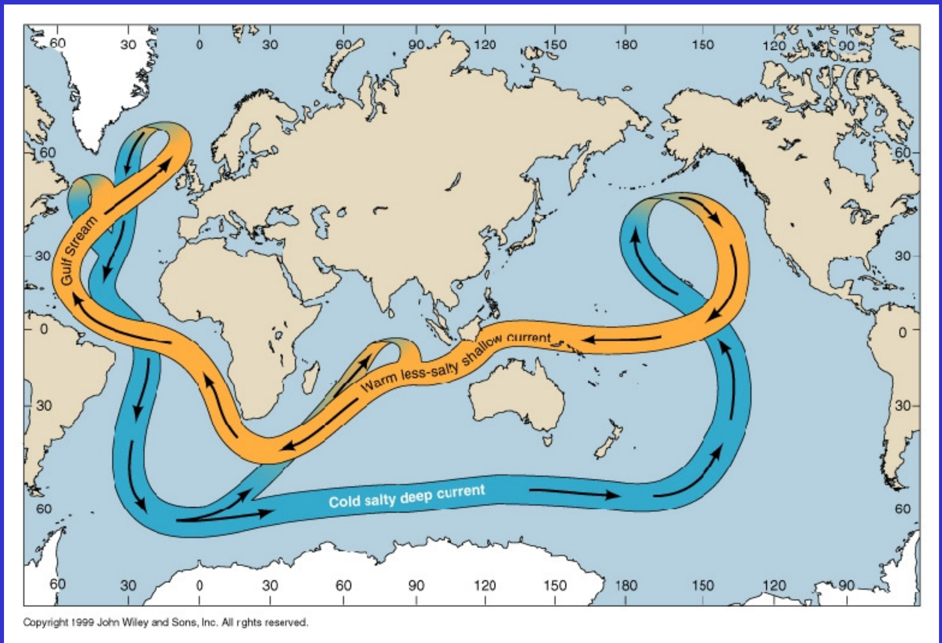
Lecture 4: OCEANS (Outline)



- Basic Structures and Dynamics
  - Ekman transport
  - Geostrophic currents
- Surface Ocean Circulation
  - Subtropicl gyre
  - Boundary current
- Deep Ocean Circulation
  - Thermohaline conveyor belt

Basic Ocean Structures

Warm up by sunlight!

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

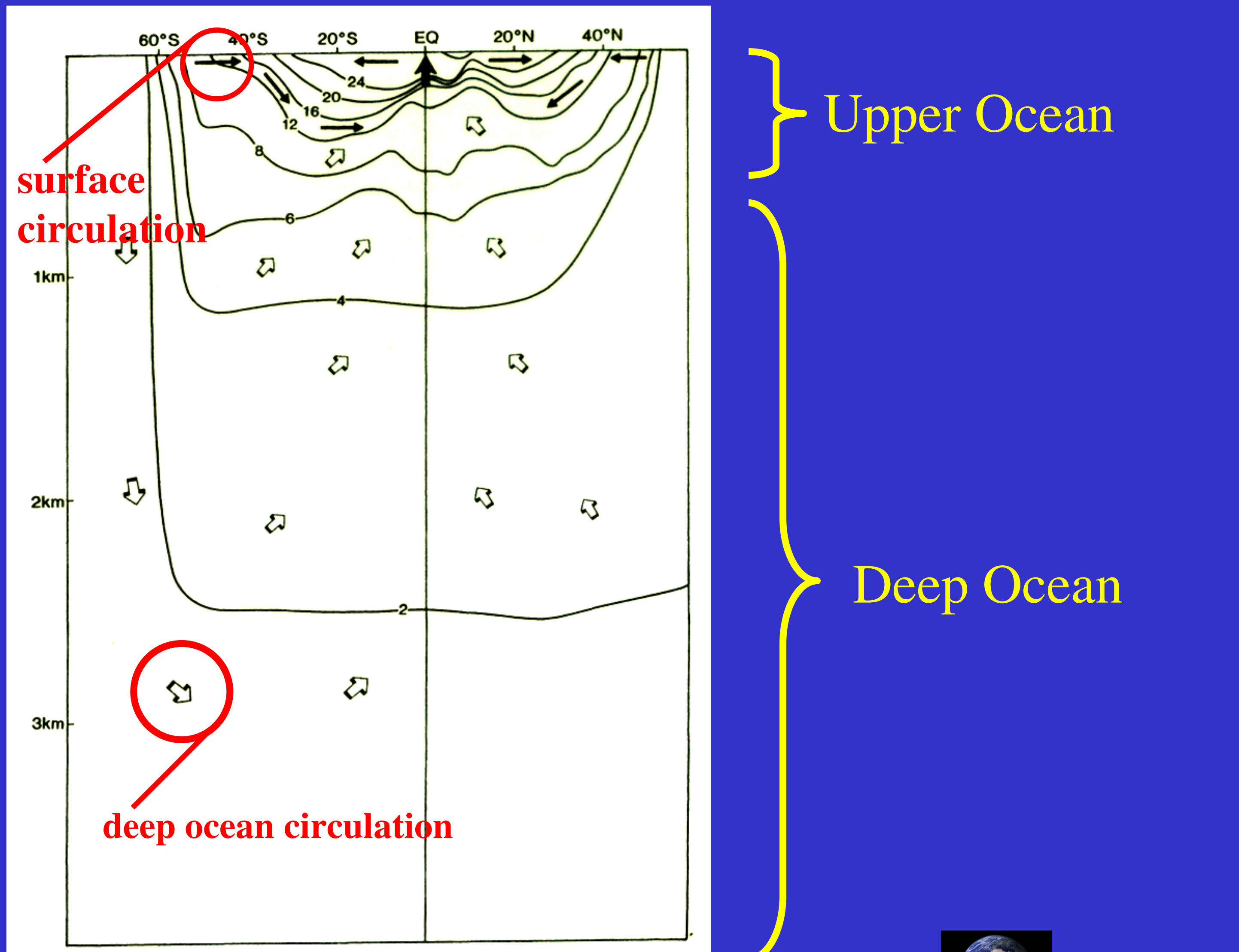
  Shallow, warm upper layer where light is abundant and where most marine life can be found.

- **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?"*)

The State of Oceans

- Temperature

  warm on the upper ocean, cold in the deeper ocean.

- Salinity

  variations determined by evaporation, precipitation, sea-ice formation and melt, and river runoff.

- Density

  small in the upper ocean, large in the deeper ocean.

Potential Temperature

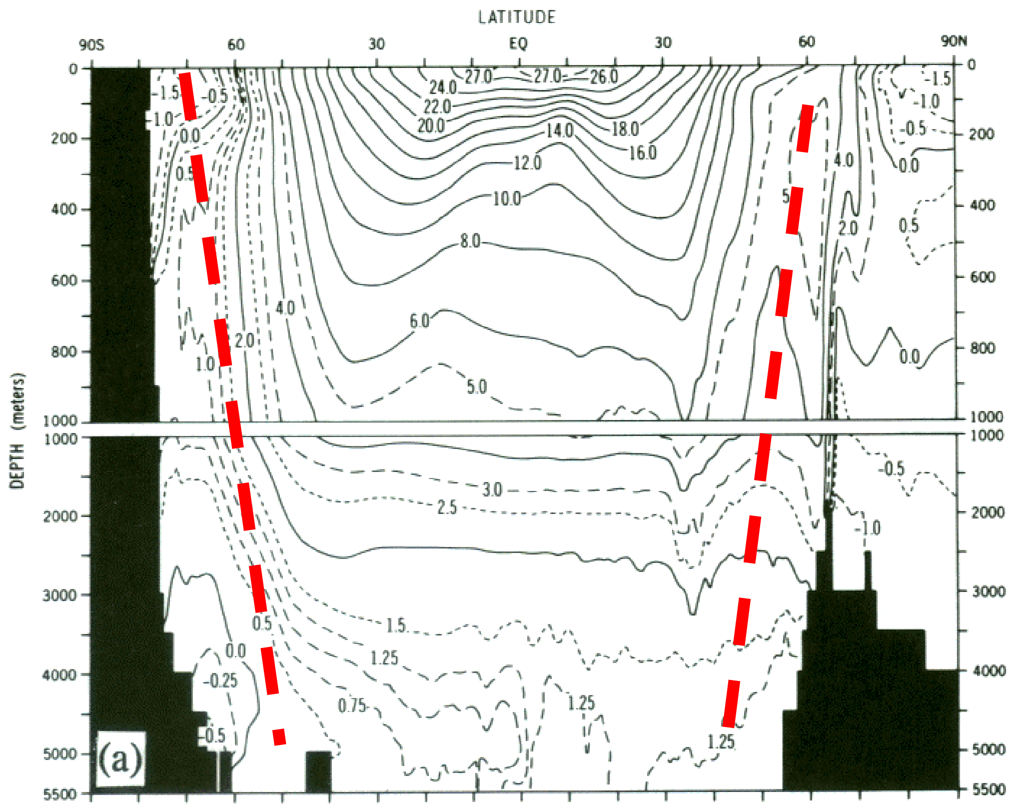


Fig. 7.1 Annual-mean zonal average for the global ocean of (a) potential temperature (°C), and (b) salinity [‰ (‰ = parts per thousand)], and (c) potential density ($\rho_t - 1000$, kg m^{-3}). [From Levitus (1982).]

(from *Global Physical Climatology*)

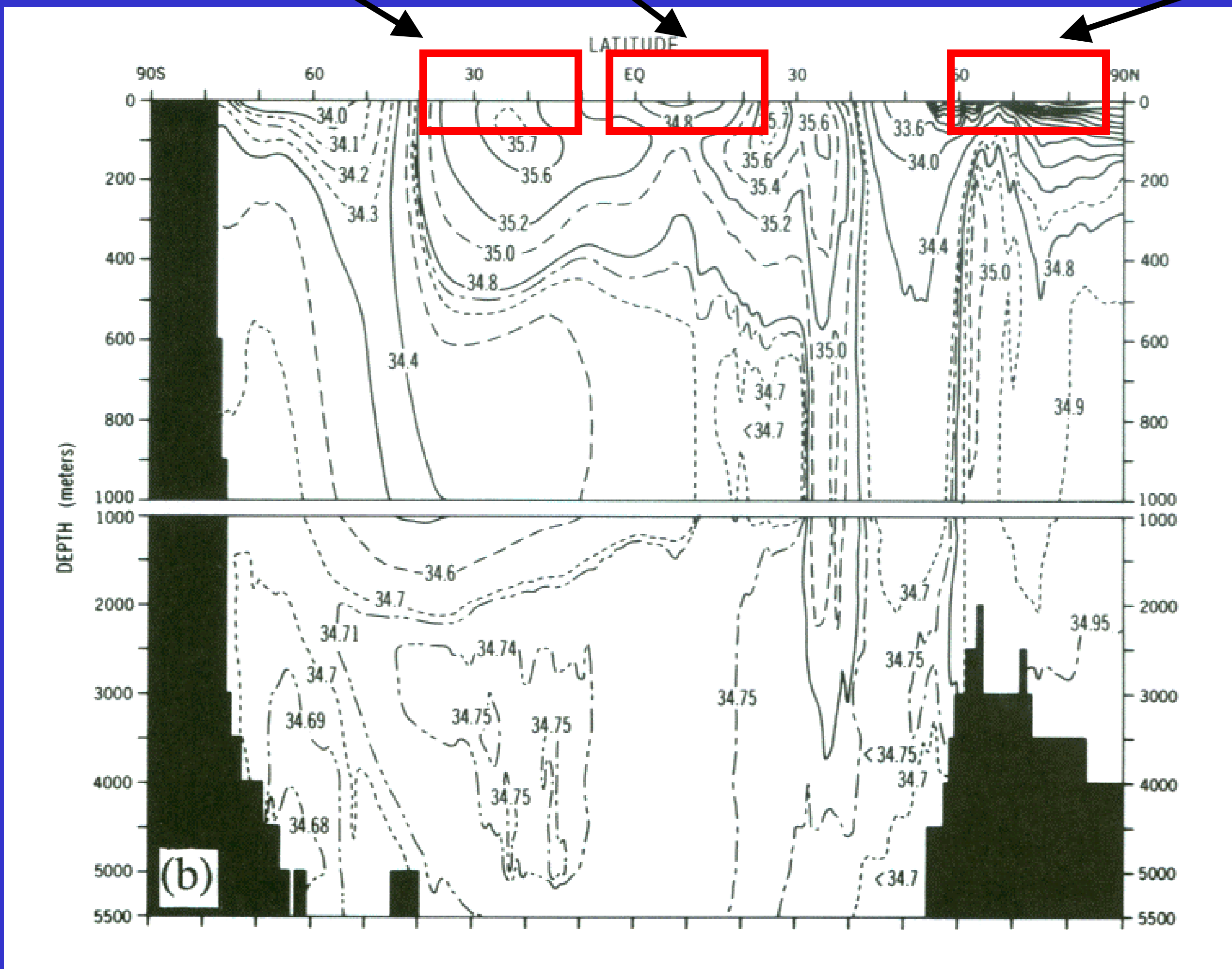
- Potential temperature is very close to temperature in the ocean.
- The average temperature of the world ocean is about 3.6°C.

Salinity

E < P

E > P

Sea-ice formation and melting

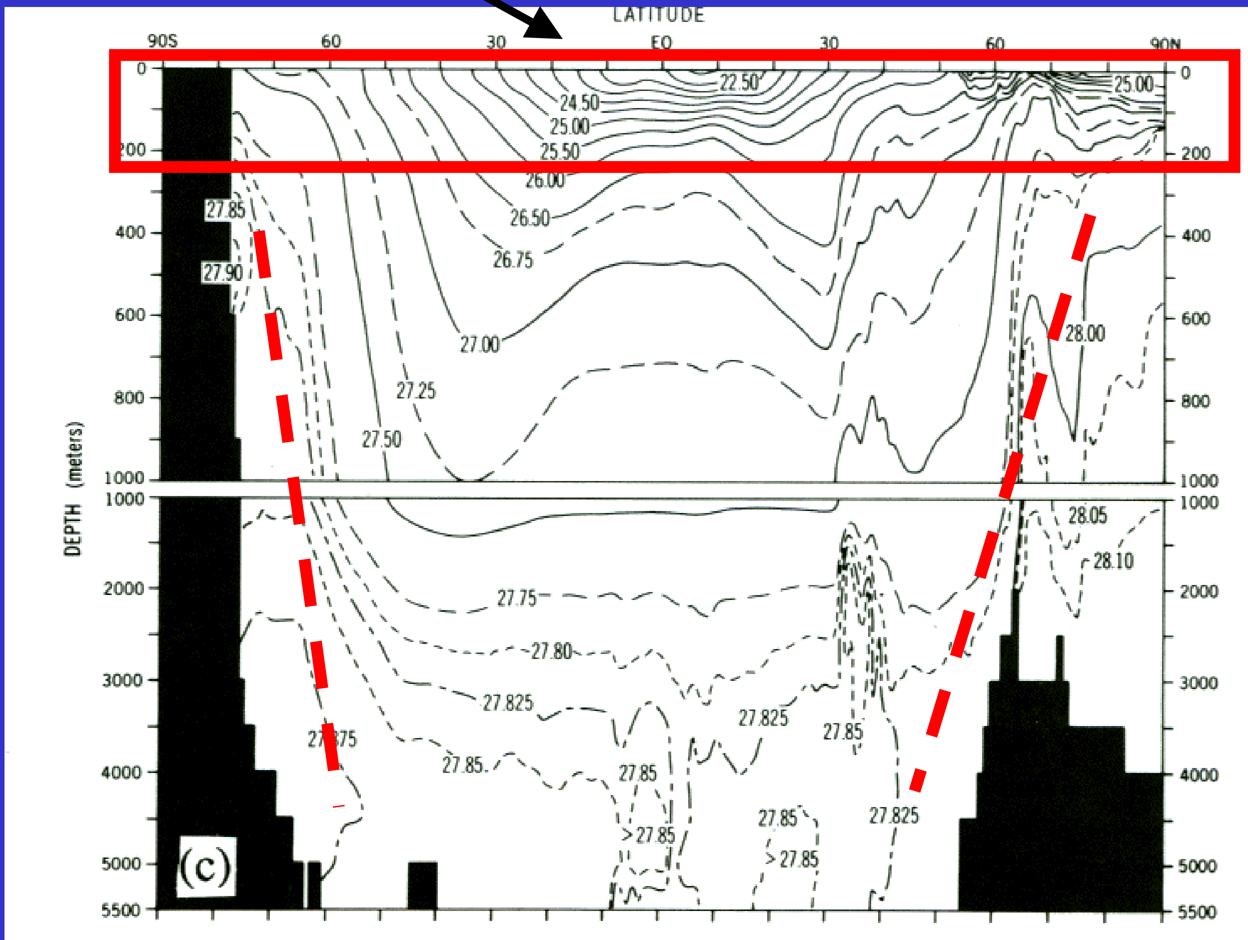


(from *Global Physical Climatology*)

- Salinity is the mass of dissolved salts in a kilogram of seawater.
- Unit: ‰ (part per thousand; per mil).
- The average salinity of the world ocean is 34.7‰.
- Four major factors that affect salinity: evaporation, precipitation, inflow of river water, and sea-ice formation and melting.

Density

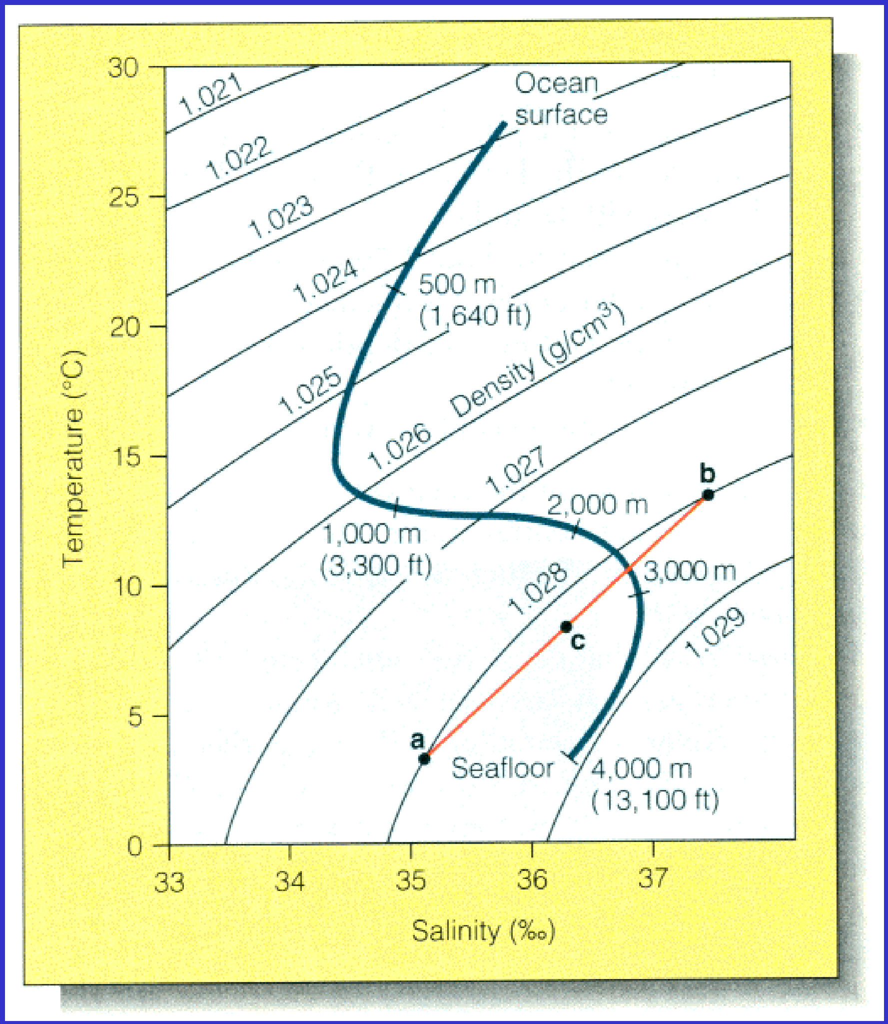
Low density due to absorption of solar energy near the surface.



