

(Schlesinger: Chapter 9)

Part 1. Ocean Composition & Circulation

Lecture Outline

1. Introduction
2. Ocean Circulation
 - a) Global Patterns in T, S, ρ
 - b) Thermohaline circulation
 - c) Wind-driven circulation
 - d) Oceanic water residence time
 - d) El Niño
3. Seawater Composition: Major Ions, Residence Times, Removal processes
4. Summary

Introduction

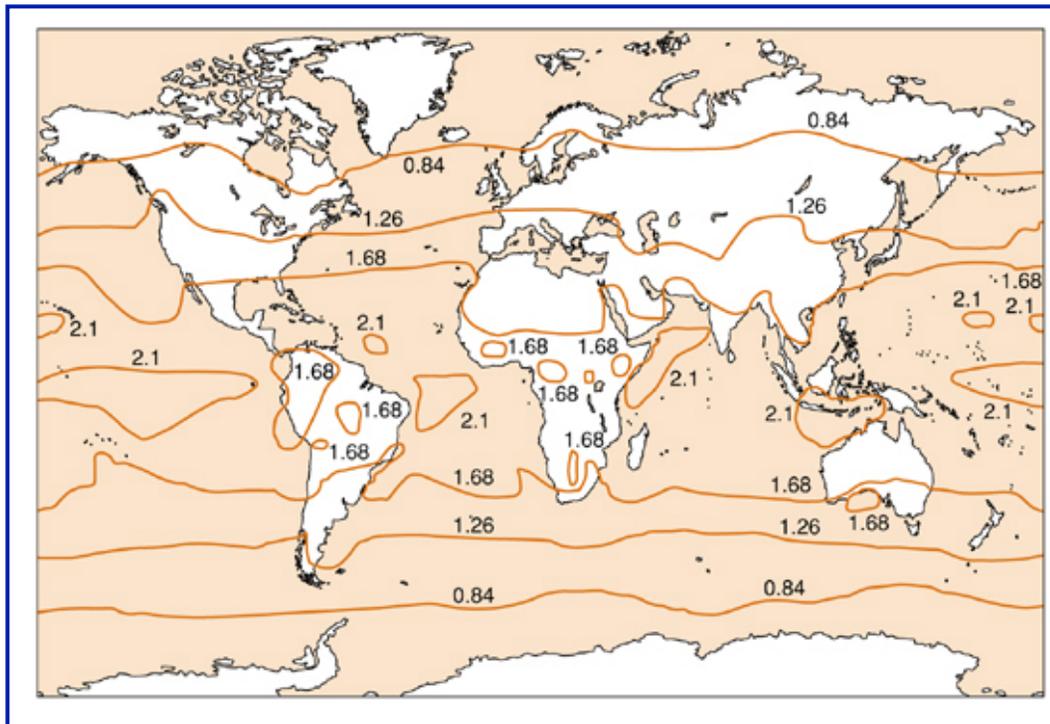
- The Earth's waters constitute its hydrosphere.
- The oceans dominate (96% of total).
- The deep ocean (>200-300 m) accounts for 91% of total
- The ocean is a major player in global biogeochemical cycles.

Table 1.1. Inventory of Water at the Earth's Surface (after Berner and Berner 1996).

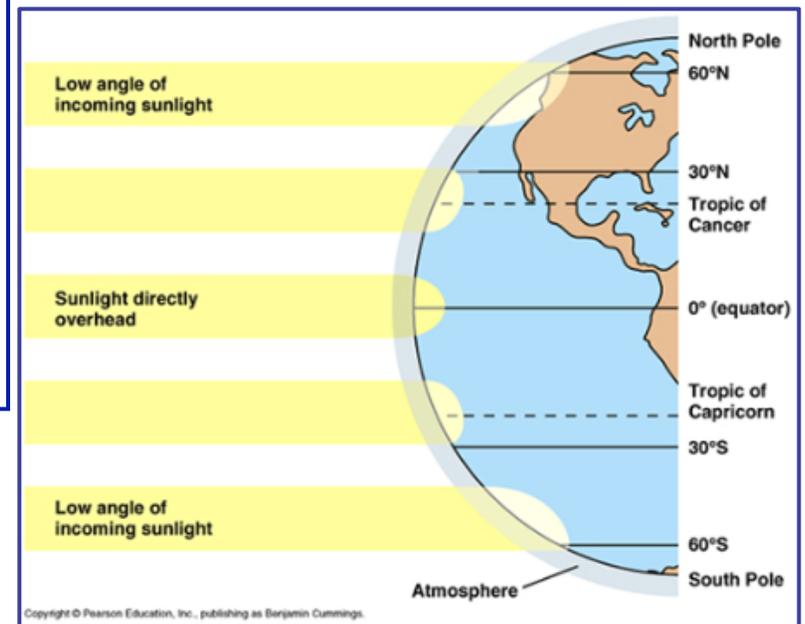
Reservoir	Volume (10^6 km^3)	Percent of Total
Oceans	1400	95.96
Ice Caps & Glaciers	43.4	2.97
Groundwater	15.3	1.05
Lakes	0.125	0.009
Rivers	0.0017	0.0001
Soil Moisture	0.065	0.0045
Atmosphere	0.0155	0.001
Biosphere	0.002	0.0001
Approximate Total	1459	

Temperature

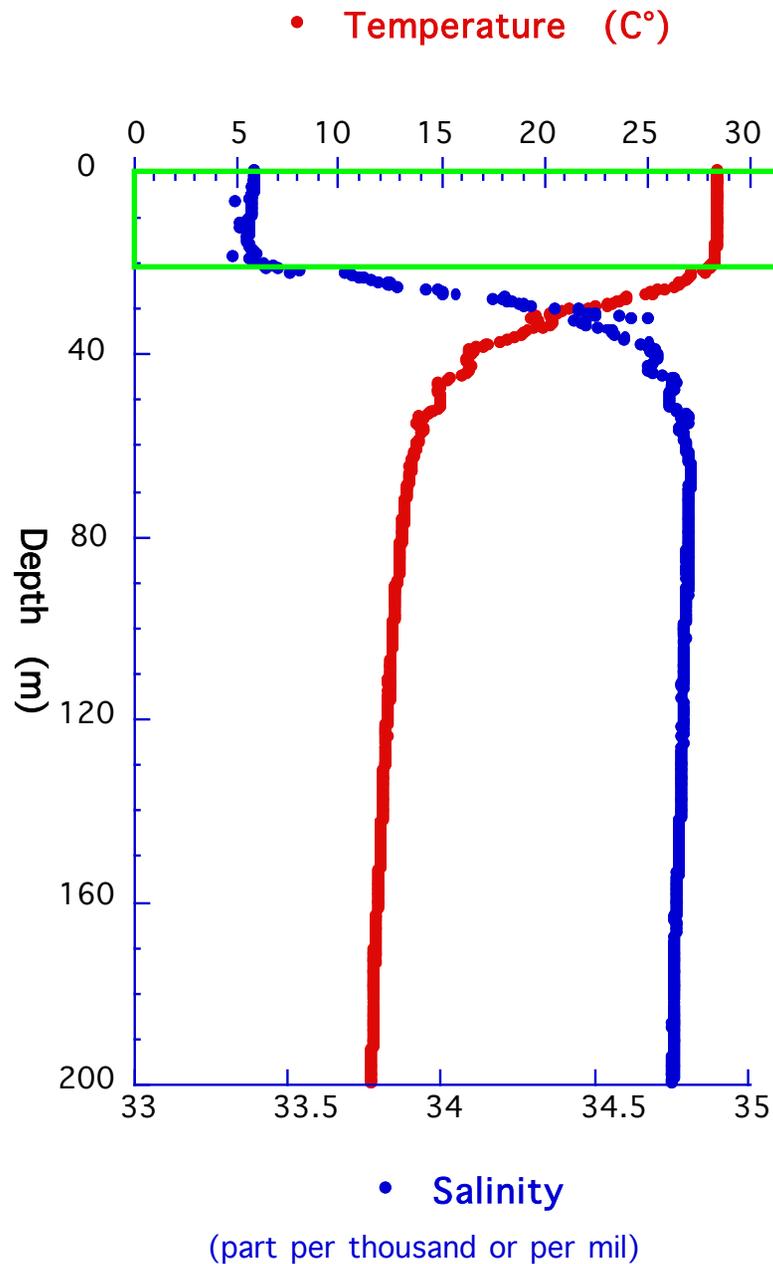
- Solar radiation heats Earth's surface
- The amount absorbed ($\text{J cm}^{-2} \text{ min}^{-1}$) varies depending on the latitude



Begon et al. (2006)



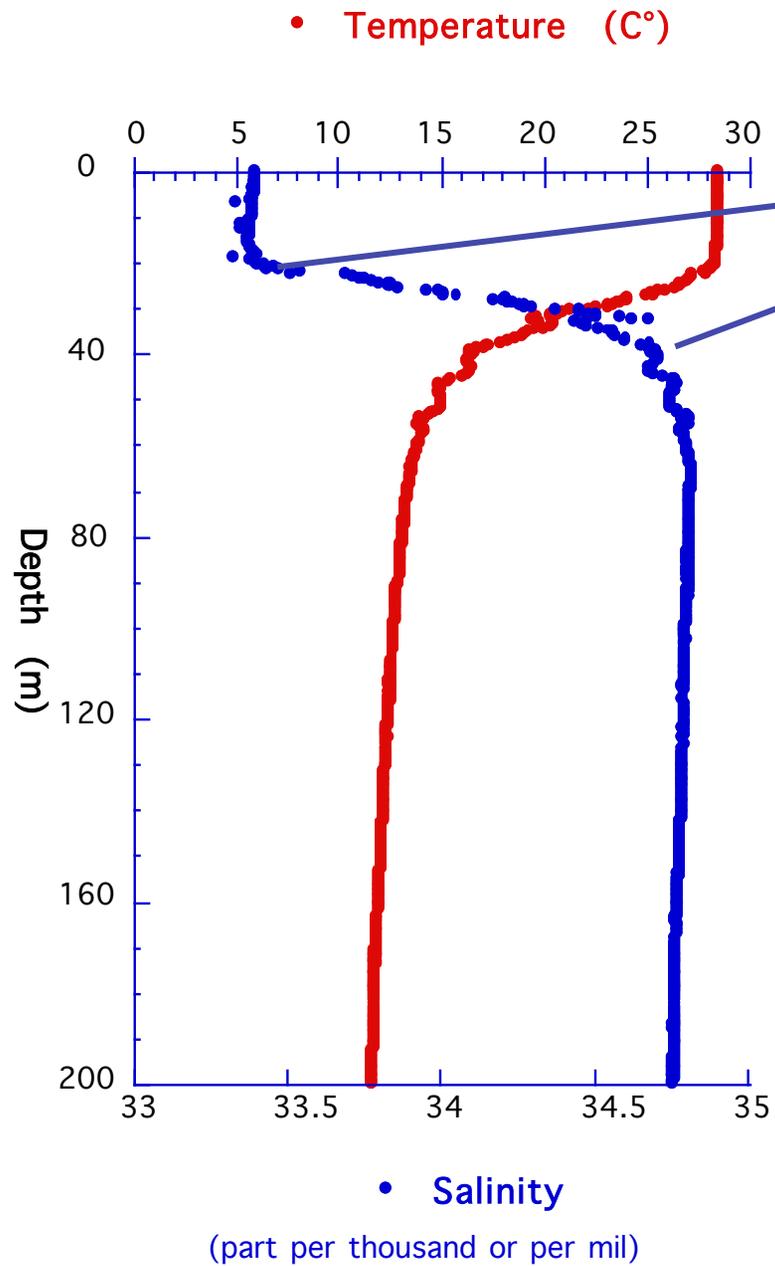
Global Circulation Patterns: Stratification



