(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:
   a) Major Ions
   b) Residence Times
   c) Removal processes
4. Summary

Introduction

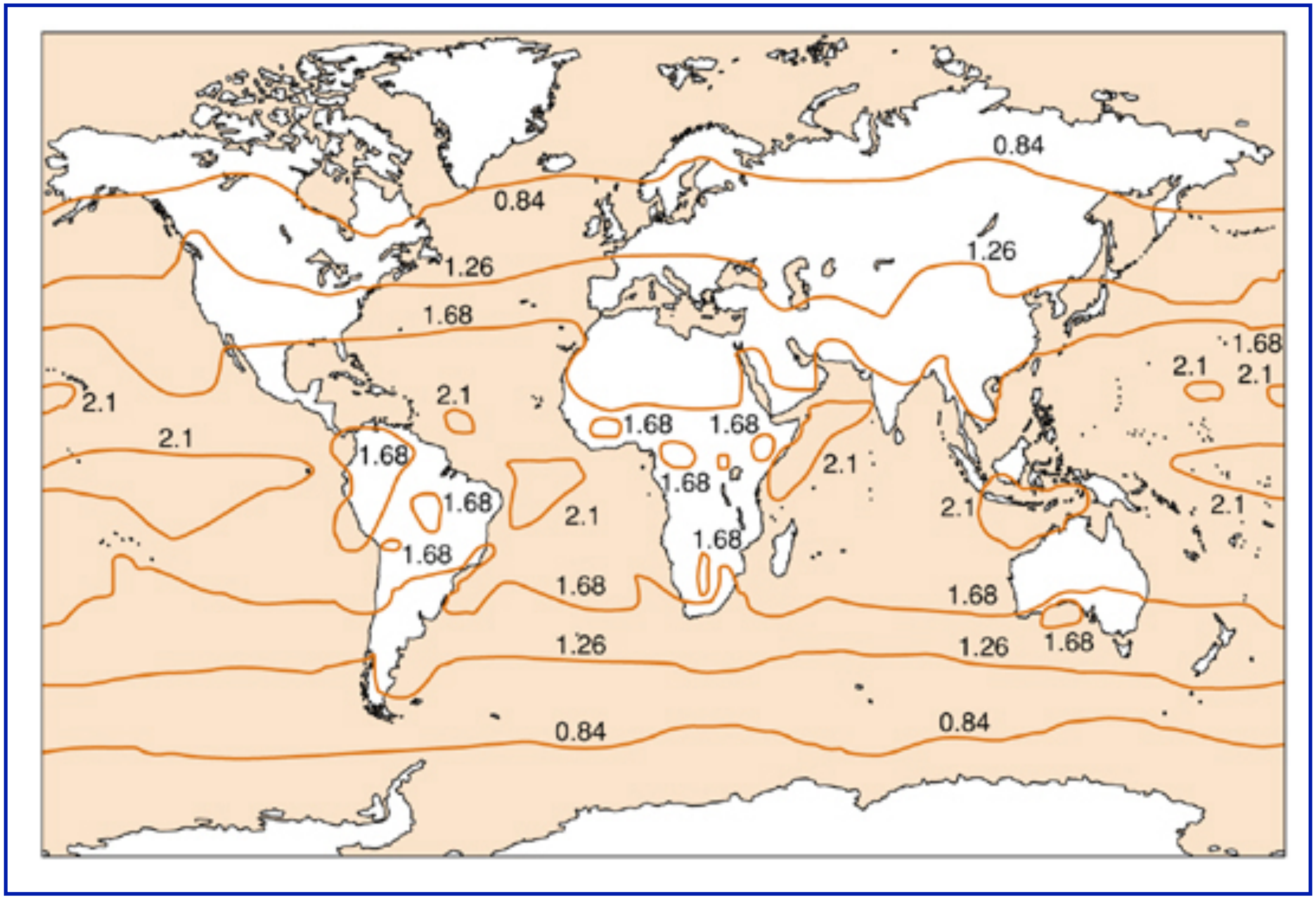
- Earth’s waters constitute its hydrosphere.
- Oceans dominate (96% of total).
- Deep ocean (>200-300 m) accounts for 91% of total
- The ocean is a major player in global biogeochemical cycles.

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	

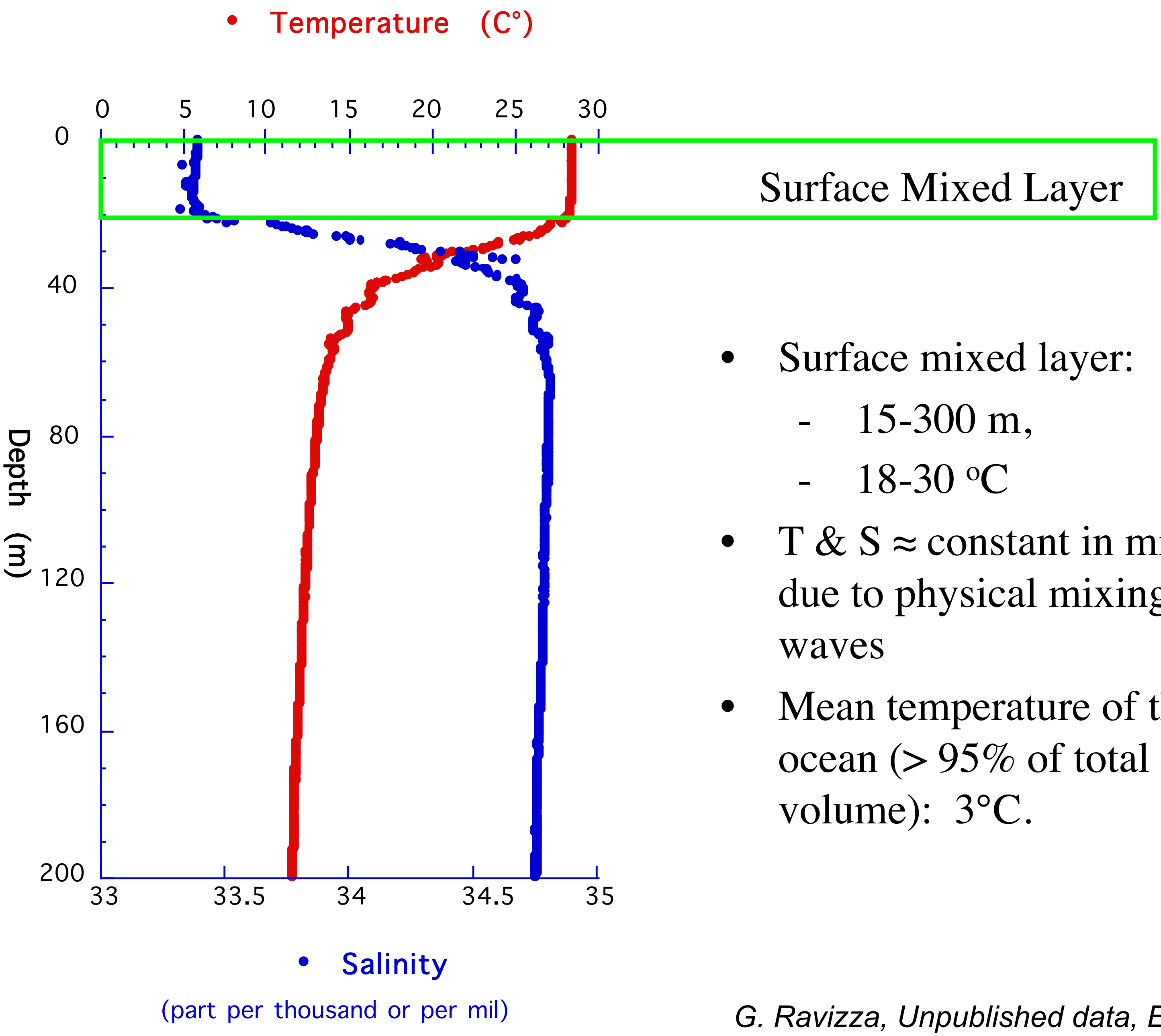
Temperature

- Solar radiation heats the Earth's surface
- Amount absorbed (J cm^{-2} min^{-1}) varies with latitude



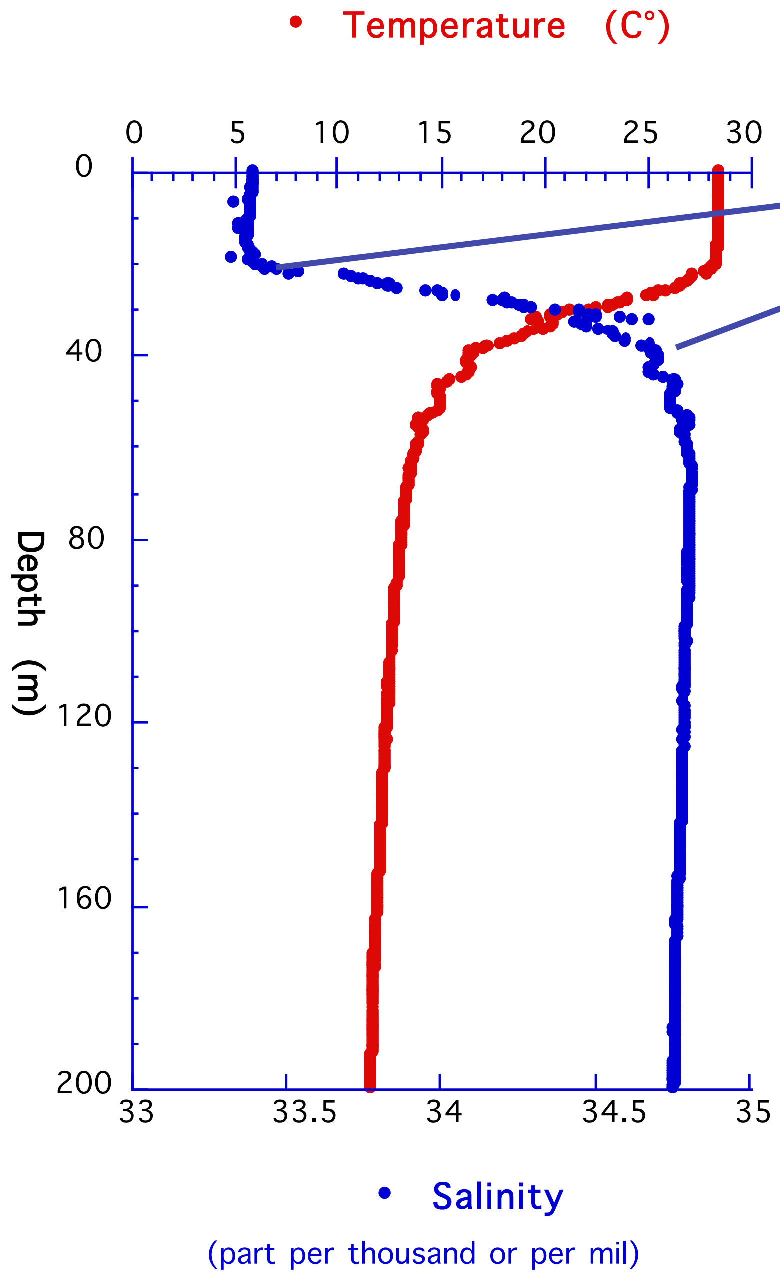
Begon et al. (2006)