(from *Global Physical Climatology*)

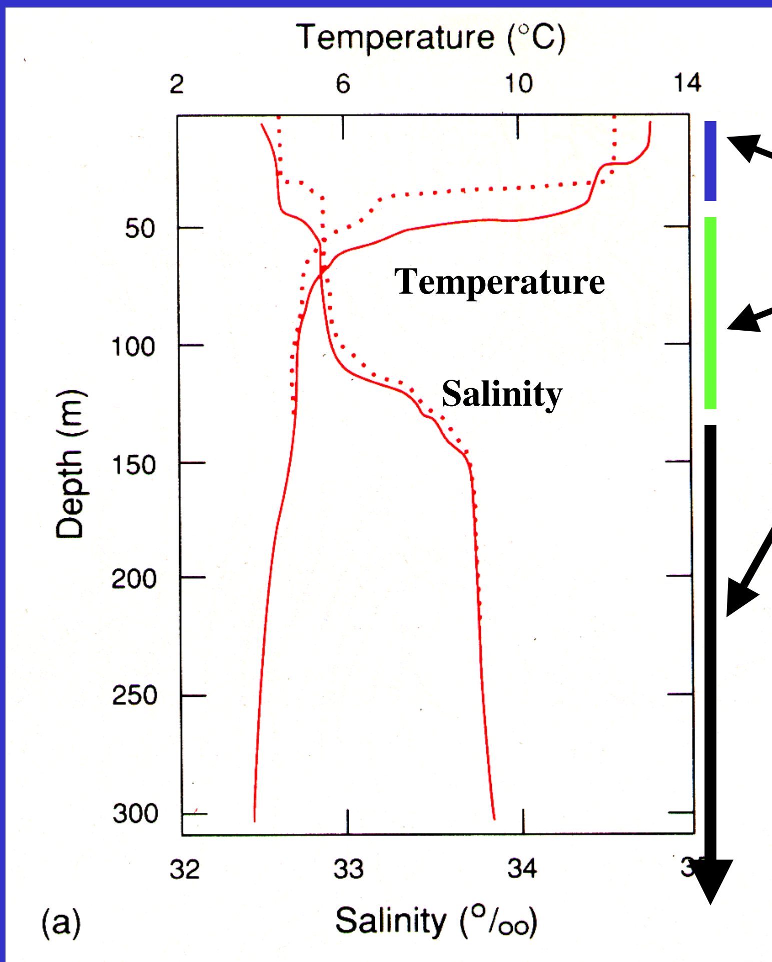
- ❑ Seawater is almost incompressible, so the density of seawater is always very close to 1000 kg/m^3.
- ❑ Potential density is the density that seawater with a particular salinity and temperature would have at zero water pressure (or at surface air pressure).
- ❑ Potential density = density – 1000 kg/m^3.

Density and Temperature and Salinity



(Figure from *Oceanography* by Tom Garrison)

Vertical Structure of Ocean



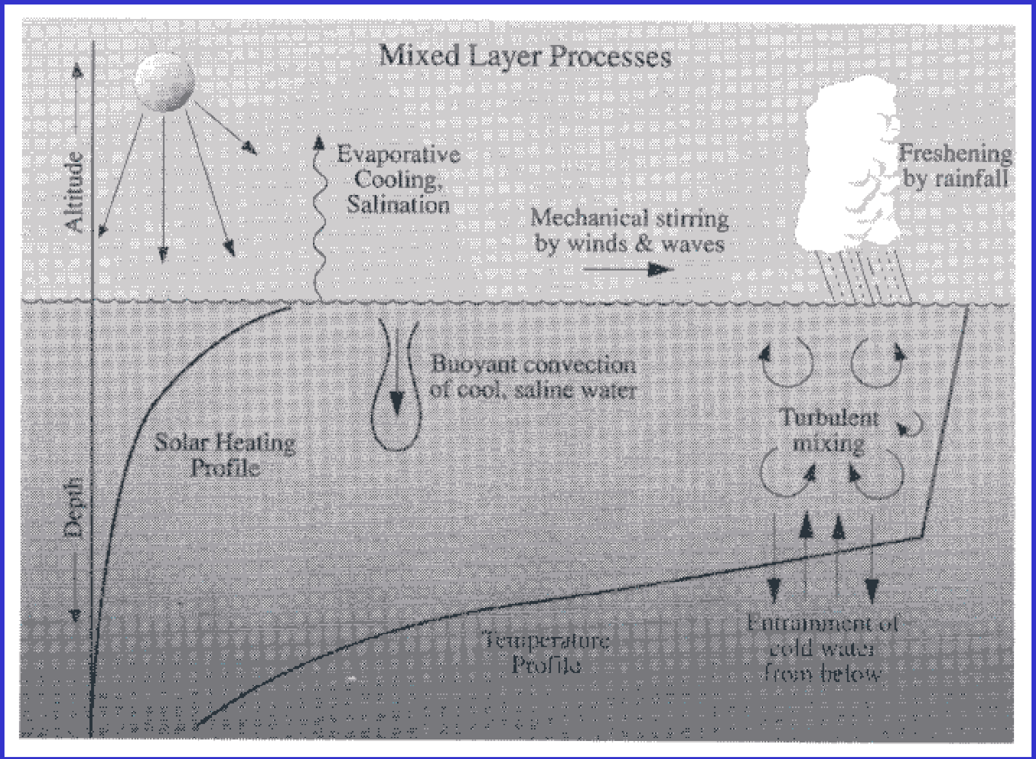
Mixed Layer: T and S well mixed by winds

Thermocline: large gradient of T and S

Deep Ocean: T and S independent of height
cold
salty
high nutrient level

(from *Climate System Modeling*)

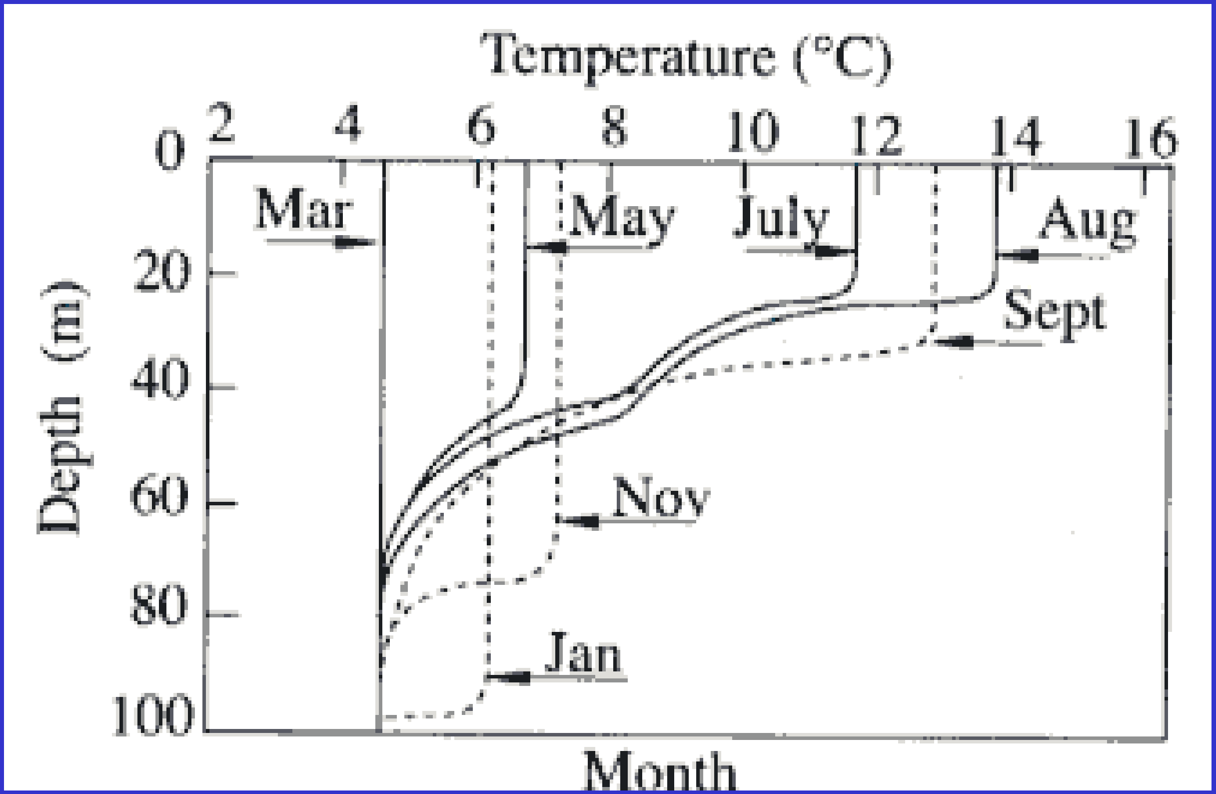
Mixed Layer Processes



(from *Global Physical Climatology*)

- The depth of the mixed layer is determined by (1) the rate of buoyancy generation and (2) the rate of kinetic energy supply.
- The atmosphere can affect the mixed layer through three processes: heating, wind forcing, and freshening (P-E).
- The global-average depth of the mixed layer is about 70 m.
- The heat capacity of the mixed layer is about 30 times the heat capacity of the atmosphere.

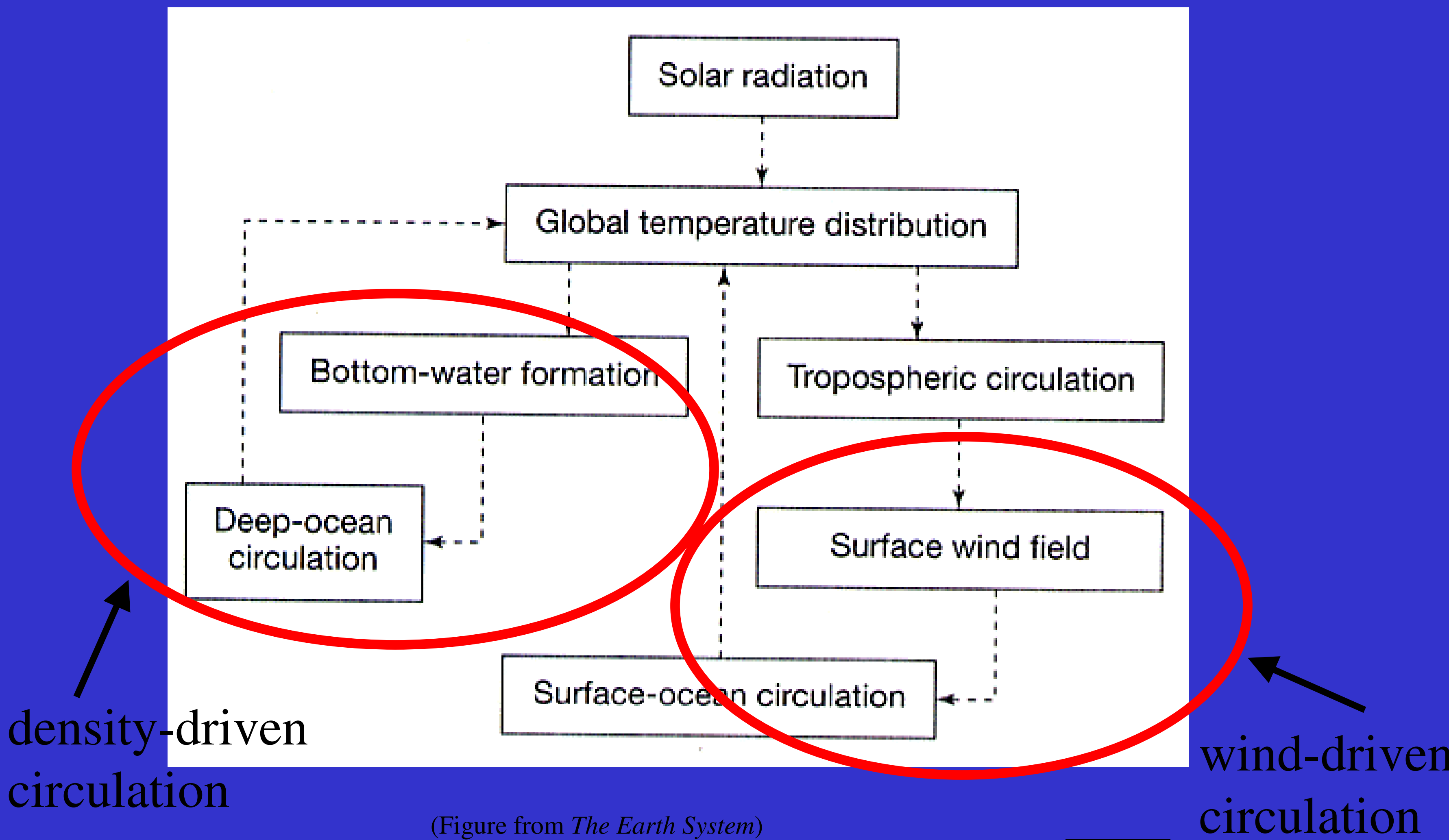
Seasonal Variation of Mixed Layer



(from *Global Physical Climatology*)

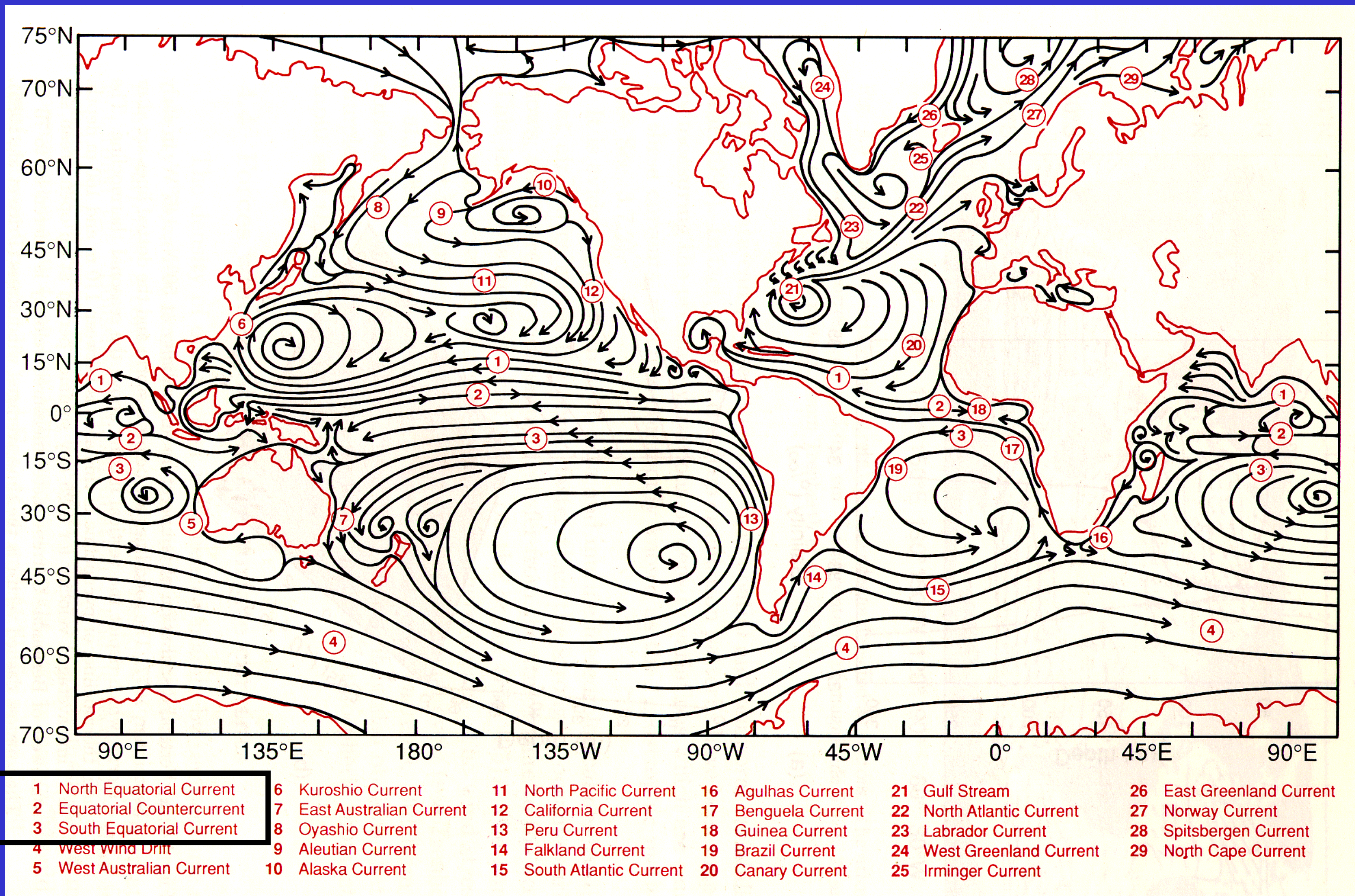
- Summer: warm and thin.
- Winter: cold and deep (several hundred meters).

Two Circulation Systems

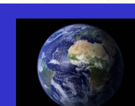


(Figure from *The Earth System*)

Global Surface Currents



(from *Climate System Modeling*)



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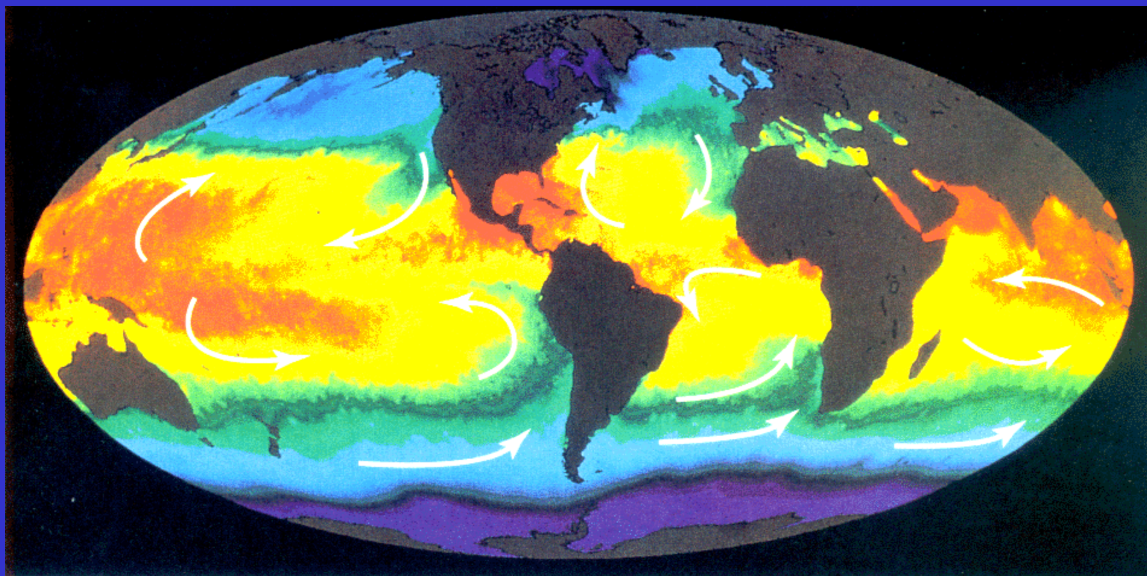
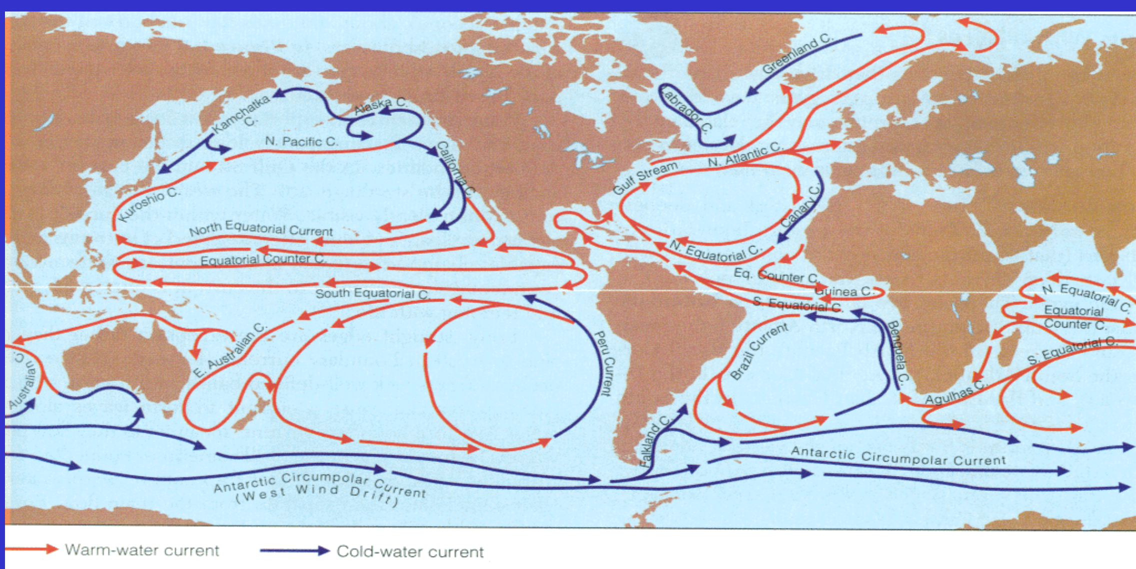
Six Great Current Circuits in the World Ocean





