Lecture 15

Guest Lecturer this week. Prof. Greg Ravizza

- The Hydrosphere and The Hydrologic Cycle – *some of this lecture should be review so we will go through it quickly*

Please read chapter 1 and chapter 3 (pages 62-86 &116-119) of Berner and Berner, “Global Environment“ for this week. A single photocopy is available outside ken’s office. Please don’t remove it for more than 3-4 hrs. so everyone has a chance to access it

Water is possibly the most important compound on Earth.

As it cycles around Earth, it interacts with every other "sphere"

(geosphere, atmosphere, biosphere, etc..)

Water cycling in the hydrologic cycle effectively transports a wide array of both essential and hazardous chemicals.

Where is all the water on Earth?

Almost all H_2O on Earth is in the oceans, with ice sheets and glaciers pulling a very distant second. The fresh water we use to nourish the world's human population is in reservoirs that amount to <0.5% of the hydrosphere!

From Faure "Inorganic Geochemistry"

Table 10.8 Inventory of Water in the Hydrosphere

Reservoir	*Volume, 10^6 km^3*	*Percent of Total*
Oceans	1370	97.25
Icesheets and glaciers	29	2.05
Deep groundwater (750-4000 m)	5.3	0.38
Shallow groundwater (<750 m)	4.2	0.3
Lakes	0.125	0.01
Soil Moisture	0.065	0.005
Atmosphere*	0.013	0.001
Rivers	0.0017	0.0001
Biosphere	0.0006	0.00004
Total	1408.7	100

* Liquid equivalent of water vapor.
SOURCE: Berner and Berner (1987)

From Berner and Berner (1996) "Global Environment"

TABLE 1.1 Inventory of Water at the Earth's Surface

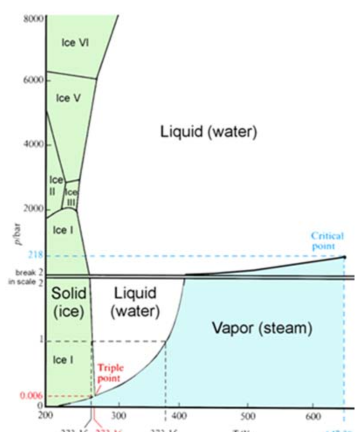
Reservoir	Volume, 106 km^3 (10^{18} kg)	Percent of Total
Oceans	1400.	95.96
Mixed layer	50.	
Thermocline	460.	
Abyssal	890.	
Ice caps and glaciers	43.4	2.97
Groundwater	15.3	1.05
Lakes	0.125	0.009
Rivers	0.00017	0.0001
Soil Moisture	0.065	0.0045
Atmosphere total[a]	0.0155	0.001
Terrestrial	0.0045	
Oceanic	0.0110	
Biosphere	0.00200	0.00010
Total	1459	

Sources: NRC 1986; Berner and Berner, 1987
[a]As liquid volume equivalent of water vapor

Notice that *both tables cite the same data source* (Berner and Berner, 1987), yet they give different total volumes of water in the hydrosphere and some of its sub-reservoirs.

For instance, groundwater, the atmosphere and the biosphere all contain less water in the "Faure" version than in the "Berner and Berner" version. This is due to slightly different reading of the same data by each.

The Specialness of Water



1. The H_2O phase diagram allows all three forms of water to exist on Earth.

Energy variations on Earth set up a cycle of evaporation/ condensing/freezing/ thawing which helps drives the hydrologic cycle.

2. Liquid H_2O is a low-viscosity, polar solvent that stabilizes almost all polar solutes (i.e., inorganic ions) as well as only slightly polar ones (i.e., many *substituted organic compounds*).

Note: a substituted organic compound is one that contains more than just C and H; it also contains O, N, P and/or S).

Other important properties of water:

Table 3.1 Important Properties of Water

Property	Effects and Significance
Excellent Solvent	Transport of nutrients and waste products, making biological processes possible in aqueous medium
Highest dielectric constant of any common liquid	High solubility of ionic substances and their ionization in solution
Higher surface tension than any other liquid	Controlling factor in physiology; governs drop and surface phenomena
Transparent to visible and longer-wavelength fraction of ultraviolet light	Colorless, allowing light required for photosynthesis to reach considerable depths in bodies of water
Maximum density as a liquid at 4°C	Ice floats; vertical circulation restricted in stratified bodies of water
Higher heat of evaporation than any other material	Determines transfer of heat and water molecules between the atmosphere and bodies of water
Higher latent heat of fusion than any other liquid except ammonia	Temperature stabilized at the freezing point of water
Higher heat capacity than any other liquid except ammonia	Stabilization of temperatures of organisms and geographical regions

The hydrologic Cycle - Review

Most broadly defined as all locales on Earth where we find solid, gaseous or liquid H_2O.

