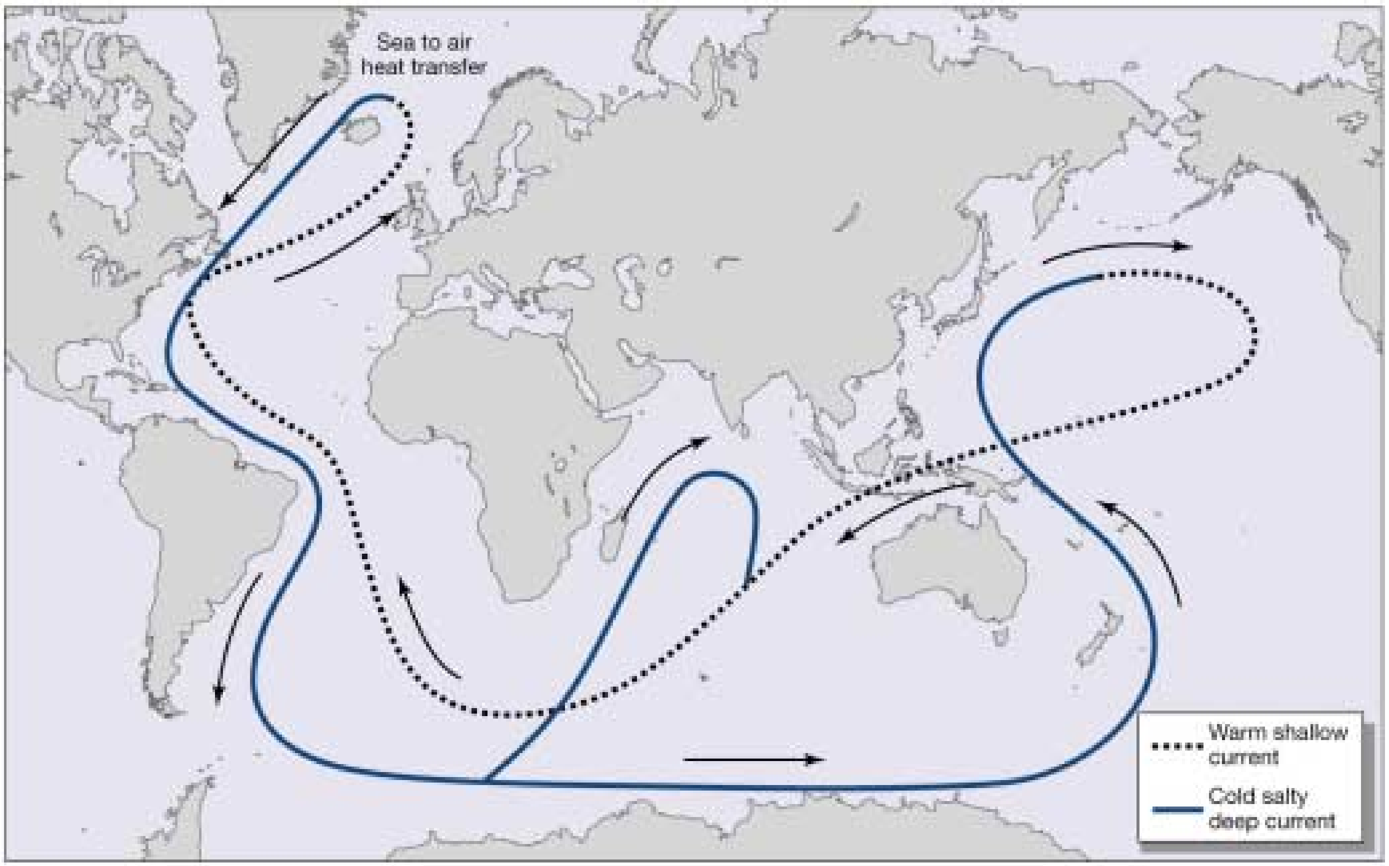
Net Poleward Heat Transport: Fig 5-16

• ocean currents transport a large fraction of total heat, especially in the Tropics