- **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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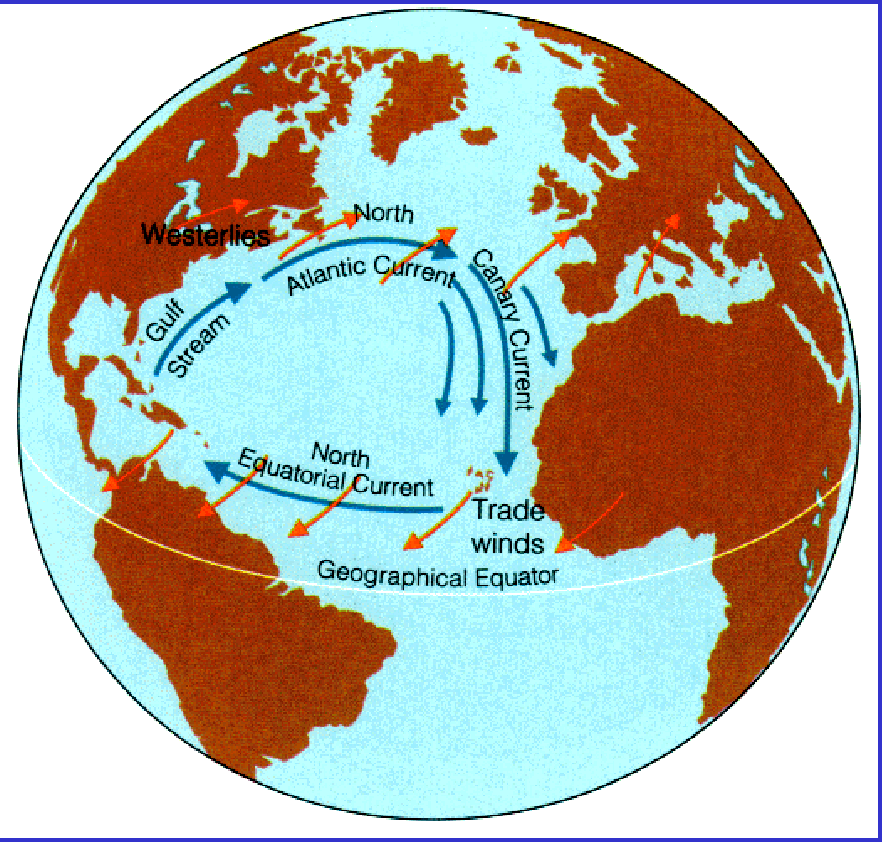
Characteristics of the Gyres

(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

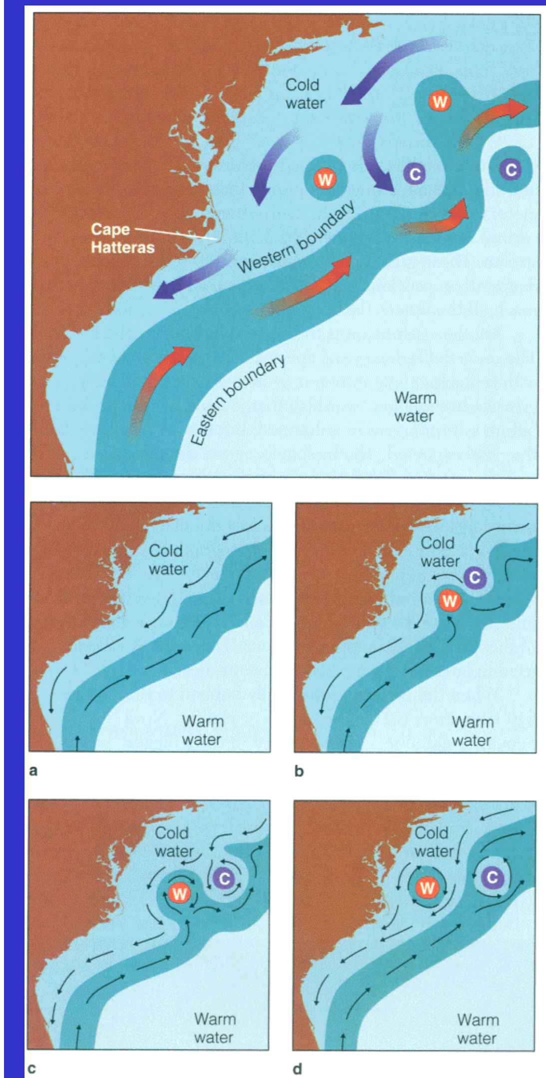
- **Eastern Boundary Current**

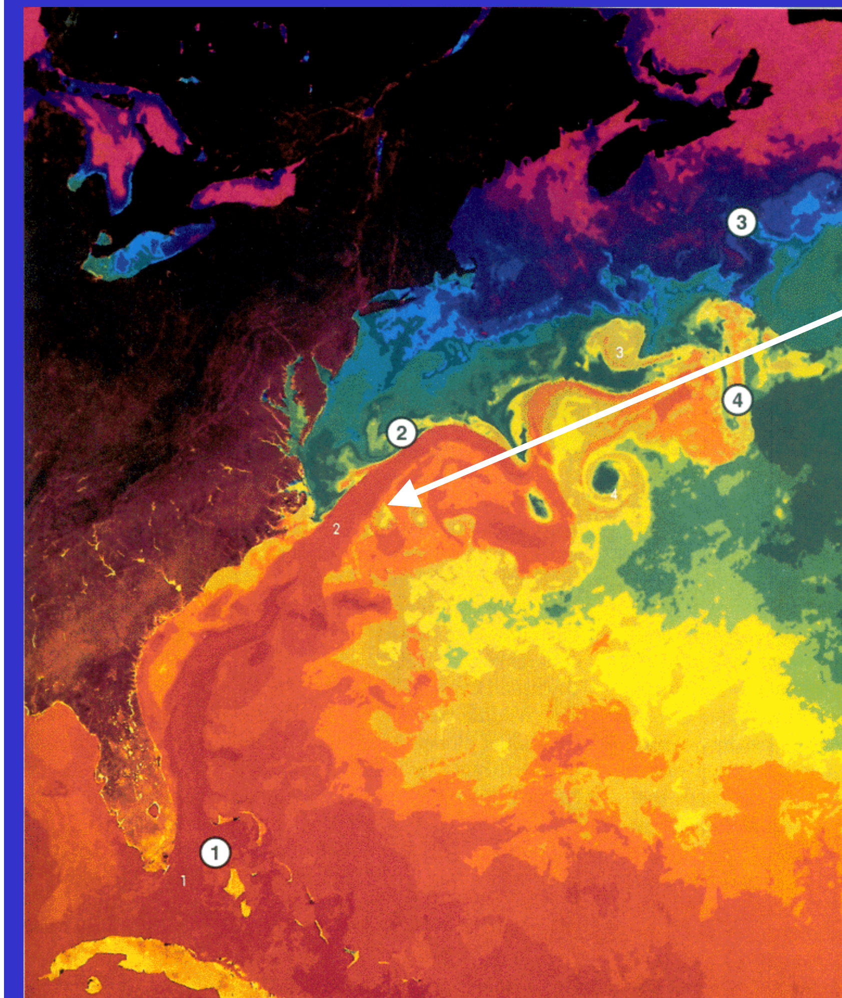
  Canary Current (in the North Atlantic)
  California Current (in the North Pacific)
  Benguela Current (in the South Atlantic)
  Peru Current (in the South Pacific)
  Western Australian Current (in the Indian Ocean)

- **Westerly-Driven Current**

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

Gulf Stream





A river of current

Jet stream in the ocean

- Speed = 2 m/sec
- Depth = 450 m
- Width = 70 Km
- Color: clear and blue

(Figure from *Oceanography* by Tom Garrison)

Surface Current – Geostrophic Gyre

- Mixed Layer

  Currents controlled by frictional force + Coriolis force
  → wind-driven circulation
  → Ekman transport (horizontal direction)
  → convergence/divergence
  → downwelling/upwelling at the bottom of mixed layer

- Thermocline

  downwelling/upwelling in the mixed layer
  → pressure gradient force + Coriolis force
  → geostrophic current
  → Sverdrup transport (horizontal)

Step 1: Surface Winds

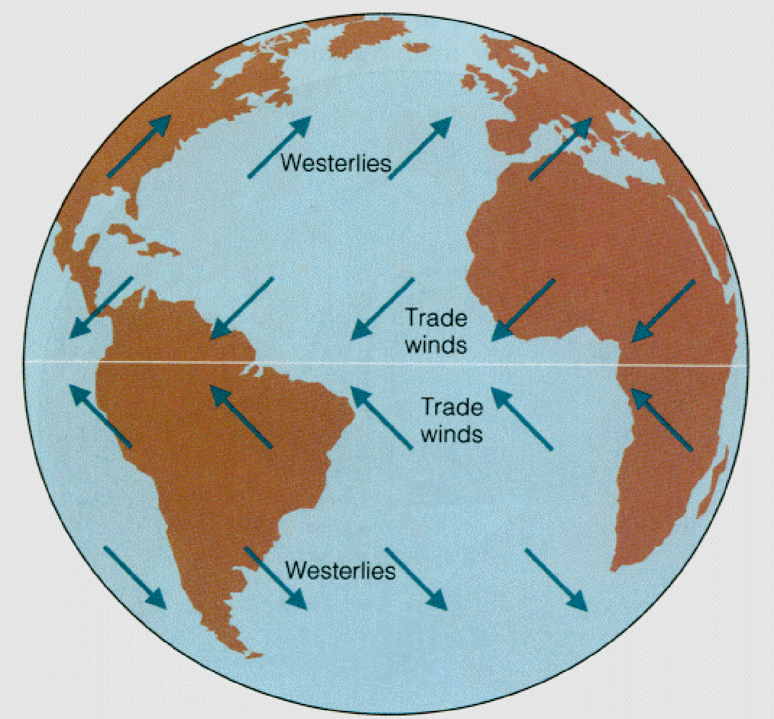


Figure 9.1 Winds, driven by uneven solar heating and Earth's spin, drive the movement of the ocean's surface currents. The prime movers are the powerful westerlies and the persistent trade winds (easterlies).

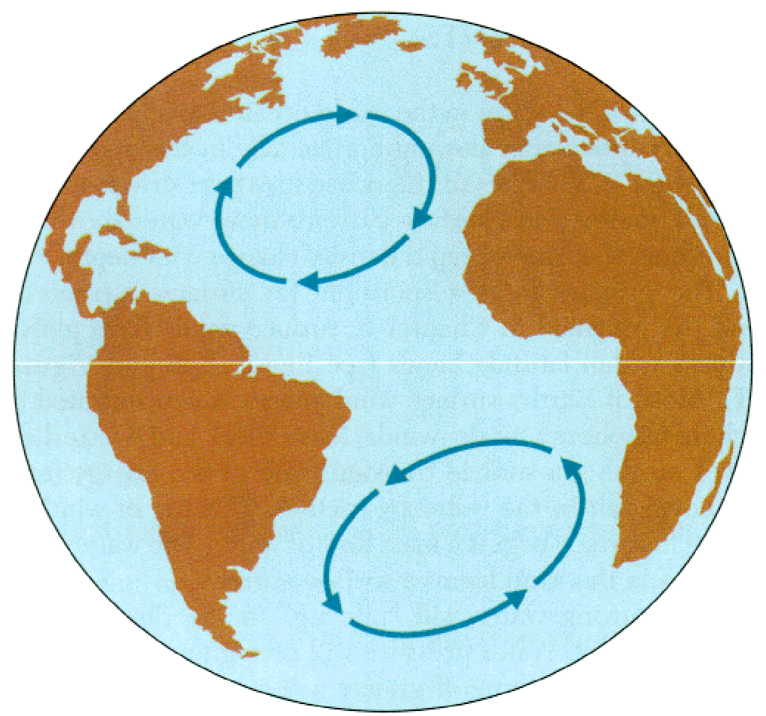
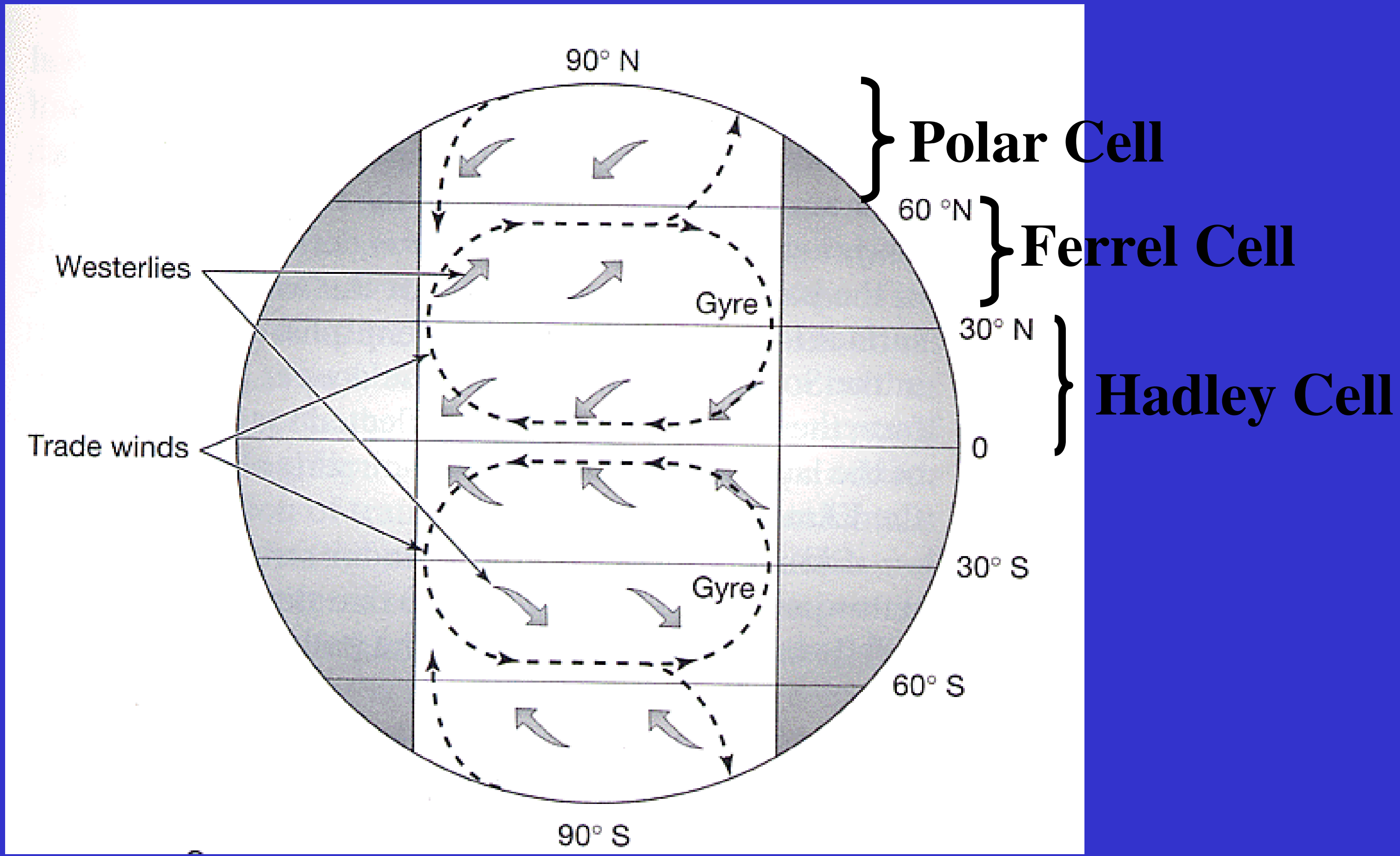


Figure 9.2 A combination of four forces—surface winds, the sun's heat, the Coriolis effect, and gravity—circulates the ocean surface clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, forming gyres.

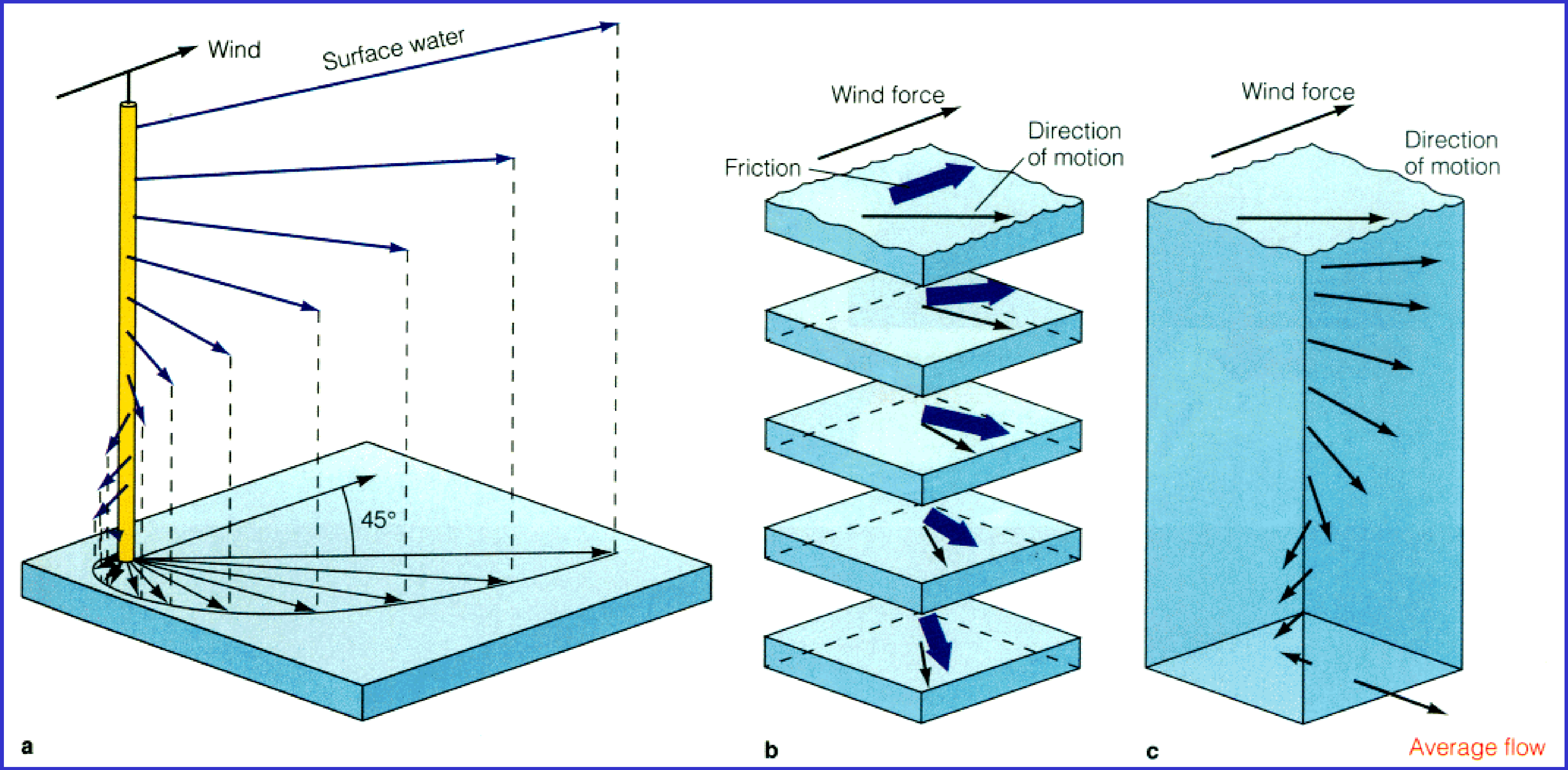
(Figure from *Oceanography* by Tom Garrison)

Winds and Surface Currents



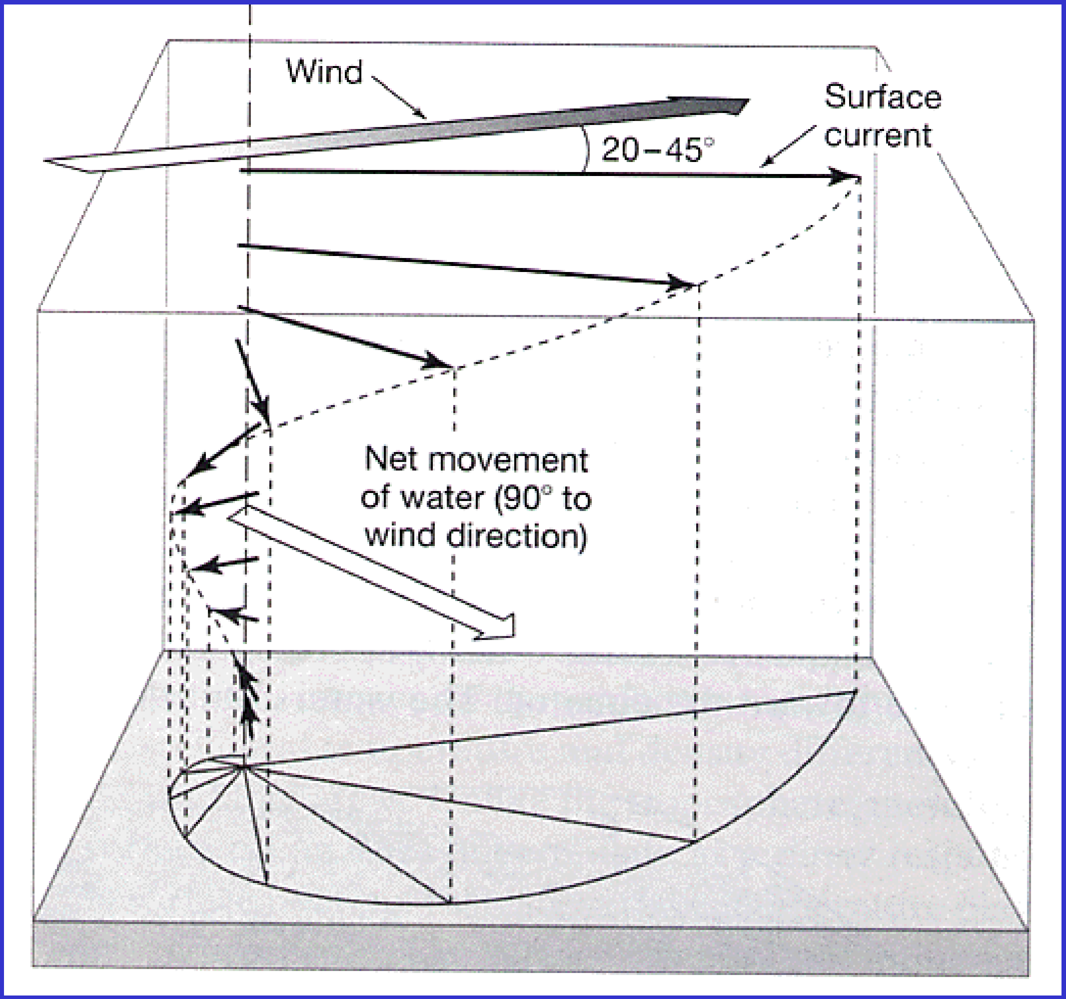
(Figure from *The Earth System*)

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



(Figure from *Oceanography* by Tom Garrison)

Ekman Spiral – A Result of Coriolis Force



(Figure from *The Earth System*)

Formula for Ekman Transport

$$U_E = \int_{-\infty}^{0} u_E \, dz = \frac{\tau_y}{\rho_o f}; \qquad V_E = \int_{-\infty}^{0} v_E \, dz = -\frac{\tau_x}{\rho_o f}$$

How Deep is the Ekman Layer?