H_2O in the Earth's interior is isolated from the rest of this "sphere" for many millions of years, so the ***hydrologic cycle*** is typically defined as an exogenic one.

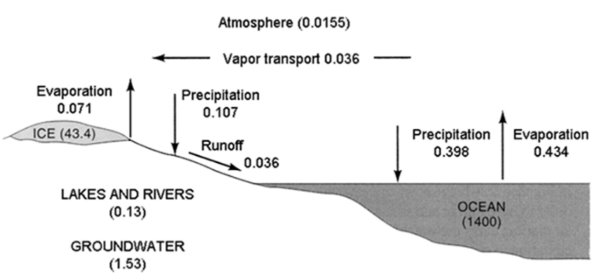


Figure 1.1 The Hydrologic cycle. Numbers in parenthesis represent inventories (in 10^6 km^3 = 10^{18} kg) for each reservoir. Fluxes are in 10^6 km^3/yr (10^{18} kg/yr). (Data from Table 1.1 and NRC 1986.)

Source: Berner and Berner, "Global Environment" (1996) Prentice Hall

Units: Reservoirs (10^6 km^3) and fluxes (10^6 km^3 per year)

Reservoirs of the hydrologic Cycle

The *complete exogenic* cycle for water on Earth involves exchanges between these reservoirs (plus the biosphere)

Reservoir	"Type"
super-surface	
gas (water vapor) liquid (droplets) solid (ice)	atmosphere
surface water:	
oceans	Geographically fixed "Holding Tanks"
lakes	Holding Tanks
rivers, streams	"Migrating reservoirs" (follows land topography and/or internal structure)
estuaries	Migrating reservoirs
glaciers	Migrating reservoirs
sub-surface water:	
groundwater	Migrating reservoirs

Water takes on variable compositions as a function of how long it stays in a reservoir and how well mixed it is.

The Residence Time Concept

How long water spends in a holding tank largely affects it's composition. We use *Residence Time* to quantify such times.

Residence time (τ):

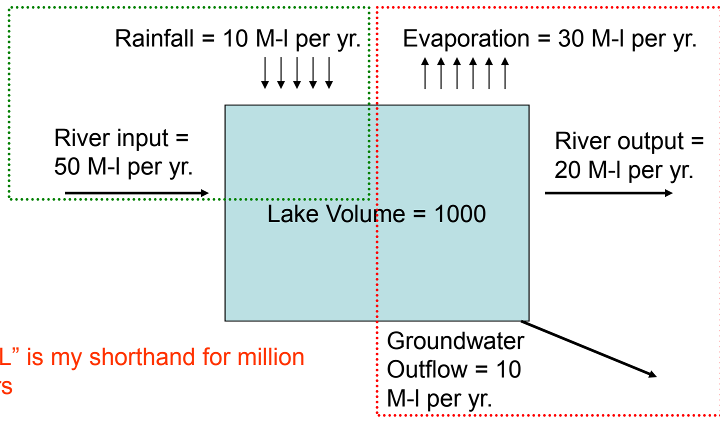
$[A]_{reservoir}$/ Flux$(A)_{in\ or\ out}$. -or- $[A]_{reservoir}/(\delta A/\delta t)$

τ is defined rigorously only for steady-state but is a useful concept for some non-steady-state conditions too.

Steady- state means the flux in = flux out of species A.

Then the reservoir size of species A ("[A]") is constant.

Let's use the reservoir and flux convention to investigate the residence time for a hypothetical holding tank reservoir, *lake Clearandfresh*



"M-L" is my shorthand for million liters

Note: Reservoir Size = Lake Volume = 1 billion liters.
Arrows depict **Fluxes.**

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Is the volume of the lake changing?

Table of average annual water fluxes in M-l/year for Lake clearandfresh

	Inputs		Outputs
River inflow	50	River Outflow	20
Rain fall	10	Groundwater Outflow	10
		Evaporation	30
Total In	60	Total Out	60

No. The volume of the lake is constant because inputs = outputs. So this lake is at Steady-State

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Calculation:
the residence time of water in the lake would be :

$$\frac{\text{1000 million liters}}{\text{60 million liters/yr}} = 17 \text{ yr}$$

The water in this lake would be 17 years old on average

This gives us a useful indication of how long it might take to flush a contaminant out of the lake

… or how long it might take to replenish the lake if the water level were severely drawn down in a drought year.