Global Circulation Patterns: Stratification



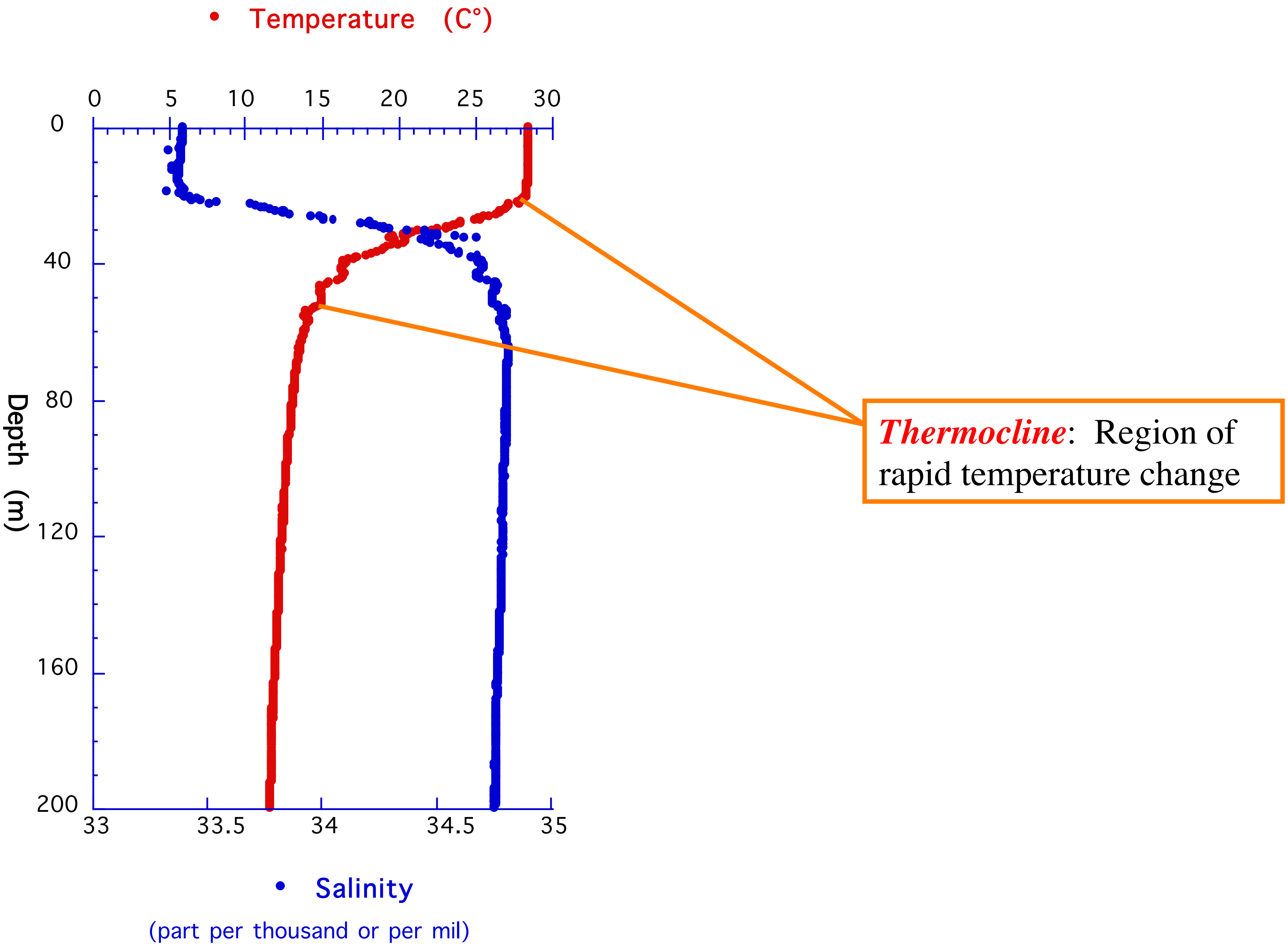
- Surface mixed layer:
  - 15-300 m,
  - 18-30 °C
- T & S ≈ constant in mixed layer due to physical mixing by wind waves
- Mean temperature of the deep ocean (> 95% of total ocean volume): 3°C.

G. Ravizza, Unpublished data, Equatorial. Pacific



Pycnocline or ***halocline:***
region of rapid salinity change

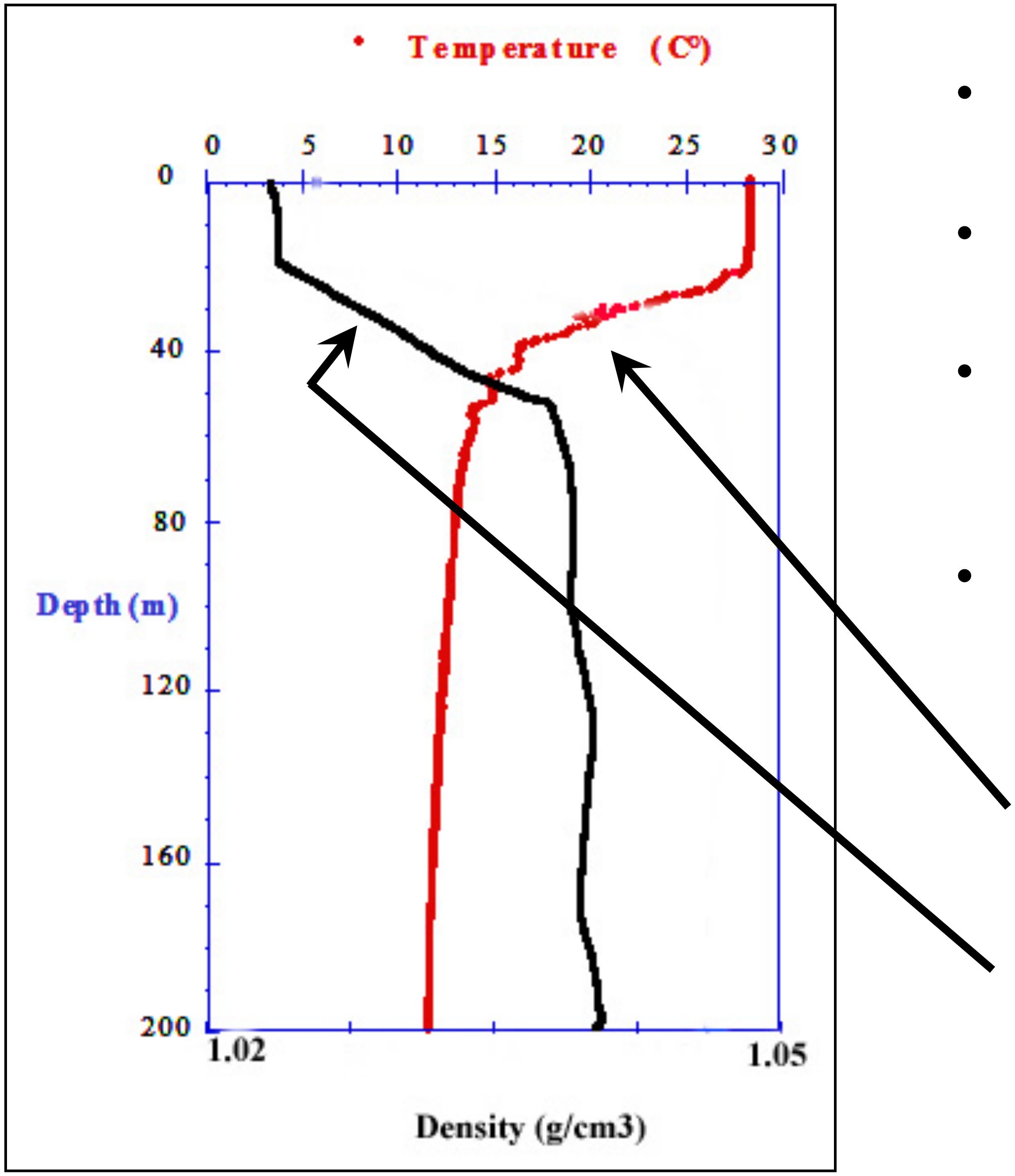
G. Ravizza, Unpublished data, Equatorial. Pacific



Thermocline: Region of rapid temperature change

G. Ravizza, Unpublished data, Equatorial. Pacific

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
- Opposite of atmospheric circulation! (Chap. 3)

- Temperature

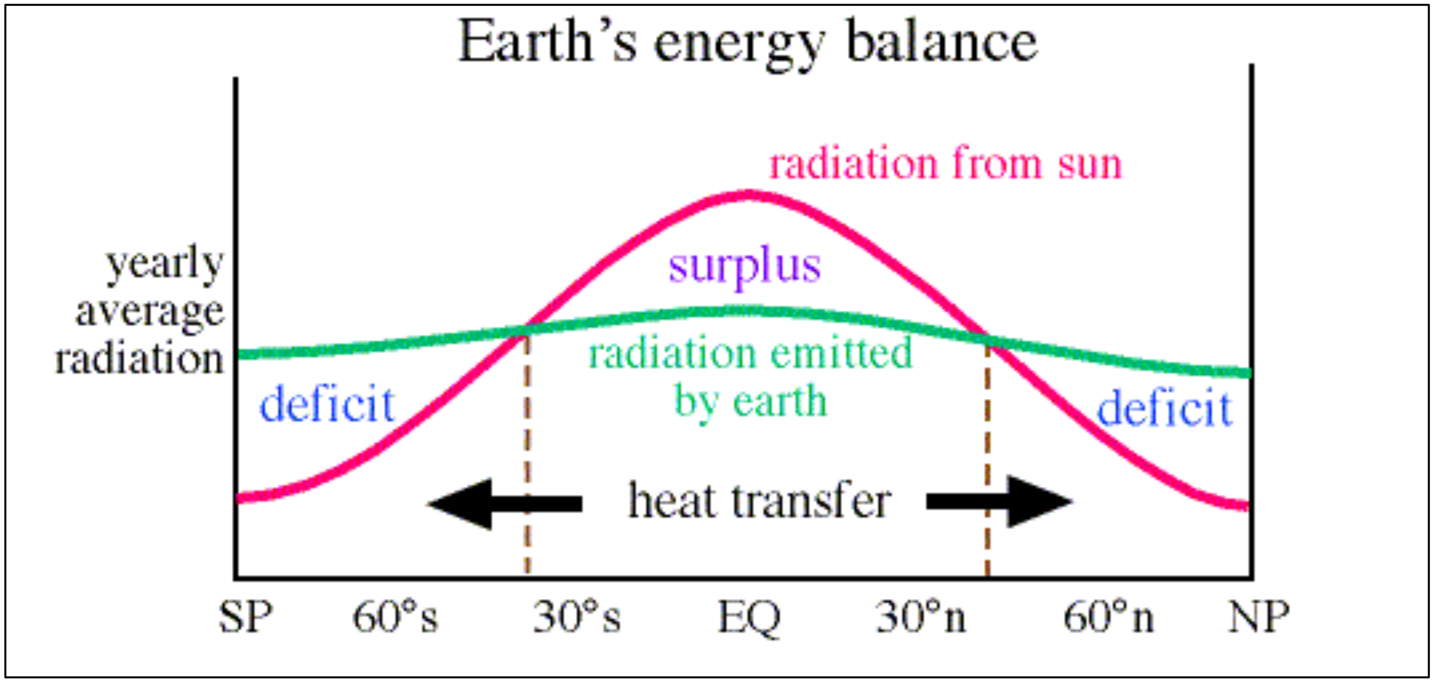
  Thermocline

- Density

  Pycnocline

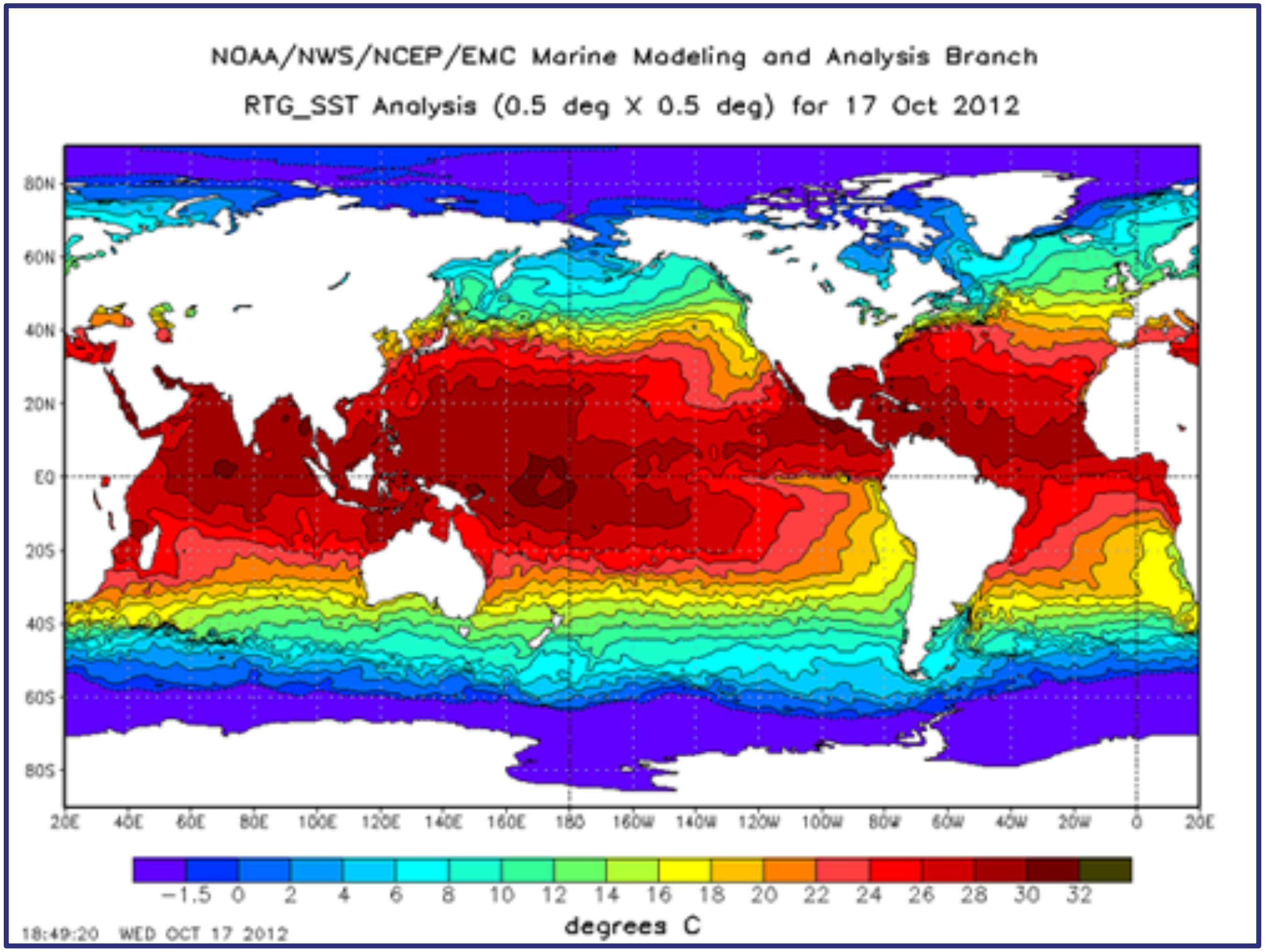
Global energy balance

To maintain a stable average temperature, incident solar energy (annual average) must be balanced by the amount of energy loss to space.