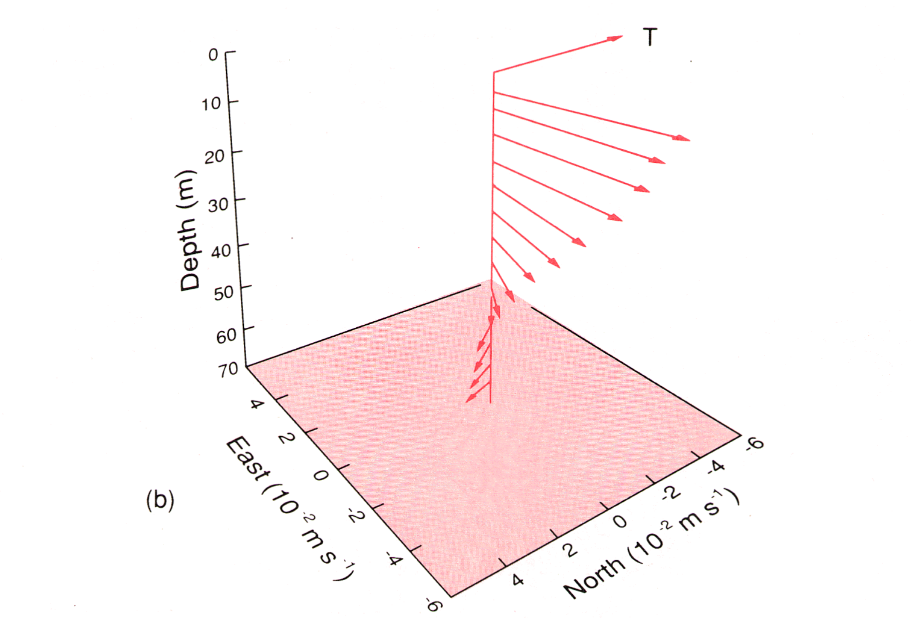


Fig. 4.4 (a) Vertical distribution of temperature and salinity at 50°N., 145°W. in early September, 1977. The solid lines are before a storm and the dotted lines are after a storm, which depict the vertical mixing above the seasonal thermocline. The main thermocline, or pycnocline in this area is between 110 m and 160 m depth. (b) Time-averaged velocity for a 25 day summer period at an open ocean site southwest of Bermuda. Current meter measured velocity is referenced to 70 m. The topmost dashed vector is the time-averaged wind stress (Price et al., 1986).

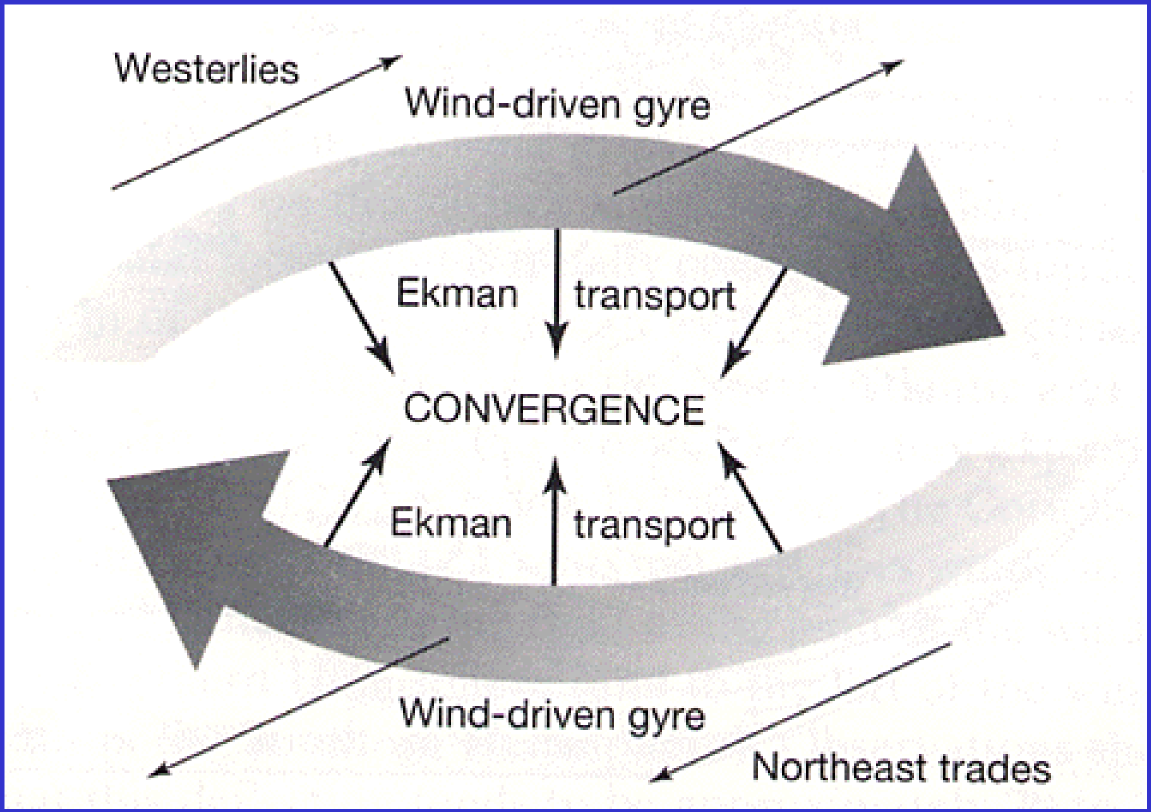
(from *Climate System Modeling*)

- $D \propto (\nu/f)^{1/2}$

ν = vertical diffusivity of momentum

f = Coriolis parameter = $2\Omega\sin\phi$

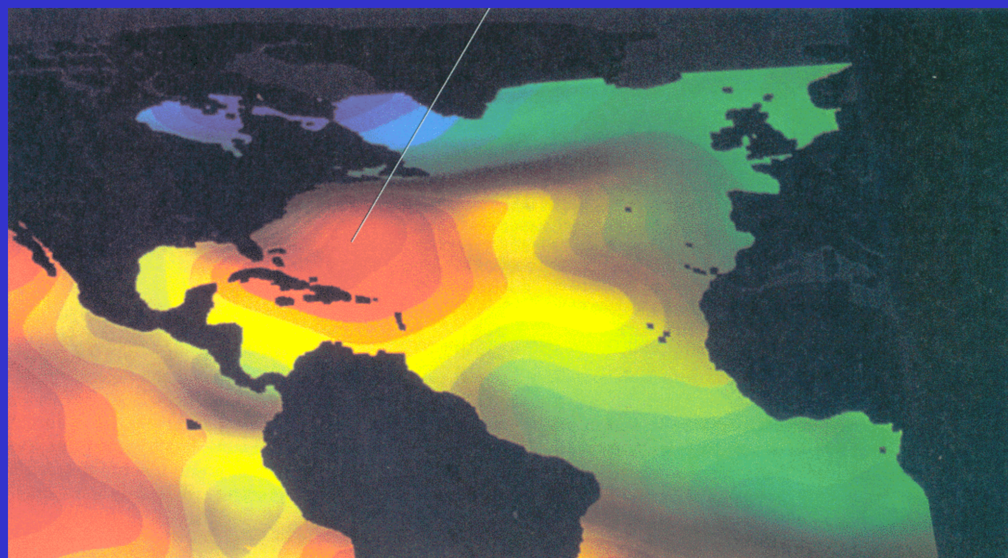
Ekman Transport



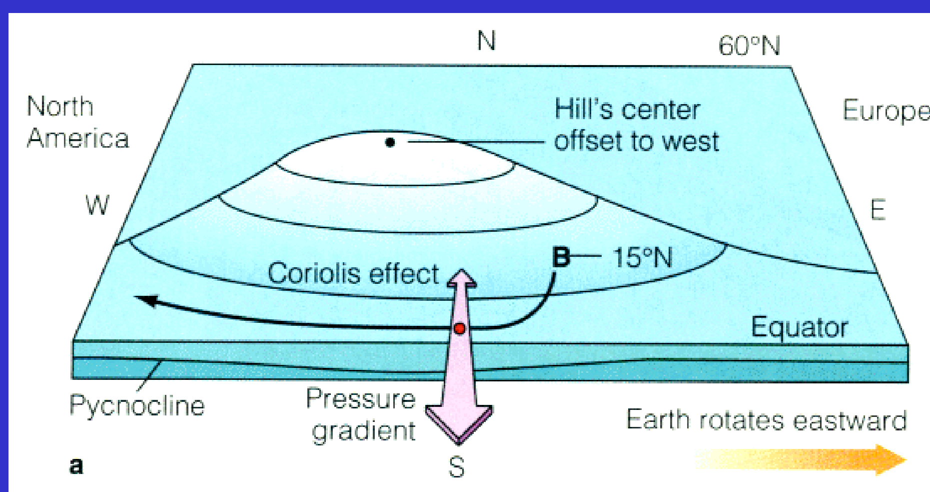
(Figure from *The Earth System*)

Step 3: Geostrophic Current

(Pressure Gradient Force + Corioils Foce)



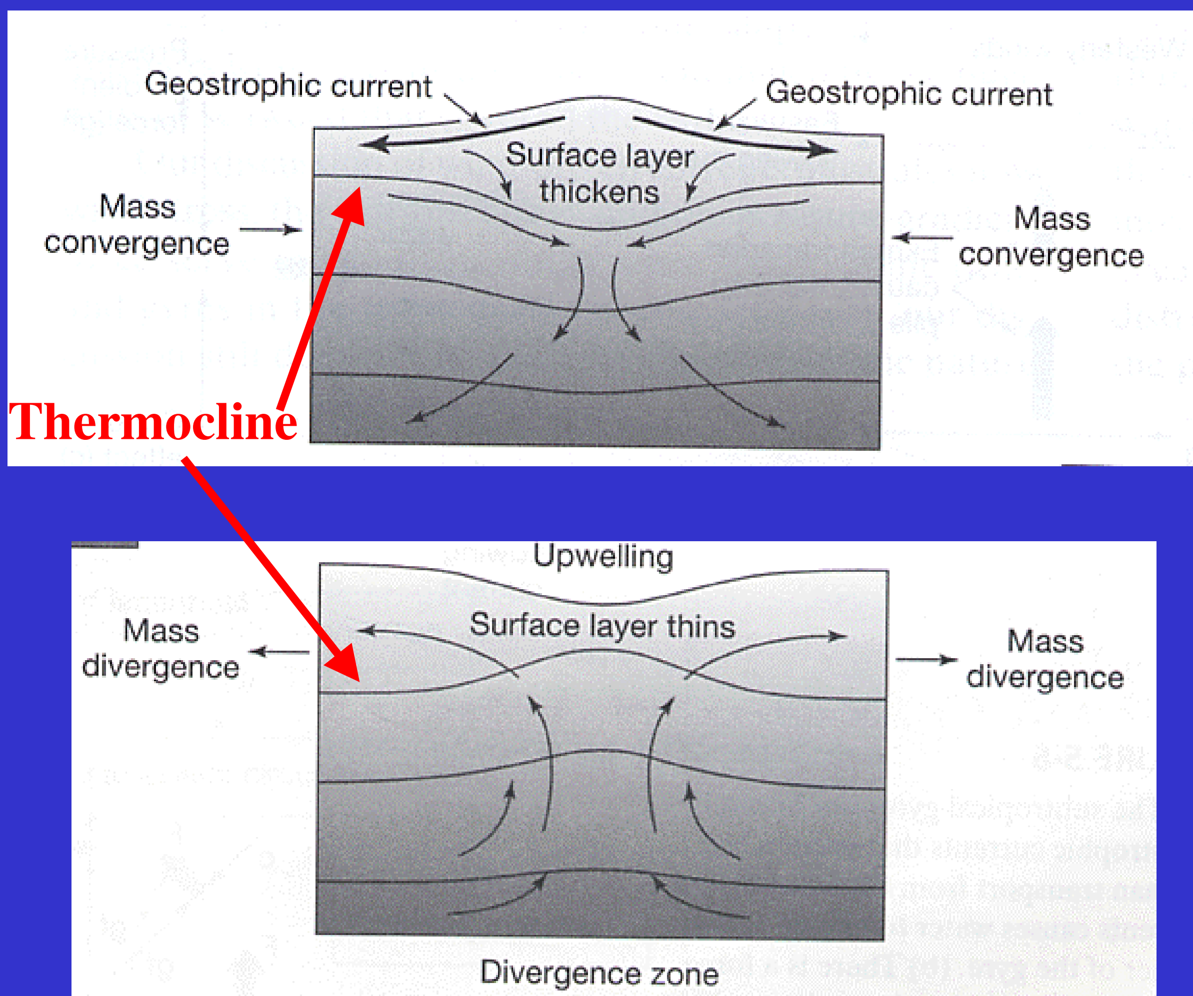
NASA-TOPEX Observations of Sea-Level Hight



(from *Oceanography* by Tom Garrison)

Ekman Transport → Convergence/Divergence

(Figure from *The Earth System*)



Surface wind + Coriolis Force

↓

Ekman Transport

↓

Convergence/divergence (in the center of the gyre)

↓

Pressure Gradient Force

↓

Geostrophic Currents

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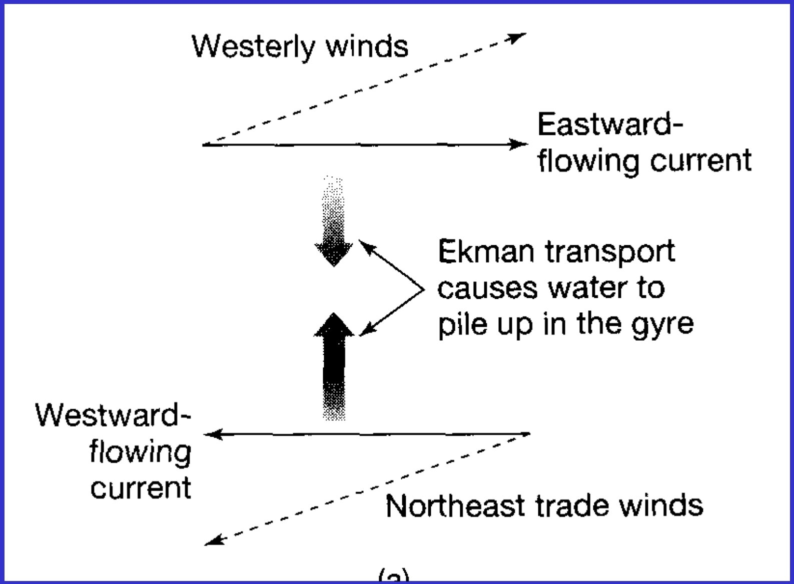
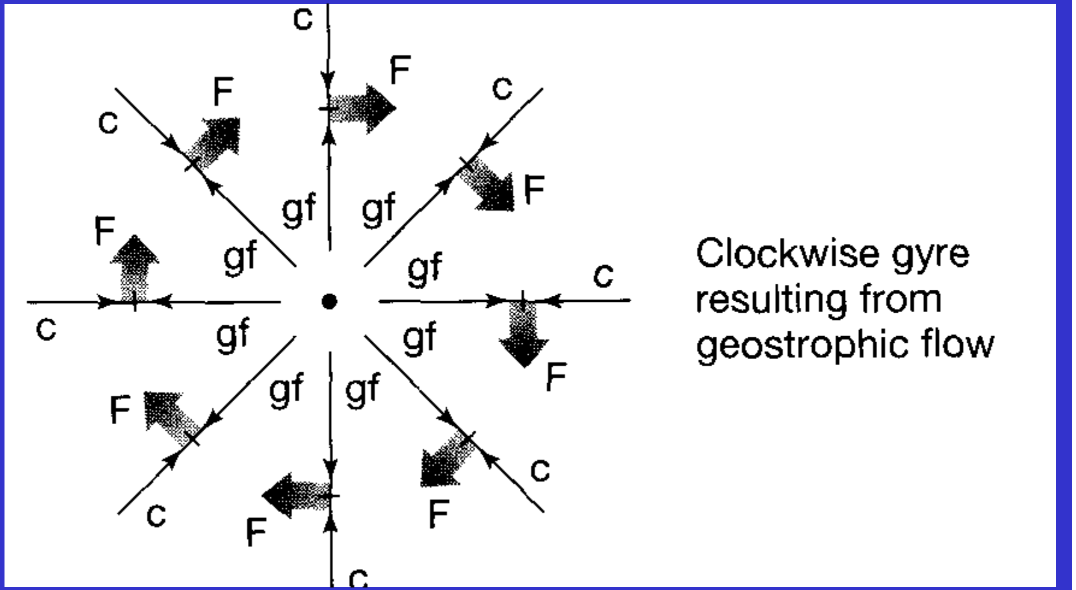
Geostrophic Current

Forces

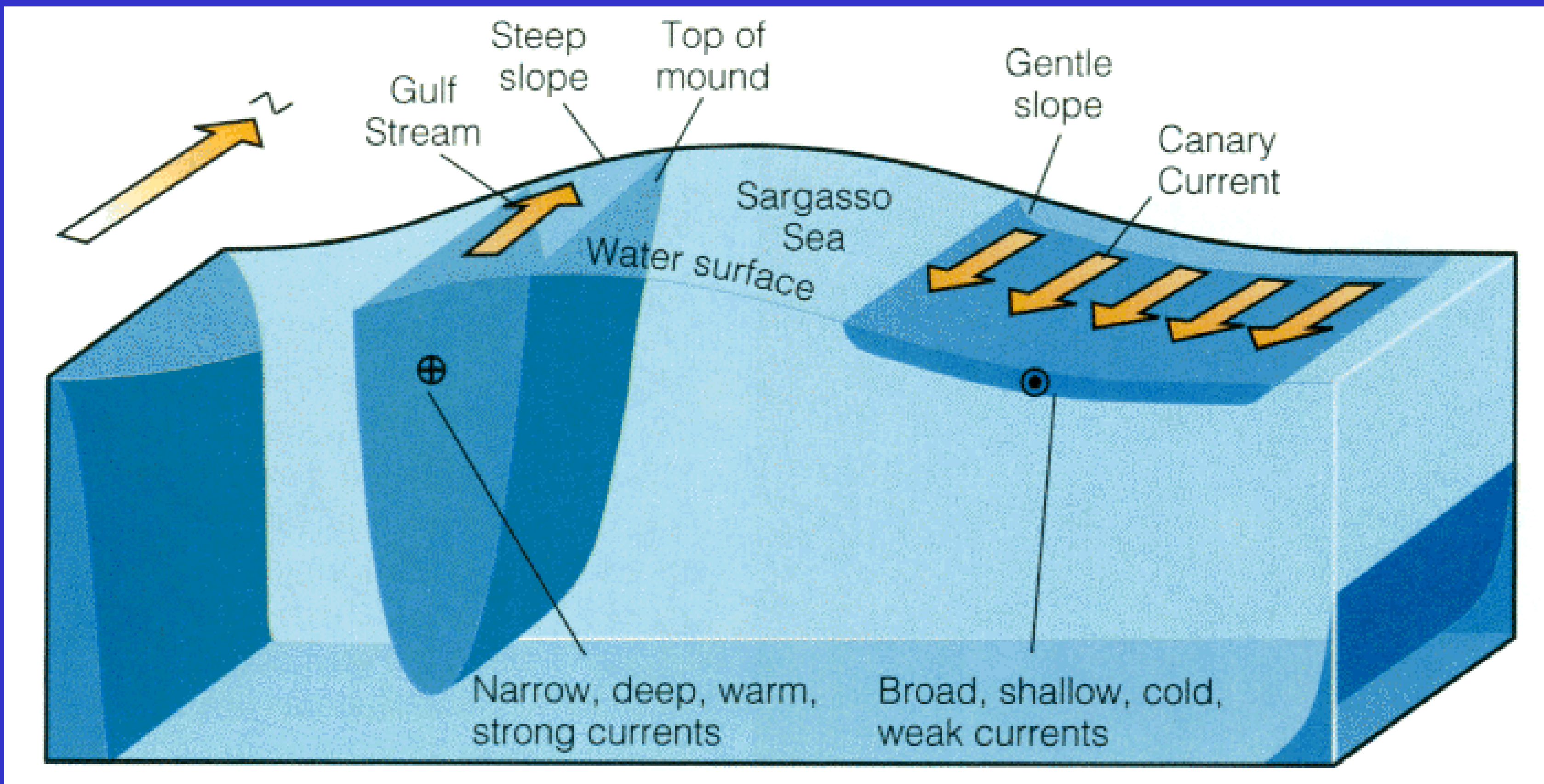


Geostrophic Gyre Currents



(Figure from *The Earth System*)