Residence Time:

Why does this matter to us? Natural Waters tend to gain ***higher TDS*** and ***more variable compositions*** with **longer residence time** in a reservoir.

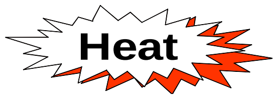
Inorganic compositions reflect ***local inputs*** from ***solids*** and ***gasses*** that are present.

Organic compositions reflect the ***local biosphere***

Area	Residence Time	TDS
Rain	T_{res} of H_2O in the atmosphere is 11 days	low (1-20 mg/L)
Rivers	days to months (location specific)	moderate (50-200 mg/l)
Lakes (fresh)	years	moderate (150-400 mg/l)

Heat in the Atmosphere-Hydrosphere System

What makes H_2O move about within the hydrosphere?



99.98% of the Earth's surficial heat comes from the sun.

Water moves through the cycle due to variable heat inputs/losses across the globe, setting up thermal gradients that cause convection within some reservoirs, and fueling evaporation and precipitation from their surfaces.

Not all locales on the Earth receive the same amount of light on a given day in the year due to vagaries in the earth's rotation relative to the sun:

The **atmosphere** is heated mostly from **below**

The **surface bodies of water** are heated mostly from **above**

Heat in the Atmosphere-Hydrosphere System - Reminder

Albedo: This is incoming light that Earth reflects in visible wavelengths. On average, the Earth reflects about 30% of its incident light through its albedo, although the albedo is not constant over the surface of the Earth.

Low Albedo
liquid water
forested regions

High Albedo
Solid water (ice)
desert regions

Roughly twice as much light is reflected to space in the infrared

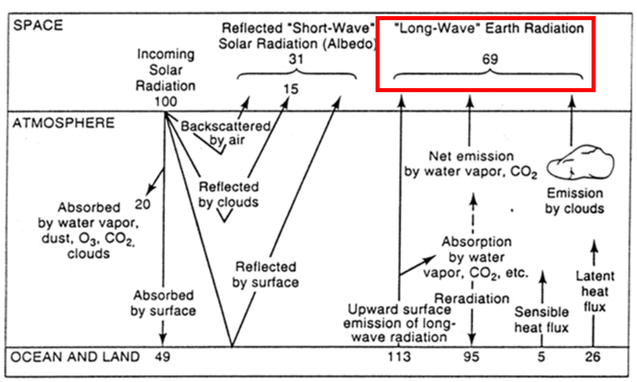


Figure 1.4 Mean annual radiation and heat balance of the atmosphere and earth. Units are assigned so that the incoming solar radiation (343 watts/m²) is set equal to 100 units; (i.e., one unit equals 3.43 watts/m²). "Short-wave solar radiation" has wavelength < 4 μm wavelength; "long-wave" earth radiation has wavelength >4 μm. Data from Ramanathan (1987), with cloud reflection of solar energy from Ramanathan et al. (1989a). The estimates of energy transfer between the top of the atmosphere and space are based on satellite measurements.

Heat in the Atmosphere-Hydrosphere System - Reminder

Most heat added to the Earth comes from “above” the hydrosphere and atmosphere system (i.e., from the Sun)

But a small amount of heat also comes from below it:

This is a combination of external heat stored by the hydrosphere, heat from internal heat sources and heat dissipation from surficial forces (i.e., tidal friction). If we sum the relative energy fluxes to the surficial earth, we find:

Solar Radiation	99.98%
Internal Heat	0.018%
Tidal Energy	0.002%

source: Berner and Berner, Global Environment

Heat in the Atmosphere-Hydrosphere System

Earth as a greenhouse: Some of the energy the earth's surface emits back to space is trapped in the atmosphere before it reaches space.

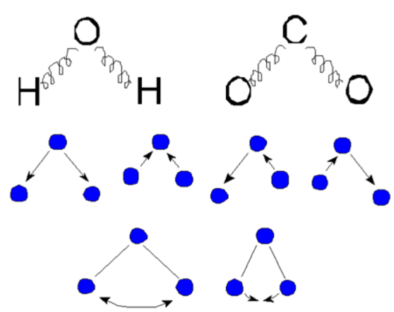
For instance chemical bonds in tri-atomic or larger molecules are "excited" by IR wavelengths. Molecules with such bonds absorb this radiation, warming the planet as in a green house (with the atmosphere being the glass walls and ceiling). This makes it a more hospitable place to live.