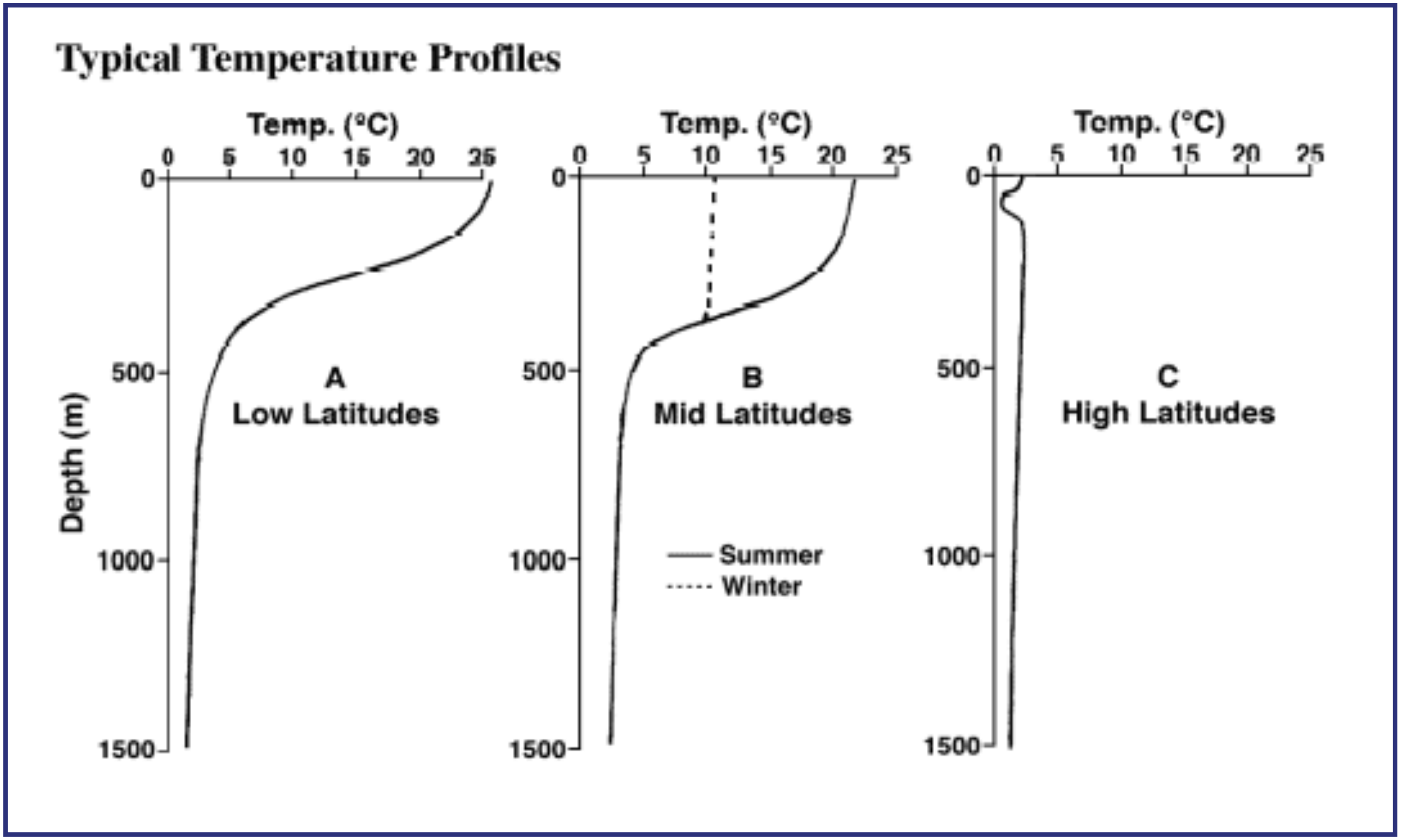
- At high latitudes (near the poles) heat loss > incident solar radiation
- At low latitudes (near the equator) the opposite is true.

Temperature: Latitudinal variation



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

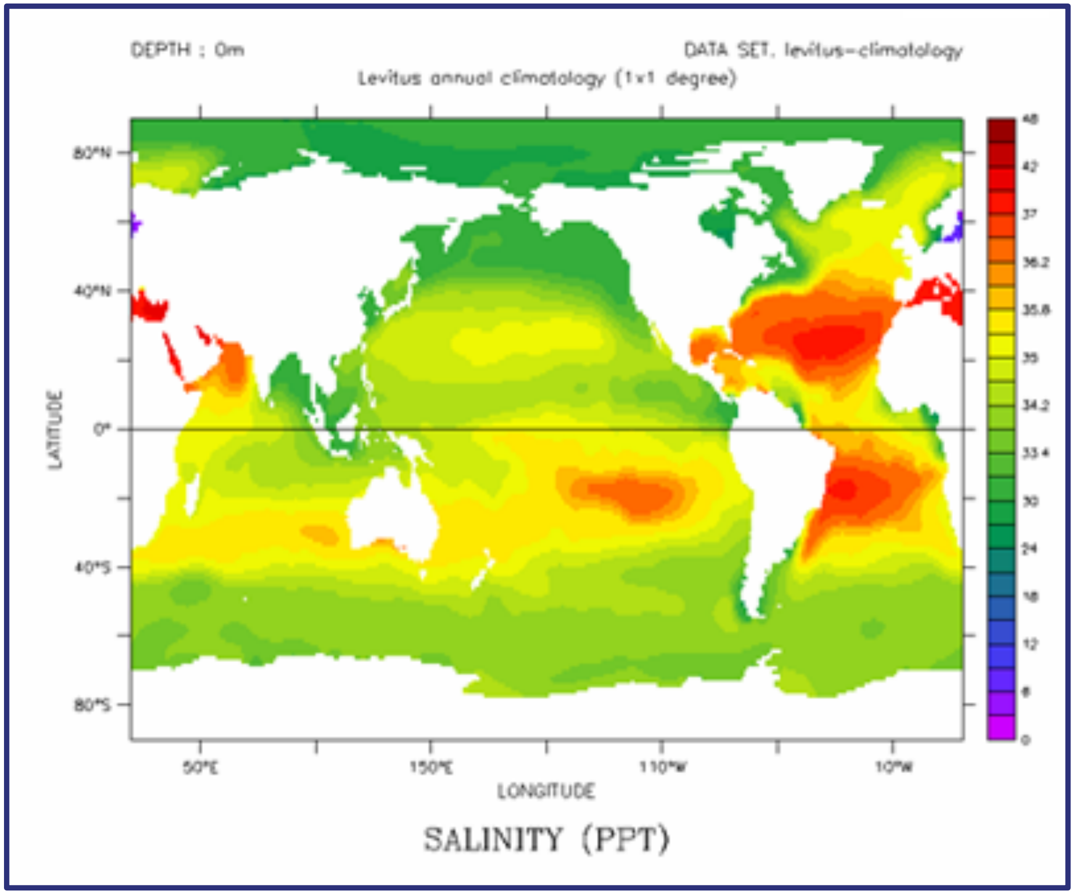
Thermocline Change with Latitude and Season



Earthguide, UCSD

Salinity: Latitudinal variation

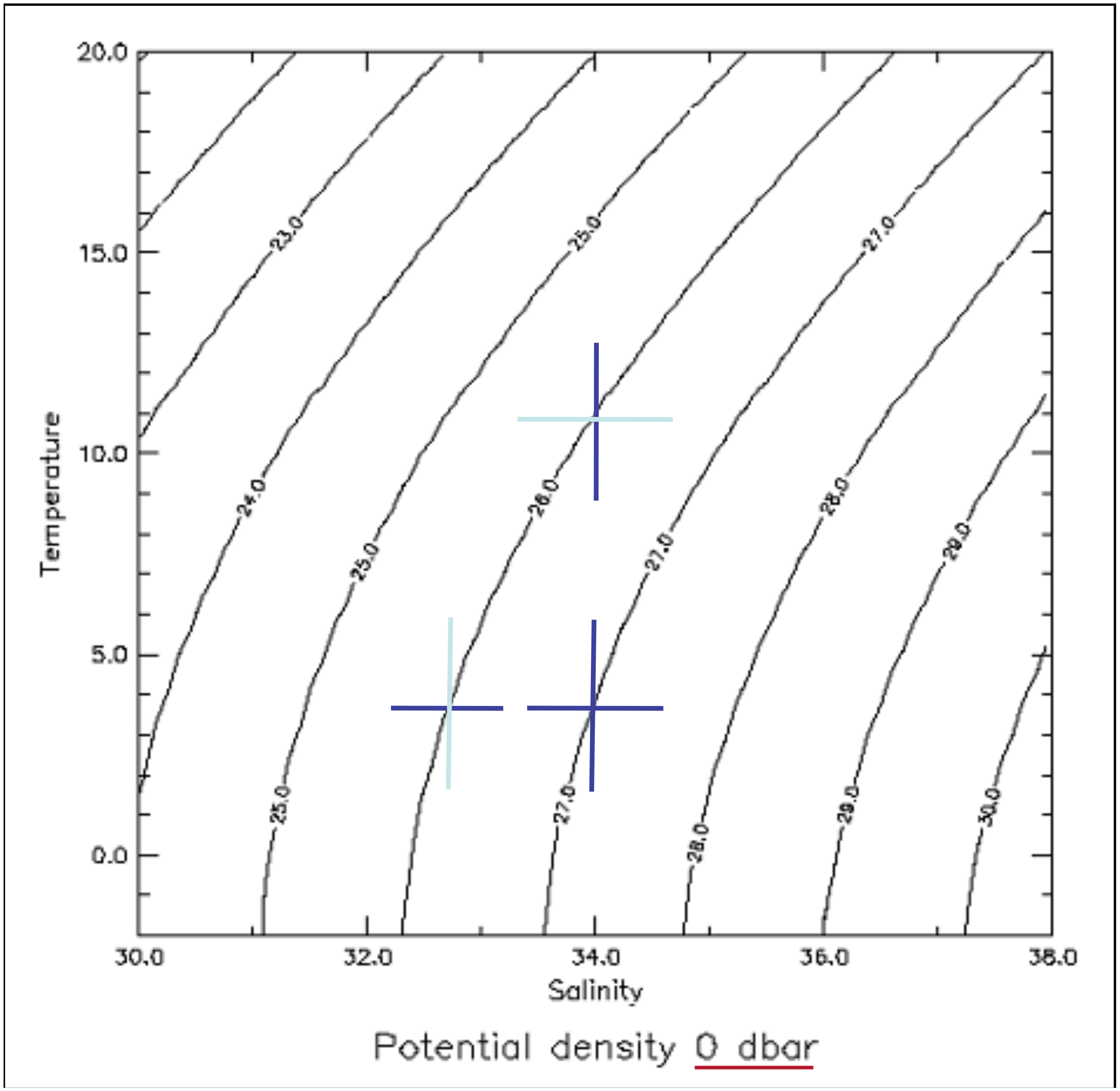
- Source of Salt:
  - continental weathering
  - release of matter from planet's interior



Ferret, NOAA/PMEL

- Average salinity: 35 (≈ 35 ‰ by weight)
- Salinity variations due to imbalance between precipitation and evaporation