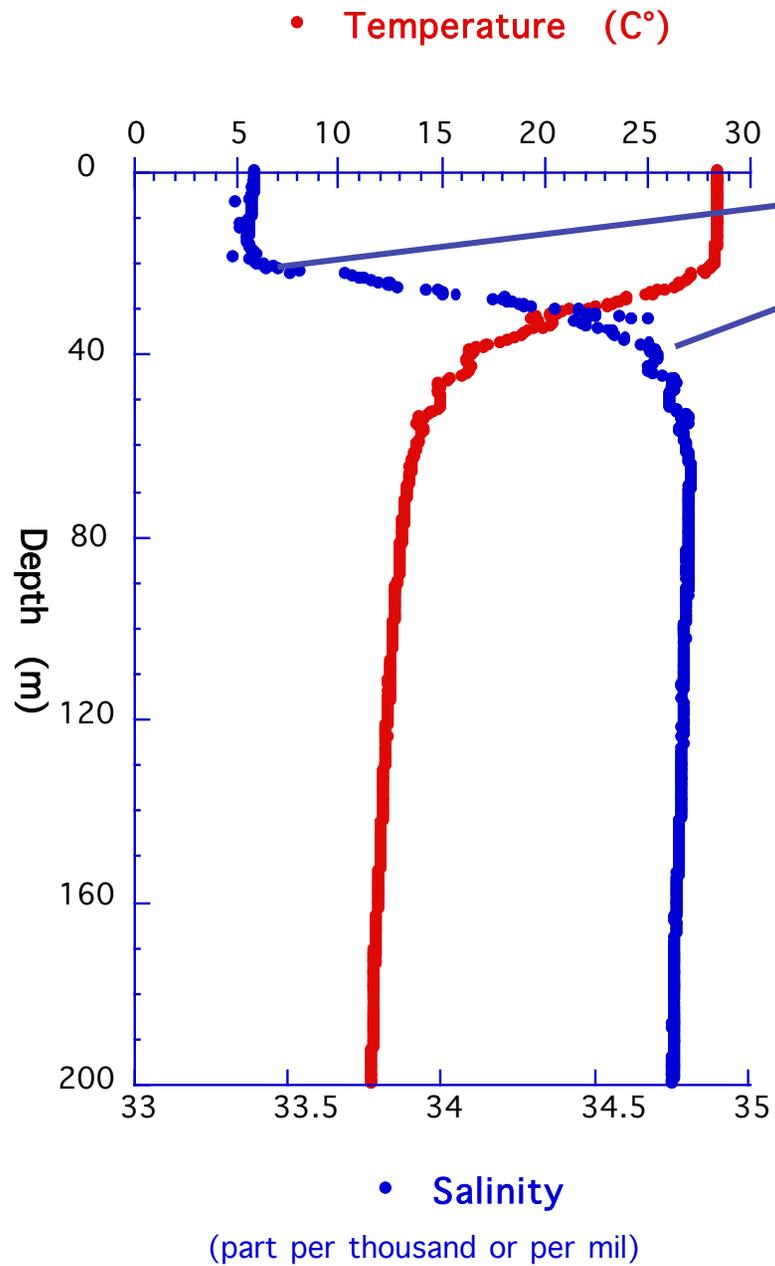
Surface Mixed Layer

- Surface mixed layer:
 - 15-300 m,
 - 18-30 °C
- Both T & S are nearly constant; due to physical mixing of the near surface by wind waves
- The deep ocean contains 95% of the total ocean volume, with a mean temperature of 3°C.

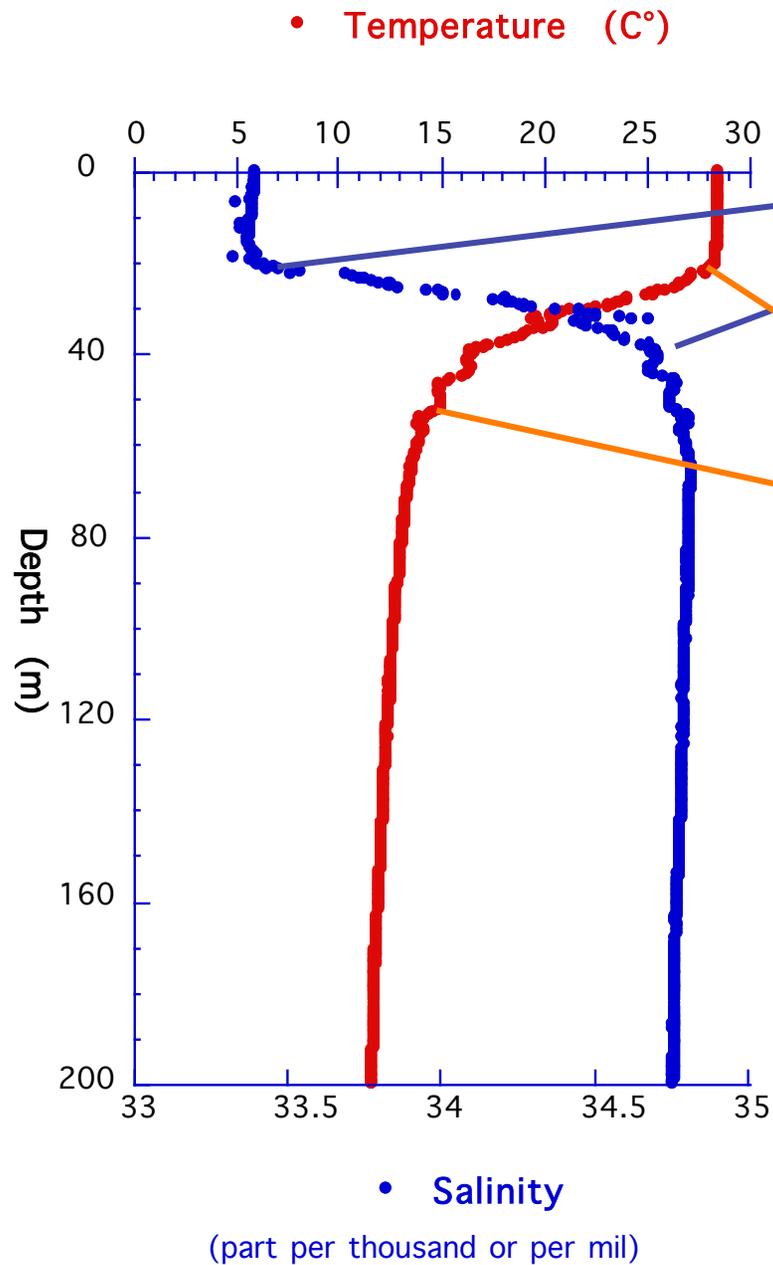
G. Ravizza, Unpublished data, Equatorial Pacific



Region of rapid salinity change is called the *halocline*.



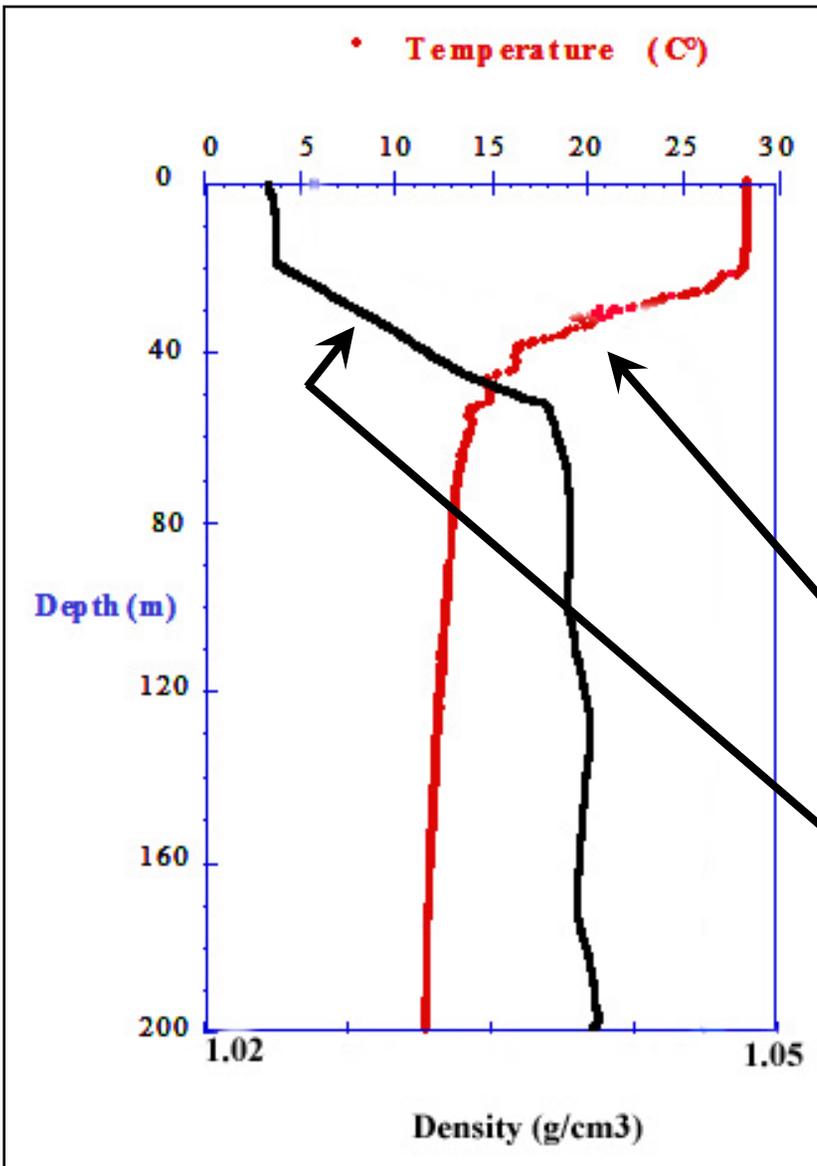
Region of rapid salinity change also represents the *pycnocline*.



Region of rapid salinity change is called the *halocline*.

Region of rapid temperature change is called the *thermocline*.

Thermal Stratification confers Stability to Water Column.



- The higher the temperature, the lower the density
- Surface waters are less dense than colder deeper waters
- Thermal stratification prevents mixing of surface and deep waters
- Same as in Lakes (Chap. 8).
- Opposite of atmospheric circulation! (Chap. 3)

• Temperature

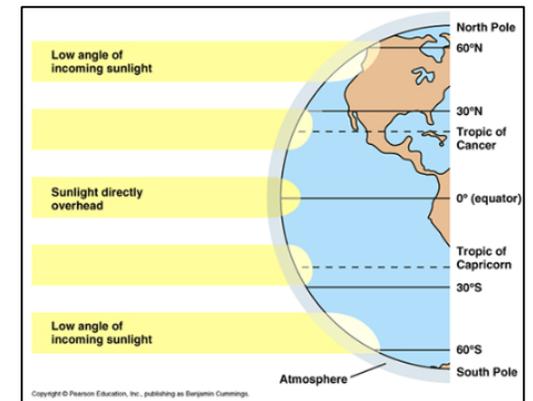
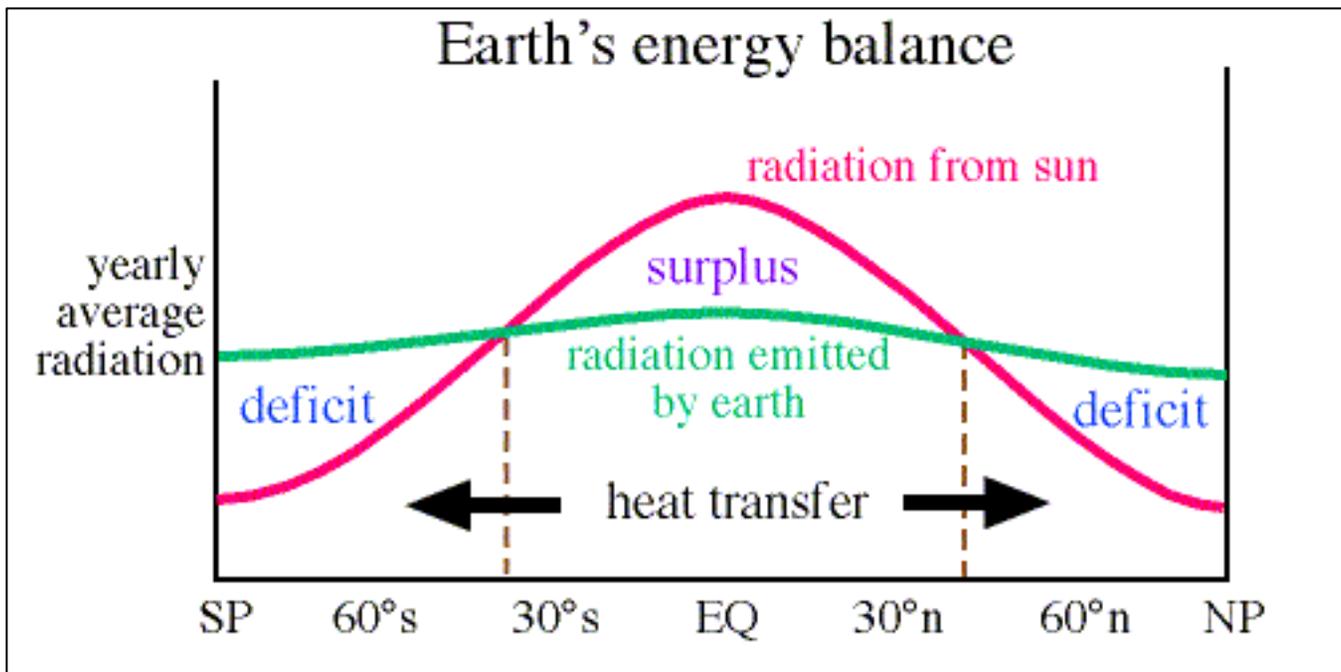
Thermocline

