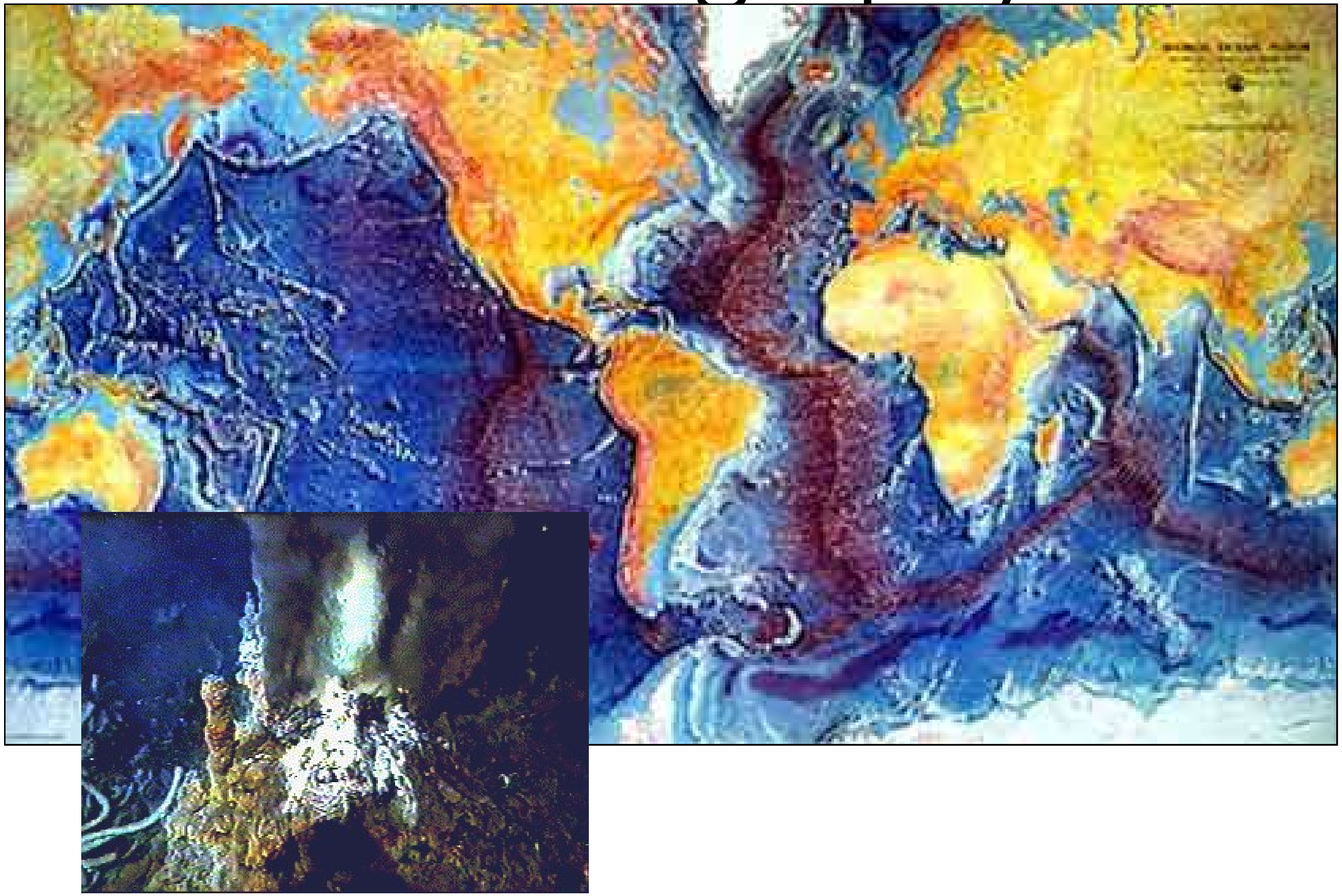
References:

- Talley, L.D. Pickard, G.L., Emery, W.J., Descriptive Physical Oceanography, 6th Edn, Elsevier , 2011
- Pond S and Pickard L., Introductory Dynamical Oceanography (2nd edition)
- Gill, A.E., Atmosphere-Ocean Dynamics, Academic Press, 1982.