Density



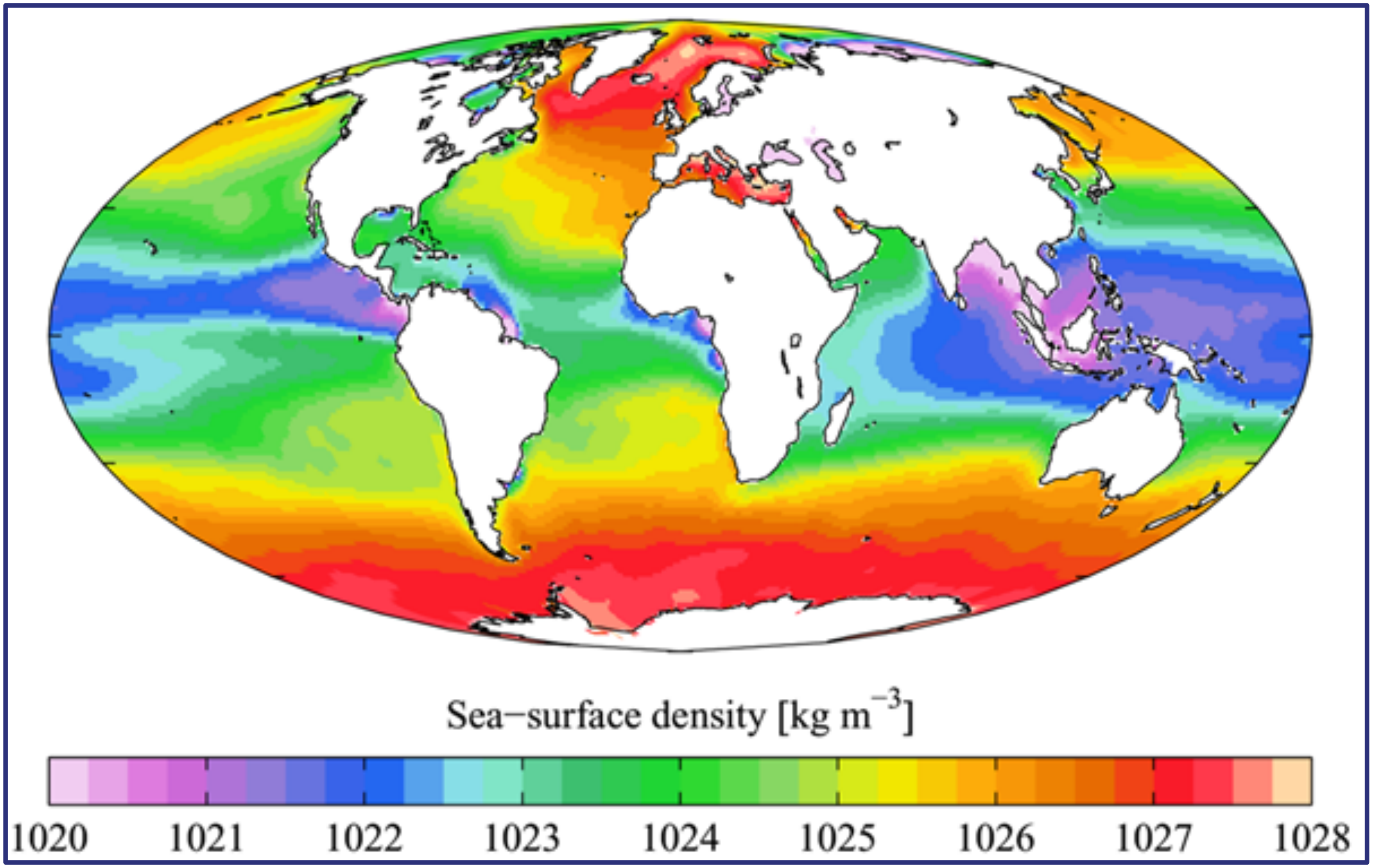
Can calculate the density of seawater if the temperature and salinity of seawater are known.

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, defined as the density anomaly, or Sigma (σ):

σ = density - 1000 kg/m^3

σ is typically 27 kg/m^3 or 27 g/cm^3

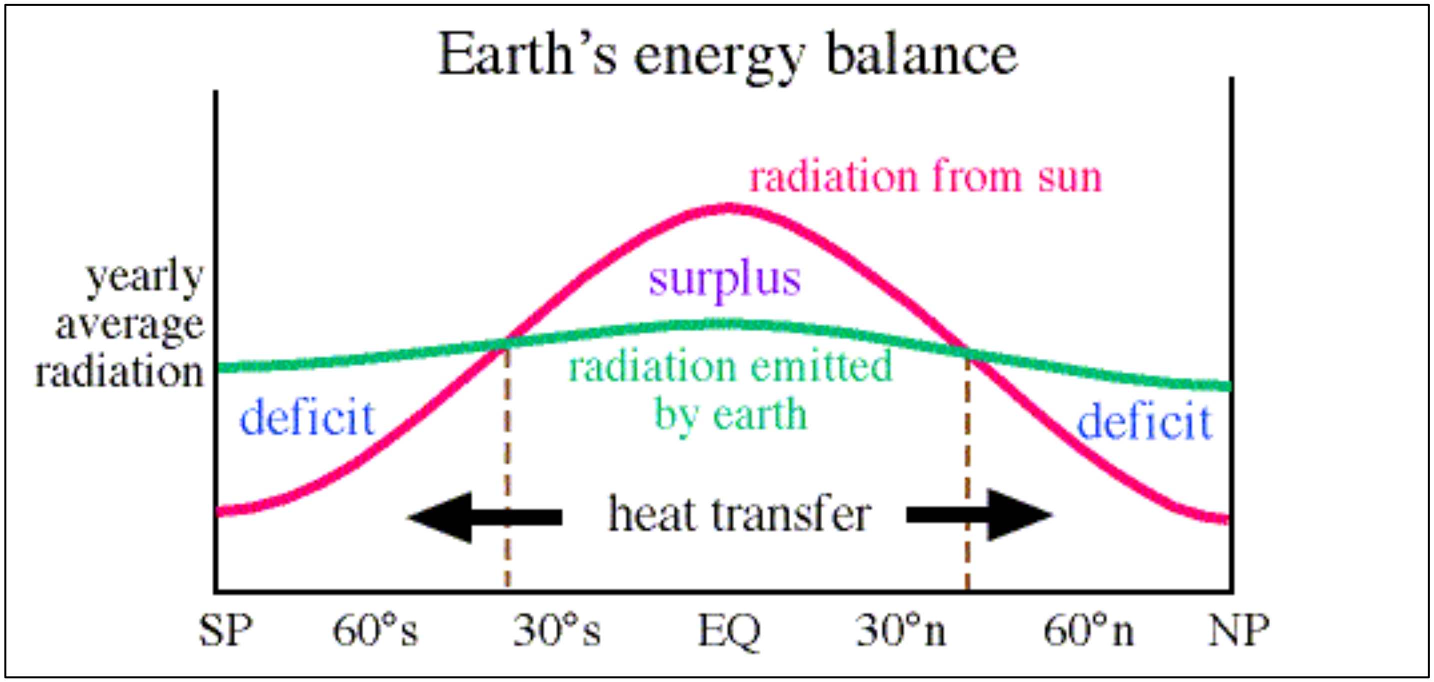
Density: Latitudinal variations



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

Global energy balance

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



Winds

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

- 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 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.

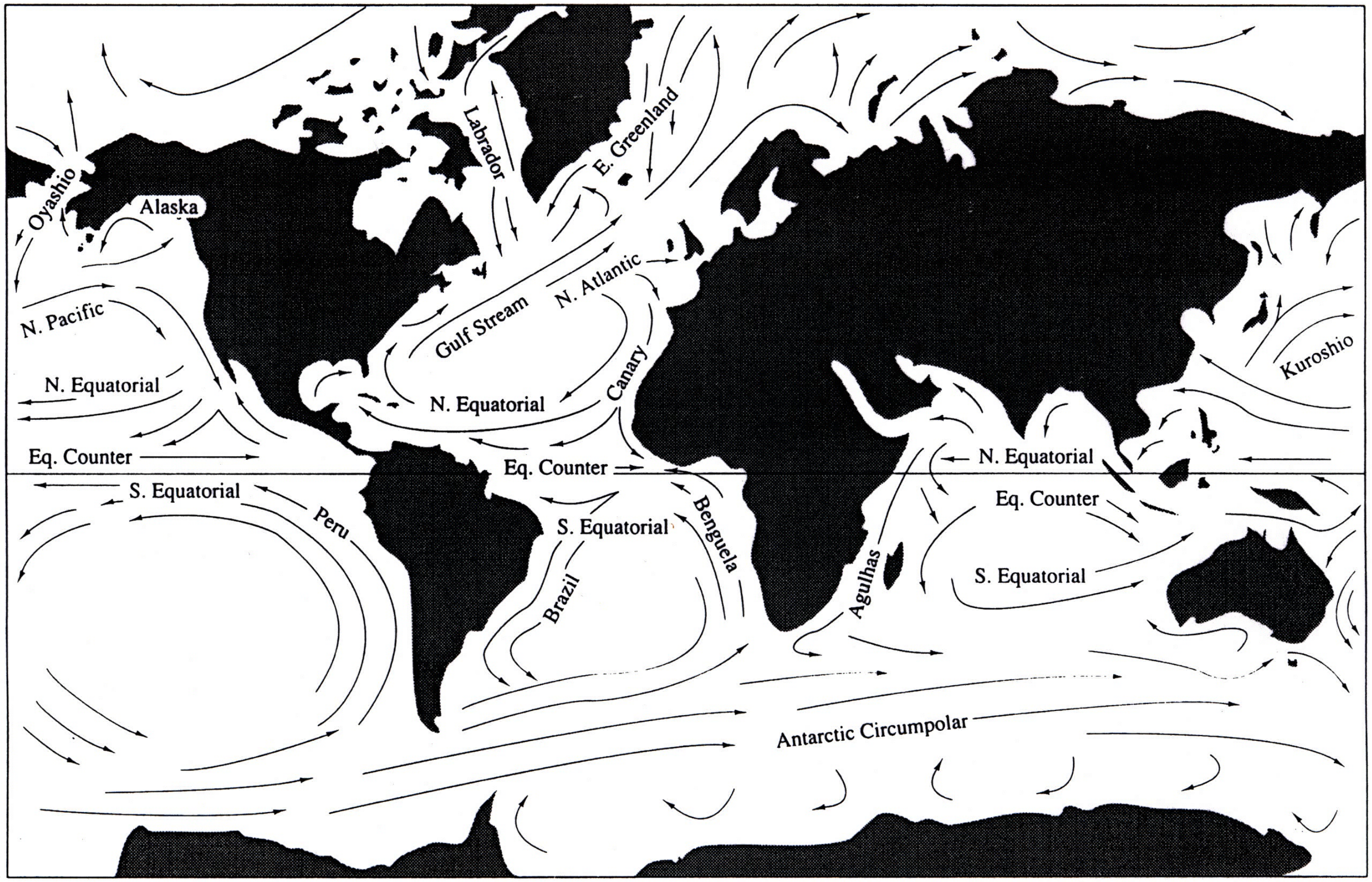


Figure 9.1 Major currents in the surface waters of the world's oceans. From Knauss (1978).

Wind-Driven Surface Water Currents

- 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 *gyres* in each major ocean.