• Density

Pycnocline

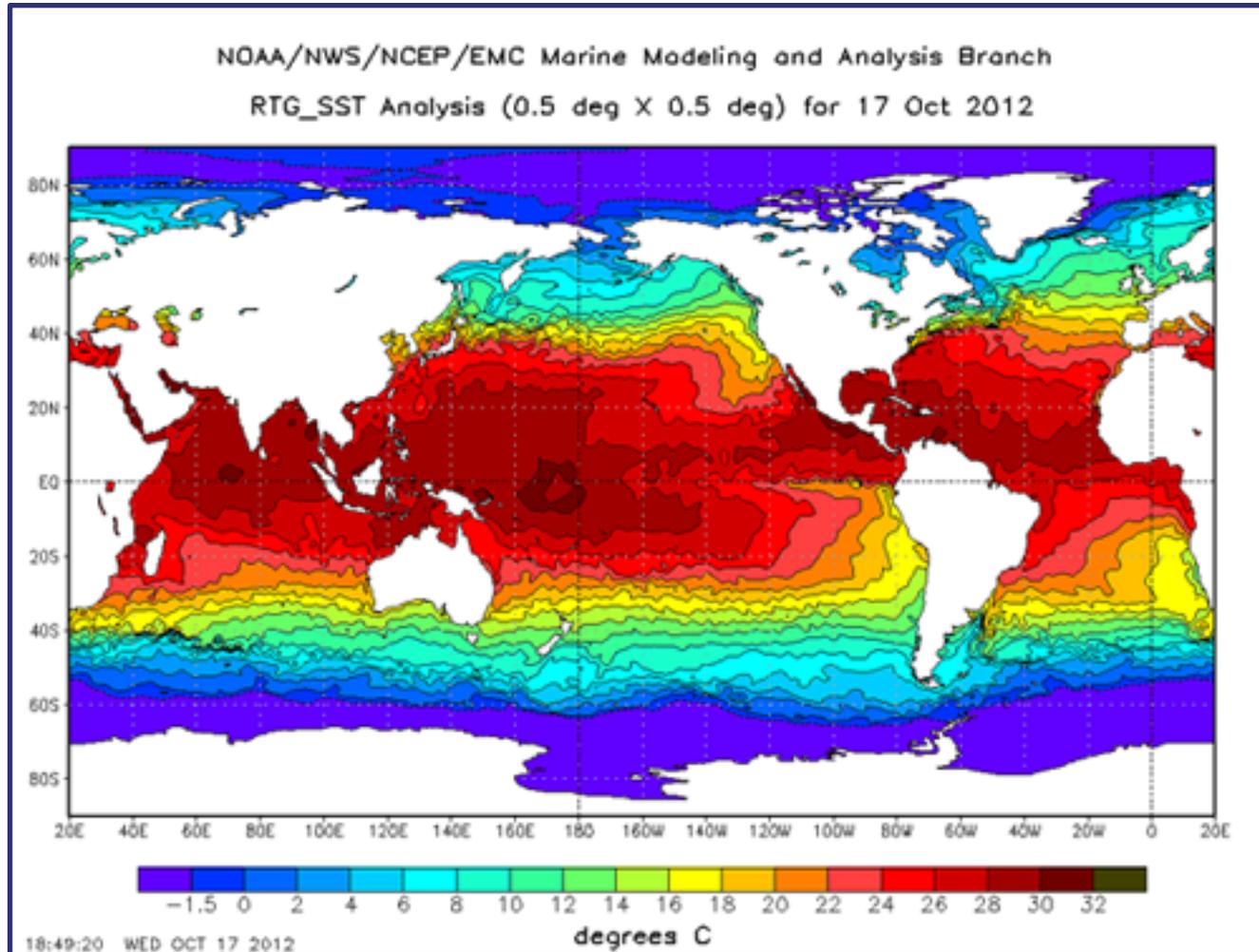
Global energy balance

For Earth to maintain a stable average temperature, **energy supplied by sun (annual average)** must be balanced by an equal amount of **energy lost to space**.



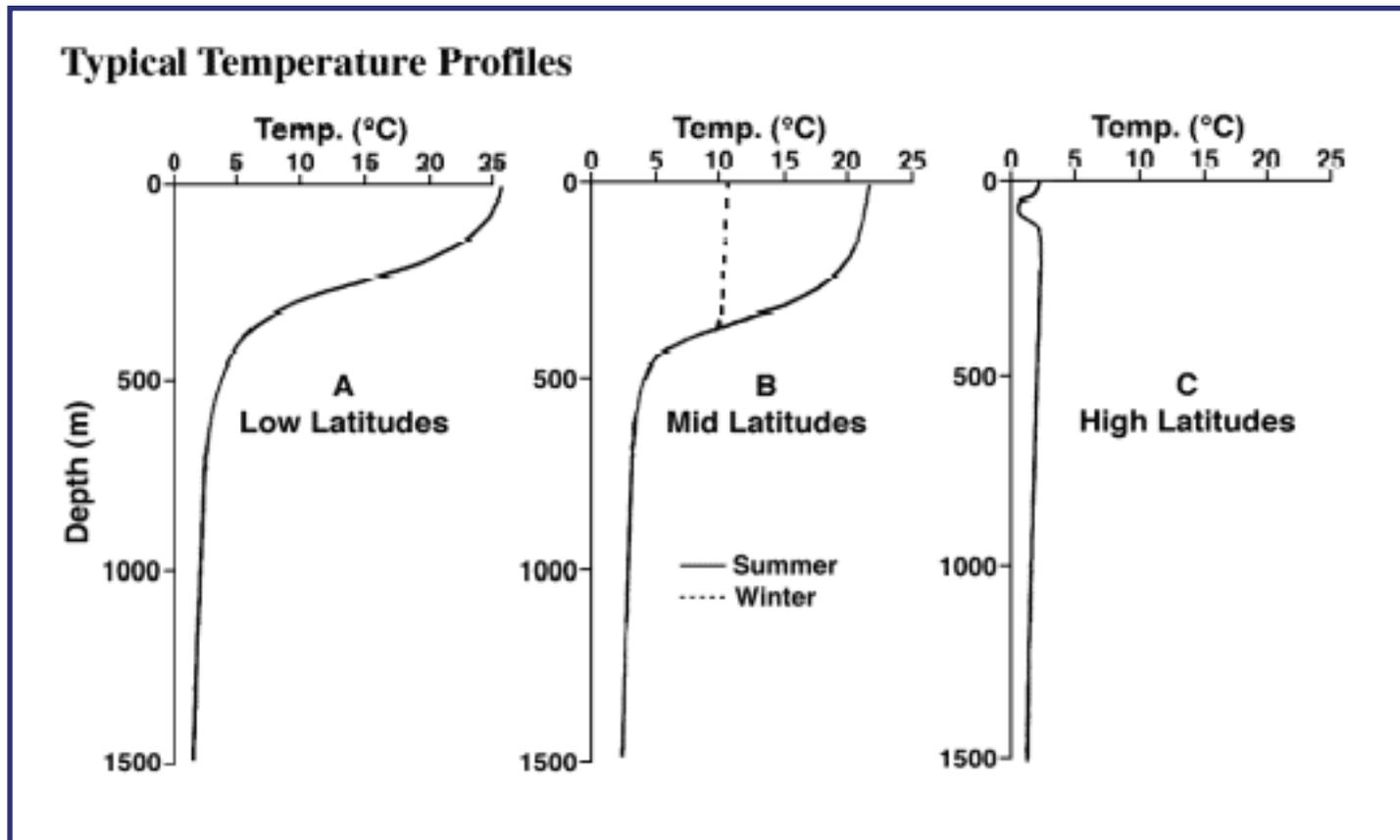
- At high latitudes (near the poles) more heat is lost than is supplied by the sun
- At low latitudes (near the equator) the opposite is true.

Temperature: Latitudinal variations



NOAA (<http://polar.ncep.noaa.gov/sst/oper/>)

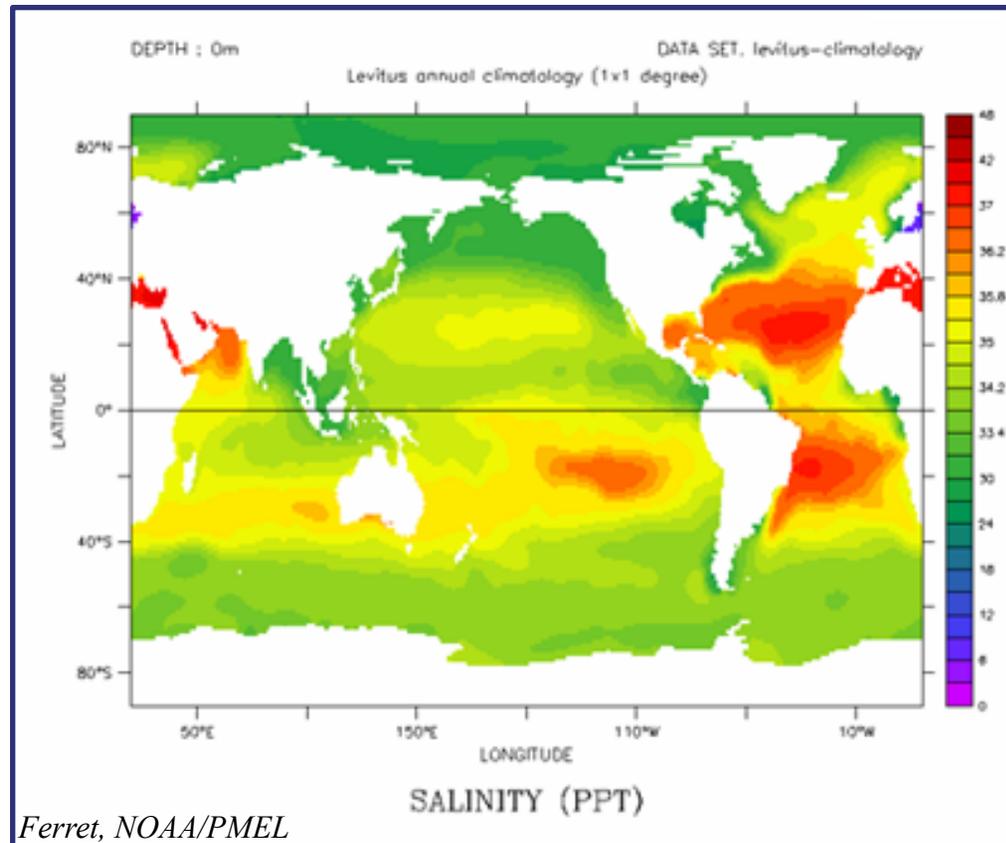
Thermocline Change with Latitude & Season