Thermo-haline circulation (THC): Fig 05_12

- causes Deep Ocean mixing
- very long timescale: ~1000 years
- driven by density variations



Thermo-haline circulation (THC)

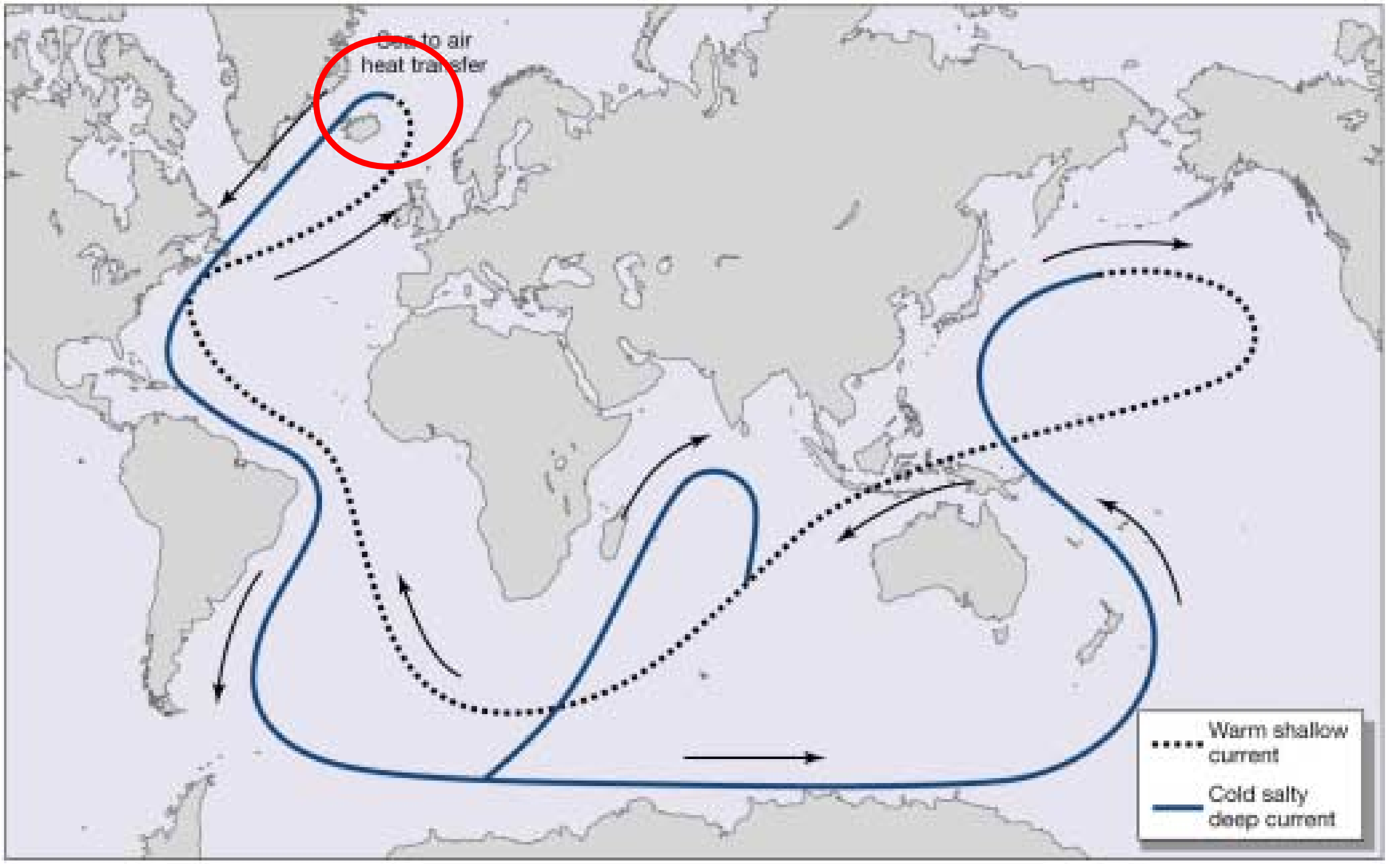
Ocean water density - two controlling factors:

- temperature (cold water is more dense)
- salinity (more saline water is more dense)

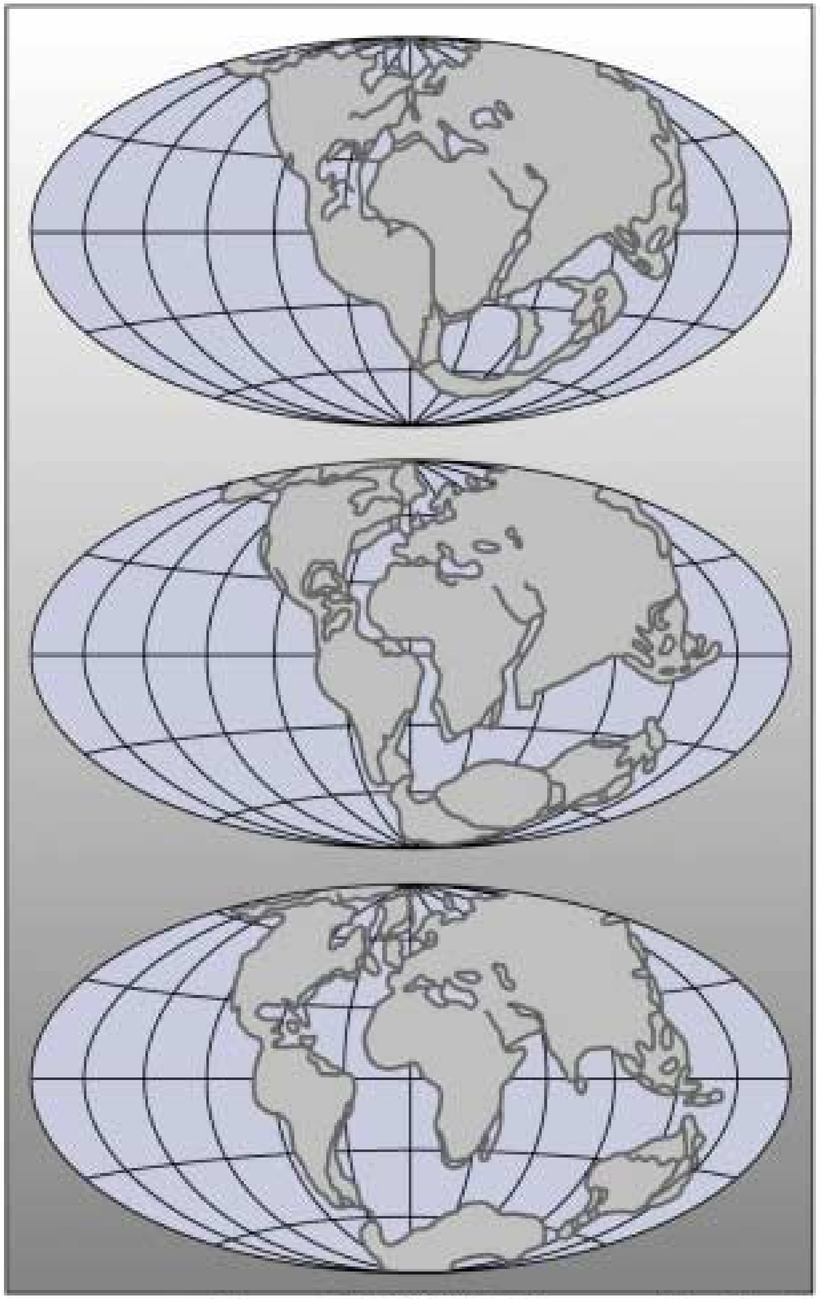
  - warm, "fresh" water stays on the surface
  - cold, saline water sinks