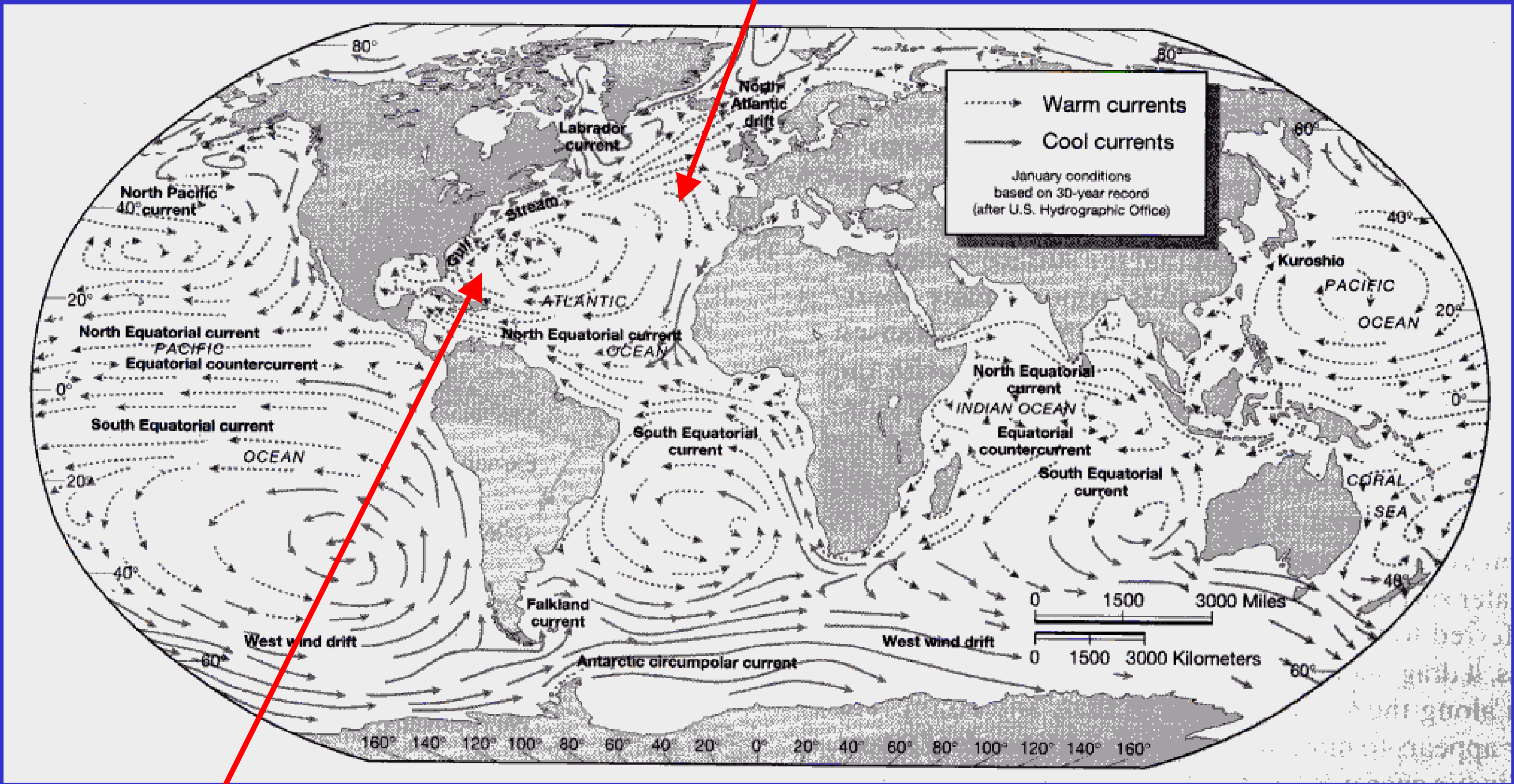
Step 4: Boundary Currents



(Figure from *Oceanography* by Tom Garrison)

Boundary Currents

Eastern boundary currents: broad and weak



Western boundary currents: narrow and strong

Eastern Boundary Current

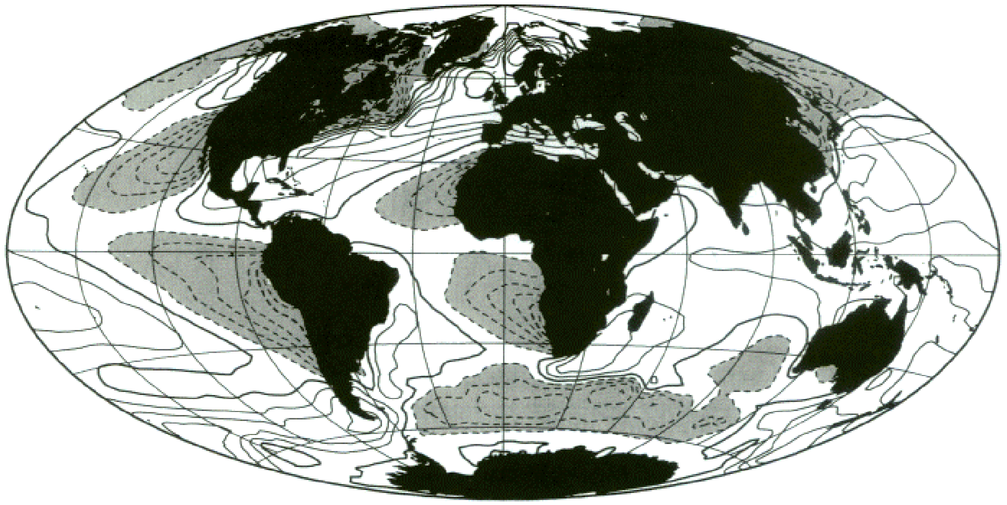
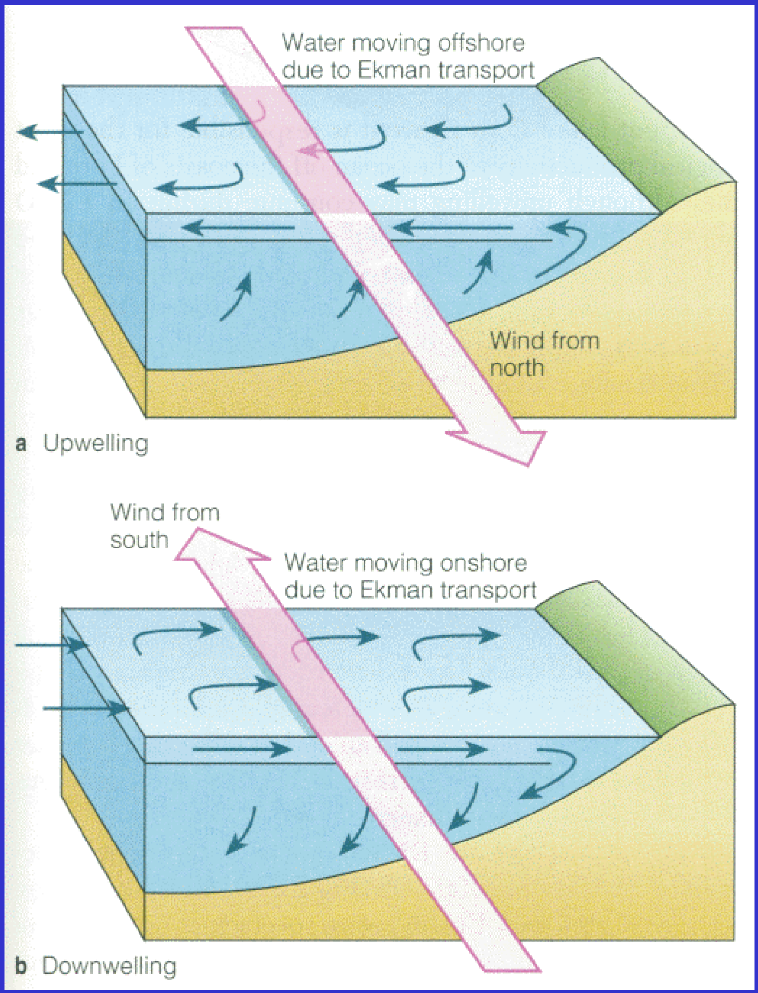


Fig. 7.11 The deviation of the July sea surface temperature from its zonal average at each latitude. Contour interval is 1°C, and values less than –1°C are shaded.

(from *Global Physical Climatology*)

- ❑ Cold water from higher latitude ocean.
- ❑ Costal upwelling associated with subtropical high pressure system.
- ❑ Atmospheric subsidence produce persistent stratiform clouds, which further cool down SSTs by blocking solar radiation.

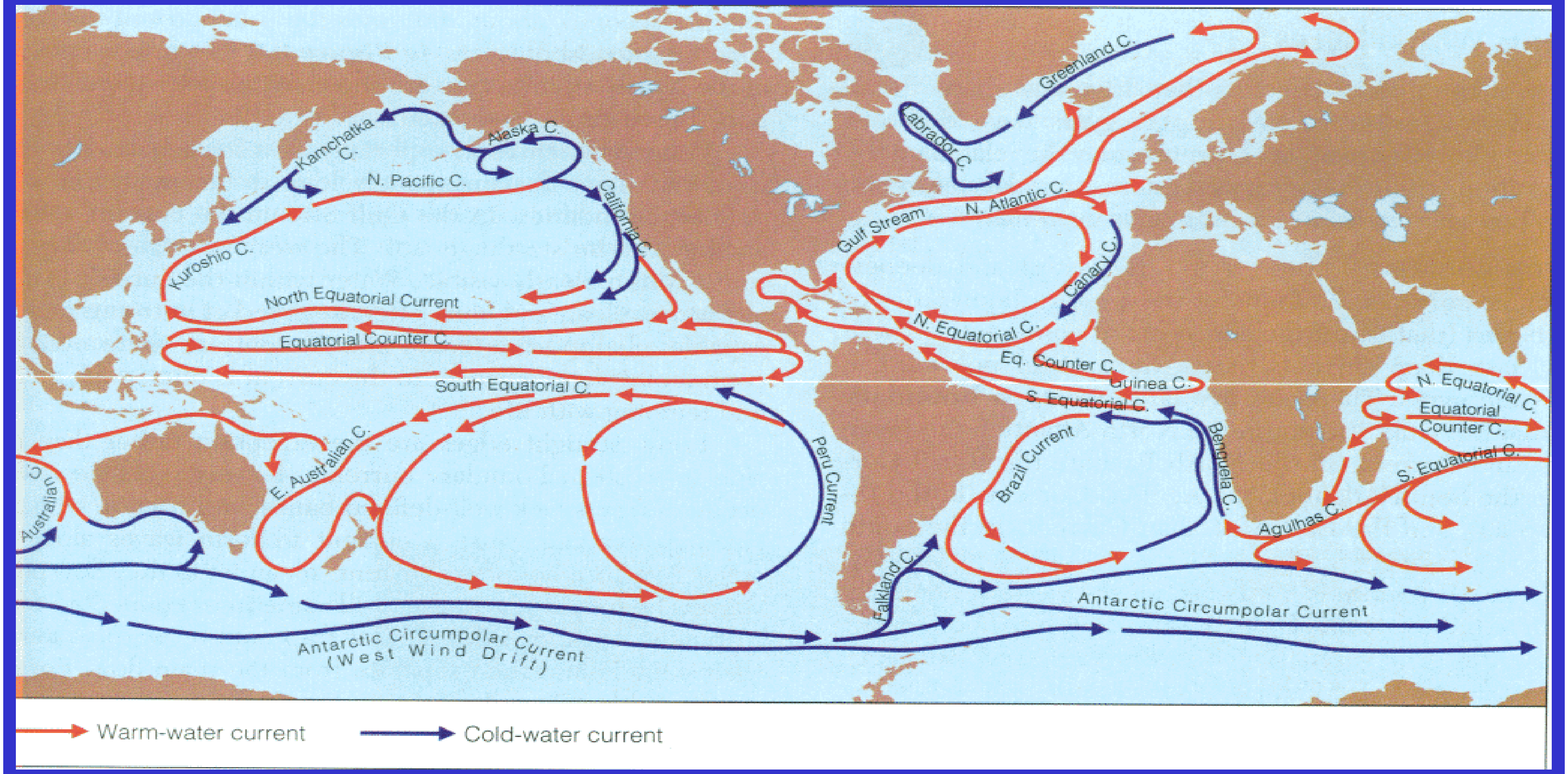
Costal Upwelling/Downwelling



- A result of Ekman transport and mass continuity.

(Figure from *Oceanography* by Tom Garrison)

Global Surface Currents



Equatorial Current System

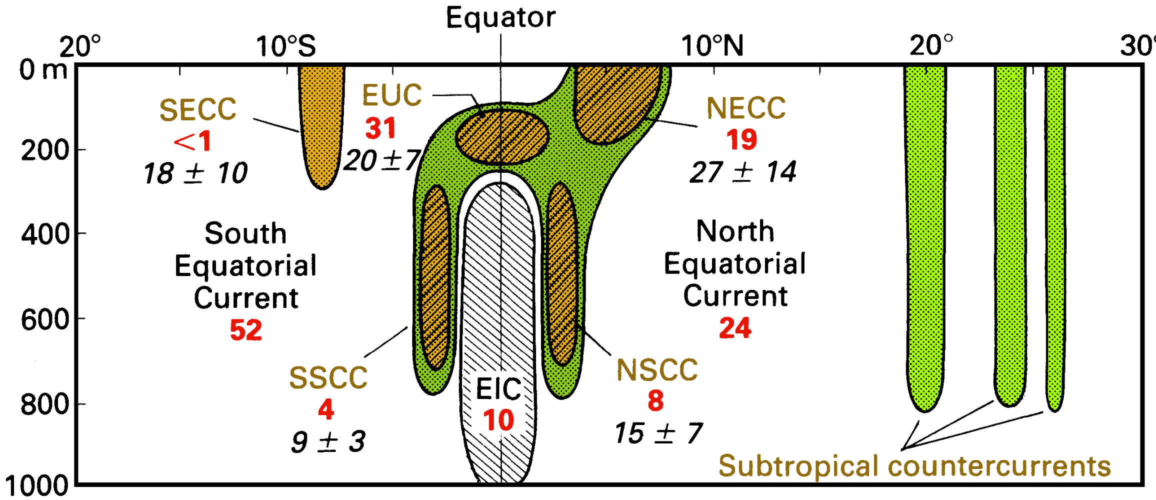


Fig. 8.7. A sketch of the structure of the equatorial current system in the central Pacific Ocean (170°W). Eastward flow is coloured. All westward flow north of 5°N constitutes the North Equatorial Current, westward flow south of 5°N outside the EIC represents the South Equatorial Current. EUC = Equatorial Undercurrent, EIC = Equatorial Intermediate Current, NECC and SECC = North and South Equatorial Countercurrents, NSCC and SSCC = North and South Subsurface Countercurrents. Transports in Sverdrups are given for 155°W (bold figures; based on observations from April 1979 - March 1980) and 165°E (italics, based on January 1984 - June 1986).

- The ***Equatorial Counter Current***, which flows towards the east, is a partial return of water carried westward by the North and South Equatorial currents.

Equatorial Under Current

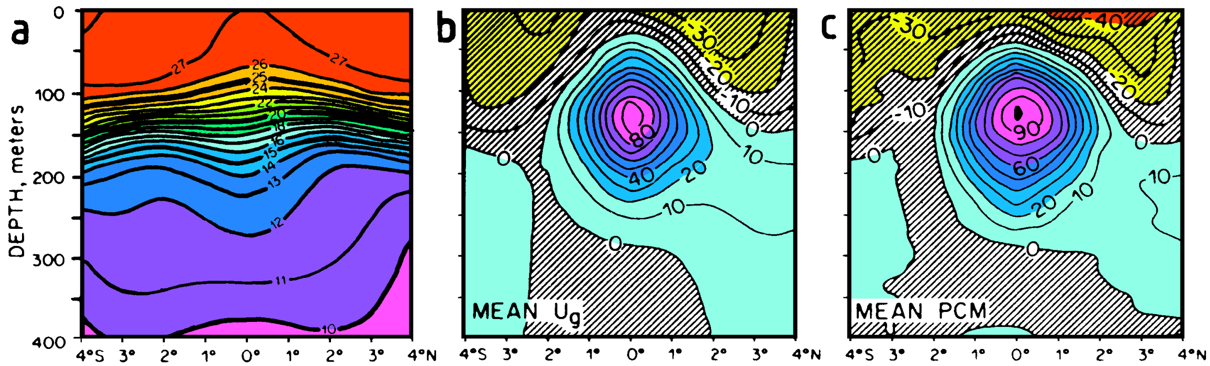
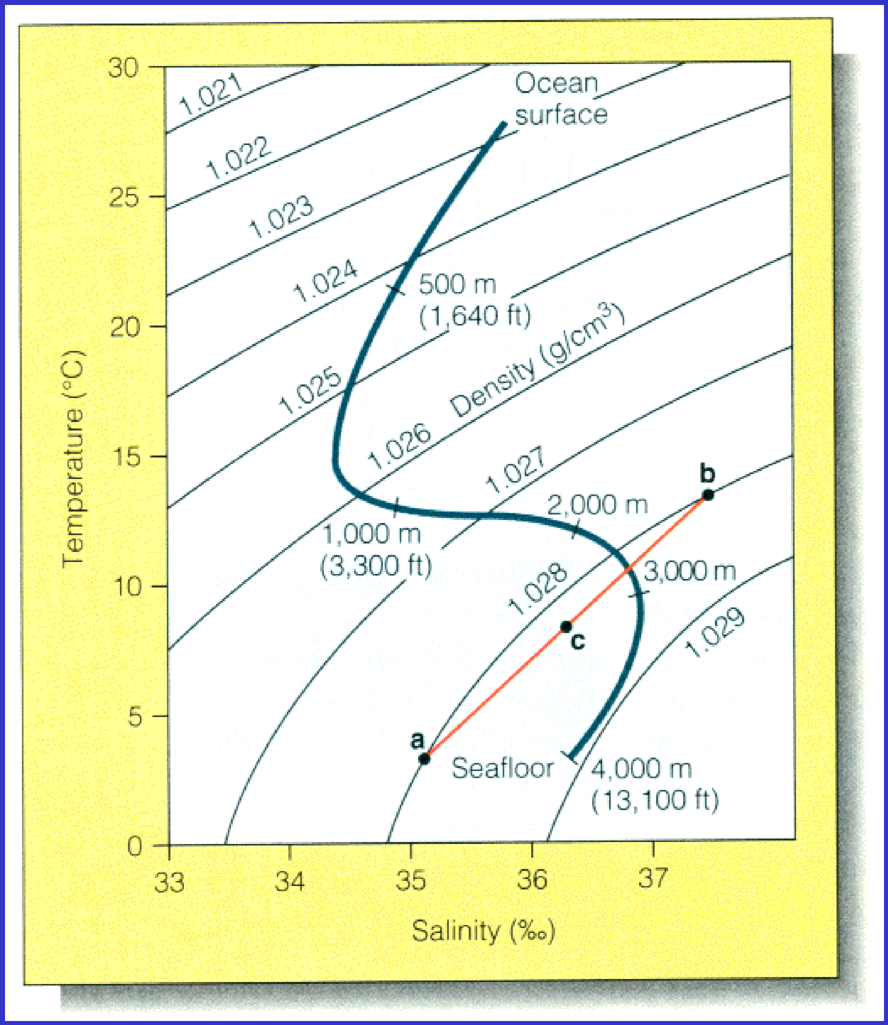


Fig. 8.8. The Equatorial Undercurrent during February 1979 - June 1980 near 155°W. (a) Mean temperature (°C), (b) mean geostrophic zonal velocity (10^{-2} m s^{-1})X, (c) mean observed zonal velocity (10^{-2} m s^{-1}). Note the spreading of the isotherms at the equator. From Lukas and Firing (1984).