Earthguide, UCSD

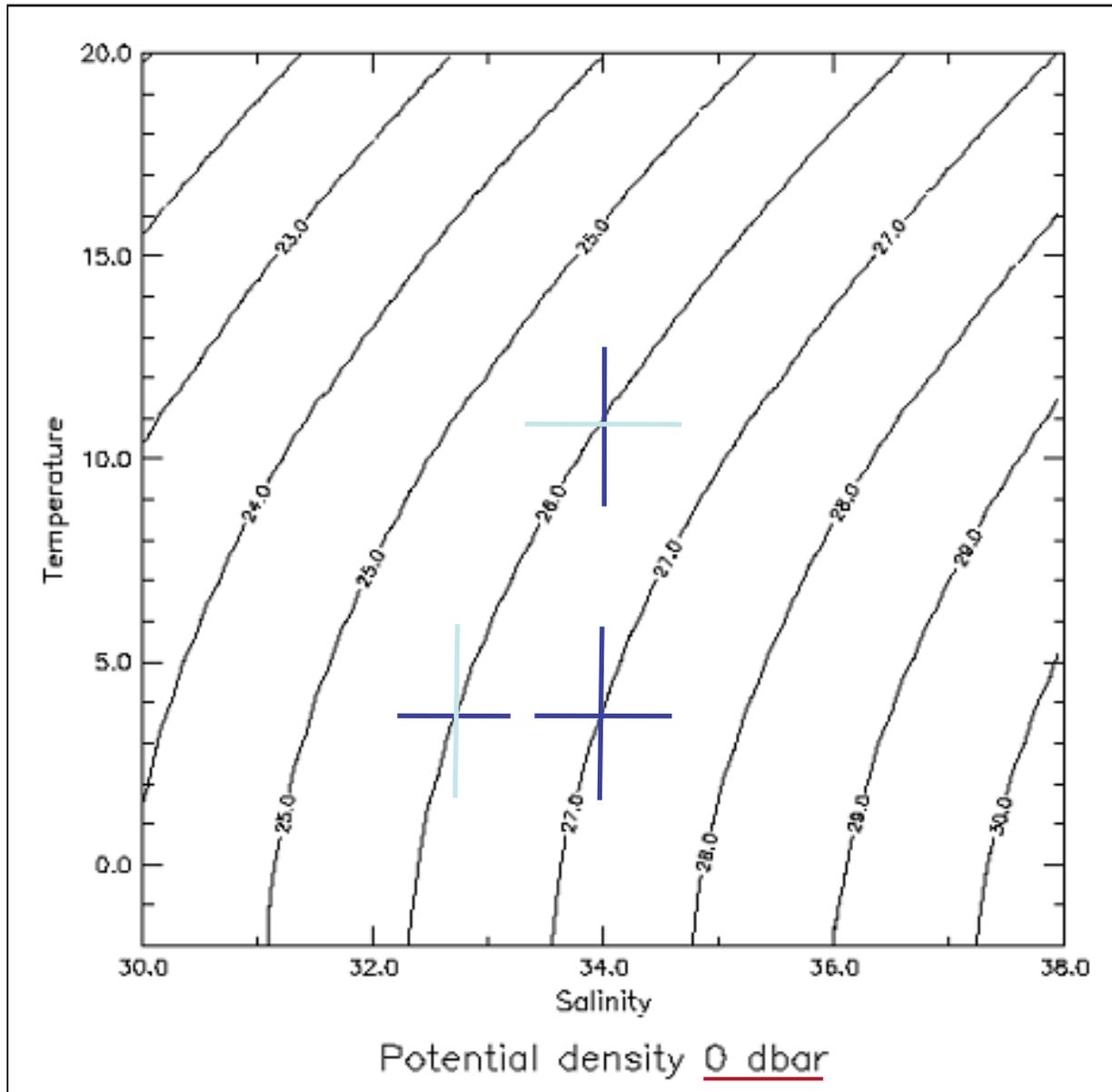
Salinity: Latitudinal variations

- Salt derives from continental weathering and erosion, as well as release of matter from the planet's interior



- Average salinity: 35 psu (roughly analogous to 35 ‰ by weight)
- Salinity variations result from imbalance between precipitation and evaporation

Density



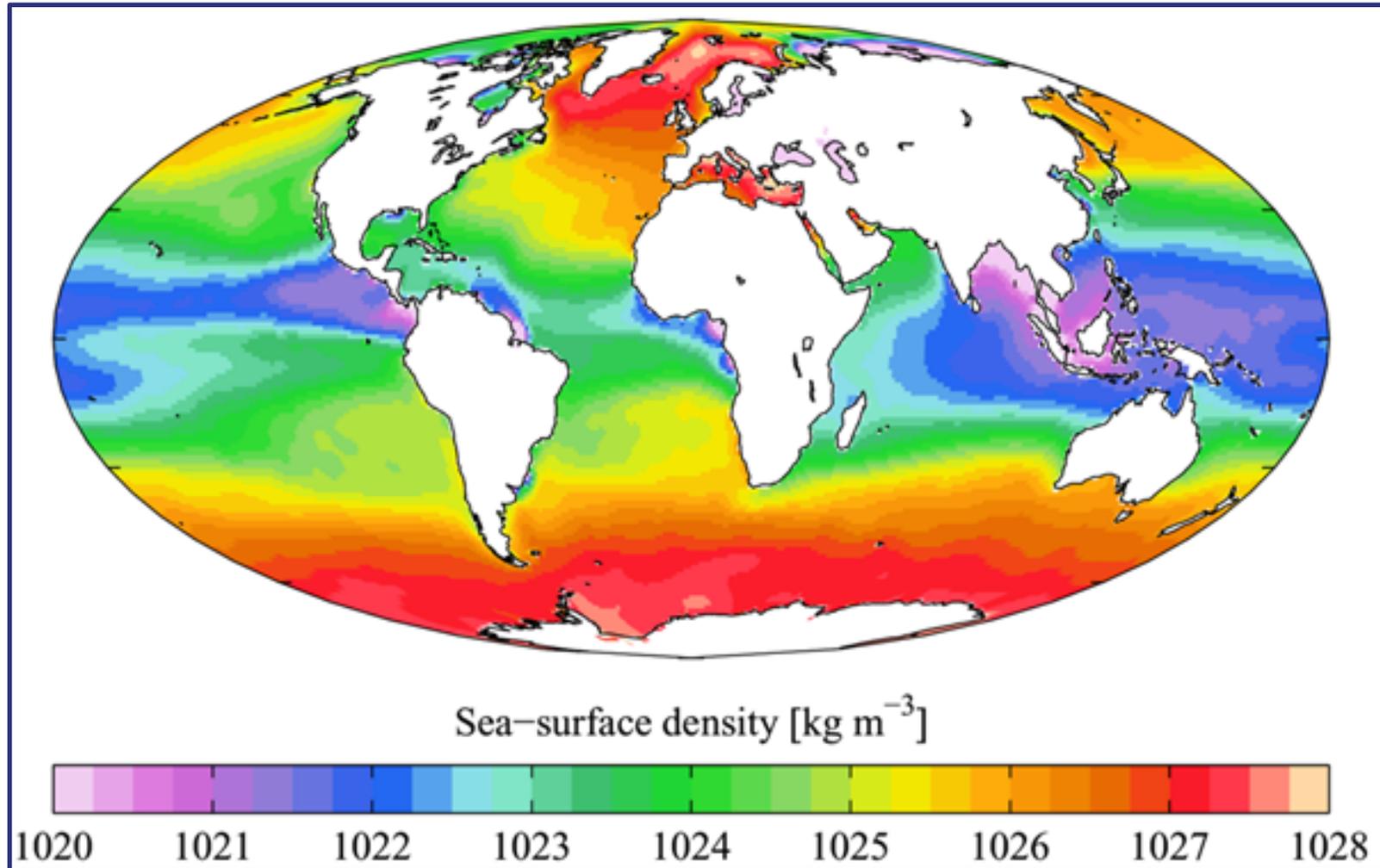
If you know the temperature and salinity of seawater, the density of seawater can be calculated directly

Density of water at the sea surface is typically 1027 kg/m^3 . For simplification, physical oceanographers often quote only the last 2 digits of the density, a quantity they call density anomaly or Sigma (σ):

$$\sigma = \text{density} - 1000 \text{ kg/m}^3$$

σ is typically 27 kg/m^3 or 27 g/cm^3

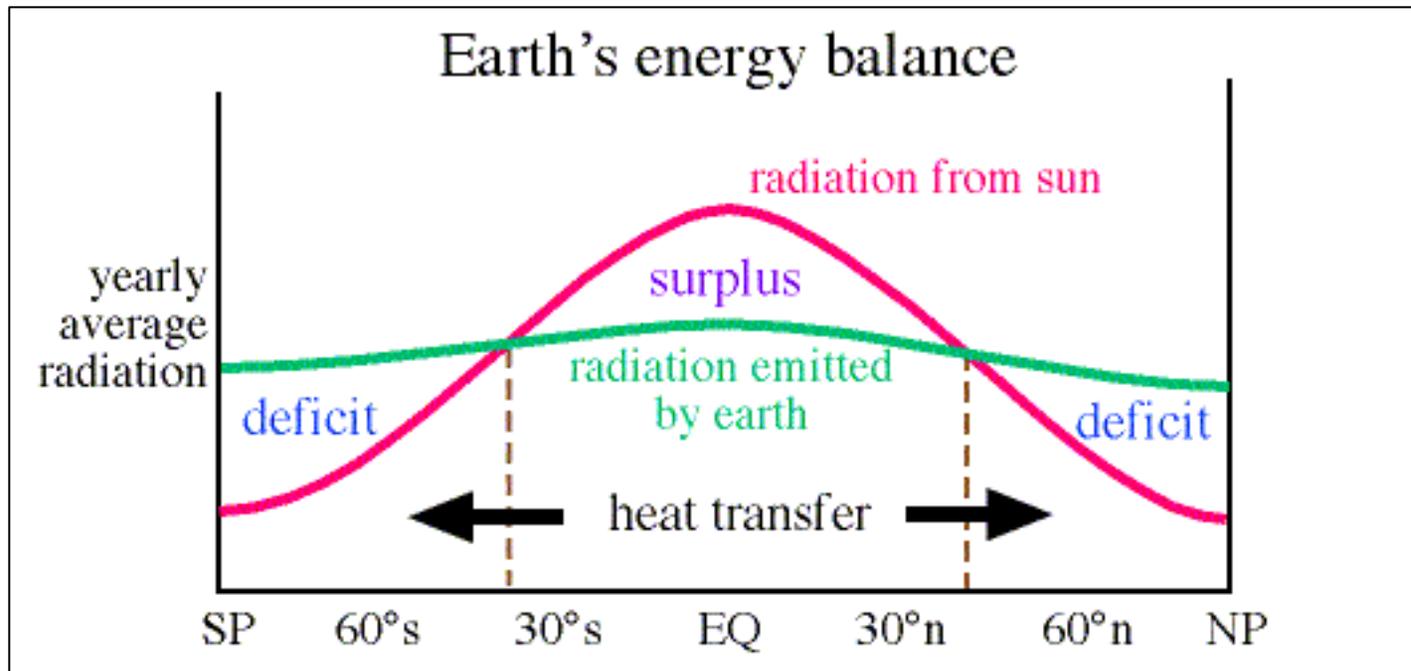
Density: Latitudinal variations



Data: World Ocean Atlas, <http://en.wikipedia.org>

Global energy balance

Latitudinal imbalance in incident radiation and loss requires redistribution of heat by the circulation of the atmosphere & ocean (Ch. 3).



Winds

(Chapter 3, Fig. 3.3 and relevant text, p. 50-53)

- Ultimately, wind direction, and consequently water motion, are controlled by:
 - friction between the atmosphere and the underlying sea surface,
 - the configuration of continental masses and oceanic basins

Wind-Driven Major Surface Water Currents

- **Trade winds** drive surface currents E-to-W along equator.
- Currents along the eastern side of continents (western boundary currents) are deflected toward the poles.
- As they move pole-ward, they are deflected by the Coriolis force.

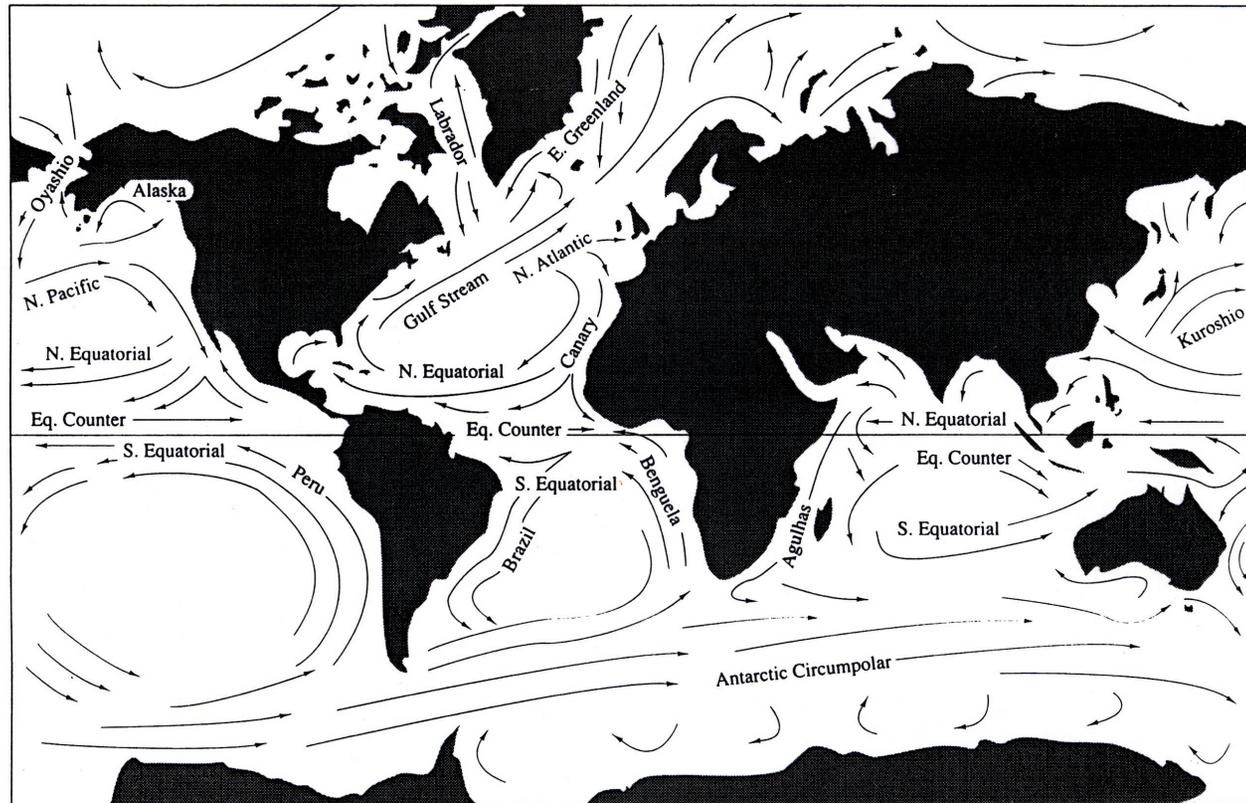


Figure 9.1 Major currents in the surface waters of the world's oceans. From Knauss (1978).