Thermo-haline circulation (THC): Fig 05_12

- Northern Atlantic Ocean is a key region where cold, saline water develops
- this may be what initiates the THC
- possible "trigger" point for global climate



Continental drift: Fig 6-1



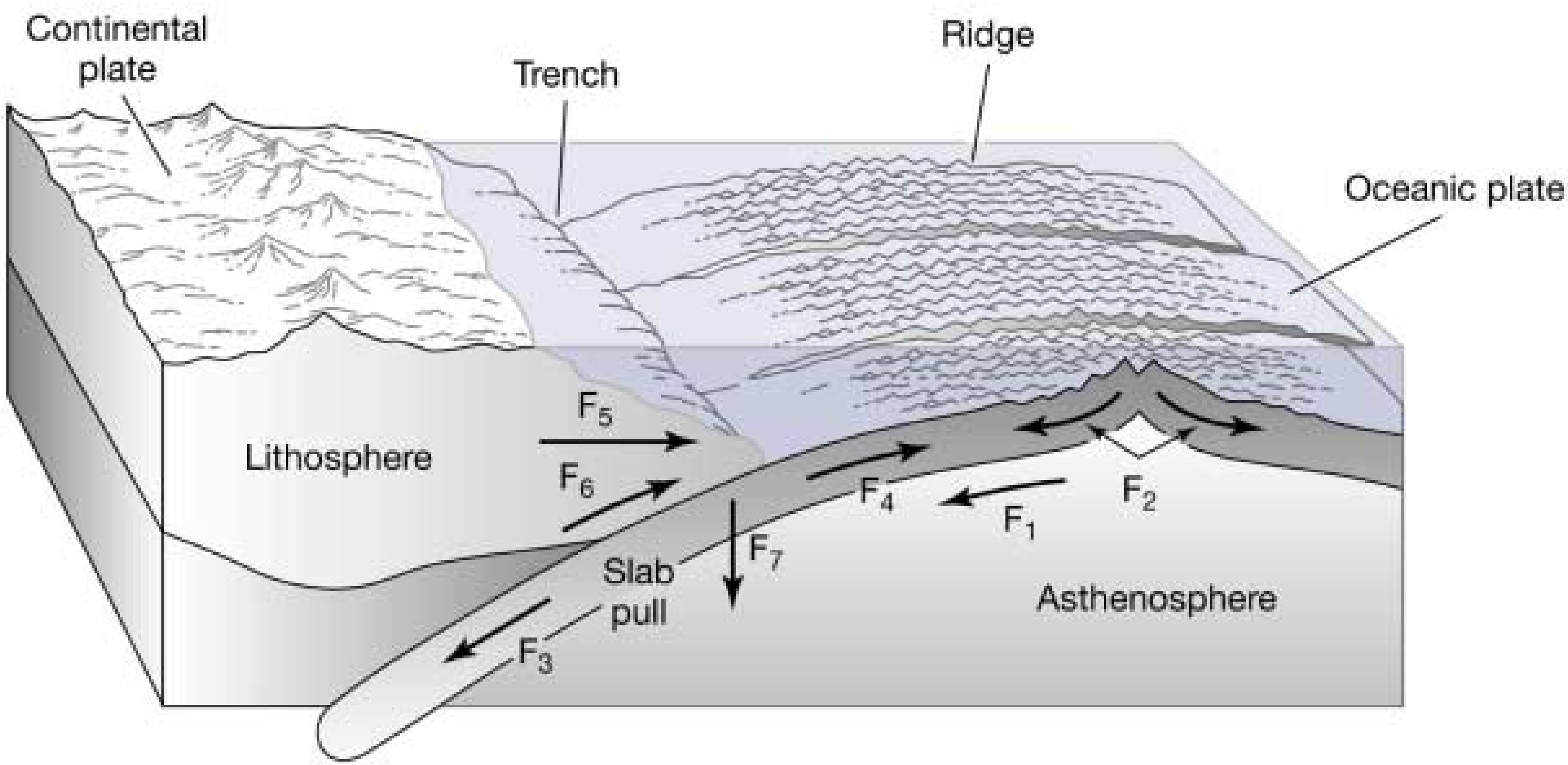
Late Carboniferous
(about 300 million
years ago)