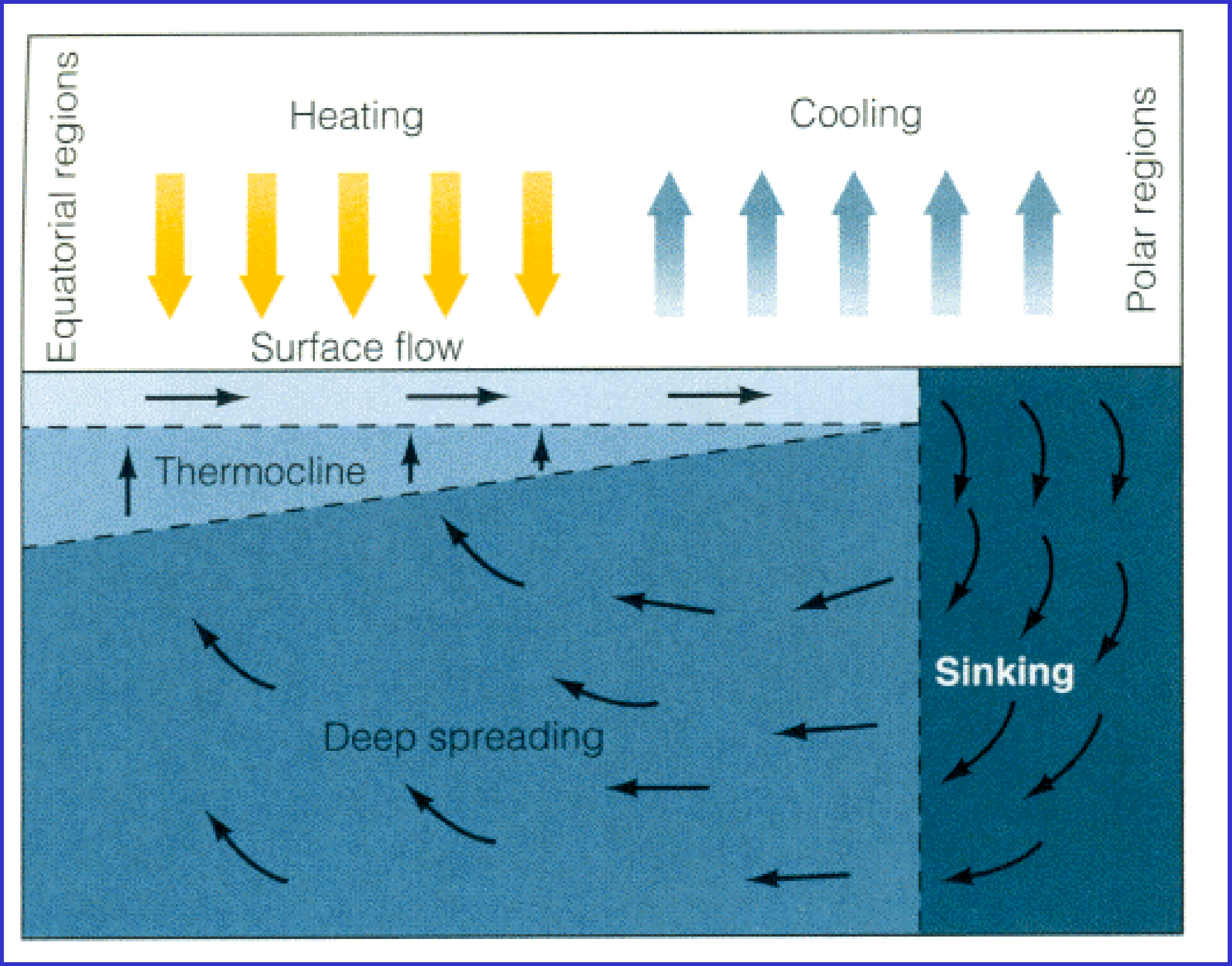
- The most prominent of all eastward flows is the ***Equatorial Undercurrent*** (EUC).
- It is a swift flowing ribbon of water extending over a distance of more than 14,000 km along the equator with a thickness of only 200 m and a width of at most 400 km.
- The current core is found at 200 m depth in the west, rises to 40 m or less in the east and shows typical speeds of up to 1.5 m s-1.
- Its existence remained unknown to oceanographers until 1952.

Deep Ocean Circulation: Density-Driven

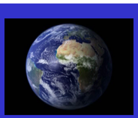


(Figure from *Oceanography* by Tom Garrison)

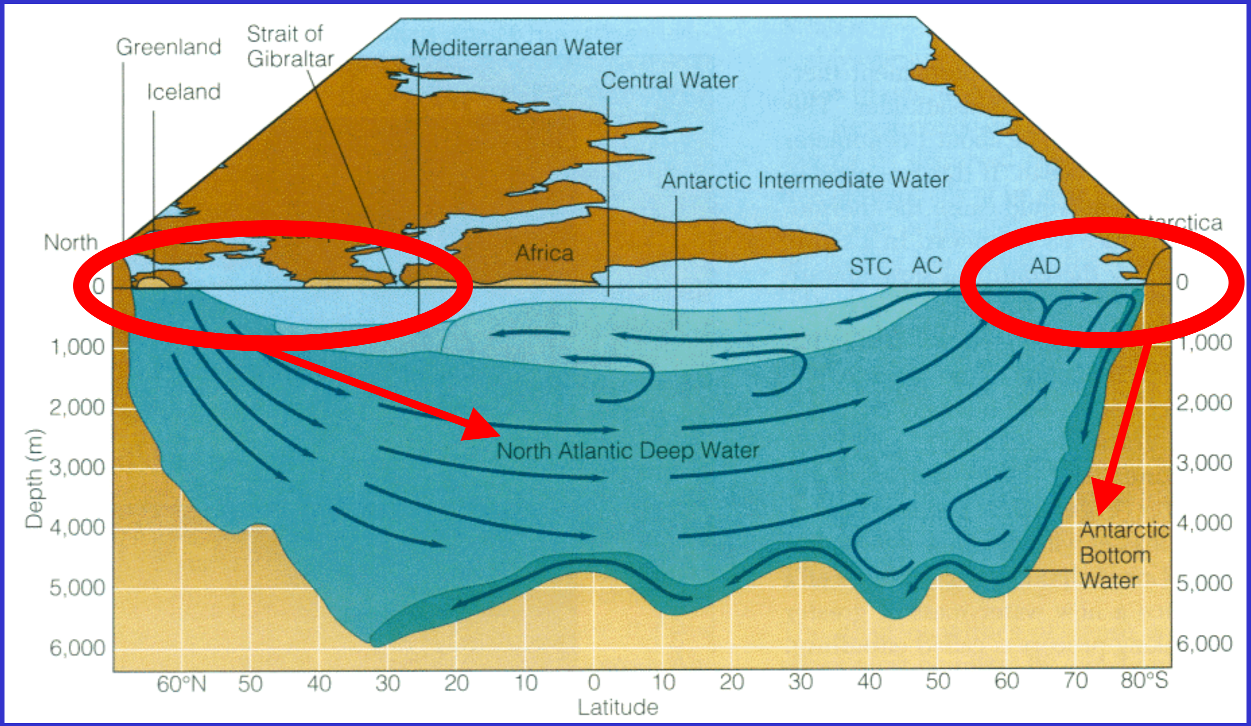
Thermohaline Circulation



(Figure from *Oceanography* by Tom Garrison)



Two Regions of Deep Water Formation



(Figure from *Oceanography* by Tom Garrison)

- ❑ Antarctic Bottom Water

  Salinity = 34.65‰

  Temperature = -0.5°C

  Density = 1.0279 g/cm^3

  Formed at Weddell Sea

  Related to ice formation

  During Winter

- ❑ North Atlantic Deep Water

  Due to winter cooling and evaporation.

Two Processes to Increase Salinity in High Latitudes

- **Evaporation**: Extremely cold, dry winter air enhances evaporation from the relatively warm ocean → increase salinity in the ocean.
- **Formation of Sea Ice**: When sea ice forms, salts are left in the ocean → increase salinity

Ocean Water Mass

Surface Water

to a depth of about 200 meters

Central Water

to the bottom of the main thermocline

Intermediate Water

to about 1500 meters

Deep Water

below intermediate water but not in contact with the bottom

Bottom Water

in contact with sea floor

• Ocean water masses possess distinct, identifiable properties and don't often mix easily when they meet.

• In stead, they usually flow above or below each other.

• Ocean water mass can retain their identity for great distance and long periods of time.

• Oceanographers name water masses according to their relative position.

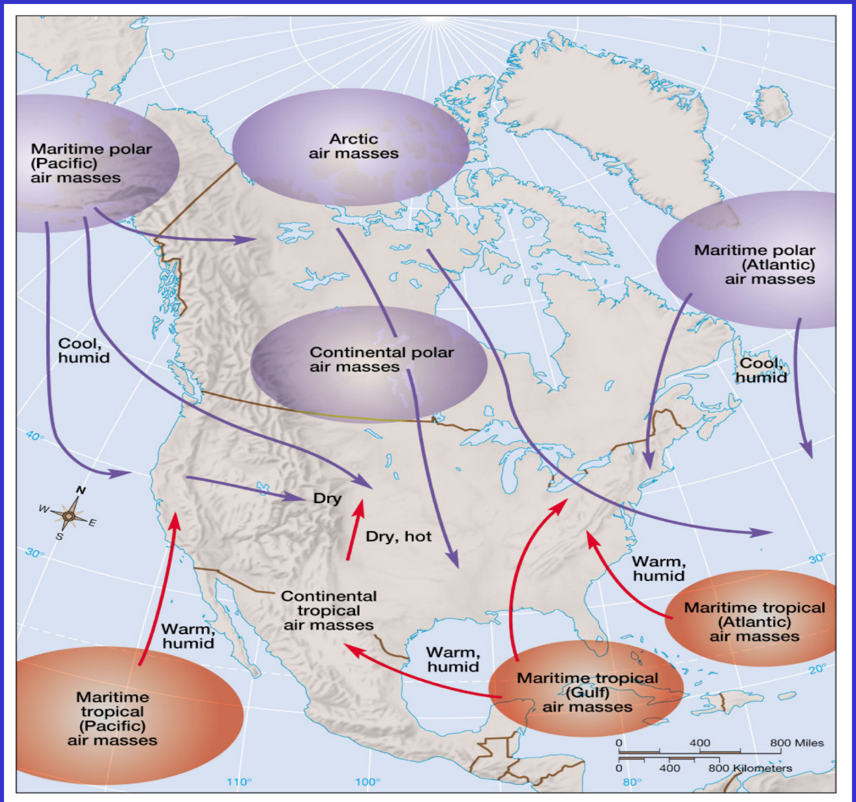
Formation of Water Mass

- Once a water parcel is removed from the surface layer its temperature and salinity do not change until it rises back up to the surface again, usually many years later.

- Water masses with well-defined temperature and salinity characteristics are created by surface processes in specific locations, which then sink and mix slowly with other water masses as they move along.

- Water masses are always identified by capitals. For example, "Bottom Water" can stand for Antarctic, Arctic, or other Bottom Water but always refers to a water mass, while water found at the bottom of an oceanic region may be referred to as "bottom water" without implying that it is a known and well defined water mass.

Five Types of Air Masses



- Theoretically, there should be 6 types of air masses (2 moisture types x 3 temperature types).
- But mA-type (maritime Arctic) does not exist.
- cA: continental Arctic

  cP: continental Polar

  cT: continental Tropical

  mP: maritime Polar

  mT: maritime Tropical

Distribution of Ekman Pumping

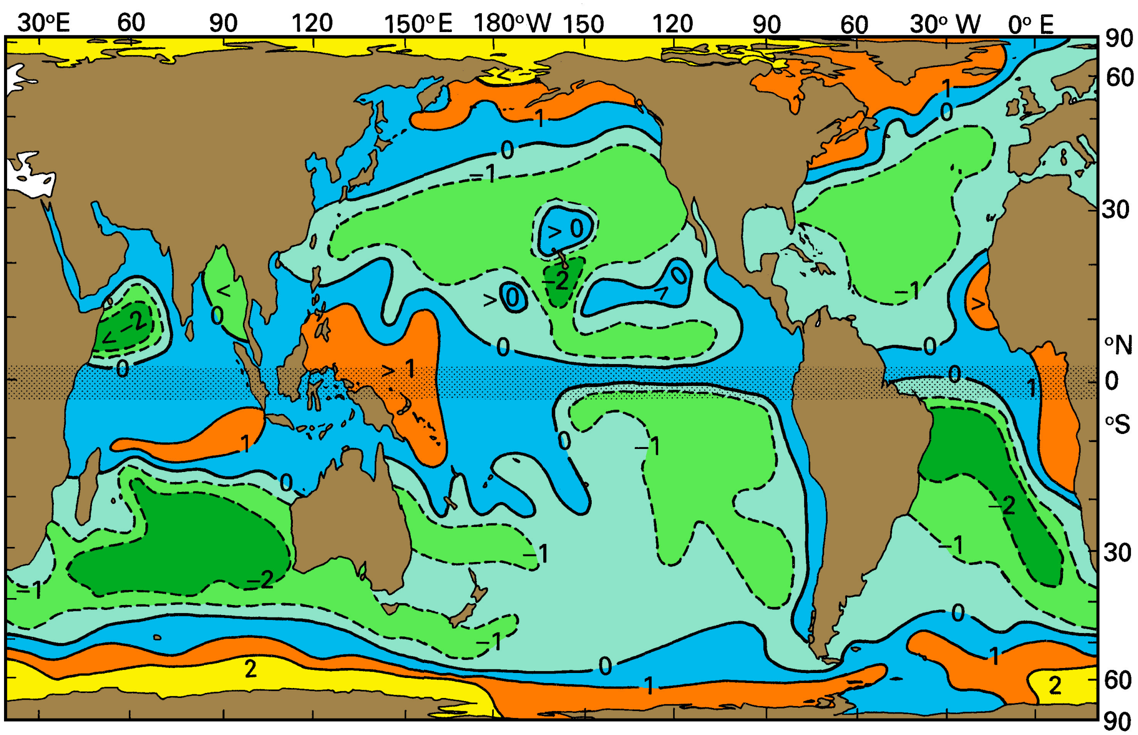


Fig. 4.3. Annual mean distribution of curl($\boldsymbol{\tau}/f$), or Ekman pumping, calculated from the distribution of Fig. 1.4 (10^{-3} kg m^2 s^{-1}). Positive numbers indicate upwelling. In the equatorial region (2°N - 2°S, shaded) curl($\boldsymbol{\tau}/f$) is not defined; the distribution in this region is inferred from the dynamical arguments of Fig. 4.1 and is not quantitative.

(from Regional Oceanography)

Subduction

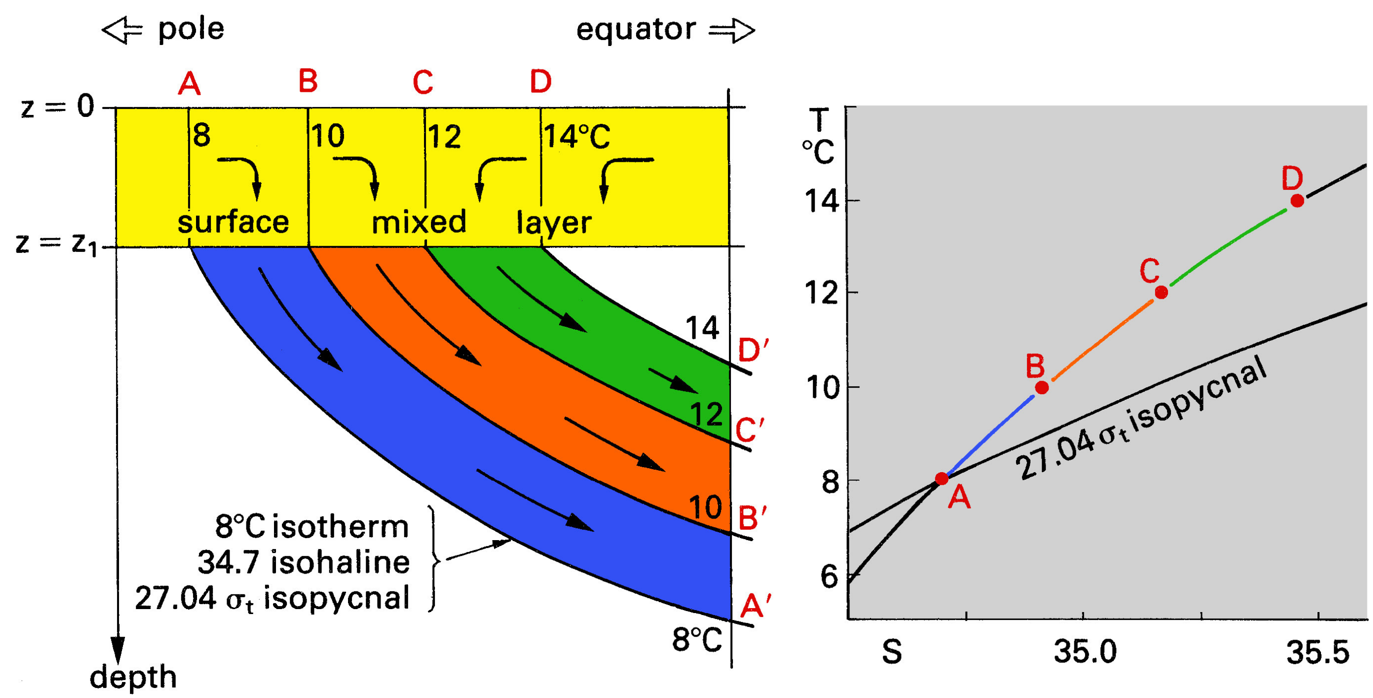


Fig. 5.3. Sketch of water mass formation by subduction in the Subtropical Convergence. The T-S diagram shows both the meridional variation of temperature and salinity between stations *A* and *D*, and the vertical variation equatorward of station *D* from the surface down along the line *A'B'C'D'*. For more detail, see text.