As we will see later this semester, humans putting extra IR absorbing molecules into the atmosphere has led to global warming.

IR absorbance increases the frequency of vibrations in chemical bonds.

We can think of the C-O and H-O bonds in CO_2 and H_2O , for instance, as springs that vibrate more in more IR-excited molecules.

Vibration takes two forms: along the bond direction and across the bond direction



Heat in the Atmosphere-Hydrosphere System

The atmospheric positive feedback loop:
The more H_2O (and CO_2) in Earth's atmosphere, in general, the more IR is held by the planet. The more longwave radiation the planet holds, the hotter it gets and the more H_2O evaporates. If left unchecked, the Earth could become very hot through this.

The atmospheric positive feedback loop:
But... as H_2O evaporates, more of it will also recondense into clouds further up in the atmosphere, thus increasing the albedo and diminishing the total incident sunlight at the surface (this negative feedback is believed to help cool the planet and counteract the positive feedback noted above).

How these two interact to affect global climate is unclear; a great deal of uncertainty regarding the extent, location and magnitude of global warming effects comes from this. We will discuss these details later in the semester.

For now, just remember that IR retention by greenhouse gasses helps make the atmosphere churn.

Heat in the Atmosphere-Hydrosphere System

IR retention by greenhouse gasses helps make the atmosphere churn.

The atmospheric positive feedback loop:
More H_2O (and CO_2) in Earth's atmosphere → more IR held by the planet → temperature increase and more H_2O evaporation → more "churning"

If left unchecked, the Earth could become very hot through this mechanism.

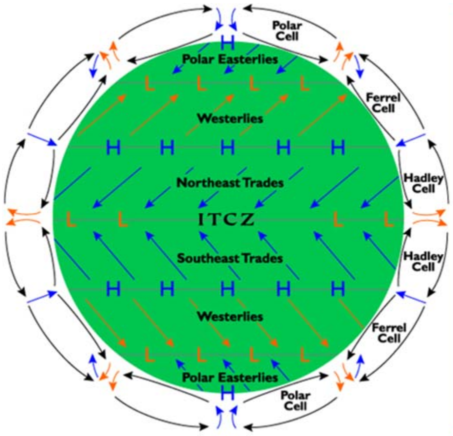
The atmospheric negative feedback loop:
But... as H_2O evaporates → more also condenses into clouds, → more albedo and diminishing the total incident sunlight at the surface
(this negative feedback is believed to help cool the planet and counteract the positive feedback noted above).

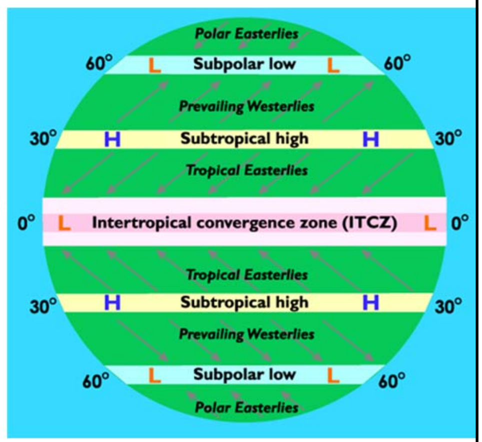
How these two interact to affect global climate is an area of active research; We will discuss these details later in the semester.

Atmospheric Circulation - Reminder

Heating and cooling sets up air movements in Earth's atmosphere and corresponding surface circulation patterns in the oceans.

Hawaii is not on this map, but we are in the latitudes of NE trade winds. That these trades aren't always blowing reminds us that these maps are schematic representations of general phenomena and average conditions.





http://www.newmediastudio.org/DataDiscovery/Hurr_ED_Center/Hurricane_Science.html

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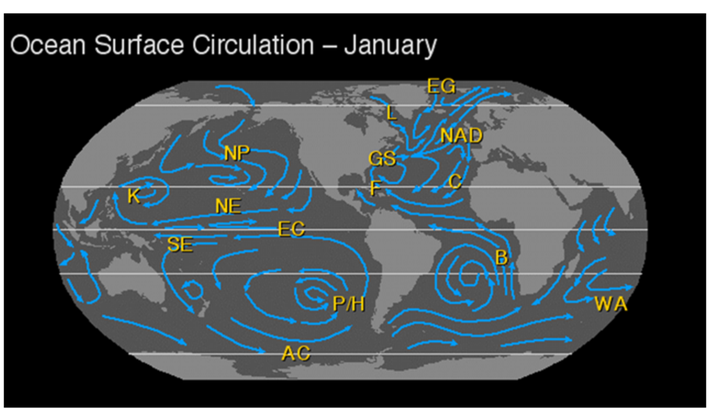
Oceanic Circulation Reminder

✓ The clockwise surface ocean rotation pattern in the low to mid northern hemisphere latitudes moves in the same direction as the prevailing winds.