Wind-Driven Major Surface Water Currents (cont' d.)

- Mid-latitude *Westerlies* drive currents W-to-E.
- Surface currents along the W side of continents (eastern boundary currents) return cold water to tropics.
- These surface currents create the circular *gyre* circulation in each major ocean.

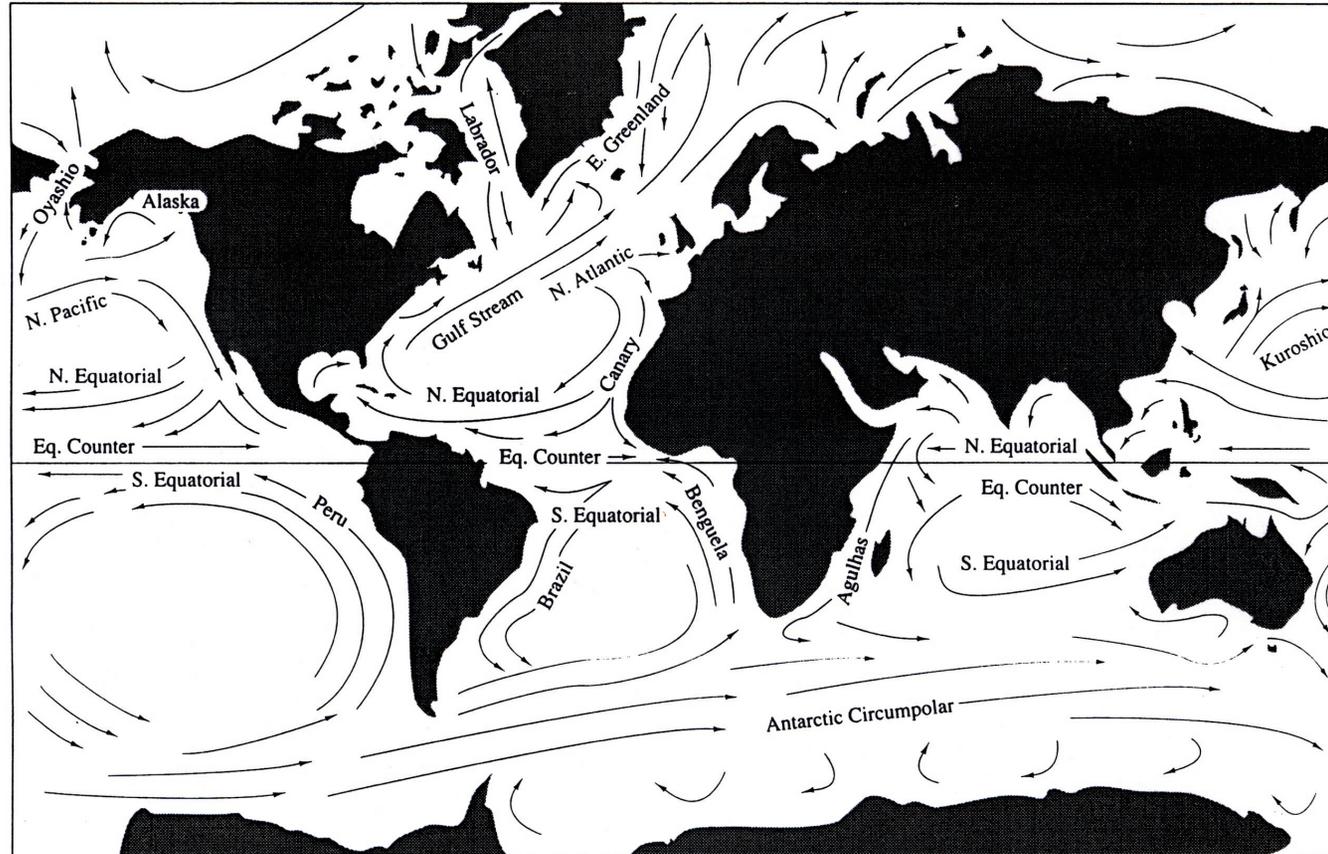
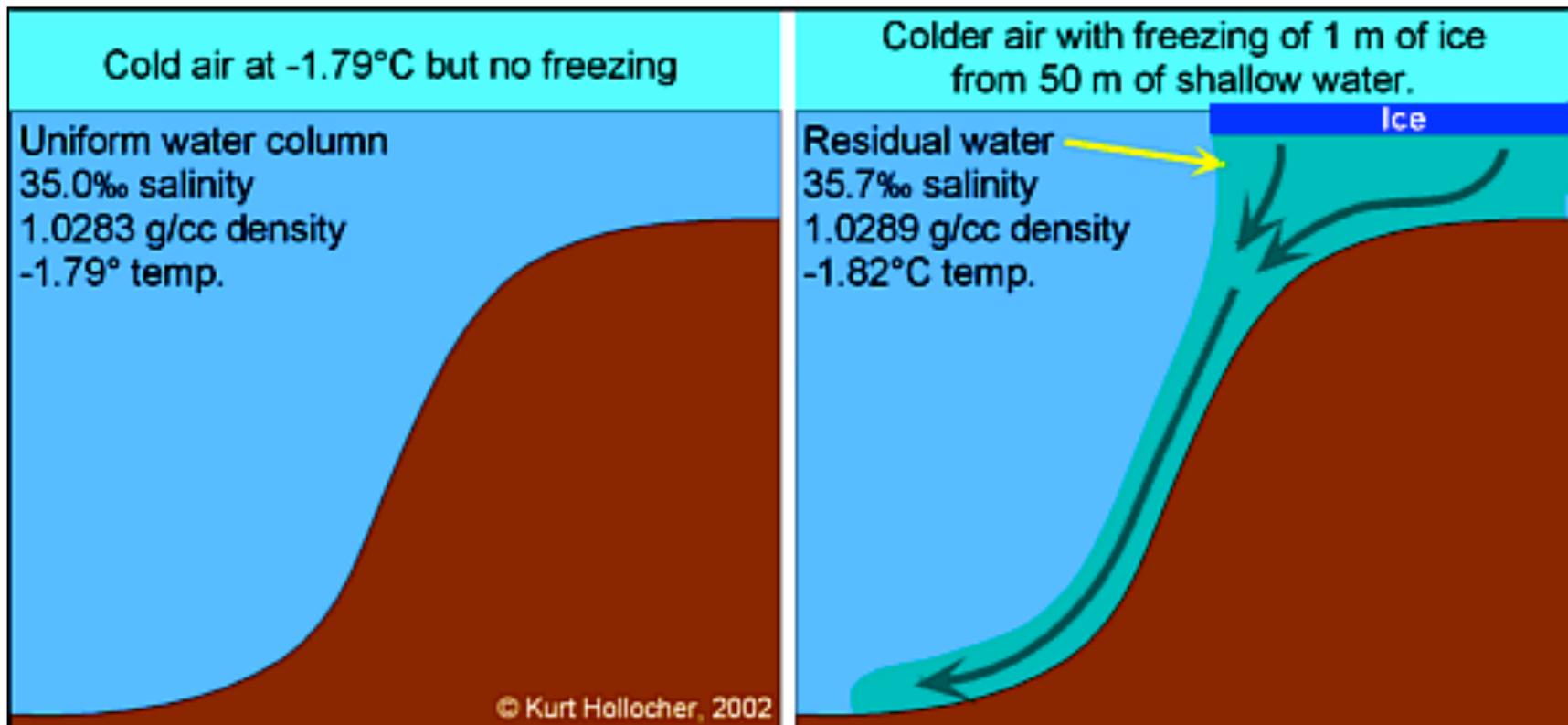


Figure 9.1 Major currents in the surface waters of the world's oceans. From Knauss (1978).

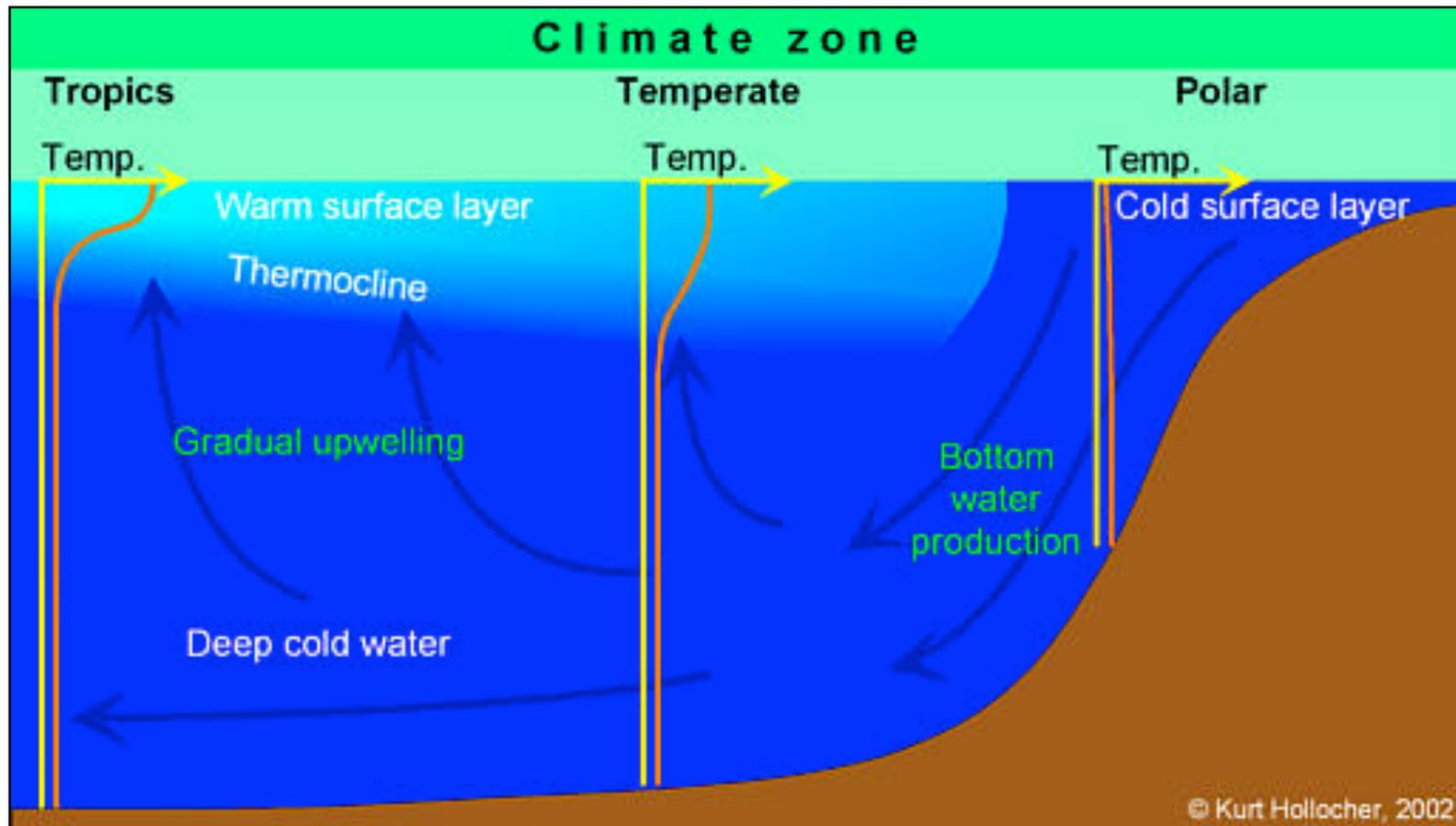
Thermohaline Circulation

- In the polar oceans in winter, fresh water freezes out of surface waters, leaving behind saltier, colder, higher density seawater that can sink to the deep ocean (*downwelling*).
- In summer, due to ice melt, surface waters are fresher and more stable.