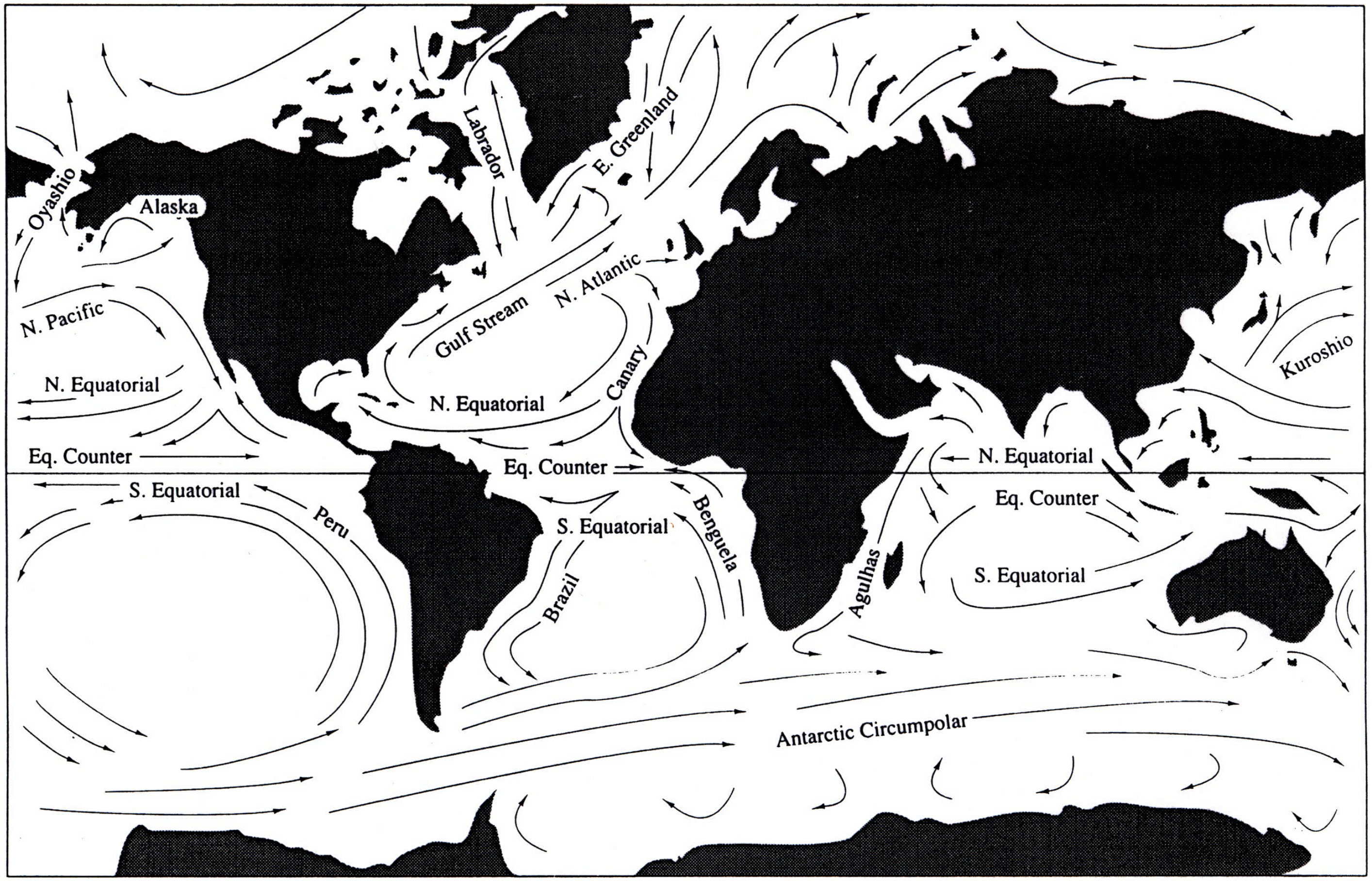
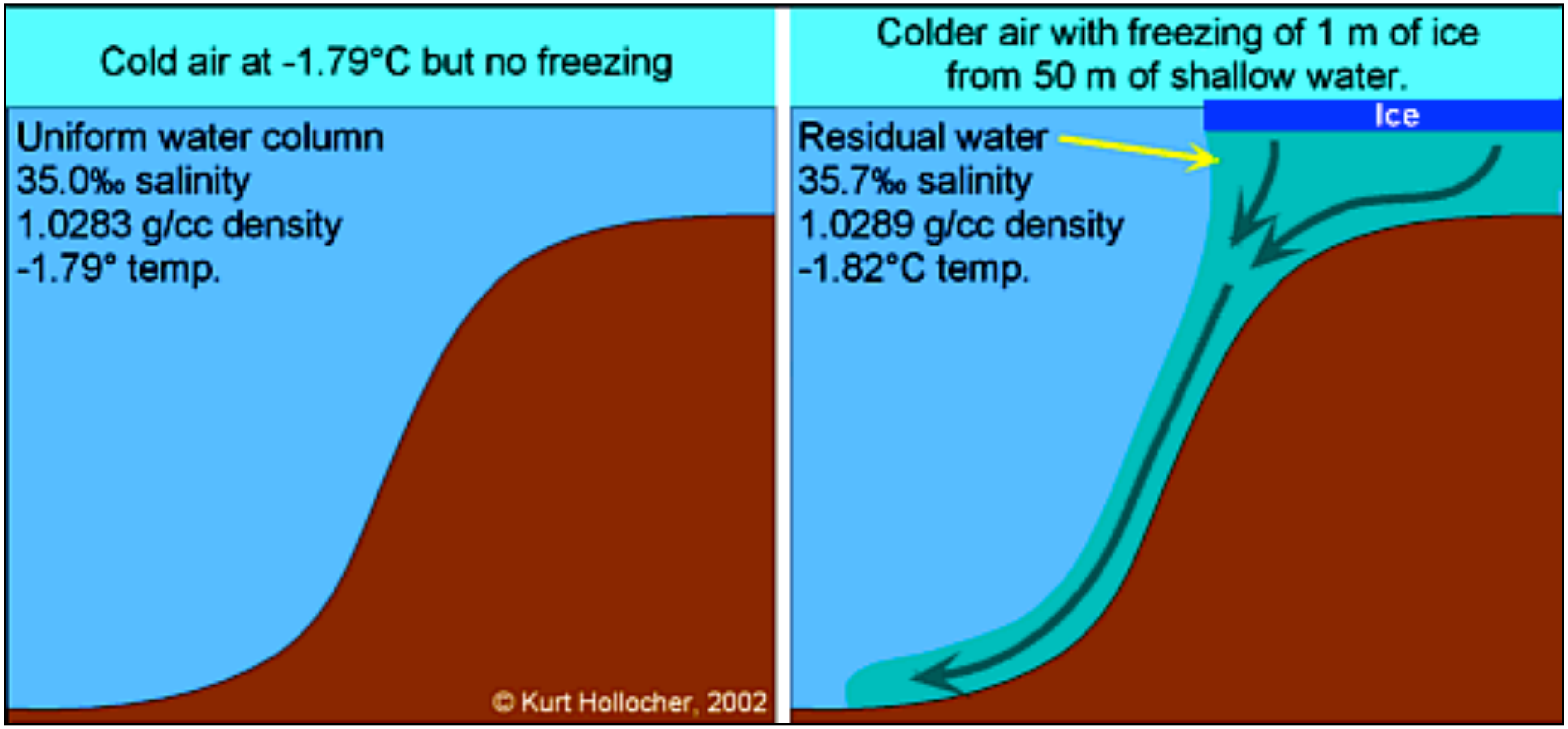


Figure 9.1 Major currents in the surface waters of the world's oceans. From Knauss (1978).

Thermohaline Circulation

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



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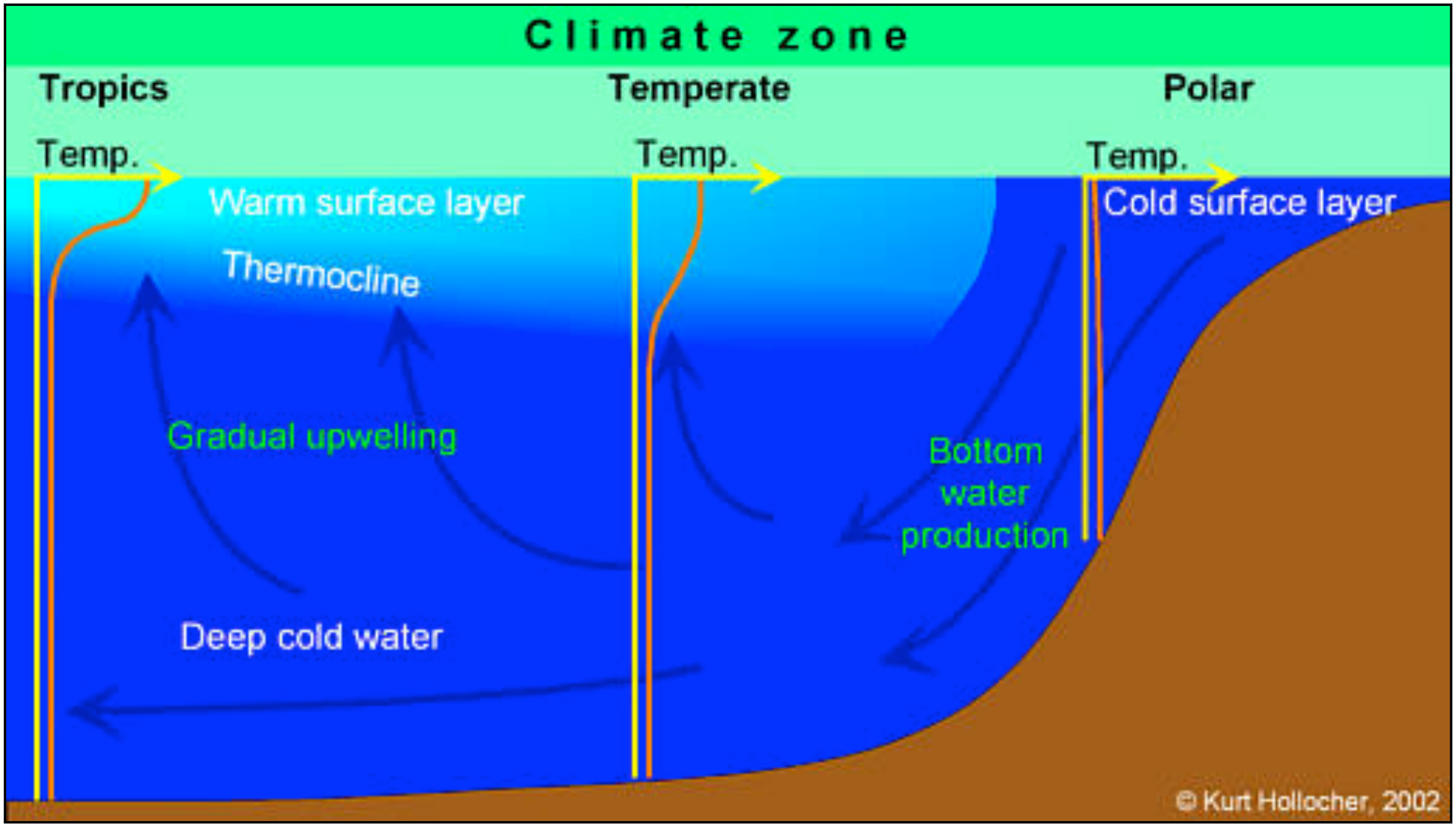
Thermohaline Circulation

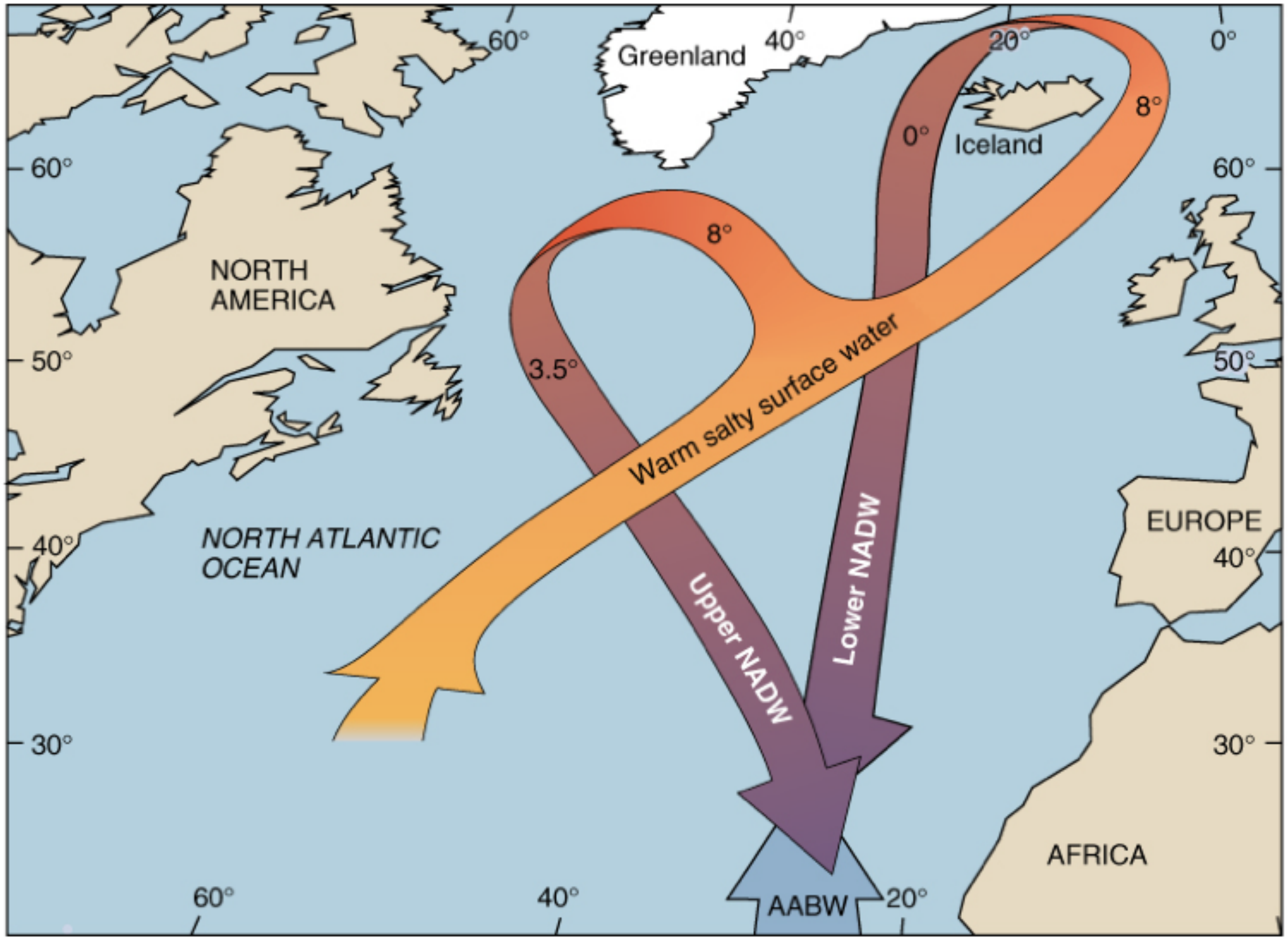
Seasonal *downwelling* of cold polar surface waters is driven both by temperature and salinity: *thermohaline circulation*.