✓ The counter-clockwise rotation in the low to mid southern ocean also coincides with wind directions.



http://www.ems.psu.edu/Courses/earth002/OSCirc.html

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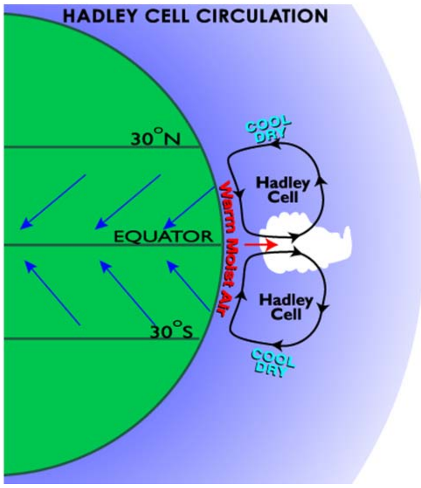
Atmospheric Circulation Reminder

Above the Earth's surface, the atmosphere rises and falls in regular patterns that also result from heat differences.

Wind and ocean circulation give rise to predictable patterns of rainfall, as rainfall requires rising moist air to reach a height where it is cool enough to allow water vapor to then recondense.

Areas of downwelling air are usually dry. Mean precipitation and evaporation patterns vs latitude cause predicable global rainfall patterns.

Rainfall causes rapid movement of water over, through and beneath the landscape, and then back to the sea, thus completing the hydrologic cycle



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Convection in Geographically fixed "Holding Tank" Reservoirs

"Holding Tank" reservoirs are a special part of the hydrologic cycle because they are places where water has a significant **residence time**, a term we will define in a moment.

"**Holding Tanks**" experience internal motion (and some stratification) driven by density gradients.

- In **fresh** water bodies, density is largely a function of temperature, with composition usually a distant second
- In **salt** water bodies, temperature and composition both play major roles in density and stratification..

We distinguish between **surface** and **internal** motions in bodies of water because they occur at different rates and result in layers in the water bodies that don't always readily exchange chemicals.

Stratification

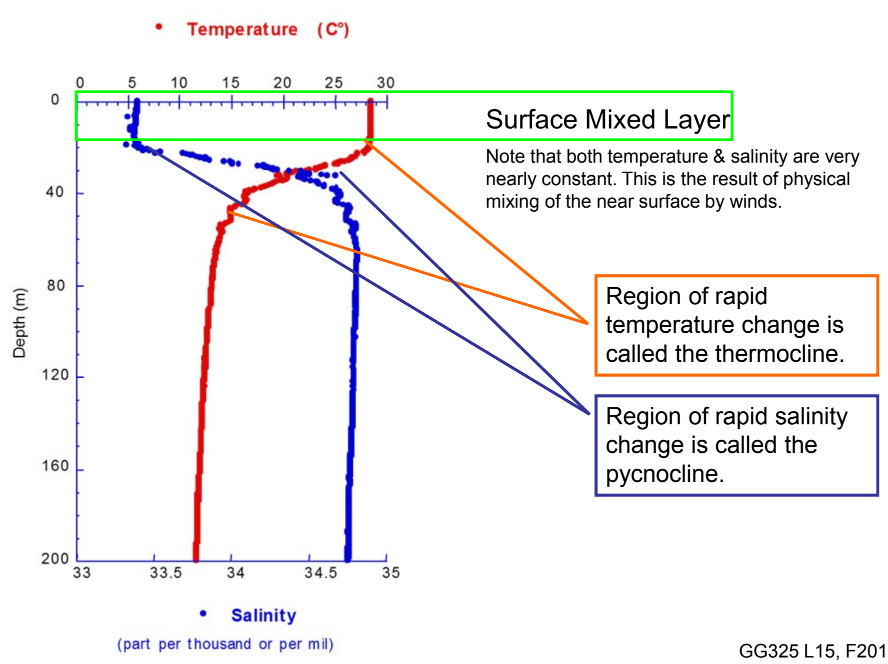
The surface layer of most holding tanks is fairly constant in temperature and is often called the ***mixed layer***