(from Regional Oceanography)

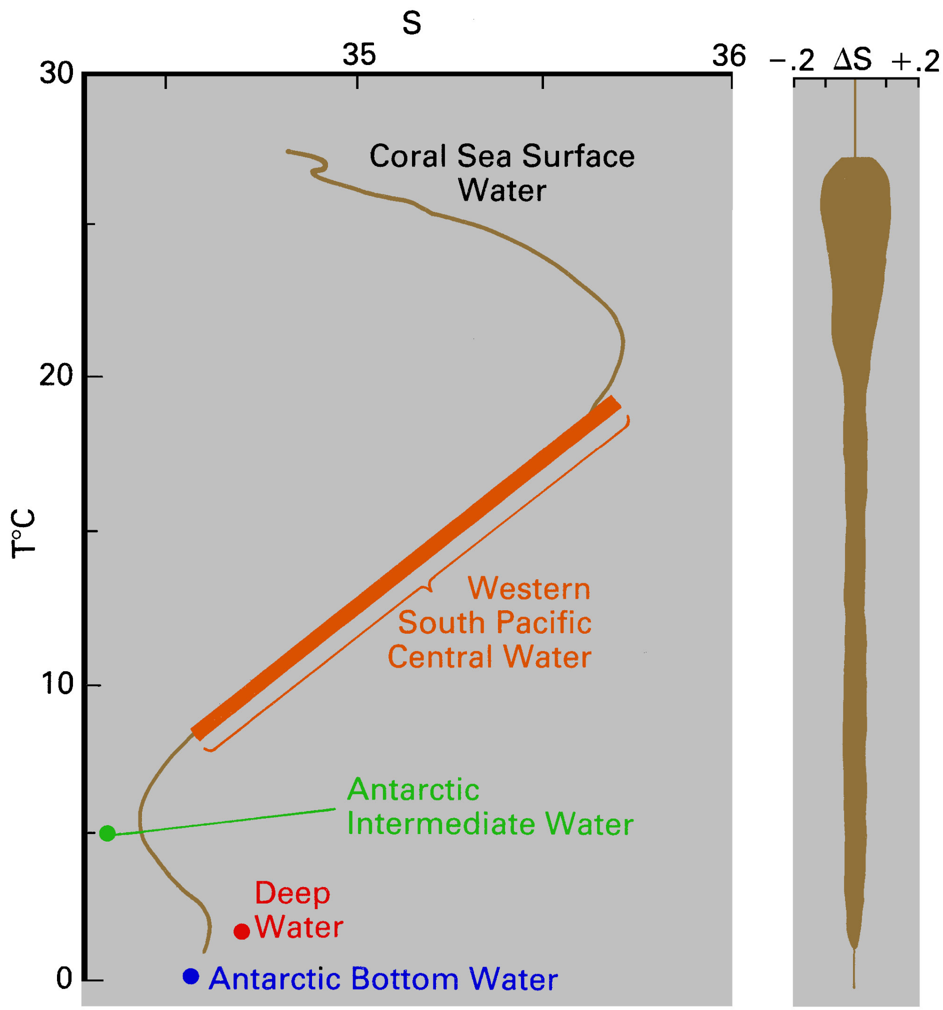
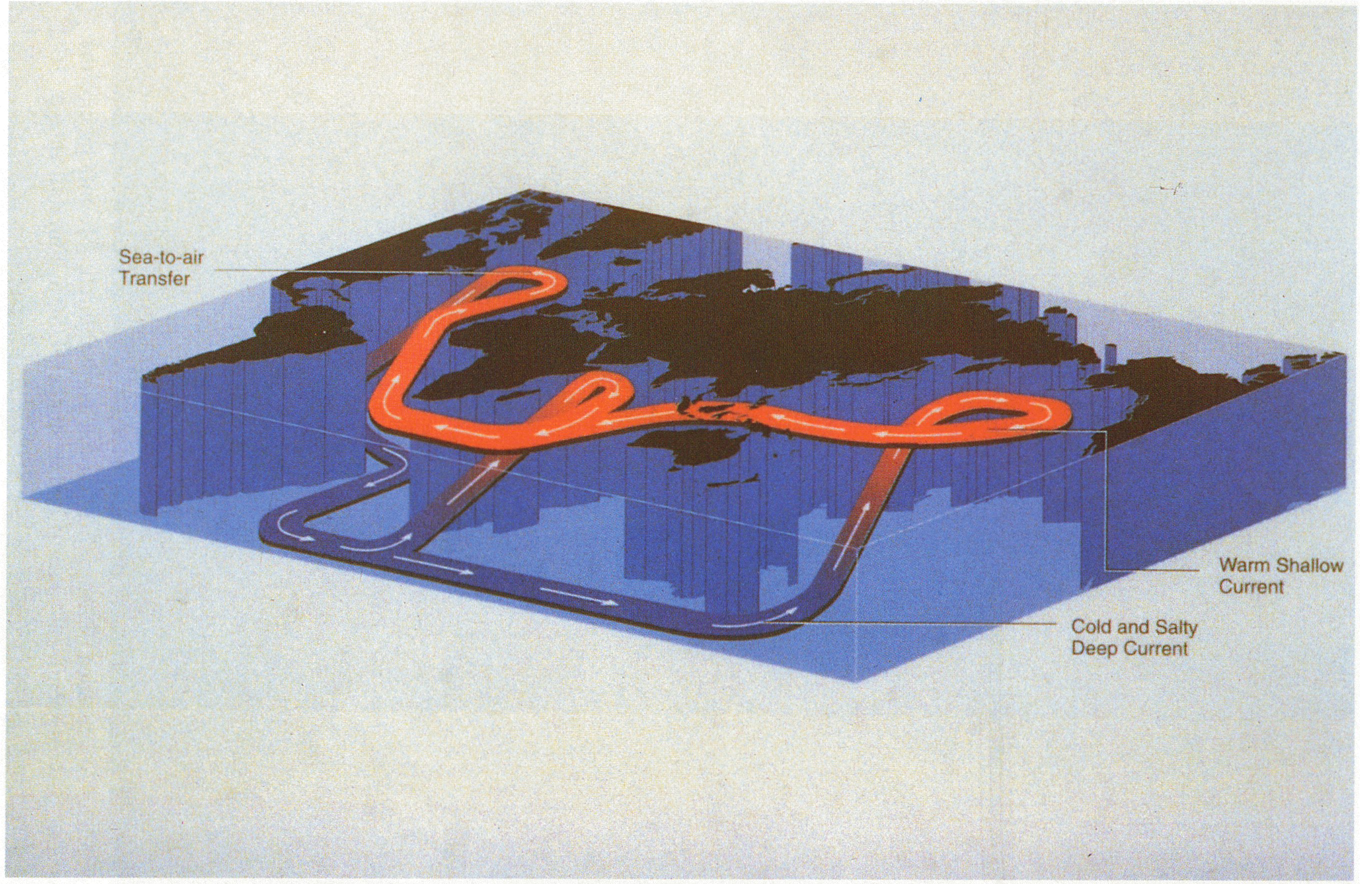


Fig. 5.1. Mean T-S diagram and standard deviation ΔS of salinity (for given temperatures) in the eastern Coral Sea, in comparison to water mass definitions in the south Pacific Ocean. Large dots and the heavy line indicate water mass properties in the formation regions, which for all but Surface Water are located far outside the Coral Sea. The standard deviation was determined by comparing stations in the region with a space average and does not include variability in time. Similar standard deviations can be derived for temperature and other properties. Based on Tomczak and Hao (1989).

Thermohaline Conveyor Belt



(Figure from *Climate System Modeling*)

Thermohaline Circulation

- Thermo → temperature
- Haline → salinity

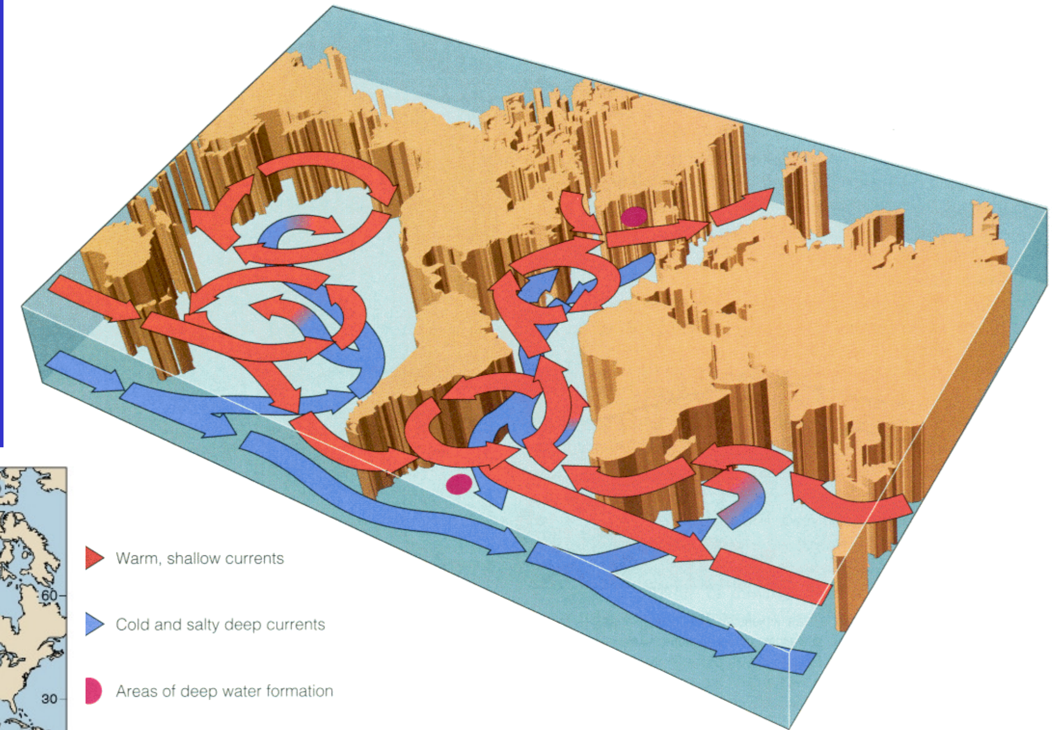
Density-Driven Circulation

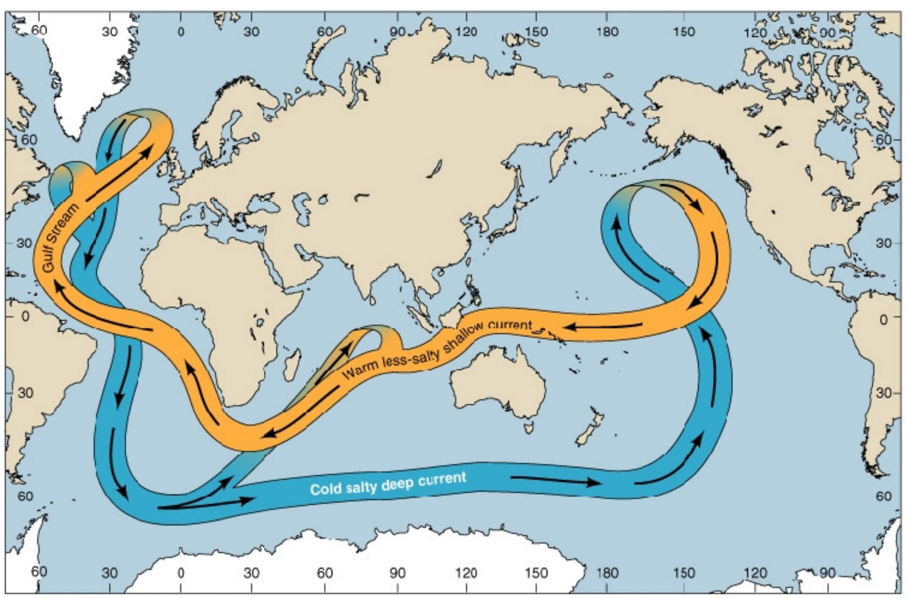
Cold and salty waters go down

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)

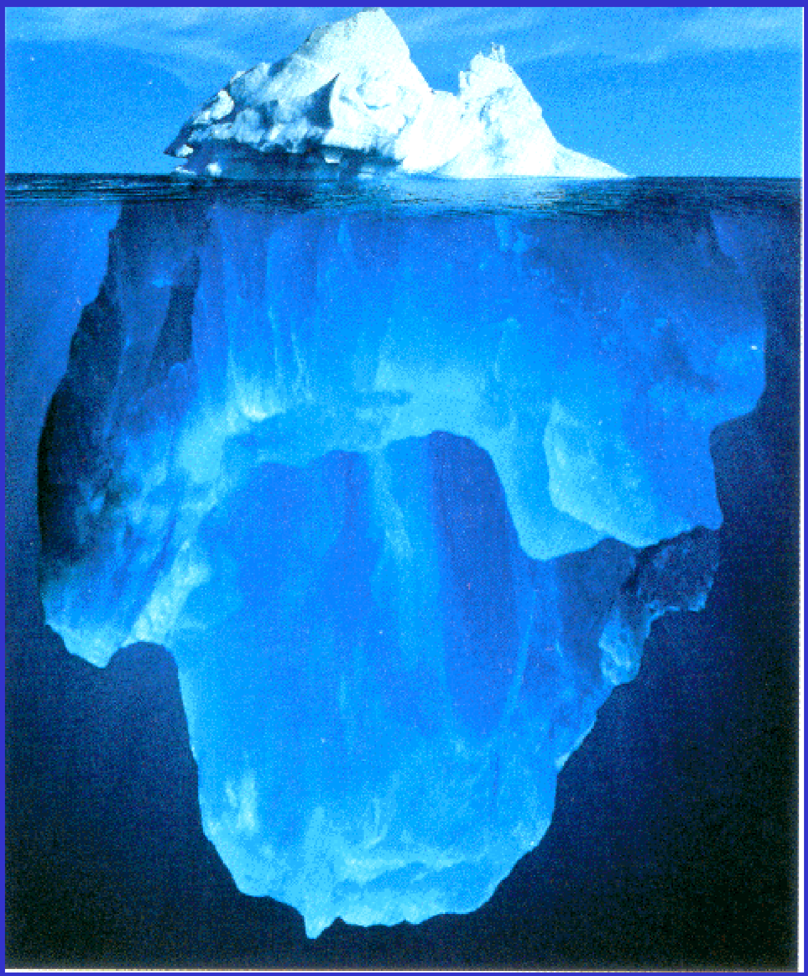
→ No more thermohalione circulation

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

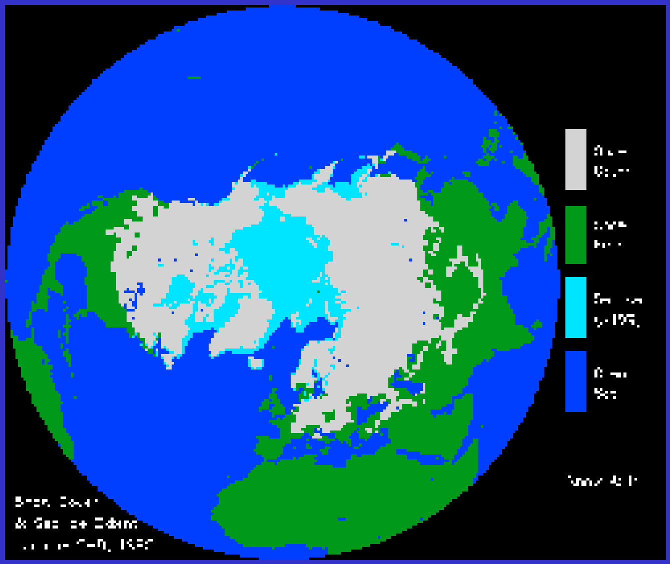
Cryosphere

Sea Ice

Land Ice

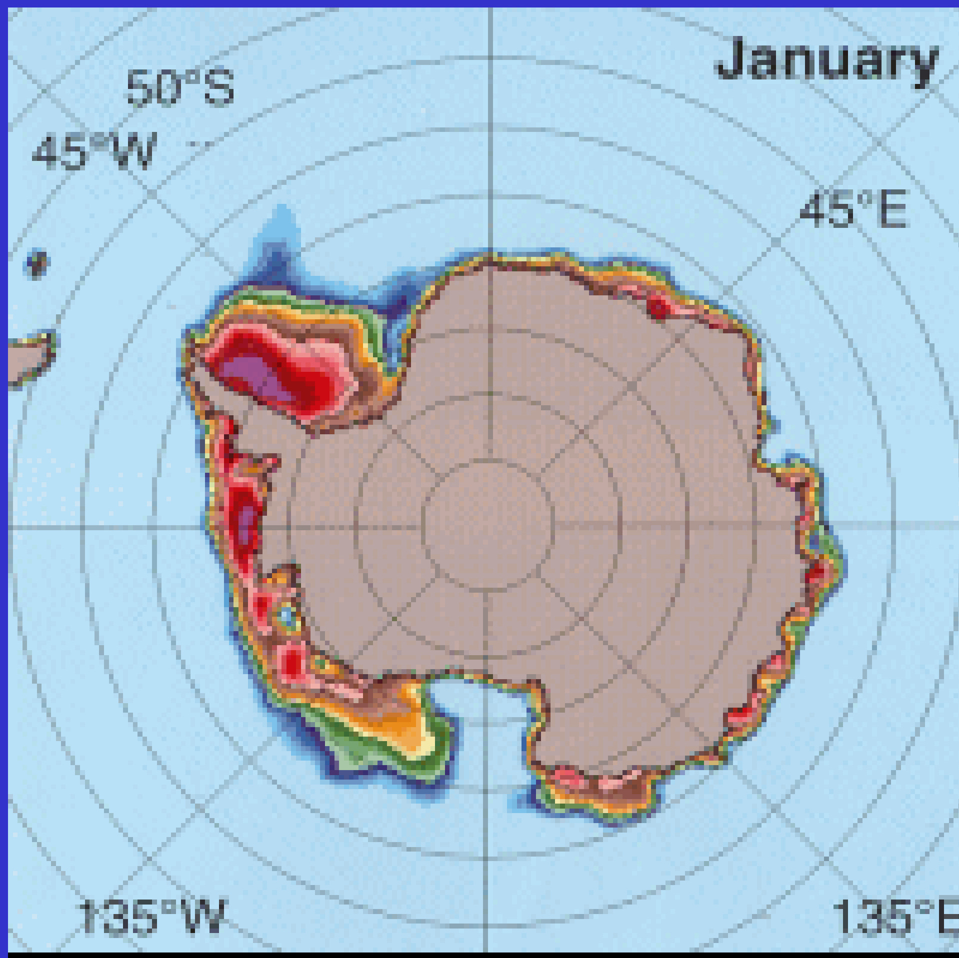


(from *The Blue Planet*)



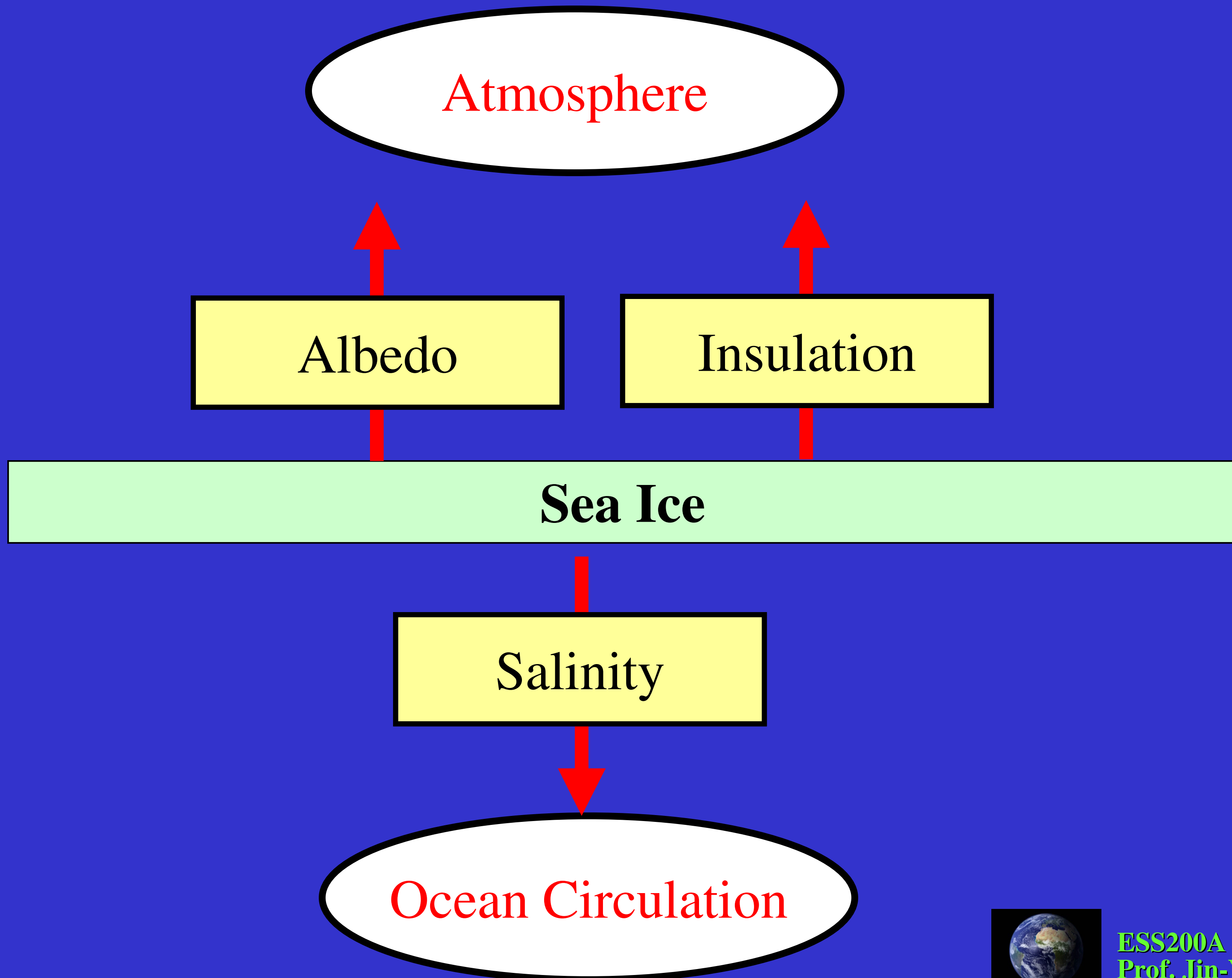
- The cryosphere is referred to all the ice near the surface of Earth: including sea ice and land ice.
- For climate, both the surface and the mass of ice are importance.
- At present, year-round ice covers 11% of the land area and 7% of the world ocean.