Kurt Hollocher, Union College

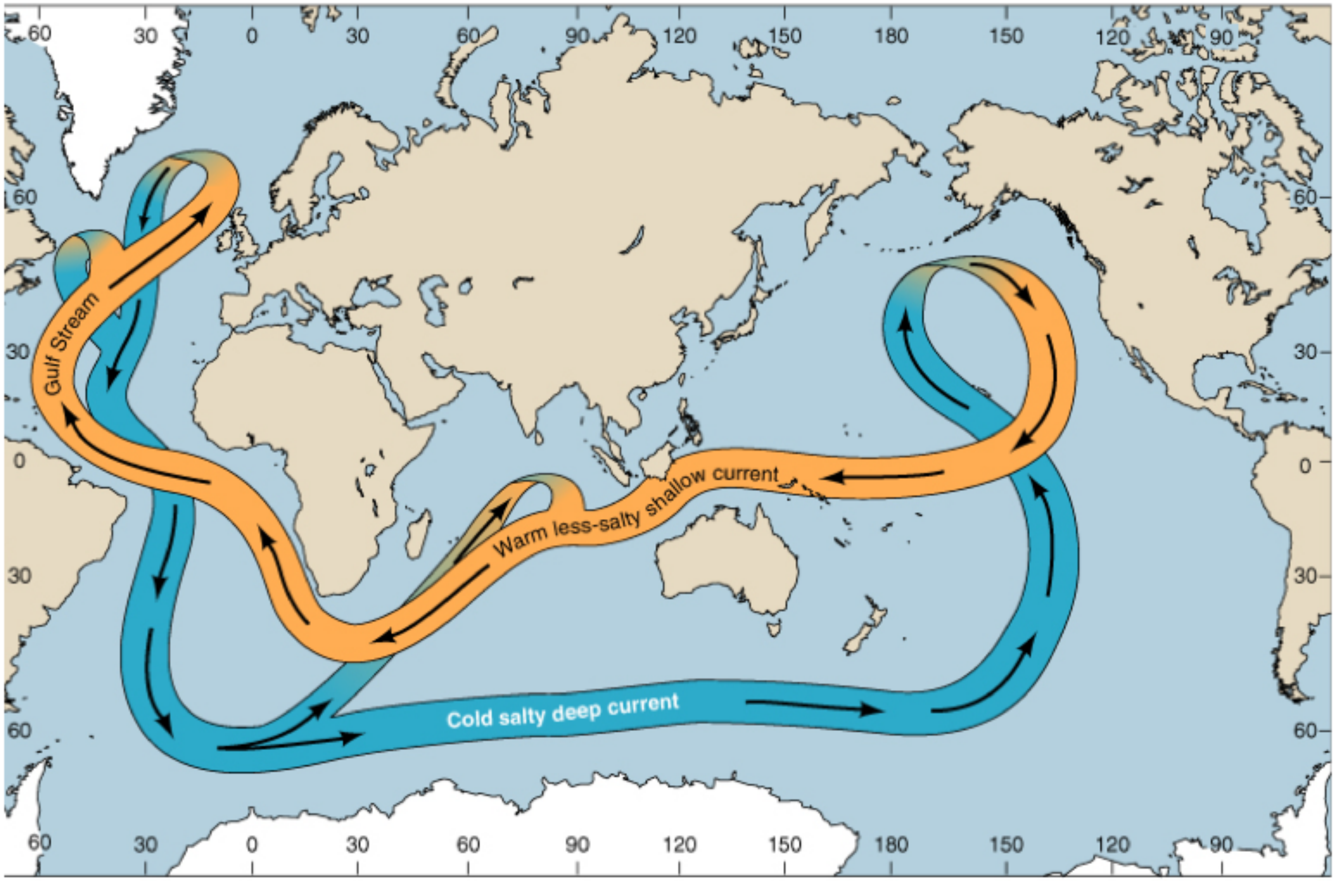
Thermohaline Circulation

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



Thermohaline Circulation: The Global Conveyer 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 in upwelling zones.



Thermohaline circulation and climate change

- Formation of deep waters may be associated with changes in global climate
- For example, 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 CO_2
  - ➢ CO_2 is more soluble in cold waters
  - ➢ Atmospheric CO_2 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 CO_2 to the deep ocean
  - ➢ Allowing warmer conditions to return: *Negative Feedback*

Oceanic Water Residence Times

- *Residence Time* (T_R) = Mass / Flux In = Mass / Flux Out.
- Residence time with respect to river flow:

  T_R = total ocean volume / annual river flow = 3400 years

  - However, most rivers mix only with surface waters, which have T_R =1700 years with respect to river waters.
  - Including rain water and upwelling input to surface waters reduces the T_R even more.

  T_R = surface water volume / (river input + ppt + upwelling input) < 1700 y

- For example, the mean T_R of North Pacific surface waters is *ca*. 9-15 y.
- Surface waters are 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

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

- ^3H_2O 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).

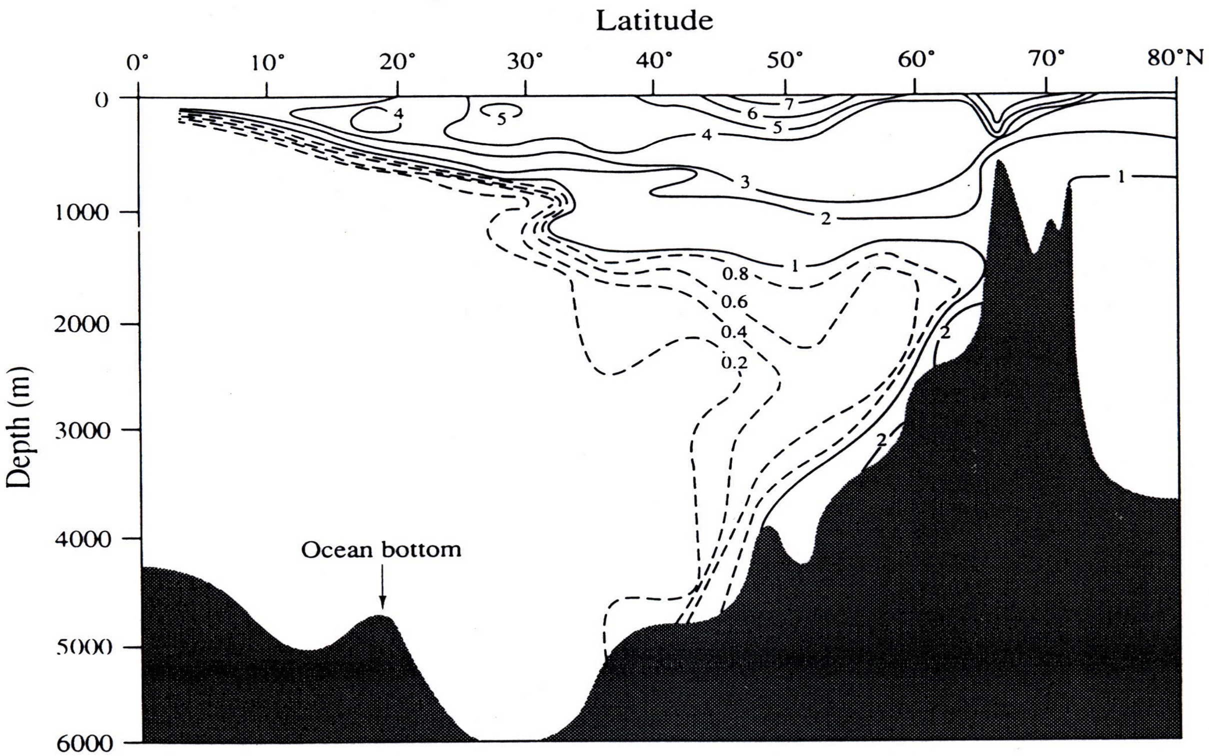


Figure 9.2 Penetration of bomb-derived tritium (^3H_2O) into the North Atlantic Ocean. Data are expressed as the ratio of $^3H/H \times 10^{-18}$ for samples collected in 1972. From Ostlund (1983).

Oceanic Water Residence Times: Implications for Paleoceanography

- 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 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 saltier than Pacific Ocean.
  - Less saline waters are returned to the Atlantic from the Pacific
  - Dense saline waters flow from deep Atlantic to Pacific & Indian Oceans.

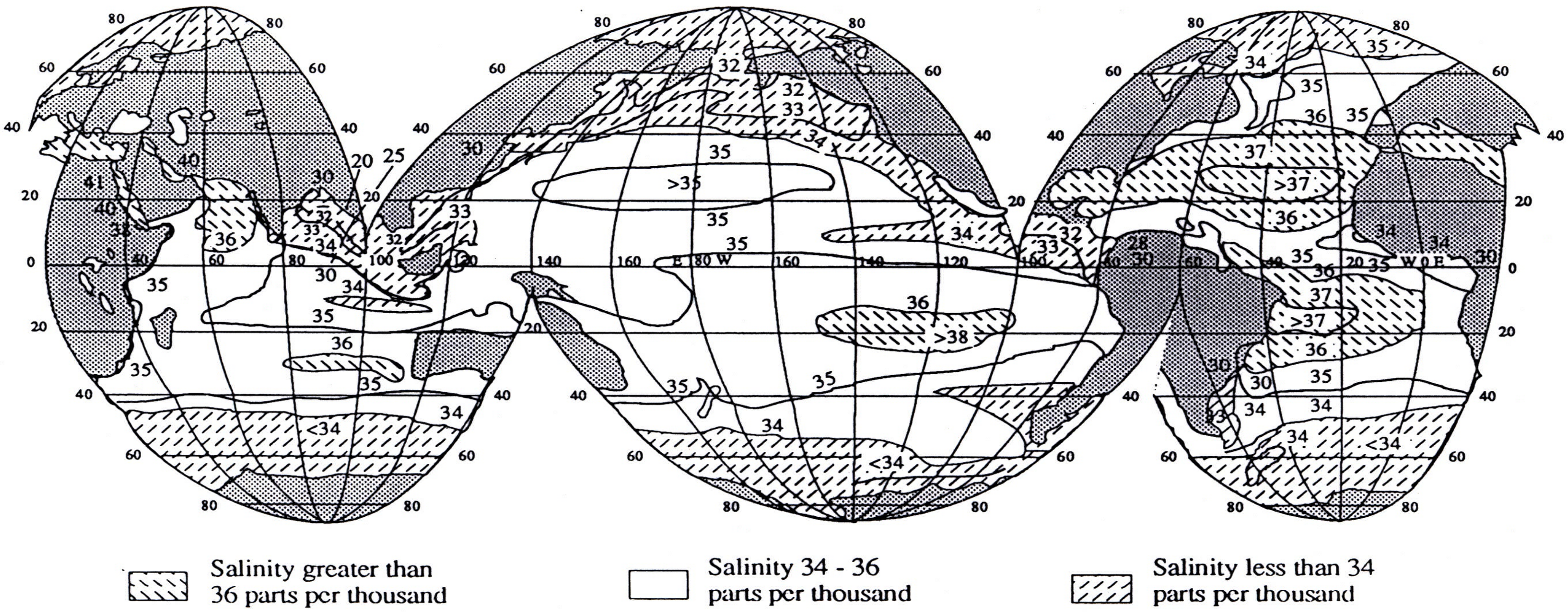
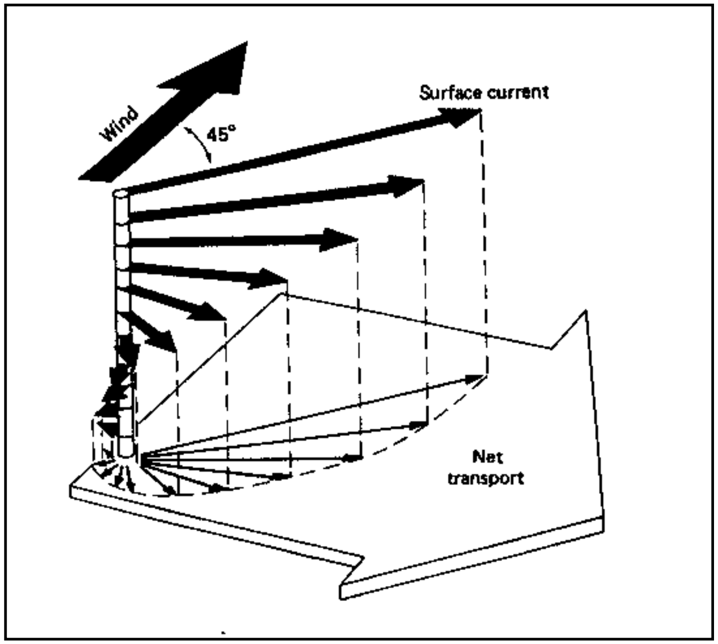


Figure 9.3 Salinity of the surface waters of the world's oceans. From Gross (1977).