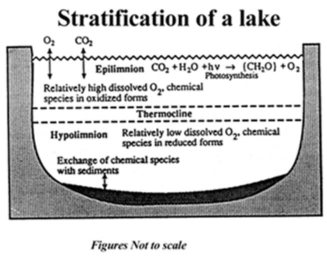
- ♣ The mixed layer exchanges gases with the atmosphere easily

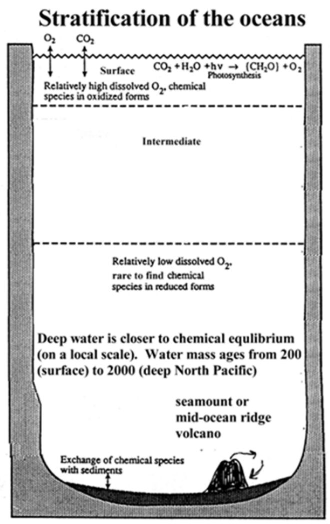
The boundary between the surface and lower layers is known as the ***thermocline*** (a place of rapid change in temperature with depth in the body of water).

Below the thermocline lies the ***deep layer(s)*** with more subtle temperature gradients.

- ♣ the deep layer can remain out of touch with the atmosphere for long periods of time (months to yrs in some lakes, thousands of yrs in parts of the Ocean).







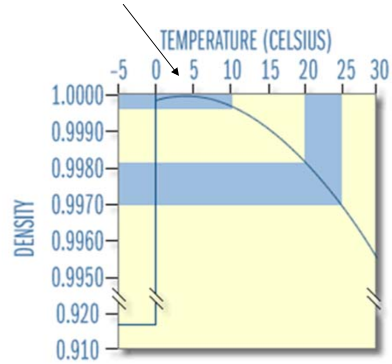
In lakes, the mixed layer is known as the *Epilimnion* and the deep layer is known as the *Hypolimnion*.

In oceans, we refer to *surface, intermediate* and *deep* layers. Intermediate waters occur in the depth over which the thermocline extends. The layer can be many 100s of m thick in the oceans. These layer names are summarized in the above figure.

Mixing in lakes

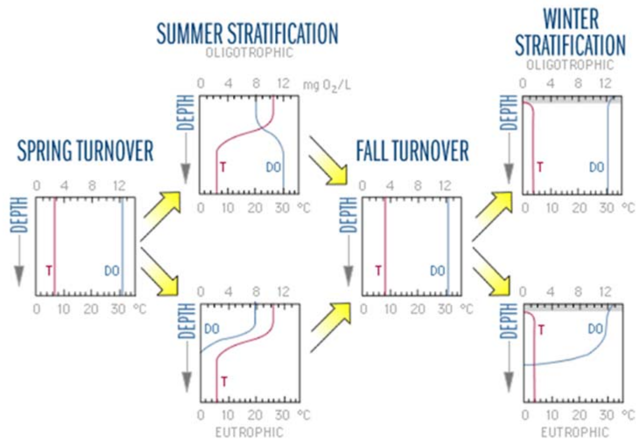
- Mixing in lakes is controlled mainly by temperature, so lakes advect mostly in direct response to the seasons.
- The temperature dependence of the density of water is central to understanding lake mixing.
- Typically the warm surface layer (epilimnion) “floats” upon colder deeper lake waters (hypolimnion) - a situation known as thermal stratification.
- Lake mixing (turn-over) happens when the density of surface water is equal to or greater than the underlying water
- Lake advection is more episodic than in the oceans. *This difference in advection style is an important control on ocean and lake composition.*

the fresh water density maximum at 4°C



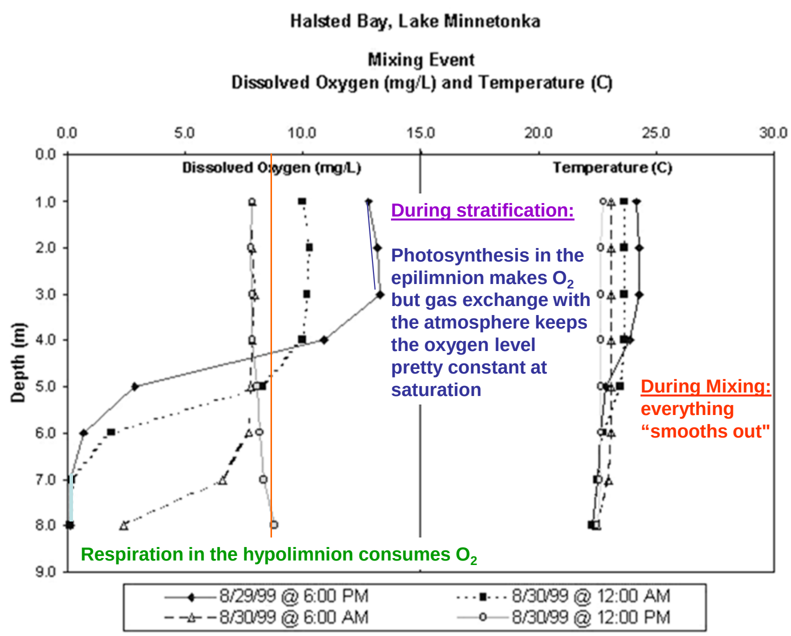
DENSITY/TEMPERATURE RELATIONSHIP FOR DISTILLED WATER. SHADED AREAS SHOW RELATIVE DIFFERENCE IN DENSITY FOR 5°C TEMPERATURE CHANGES.