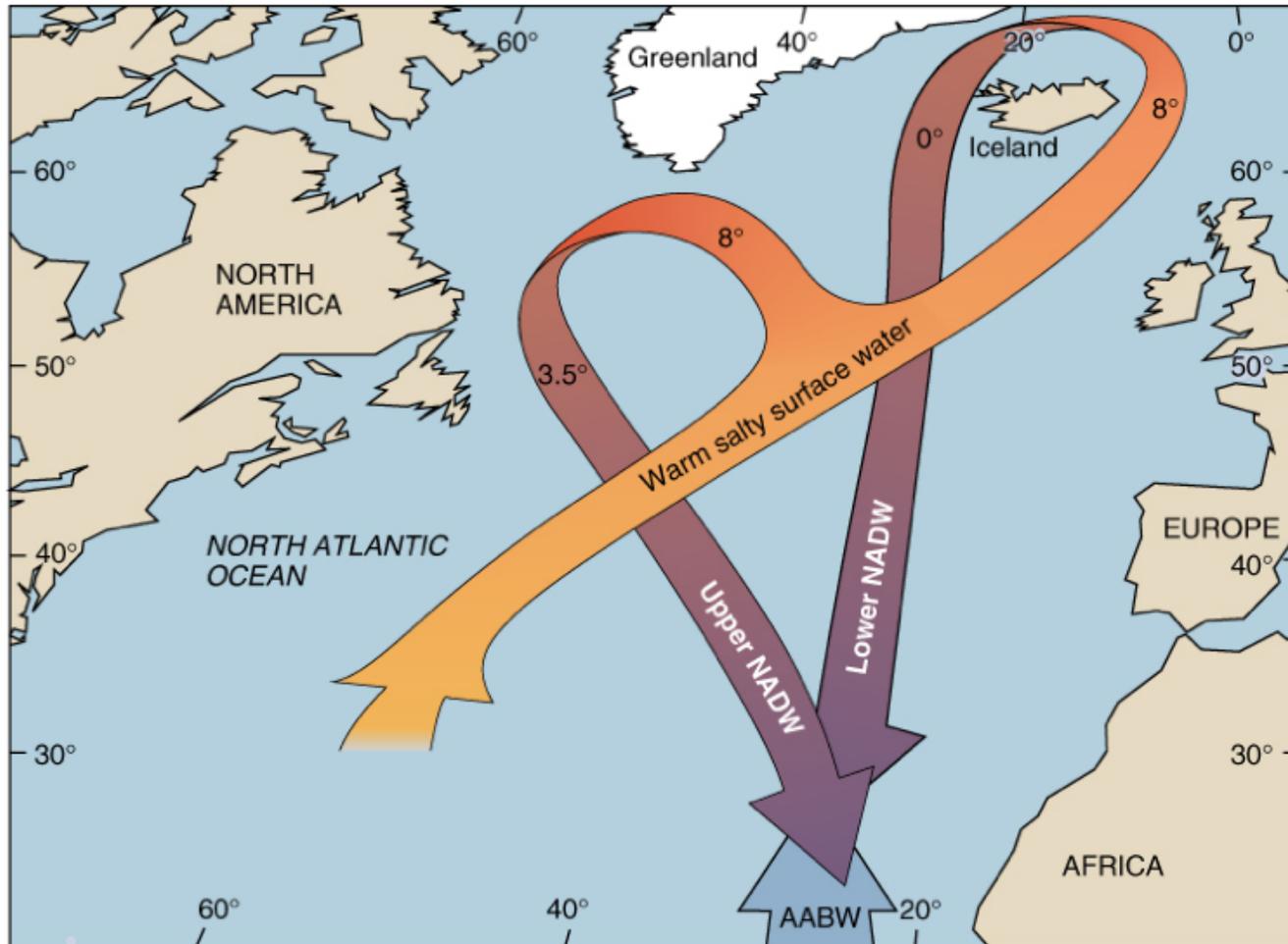
Thermohaline Circulation

Because seasonal *downwelling* of cold polar surface waters is driven both by temperature and salinity, it is called *thermohaline circulation*.



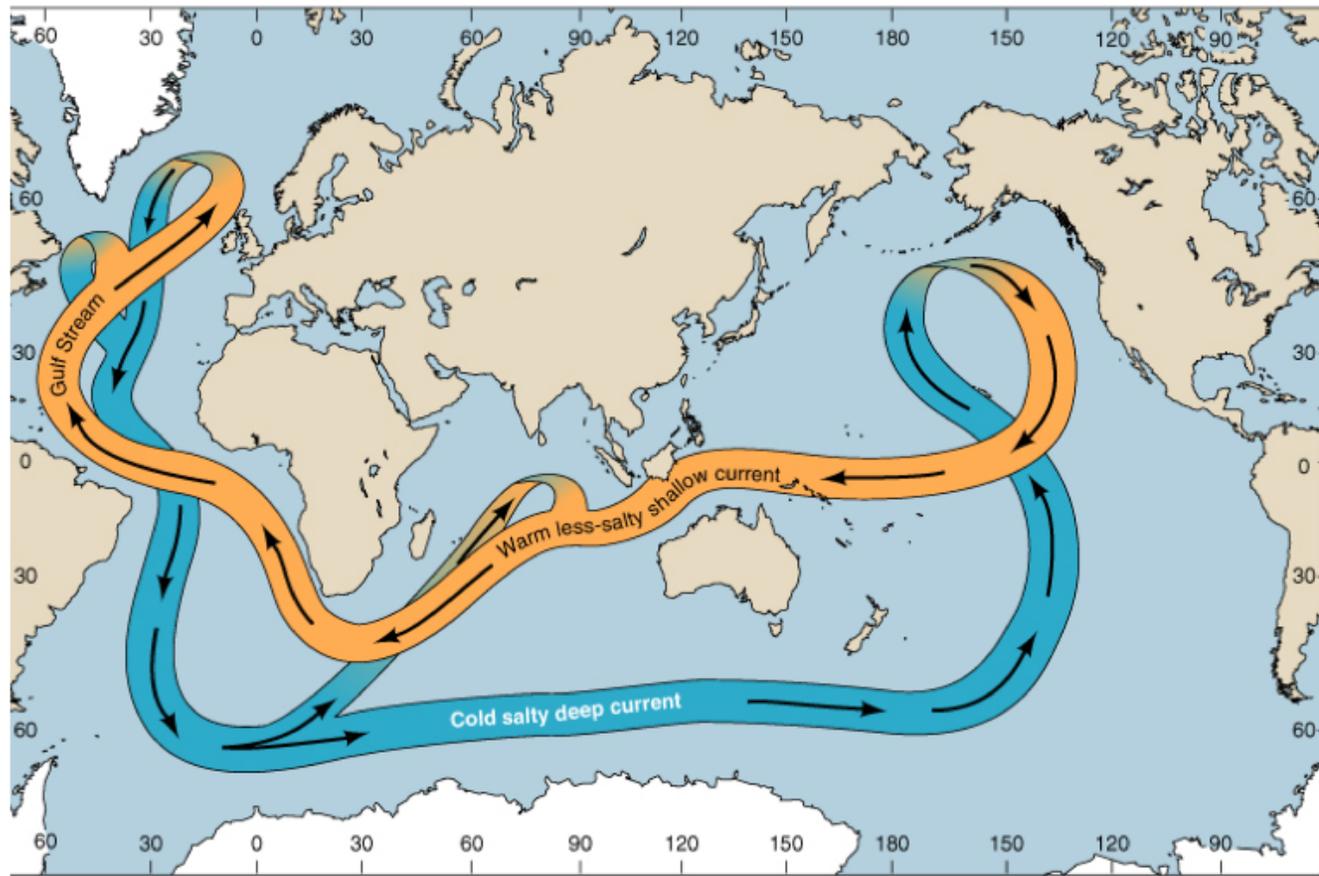
Thermohaline Circulation (cont' d.)

North Atlantic Deep Water (NADW) forms near Greenland, *downwells* and moves south through the deep Atlantic.



Thermohaline Circulation: The Global Conveyor Belt

- NADW moves south through the deep Atlantic, into the Indian and Pacific Oceans.
- *Upwelling* occurs in the Indian, Pacific and Southern Oceans.
- Deep waters are nutrient-rich, so high NPP is found in upwelling zones.



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Thermohaline circulation and climate change

- Formation of deep waters may be associated with changes in global climate
- An increase in the rate of downwelling of cold, saline North Atlantic waters at the start of the last glacial epoch may have resulted in a lowering of atmospheric CO₂
 - CO₂ is more soluble in cold waters
 - Atmospheric CO₂ during last glacial was 200 ppm, vs. pre-industrial 280 ppm
- However, deep water formation depends on the contrast in temperature and density between surface and deep waters - once the glacial epoch was fully developed, NADW production likely declined
 - Causing a reduction in transport of atmospheric CO₂ to the deep ocean
 - Allowing warmer conditions to return: *Negative Feedback*

Oceanic Water Residence Times

- *Residence Time* (T_R) = Mass / Flux In, or T_R = Mass / Flux Out.

- Residence time with respect to river flow:

$$T_R = \text{total ocean volume} / \text{annual river flow} = V_{\text{ocean}} / F_{\text{rivers}} = 3400 \text{ years}$$

- But, most rivers mix only with surface waters: $T_R = V_{\text{surf oc}} / F_{\text{rivers}} = 1700$ years, with respect to river waters.
- Considering rain water and upwelling input to surface waters reduces the T_R even more: Flux in = $F_{\text{rivers}} + F_{\text{rain}} + F_{\text{upwelling}}$
- For example, the mean T_R of North Pacific surface waters is *ca.* 9-15 years.
- Surface waters are also in rapid gaseous equilibrium with the atmosphere.
 - The mean T_R of CO_2 in the surface ocean is *ca.* 6 years.

Oceanic Water Residence Times (cont' d.)

T_R estimates can be constrained using *transient tracers* (e.g., bomb tritium: ^3H , bomb carbon-14: ^{14}C).

- $^3\text{H}_2\text{O}$ dating of downwelling polar waters reveals that NADW transport toward the equator is *ca.* 10 x faster than the annual rate of riverine input to the ocean (downwelling also occurs in southern ocean).

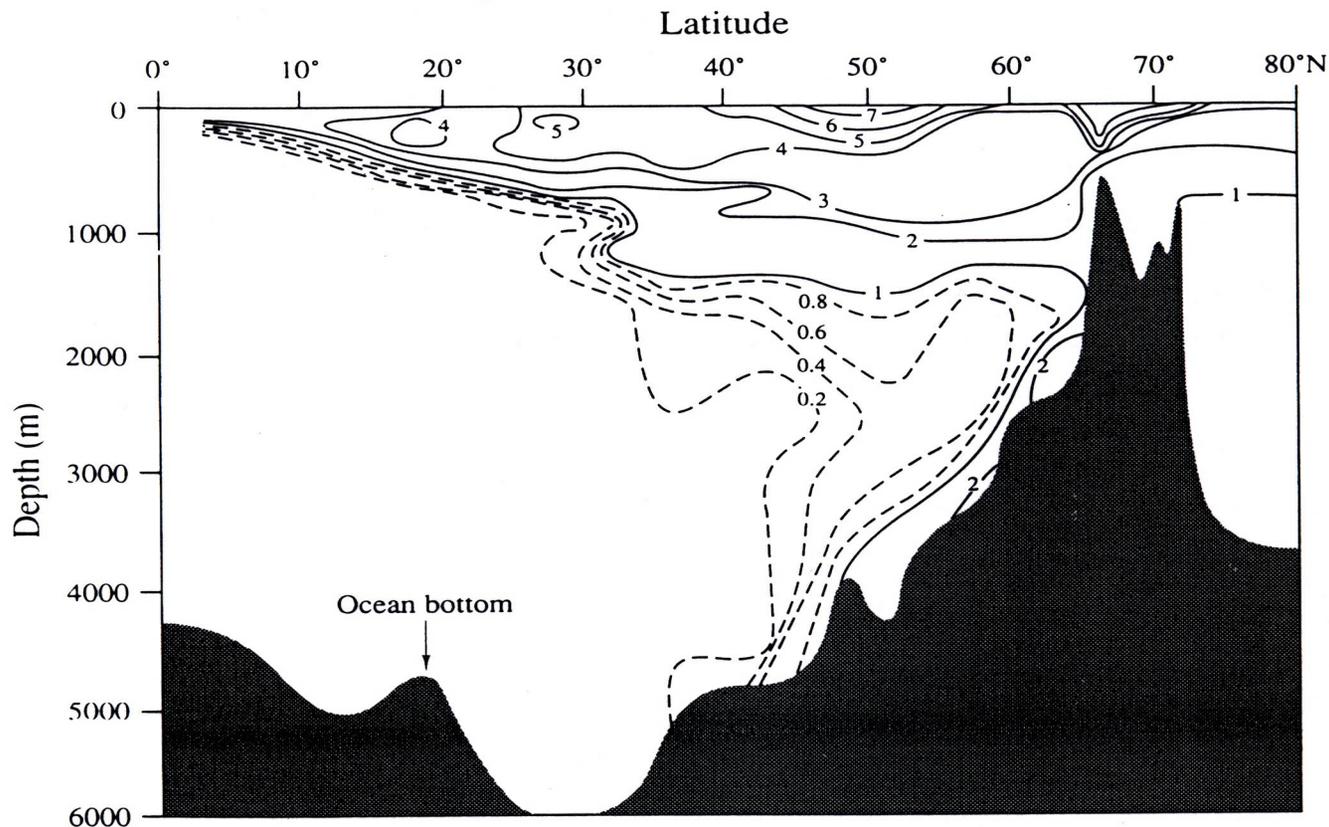


Figure 9.2 Penetration of bomb-derived tritium ($^3\text{H}_2\text{O}$) into the North Atlantic Ocean. Data are expressed as the ratio of $^3\text{H}/\text{H} \times 10^{-18}$ for samples collected in 1972. From Ostlund (1983).