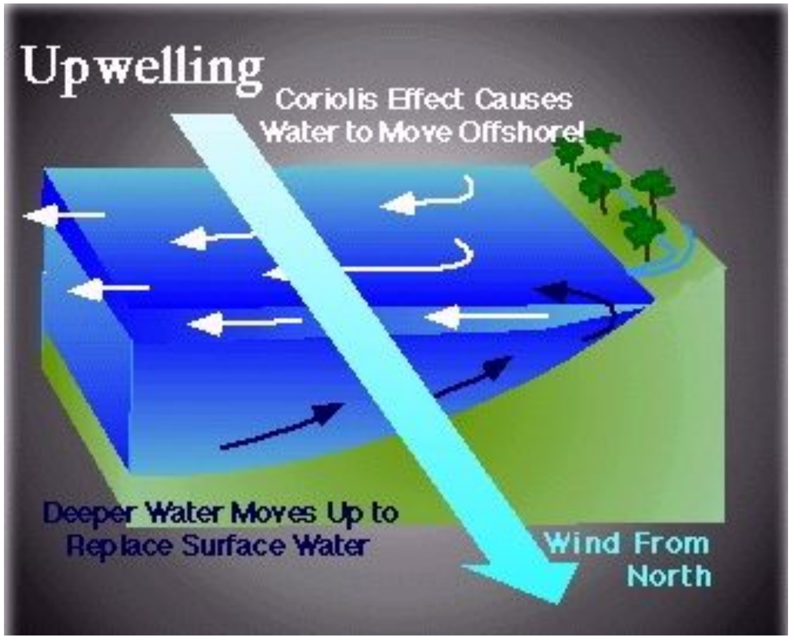
El Niño

- El Niño is one example of shorter time-scale (year-to-year) variations in ocean currents that can affect biogeochemistry and global climate.

- El Niño 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 & N. America.



Shown: Northern Hemisphere



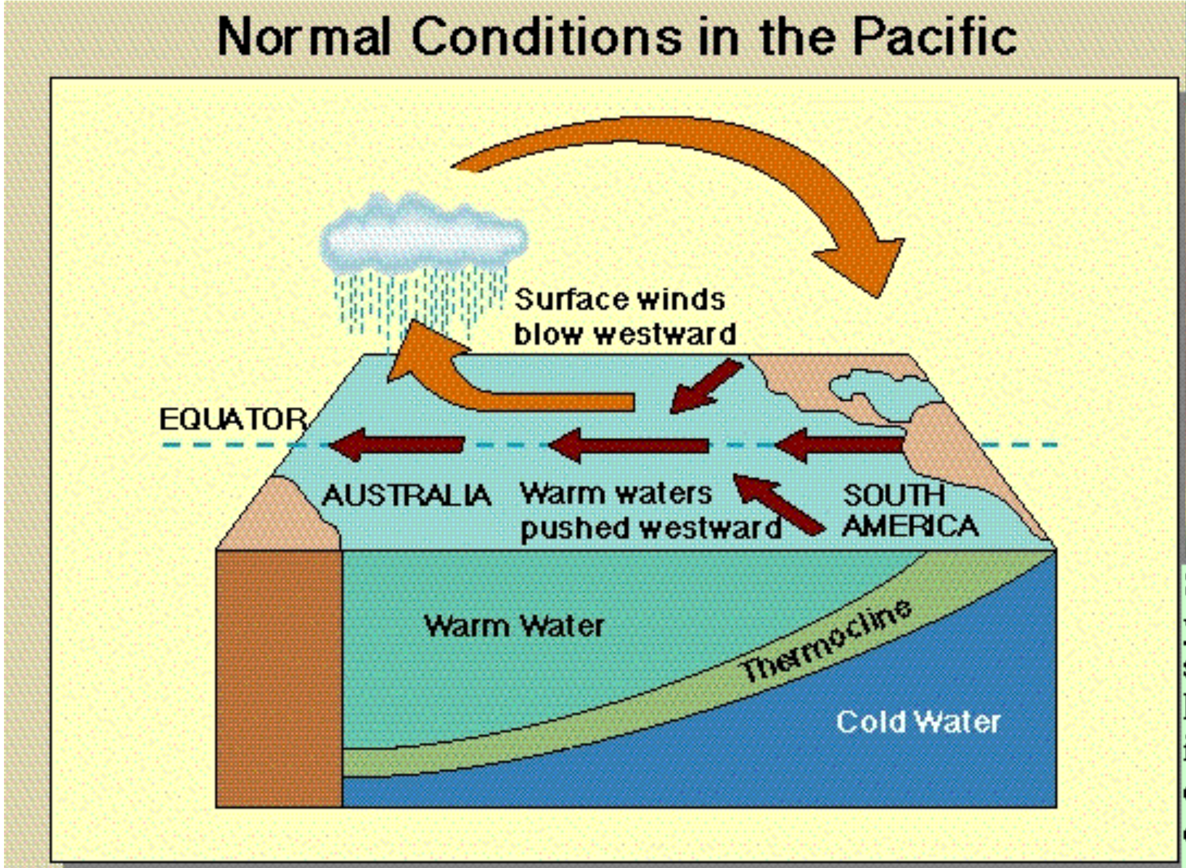
http://www.brookes.ac.uk/geology/sedstruc/upwell/ocean.htm

El Niño

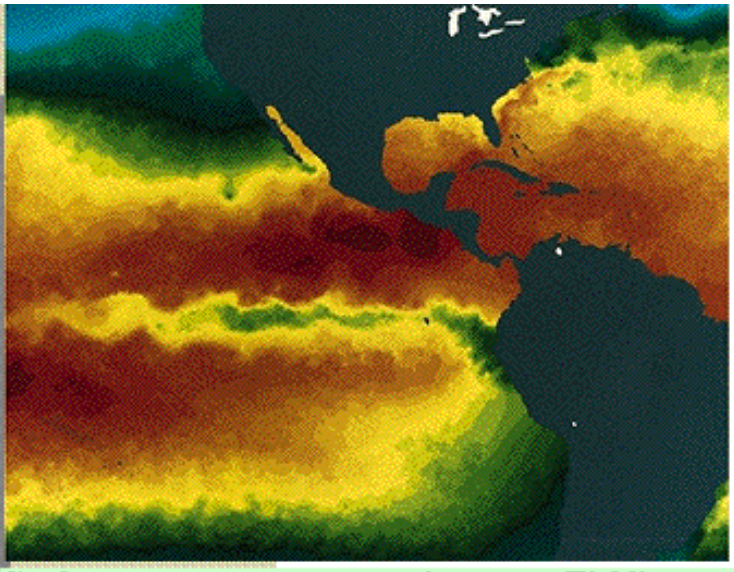
- High nutrients are carried with the deep upwelled waters, fueling phytoplankton growth and important fisheries industries, especially in Peru.

- 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 deep waters; fisheries collapse.



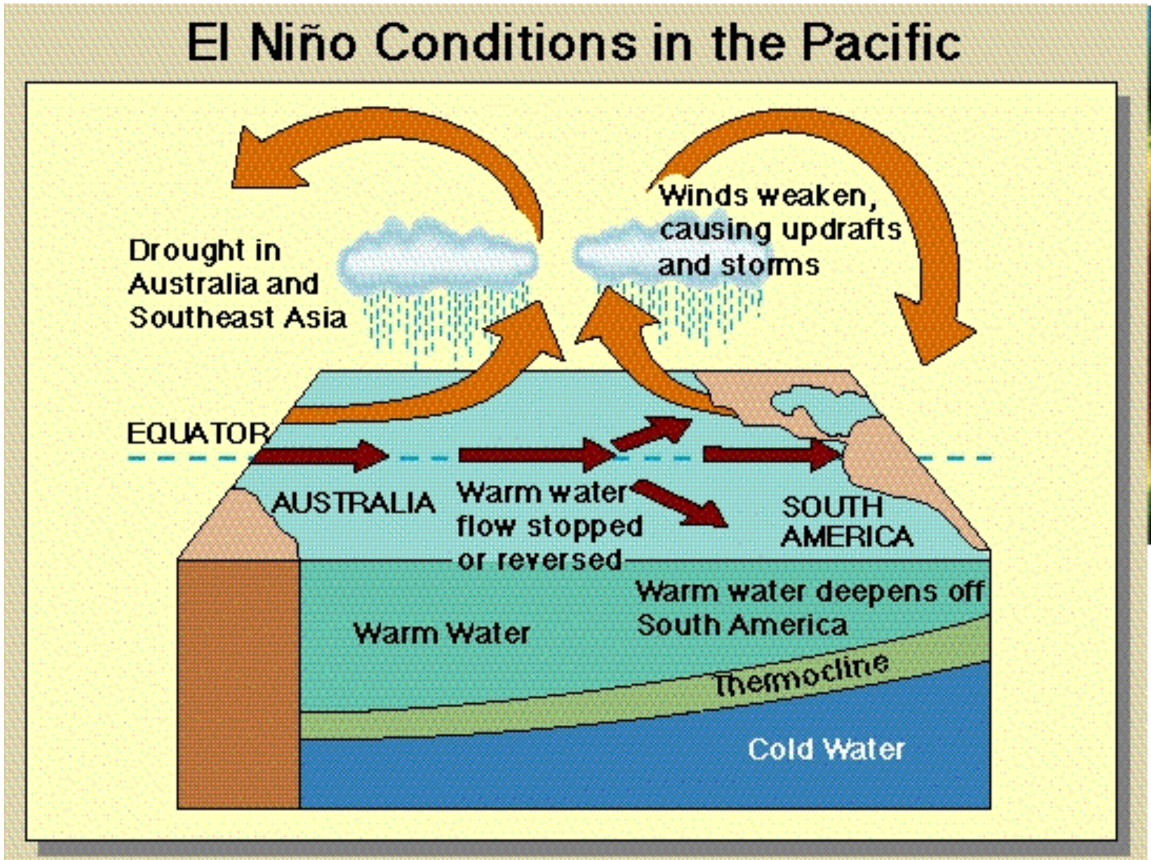
Diagrammatic view of a non-El Niño year. Normally air and surface water flow westward, the thermocline rises, and upwelling of cold water occurs along the west coast of Central and South America.



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.

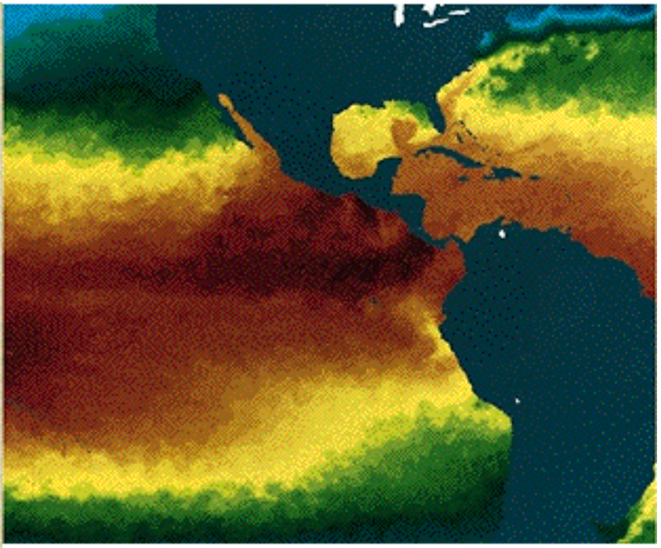
(Figures and figure links listed refer to figures in Garrison, Oceanography: An Invitation to Marine Science 4th Ed.)