http://lakeaccess.org/ecology/lakeecologyprim4.html



• At non-advecting times, a typical thermal *profile* in a lake looks similar to that of the ocean. Water at the top is less dense (warmer) so stratification is preserved.
• In Autumn, the lake surface typically cools sufficiently to cause a density inversion, so the lake advects, smoothing out the density gradient temporarily. This is an idealized case; not all lakes respond as simply to seasonal variations (especially in places where seasonal variations are small).
• In spring a second overturn can occur for lakes that freeze in winter, because the density maximum at 4°C is reached in the meltwater as it warms up.

Why does dissolved oxygen ("DO") change during this cycle?



http://es.epa.gov/ncer/progress/grants/98/empact/barten99.html

Ocean Circulation

<u>Oceans are the major hydrologic "holding tank".</u>

<u>Shallow currents</u> are driven by surface winds.

<u>Deep currents</u> arise from internal density (ρ) gradients

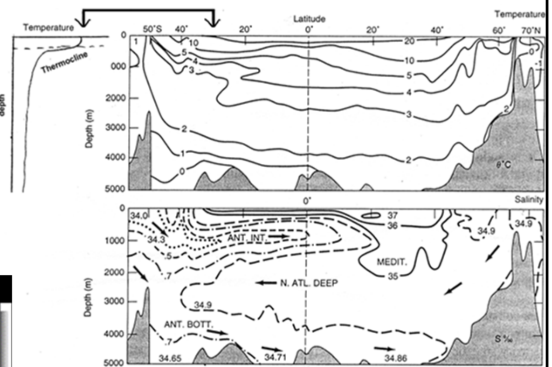
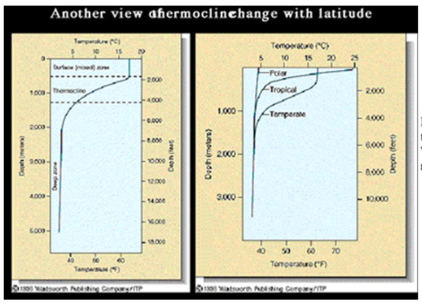
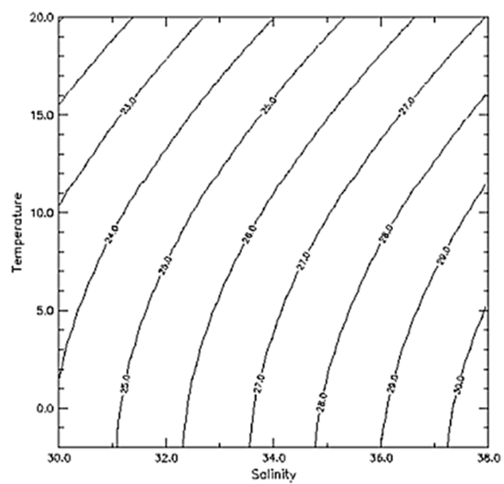


Figure 1.13 South–north vertical section of water properties of the Atlantic Ocean along the western trough as delineated by lines of constant temperature and salinity. N. Atl. Deep = North Atlantic Deep Water; Ant. Bott. = Antarctic Bottom Water; Ant. Int. = Antarctic Intermediate Water; Medit. = Mediterranean Water. [Adapted from Pickard and Emery (1982), based on data from Bainbridge (1976).]



Density differences are driven by salt content and temperature. Salt content varies mostly due to additional or removal of fresh water.

With temperature, salinity and pressure (=depth) of seawater, the density can be calculated directly.