Oceanic Water Residence Times (cont' d.)

- Volume of water entering deep ocean >>> riverine inflow, so T_R <<< 3400 years.
- ^{14}C dating of dissolved CO_2 yields residence times that range from 275 years for the Atlantic Ocean to 510 years for the Pacific Ocean.
- Scale of residence time tells us that deep waters maintain an historical record of surface ocean conditions back several centuries.

Deep Water Currents and Ocean Salinity

- Deep currents also transfer seawater between ocean basins as a result of the Antarctic circumpolar current (Fig. 9.1).
- In the Atlantic, evaporation > precipitation + river inflow
 - Atlantic Ocean is more saline than the Pacific Ocean.
 - Less saline waters are returned to the Atlantic from the Pacific via the ACC.
 - Dense saline waters flows out of deep Atlantic to Pacific and Indian Oceans.

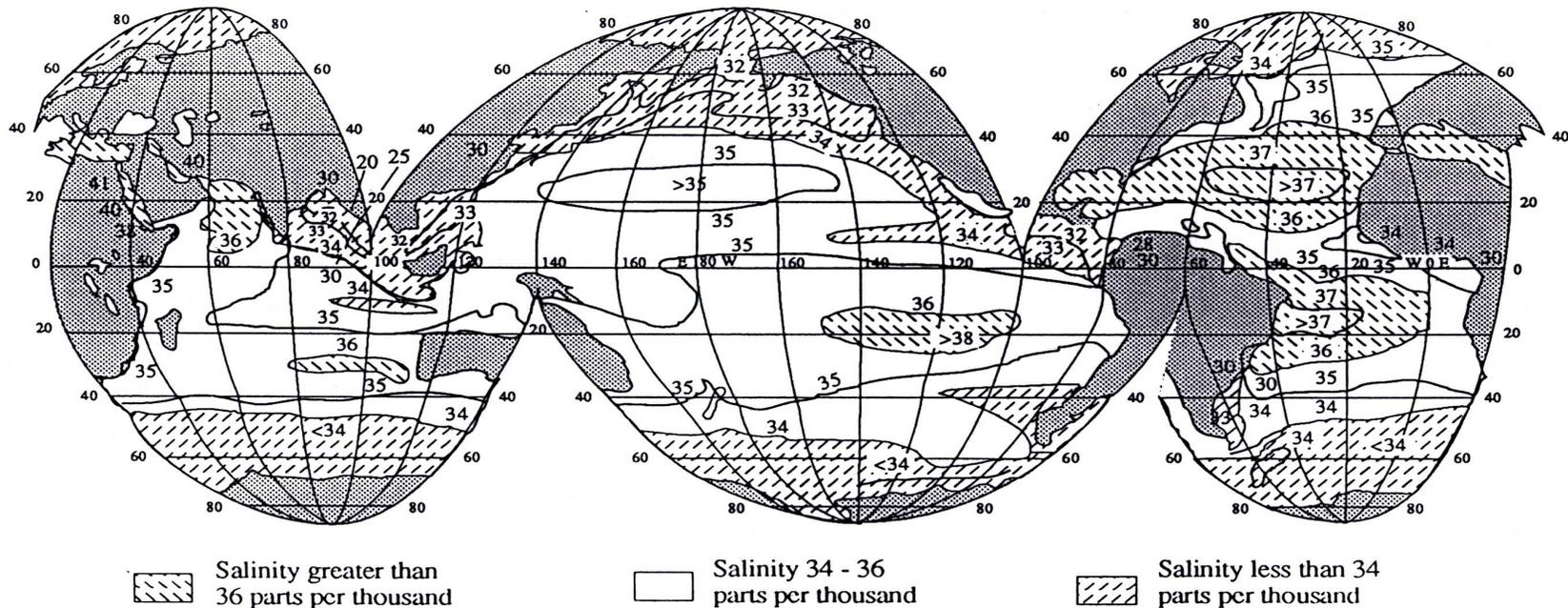
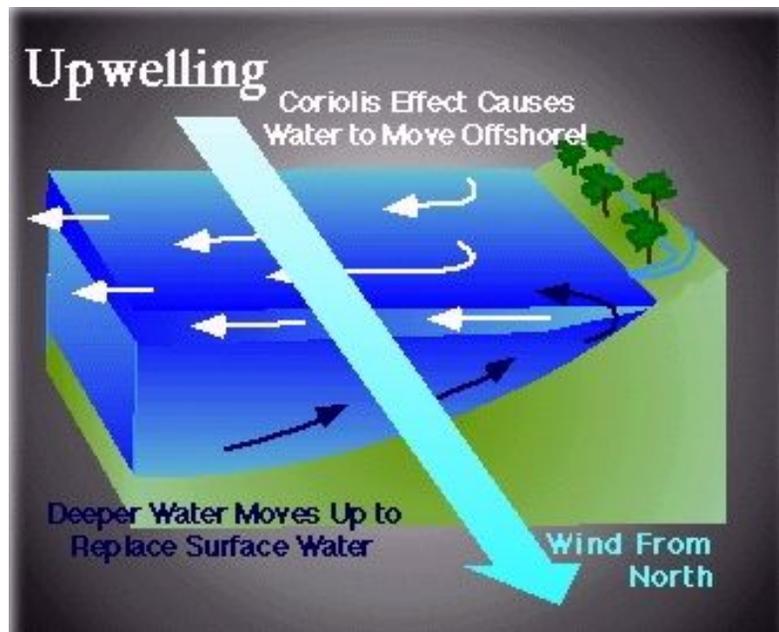


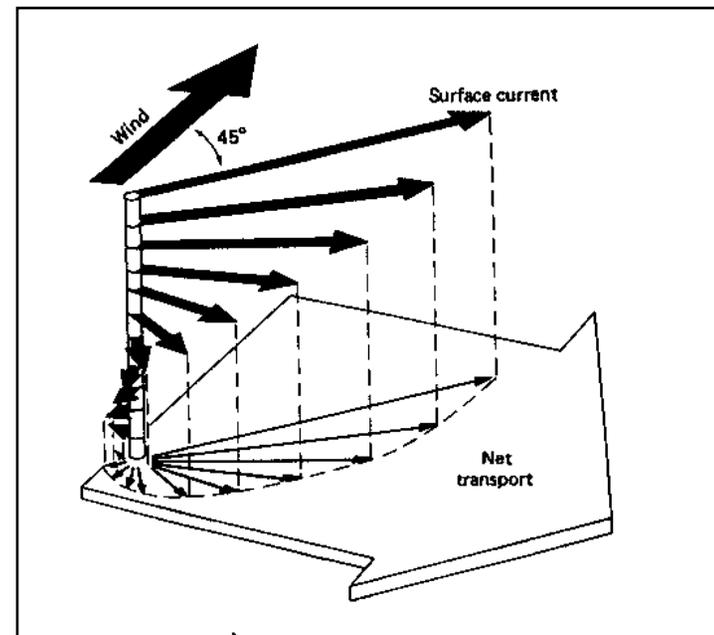
Figure 9.3 Salinity of the surface waters of the world's oceans. From Gross (1977).

El Niño

- An example of shorter time-scale (year-to-year) variation in ocean currents that can affect biogeochemistry and global climate.
- Occurs in the central Pacific Ocean.
 - Under normal conditions, trade winds blow warm surface waters E to W
 - Displacement of warm surface waters in the E. Pac. drives upwelling of cold bottom waters along the west coast of S. America & southern N. America.



Shown: Northern Hemisphere, Normal Conditions

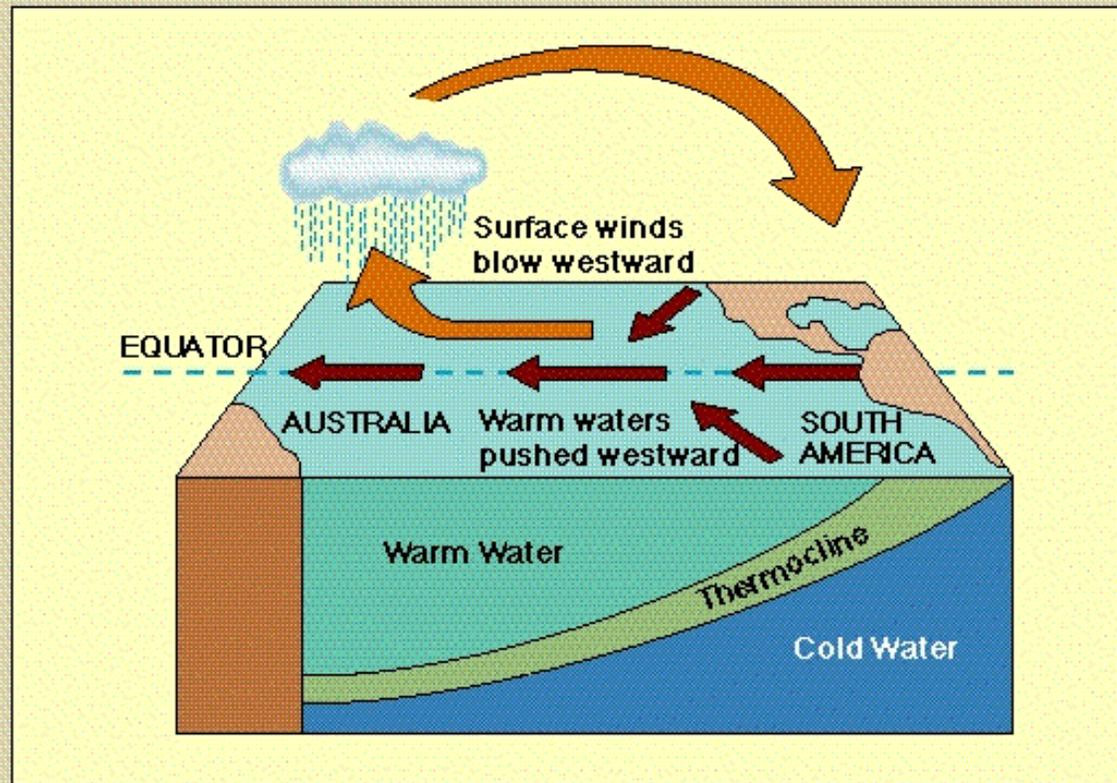


<http://www.brookes.ac.uk/geology/sedstruc/upwell/ocean.htm>

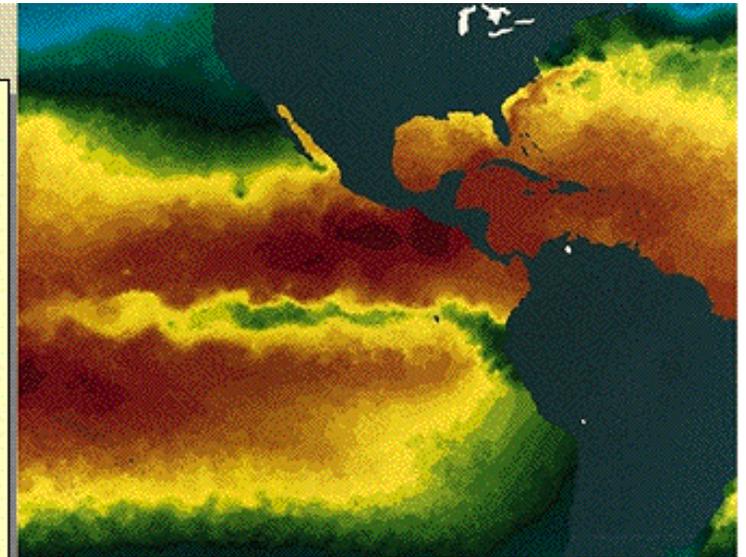
El Niño (cont'd.)