Eocene
(about 50 million
years ago)

Pleistocene Glacial
(about 1 million
years ago)

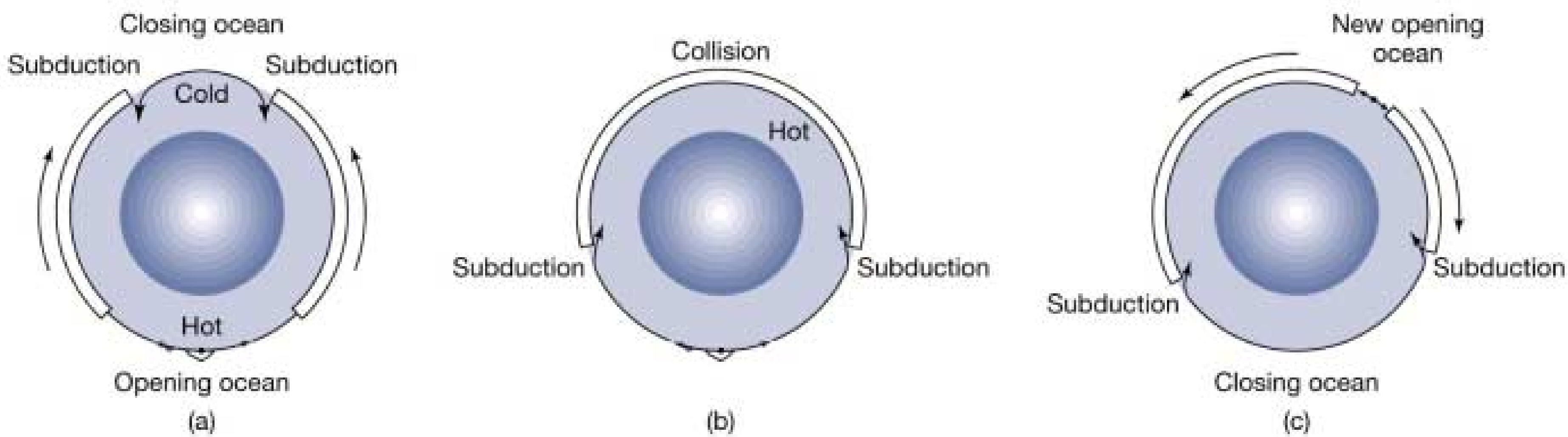
Plate tectonics: Fig 6-21

- another "pump"
- driven by circulations in the upper mantle; ultimately, by radioactive decay, releasing heat within the Earth's interior
- recycles key substances like mineralized carbon



Wilson Cycle: Fig 6-27

• continents group together then spread apart
• timescale is ~500 million years
• major climatic consequences (e.g. linked to "Snowball Earth" and mass extinction events)



Summary

Three BIG Pumps

• Atmosphere/Surface Ocean
  - distributes heat poleward
  - cause of regional and seasonal climates
  - mixing timescale is ~1 week

• THC
  - mixes deep ocean
  - timescale of mixing is about 1000 years
  - may shut on and off as conditions change in N. Atlantic
  - possible "trigger" for global climate

•Wilson Cycle
  - continents group and then spread
  - timescale is ~500 million years
  - major climatic effects
  - recycles key material from rocks back to the atmosphere