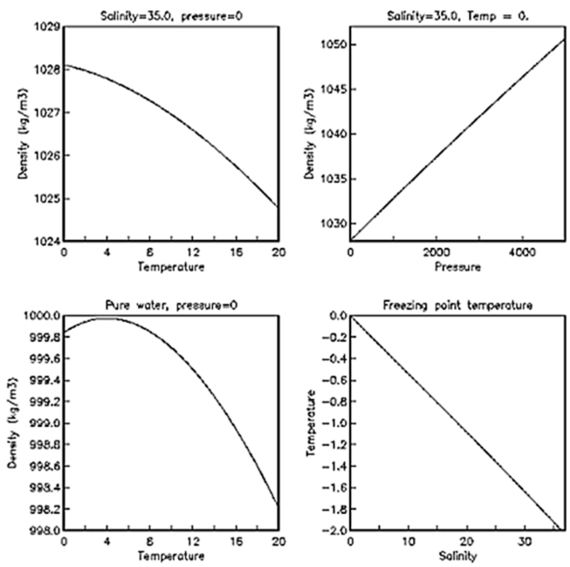
Potential density 0 dbar

(Potential density is the density water has at a certain reference depth, such as the surface.)

The temperature dependence of seawater density differs from freshwater in that there is no 4°C density maximum.

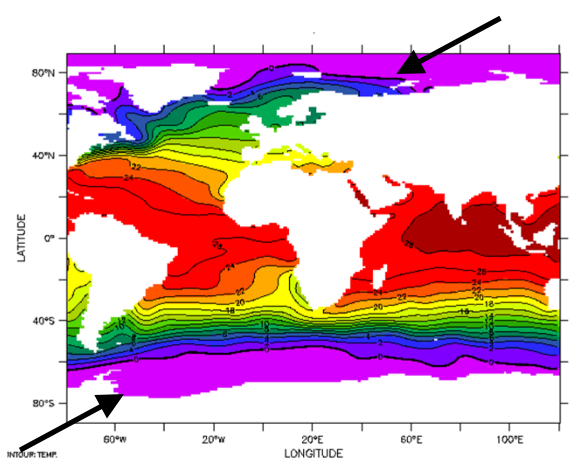
...so large scale vertical mixing in the oceans is driven by a combination of heat and salt content, rather than just heat as it is in lakes.

The mixing is also much less seasonal in the oceans.



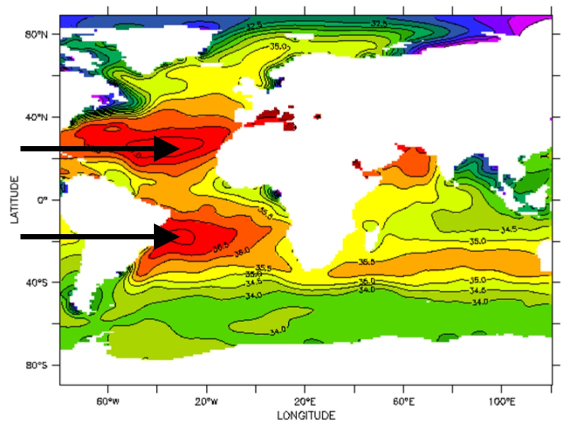
http://sam.ucsd.edu/sio210/gifimages/dens.gif

Cold water near the poles tends to make seawater more dense at high latitudes.



Temperature at 10 m, ann. ave. (Levitus, 1982)

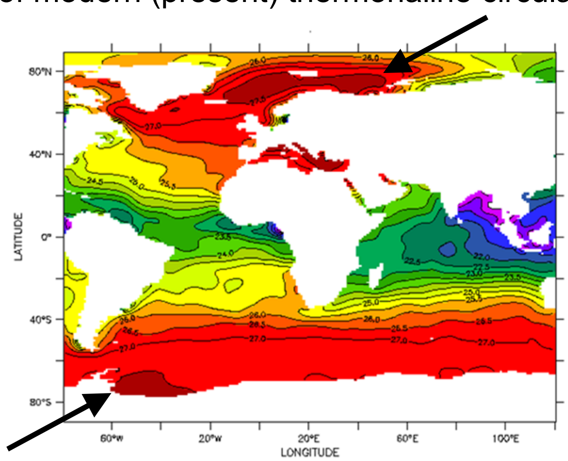
But net evaporation near the equator tends to make low latitude waters more salty.



Salinity at 10m, ann. ave. (Levitus, 1982)

Which process "wins" the battle to dominate seawater density temperature or salinity?

Temperature wins - the densest water is at high latitudes. Sinking of water at high latitudes is a key feature of modern (present) thermohaline circulation.



Potential density at 10 m, annual average