- High nutrients deep upwelled waters fuel phytoplankton growth; supporting important fisheries industries, e.g., Peru.
- Periodically (every 3-5 years), this surface transport breaks down in an event called: the *El Niño-Southern Oscillation (ENSO)*.
- During El Niño years, warm surface waters remain along the coast of Peru, preventing upwelling of nutrient rich bottom waters; fisheries collapse.

Normal Conditions in the Pacific



Diagrammatic view of a non-El Niño year. Normally air and surface water flow westward, the thermocline rises, and upwelling of cold water occurs along the west coast of Central and South America.

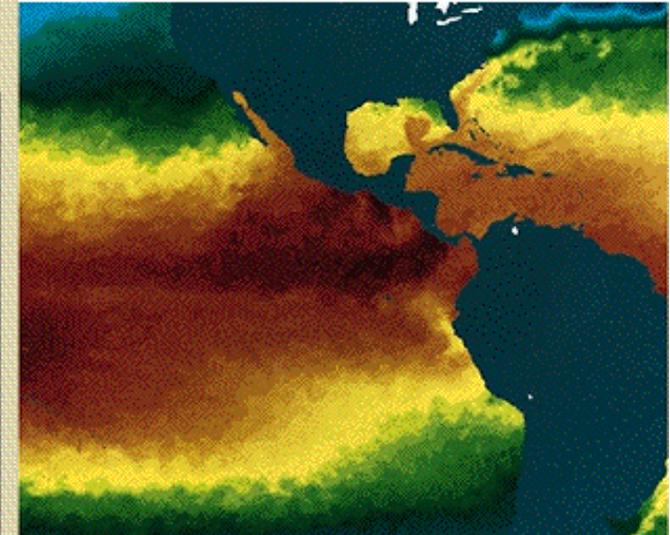
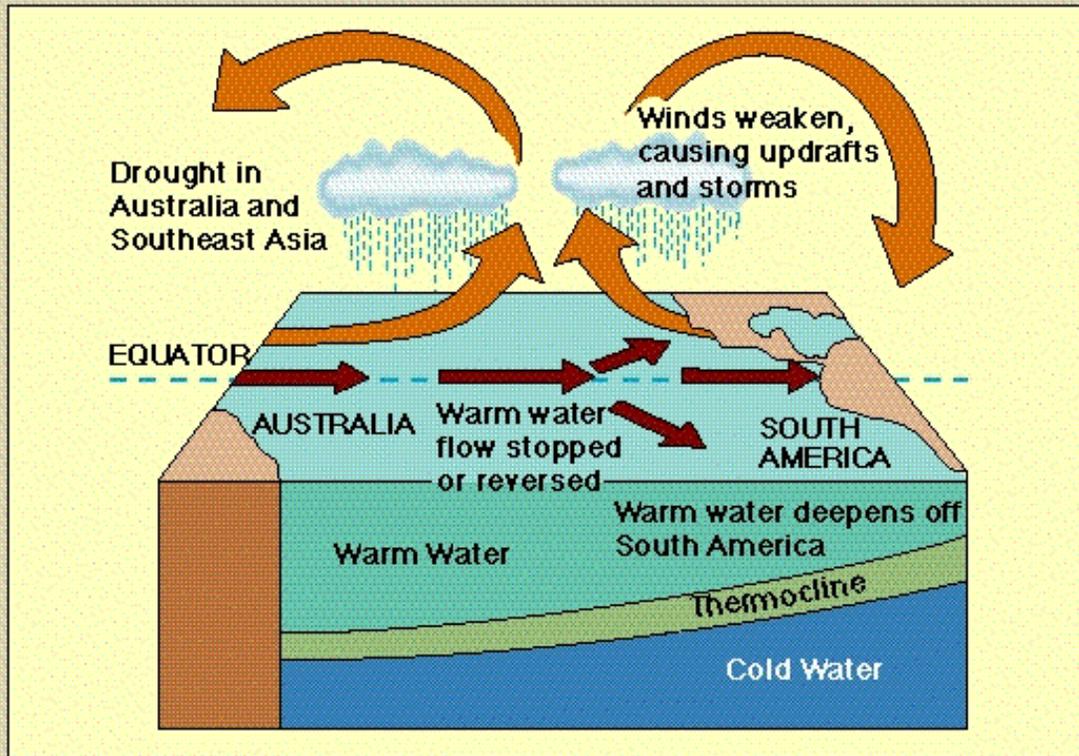


Surface water temperature in a non-El Niño year. This map, produced from satellite data, shows the surface temperature of the equatorial Pacific on 31 May 1988. The warmest water is indicated by the dark red, and progressively cooler water by yellow and green. Note the coastal upwelling along the South American coast at the lower right of the map, and the tongue of recently upwelled water extending westward along the equator from the South American coast.

(Figures and figure links refer to figures in Garrison, [Oceanography: An Invitation to Marine Science 4th Ed.](#))

<http://www.geology.wmich.edu/kominz/C9normaleqPac.gif>

El Niño Conditions in the Pacific



Surface water temperature in an El Niño year. This map, produced from satellite data, shows the surface temperature of the equatorial Pacific on 13 May 1992. The thermocline was deeper than normal, and equatorial upwelling was suppressed. Note the absence of coastal upwelling along the coast and the lack of the tongue of recently upwelled water extending westward along the equator.

Diagrammatic view of an El Niño year. When the Southern Oscillation develops, the trade winds diminish and then reverse, leading to an eastward movement of surface waters along the equator. The surface waters of the central and eastern Pacific become warmer, coastal upwelling along the South and Central American coast decreases, and storms over land may increase.

(Figures and figure links refer to figures in Garrison, [Oceanography: An Invitation to Marine Science 4th Ed.](#))

<http://www.geology.wmich.edu/kominz/C9elnino1.gif>

Global Consequences of El Niño

- Other climatic changes associated with El Niño:
 - exceptionally warm winters and high rainfall in western N. America.
 - reduced monsoon intensity in S. E. Asia and India due to absence of warm surface waters in the W. Pac
- El Niño events are part of a cycle, alternating with opposite but equally extreme conditions during non-El Niño years, known as La Niña conditions.
 - Upwelling of cold, deep waters during La Niña years results in lower atmospheric temperatures over much of the N. hemisphere.
 - Trigger for switch between El Niño and La Niña poorly understood.
- Some consequences of the El Niño-La Niña cycles:
 - Added variation to global temperature makes it difficult to discern atmospheric warming due to the Greenhouse Effect.
 - Affects atmospheric chemistry: CO₂ release from cold, upwelled waters is lower during El Niño years.
 - Denitrification rates 25% lower during El Niño vs La Niña yrs.

Seawater Composition: Major Ions

- T_R for major ions much longer than T_R for water in the oceans: uniform distribution.
- Major ions are *conservative*: maintain the same ratio to each other throughout oceanic waters, even if salinity changes.

Table 9.1 Major Ion Composition of Seawater, Showing Relationships to Total Salinity and Mean Residence Times for the Elements with Respect to River Water Inputs

Constituent	Concentration in seawater ^a (mg/kg)	Chlorinity ratio ^a	Concentration in river water ^b (mg/kg)	Mean residence time (10 ⁶ yr)
Sodium	10,760	0.5561	5.15	75
Magnesium	1,294	0.0668	3.35	14
Calcium	412	0.0213	13.4	1.1
Potassium	399	0.0206	1.3	11
Strontium	7.9	0.00041	0.03	12
Chloride	19,350	1.0000	5.75	120
Sulfate	2,712	0.1400	8.25	12
Bicarbonate	145	0.0075	52	0.10
Bromide	67	0.0035	.02	100
Boron	4.6	0.00024	0.01	10.0
Fluoride	1.3	0.000067	0.10	0.5
Water				0.034

^a Holland (1978).

^b Meybeck (1979) and Holland (1978).

Seawater Composition: Major Ions (cont' d.)

- Because major ions are conservative, can calculate total salinity from the concentration of a single ion, typically Chloride is used:

$$\text{salinity } \text{‰} = 1.81 (\text{Chloride } \text{‰}), \text{ where } \text{‰} = \text{parts per thousand (ppt)} \\ = \text{g/kg of water}$$

- Mass Balance of Major Elements in Seawater (e.g. Steady State):
 - Major element composition has remained constant for long periods of time.
 - Requires processes that remove ions from the oceans to balance new riverine inputs.
 - Residence times for major elements (Table 9.1) vary from 120 Ma for Cl^- to 1.1 Ma for Ca^{2+} ; T_R provides a measure of how reactive an element is.
 - The shorter T_R for Ca^{2+} reflects biological removal as calcium carbonate and deposition in sediments; there is no similar removal process for Cl^- .

Processes that Remove Ions from Seawater

- **Cyclic Sea Salts.**
 - Wind blown sea-spray forms aerosols containing seawater ions (Chap. 3)
 - A significant portion of river-transported Cl^- derives from these aerosols, returning them to the sea -- *cyclic seasalts*.
 - This process removes ions in proportion to their concentration in seawater.
- **Ion Exchange** on river-borne Clays Entering the Ocean
 - Most of the cation exchange sites on clays are occupied by Ca^{2+} .
 - Upon exposure to seawater, Ca^{2+} is released, and replaced by other seawater cations, especially Na^+ , K^+ , and Mg^{2+} .
 - Most deep sea clays have higher Na^+ , K^+ , and Mg^{2+} concentrations than riverine clays (Martin and Meybeck 1979).
 - As these clays settle out onto the seafloor these ions are removed from sw.
- **Burial** of dissolved ions (particularly Na^+ and Cl^-) in sediment pore waters.
- **Deposition** of biogenic CaCO_3 : dominant process removing Ca^{2+} from seawater.

Processes that Remove Ions from Seawater (cont' d.)

- **Biogenic removal** of S and Fe resulting from sulfate reduction and formation of pyrite (FeS_2), a secondary, *authigenic* mineral.
- **Evaporite minerals** (salt flats, sabkhas)
 - Vast deposits of evaporite minerals formed in the geologic past when seawater evaporated from shallow, enclosed basins.
 - An important process for Na^+ , Cl^- and SO_4^{2-} removal from seawater during certain periods of Earth's history.
- **Reverse Weathering**, an old idea recently (mid-1990s) confirmed.
 - Formation of secondary, *authigenic* silicate minerals within sediments
 - Important for removing Mg^{2+} , K^+ , H_4SiO_4 .
- **Removal at Hydrothermal Vents.**
 - Especially important for Mg^{2+} (Mg-silicate ppt), but also for SO_4^{2-} .

Summary of Major Ion Removal Processes

- Most Na^+ and Cl^- are removed in pore water burial, sea spray, and in evaporite deposits.
- Mg^{2+} is largely removed in hydrothermal exchange.
- Ca^{2+} and SO_4^{2-} are removed by deposition in biogenic sediments.
- K^+ is removed by exchange with clay minerals and reverse weathering.
- Eventually, over long periods of time, ocean sediments are subducted into the Earth's mantle
 - Non-volatile components are melted under pressure and converted into primary silicate minerals.
 - Volatile components are released as volcanic gases (H_2O , CO_2 , Cl_2 , SO_4)

Lecture Summary

- Temperature and salinity differences between surface and deep water result in stable stratification of the water column; reduction of this contrast in high latitudes leads to *isopycnal* mixing and deep water formation.
- *Thermohaline circulation* is driven by *downwelling* of cold, dense surface waters at high latitudes to form deep waters; cold, deep waters are transported equator-ward, with a counter-balancing flow of warm surface waters from equator to pole.
- Thermohaline circulation is an important mechanism for redistributing heat energy on the Earth's surface.
- Wind driven surface currents lead to formation of *central ocean gyres* and *upwelling*.
- El Niño-Southern Oscillation results from changes in surface current and upwelling patterns, and leads to global climate change.
- Residence time (T_R) of elements in the ocean ranges from <100 yr to >100 Ma.
- T_R indicates relative reactivity of elements, i.e. efficacy of removal processes.