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



El Niño Conditions in the Pacific

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.



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.

(Figures and figure links listed refer to figures in Garrison, O<u>ceanography: An Invitation to Marine Science 4th Ed.)</u>

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

El Niño

- Other climatic changes associated with El Niño:
  - exceptionally warm winters and high rainfall in western N. America.
  - absence of warm surface waters in the W. Pac reduces monsoon intensity in S. E. Asia and India.

- El Niño events are part of a cycle, alternating with opposite but equally extreme conditions during non-El Niño years: La Niña conditions.
  - Upwelling of cold, deep waters during La Niña years results in lower atmospheric temperatures over much of the N. hemisphere.
  - The trigger for the switch between El Niño and La Niña is poorly understood.

- Some consequences of the El Niño-La Niña cycles:
  - Add variation to global temperature, making it difficult to perceive atmospheric warming due to the Greenhouse Effect.
  - CO_2 release from cold, upwelled waters is lower during El Niño years, affects atmospheric CO_2.
  - Denitrification rates 25% lower during El Niño years.

Seawater Composition: Major Ions

- T_R for major ions >>> T_R for water in the oceans $\longrightarrow$ uniform distribution
- Major ions are *conservative*; maintain the same ratio to each other throughout oceanic waters, even if salinity changes

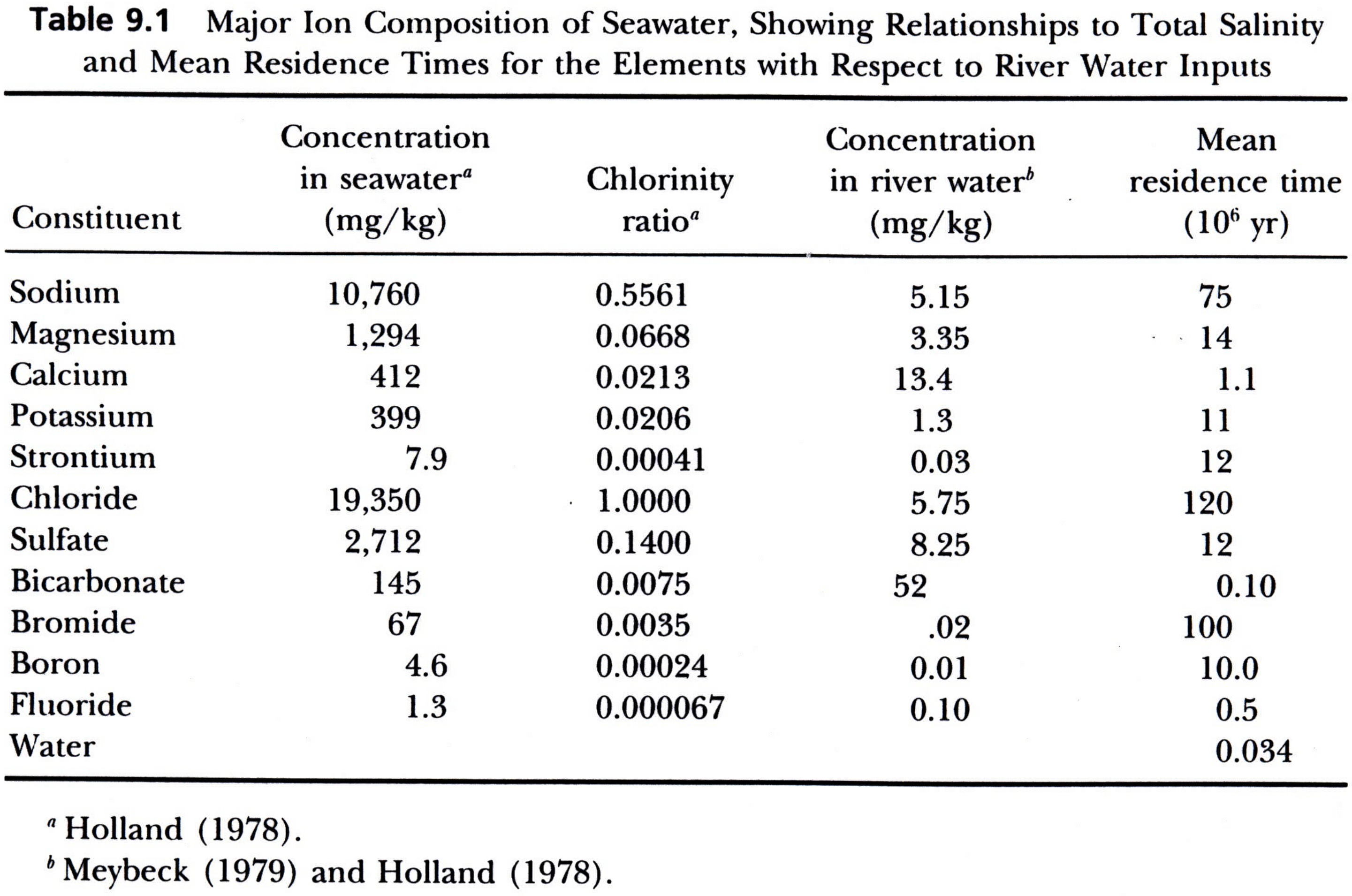


Table 9.1 Major Ion Composition of Seawater, Showing Relationships to Total Salinity and Mean Residence Times for the Elements with Respect to River Water Inputs

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

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

salinity ‰ = 1.81 (Chloride ‰), where ‰ = parts per thousand (ppt)
= 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.

-This requires processes that remove ions from the oceans to balance new riverine inputs.

- Residence times for major elements 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 $CaCO_3$, 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 of seawater ions (Chap. 3)
  - A significant portion of river-transported Cl^- derives from these aerosols, returning them to the sea → *cyclic seasalts*.
  - Removes ions in proportion to their concentration in seawater.

- **Ion Exchange on River-borne Clays Entering the Ocean**

  - Most 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).
  - Deposition onto the seafloor removes these ions from seawater.

- **Burial** of dissolved ions (particularly Na^+ &Cl^-) in sediment pore waters.

- **Deposition** of biogenic $CaCO_3$ major sink of Ca^{2+} from seawater.

Ion Remove Processes (cont'd.)

- **Biogenic removal** of S and Fe resulting from sulfate reduction and formation of pyrite (FeS_2), a secondary, *authigenic* mineral.

- **Evaporites** (salt flats, sabkhas)

  - In the geologic past, vast deposits of evaporite minerals formed when seawater evaporated from shallow, enclosed basins.
  - Although limited in areal extent, this process has been important 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**

  - Particularly important for Mg^{2+} (Mg-silicate formation) and SO_4^{2-}.

Mean Seawater T_R correlates with Solubility

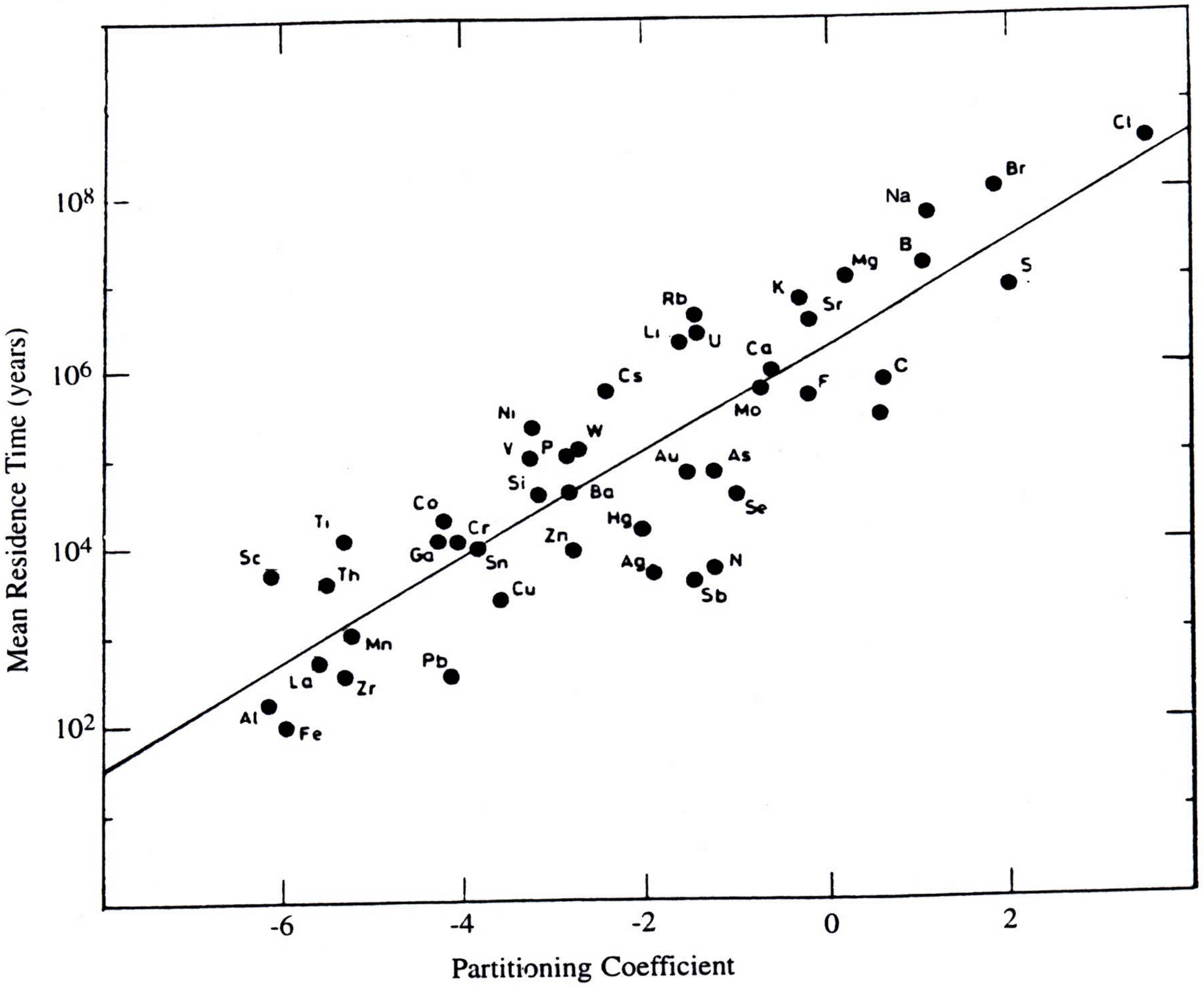


Figure 9.4 Mean residence time of elements in seawater as a function of their concentration in seawater divided by their mean concentration in the Earth's crust—with high values of the index indicating elements that are very soluble. From Whitfield and Turner (1979).

Partition Coefficient Definition:

$K_D = C_{diss} / C_{part}$

From Rivers lecture: $K_D = C_{part} / C_{diss}$

Comparison of Dissolved and Suspended fluxes in Rivers

Element	Dissolved Flux	Particulate Flux	Part:Diss
	10^6 t/yr	10^6 t/yr	
Al	2	1457	729
Ca	501	333	0.7
Fe	1.5	744	496
K	49	310	6
Mg	125	183	1.5
Na	193	110	0.6
Si	181	4418	24
P	1	18	18

Considerable variation among chemical species

Summary of Major Removal Processes & Fate of Ions

- **Summary of Removal Processes:**
  - Most Na^+ and Cl^- are removed in pore water burial, sea spray, and in evaporitic 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.

- **Ultimate Fate of Sequestered Ions:**
  - Eventually, 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

- Stable water column stratification results from temperature and salinity differences between surface and deep water; reduction of this contrast in high latitudes leads to *isopycnal* mixing and deep water formation.

- *Thermohaline circulation* driven by *downwelling* of cold, dense surface water at high latitudes forming deep waters; transport of deep water equator-ward counter-balanced by flow of warm surface waters from equator to pole.

- Thermohaline circulation: an important mechanism for redistributing heat energy on Earth's surface.

- Wind driven surface currents drive formation of *central 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 reflects how much time an element spends in the ocean before removal, range: <100 y to >100 Ma

- T_R indicates relative reactivity of elements, i.e. efficacy of removal processes.