Seasonal Cycle of Antarctic Ice

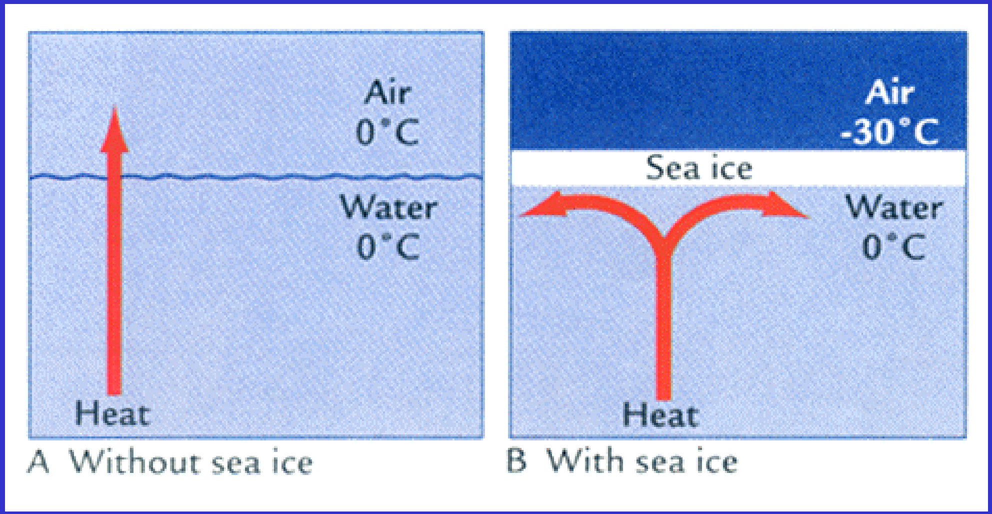


(figures from Gloersen, P. et al. 1992; animated by D. B. Reu)

Climate Roles of Sec Ice



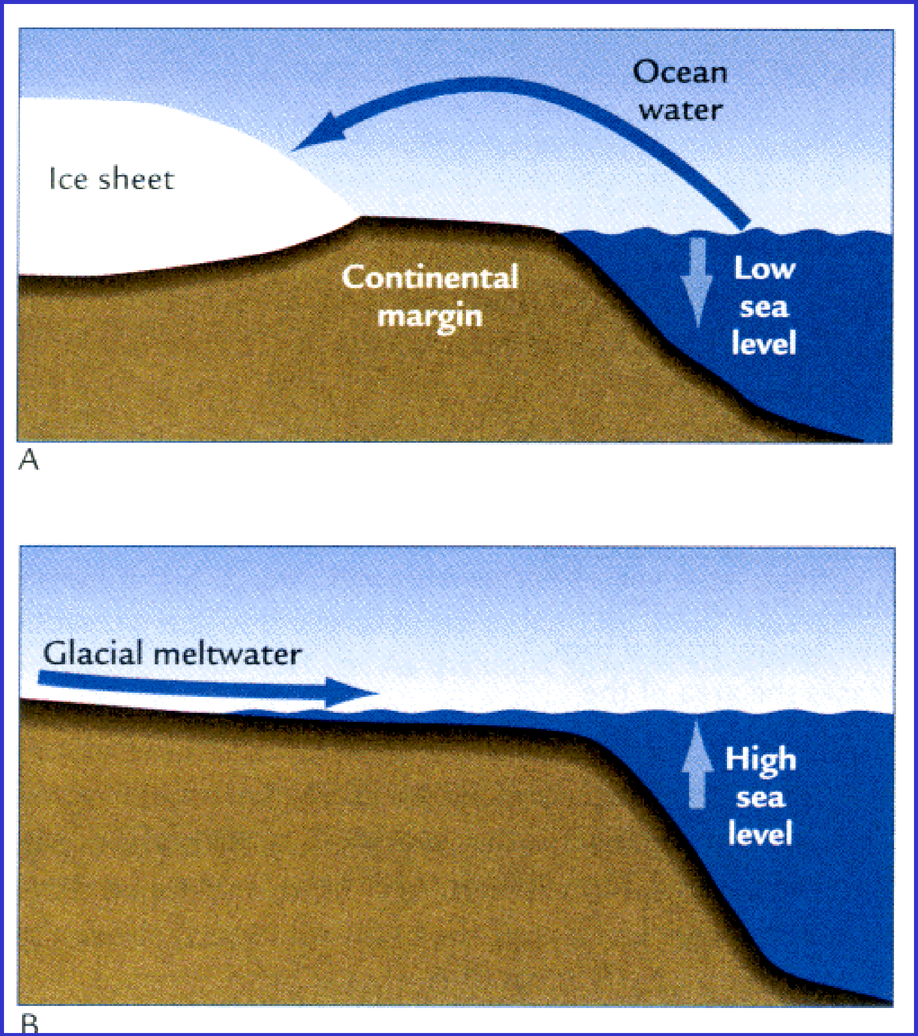
Sea Ice



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

- One major climate effect of sea ice is to seal off the underlying ocean from interaction with the atmosphere.
- Without an sea ice cover, high-latitude oceans transfers large amount of heat to the atmosphere, especially in winter.
- With an sea ice cover, the heat flux into the atmosphere is stopped. In addition, the ice surface absorbs little incoming solar radiation. Winter air temperature can cool 30°C or more near a sea-ice cover.

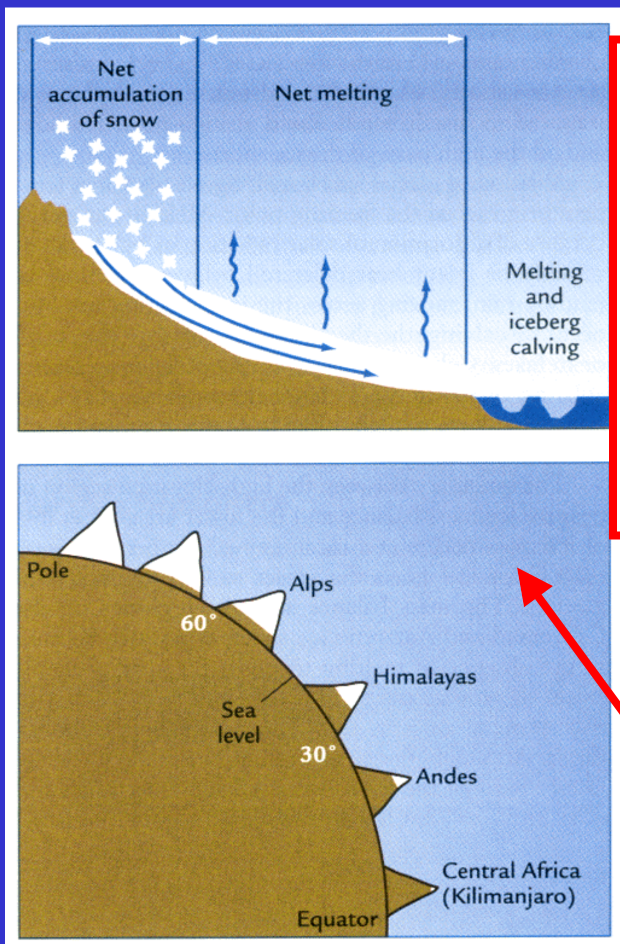
Land Ice and Sea Level



- The Antarctic Ice Sheet holds the equivalent in seawater of 66 meters of global sea level.
- The Greenland Ice Sheet holds the equivalent of 6 meters of global seawater.

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

Land Ice



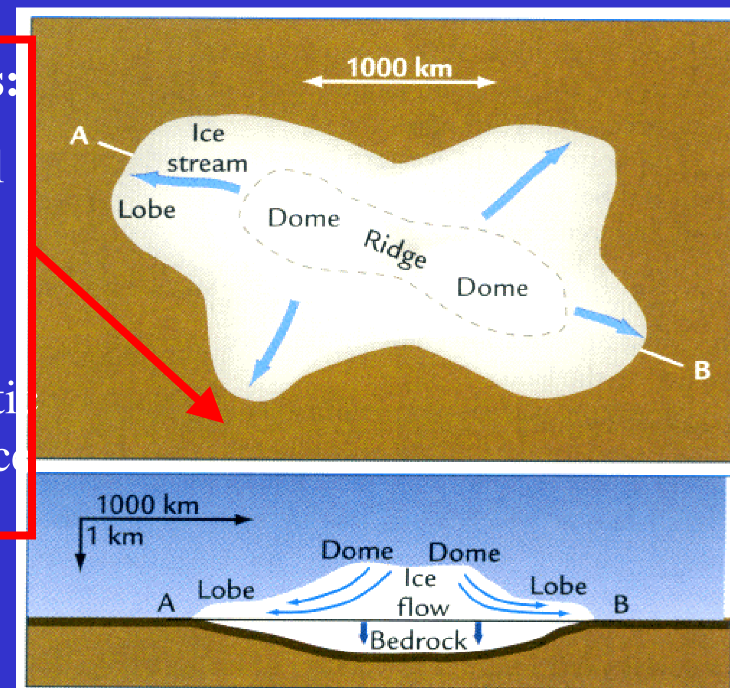
(from *Earth's Climate: Past and Future*)

❑ **Continental Ice Sheets:**

100-1000 km in horizontal extend.

1-4 km in thickness.

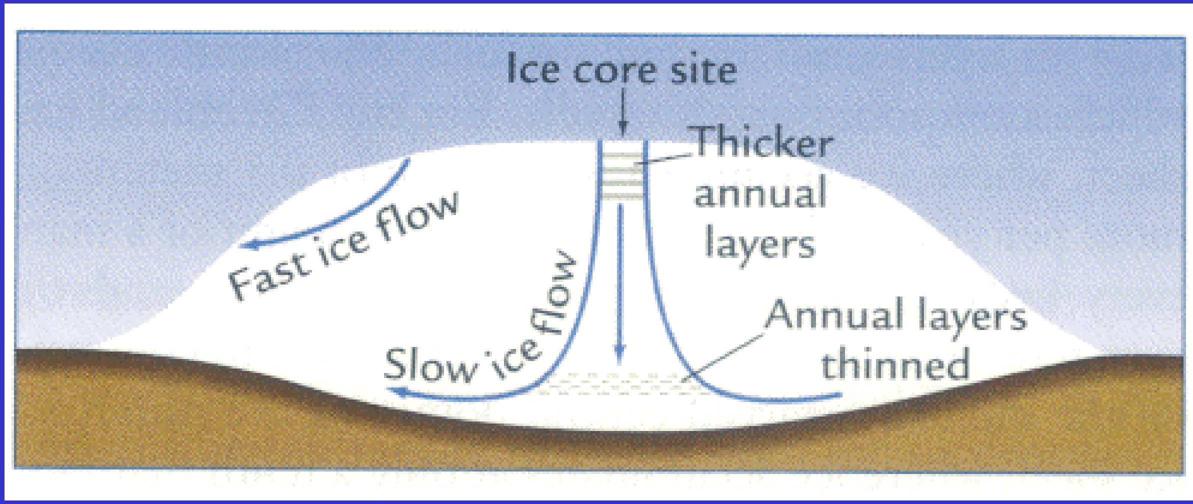
Two larges sheets: Antarctic Ice Sheet and Greenland Ice Sheet.



❑ **Mountain Glaciers:** a few kilometers in length and 10-100 meters in width and thickness.

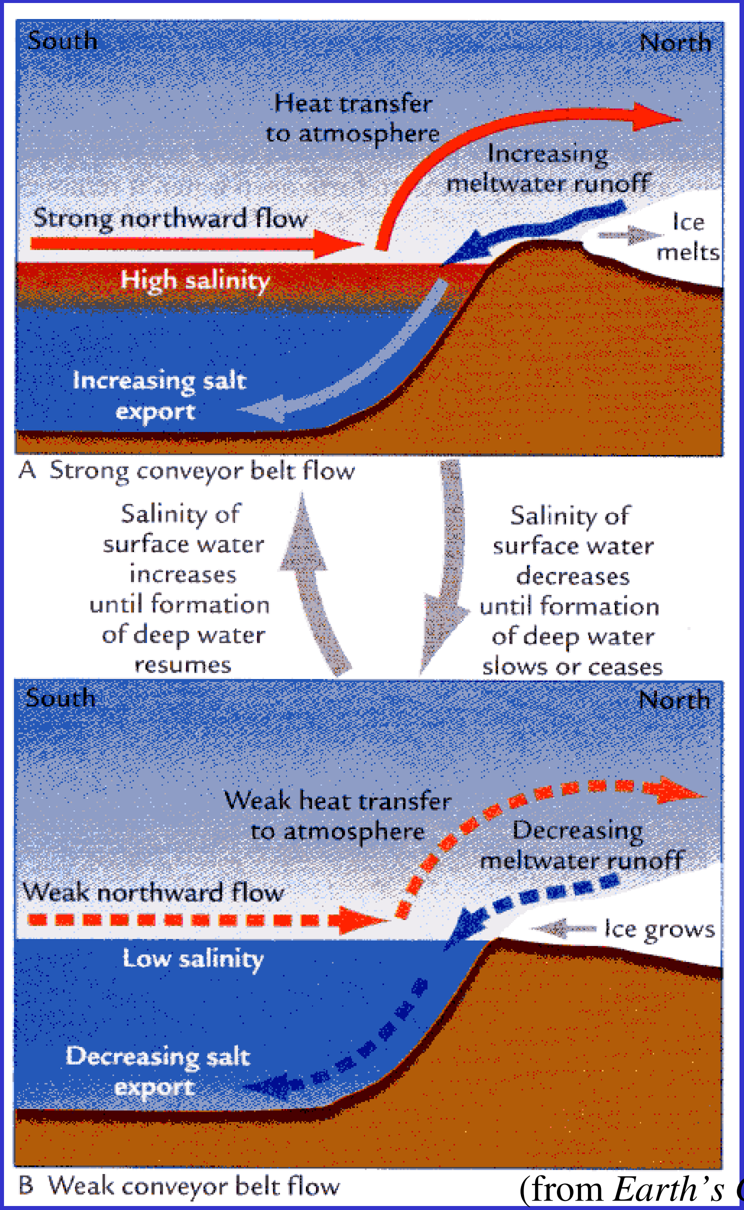
Glacial Ice

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



- Ice cores retrieve climate records extending back thousands of years in small mountain glaciers to as much as hundreds of thousands of years in continental sized ice sheets.
- The antarctic ice sheet has layers that extend back over 400,000 years.
- The Greenland ice sheet has layers that extended back 100,000 years.

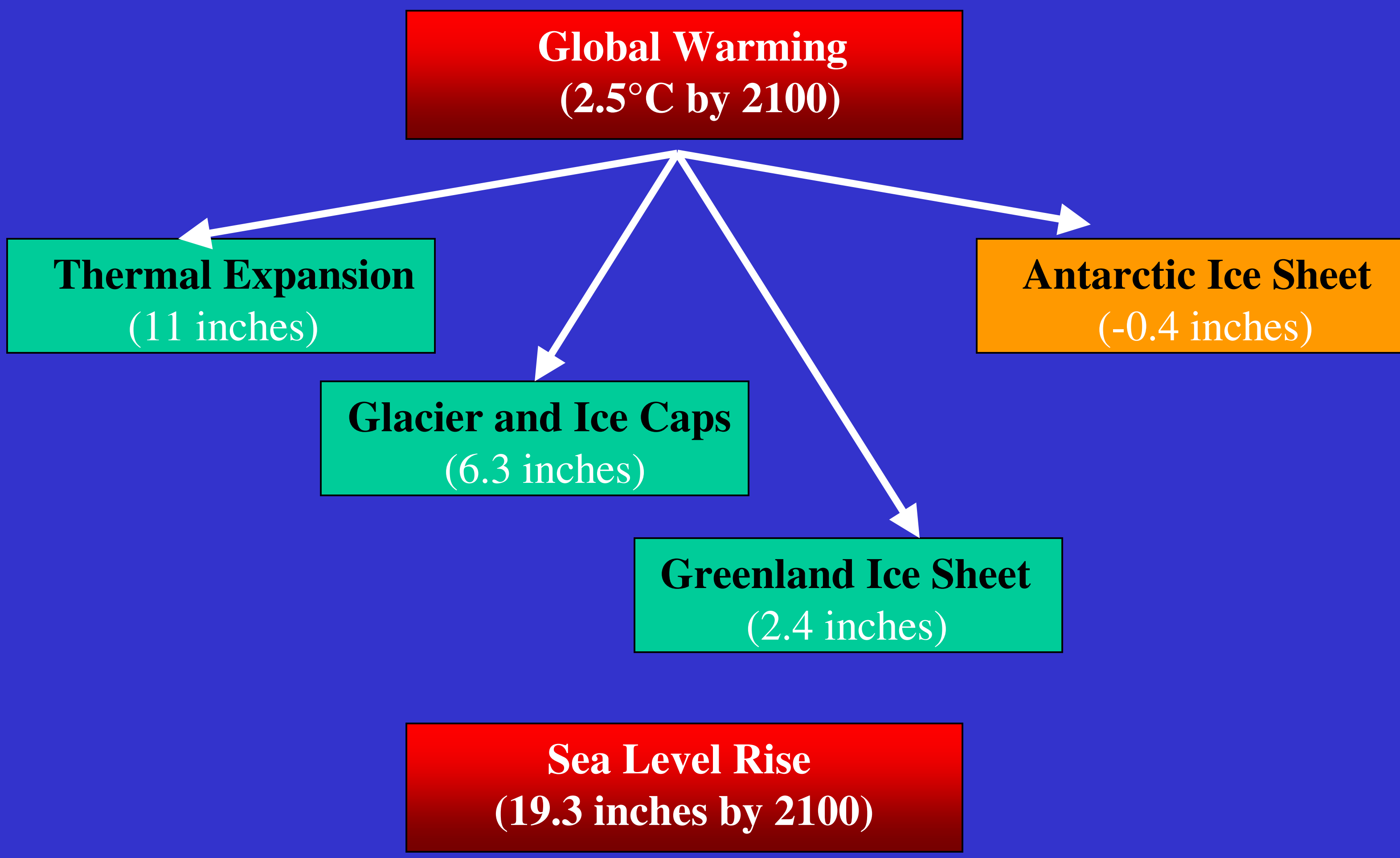
Interactions between Ice and Ocean



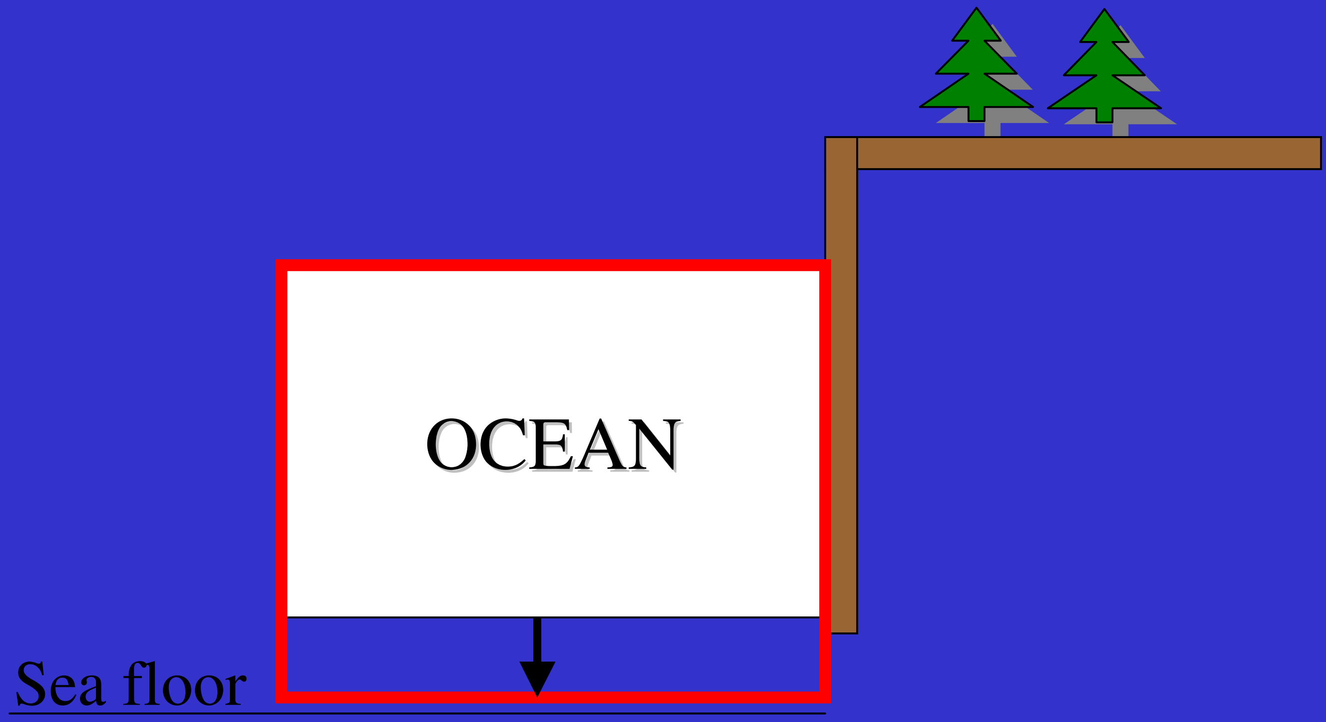
(from *Earth's Climate: Past and Future*)

- 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.

Global Warming and Sea-Level Change



Sea Level Rise .vs. Sea Floor Sink



After a certain amount of land-supported ice melts, in stead of saying the sea level will rise “so much”, we should say the oceans will get “so much” deeper. -- (Kivioja 2003; *EOS*)