Oceanography



Oceanography and Our Oceans

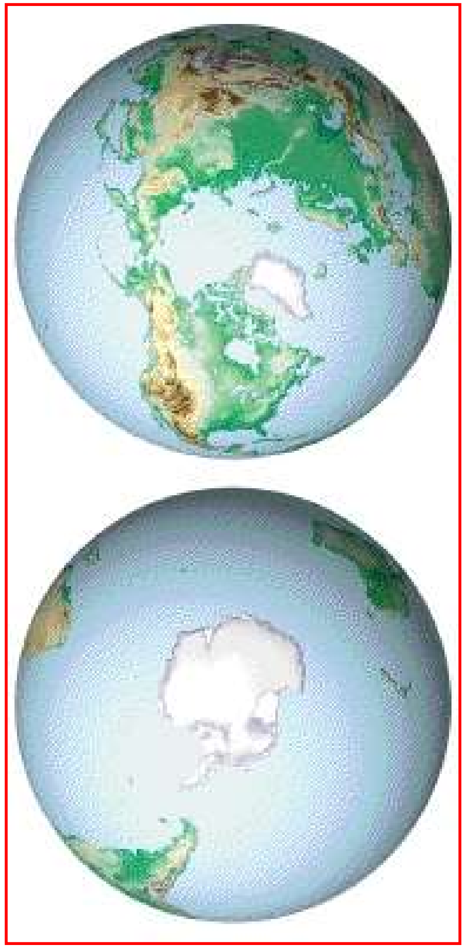
*71% of Earth's surface is covered with water, so it is important we know something about the water surrounding us.

Oceanography is the science of our oceans that mixes biology, geology, chemistry, and physics (among other sciences) to unravel the mysteries of our seas.

In the Northern Hemisphere, 61% is water and 39% is land, thus it is called the "Land Hemisphere".

In the Southern Hemisphere, 81% is water and 19% is land, thus it is called the "Water Hemisphere".

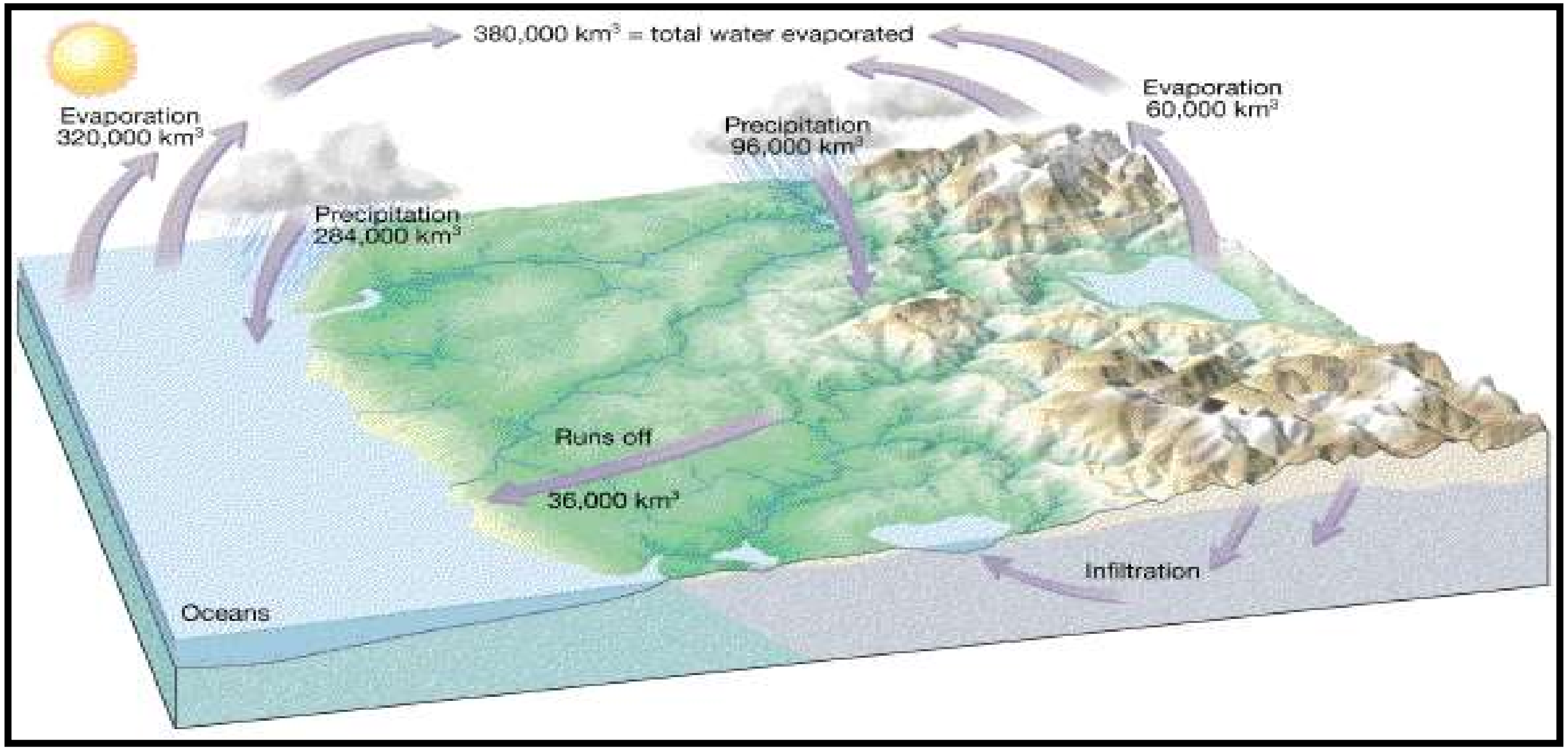
The Hemispheres of the Earth



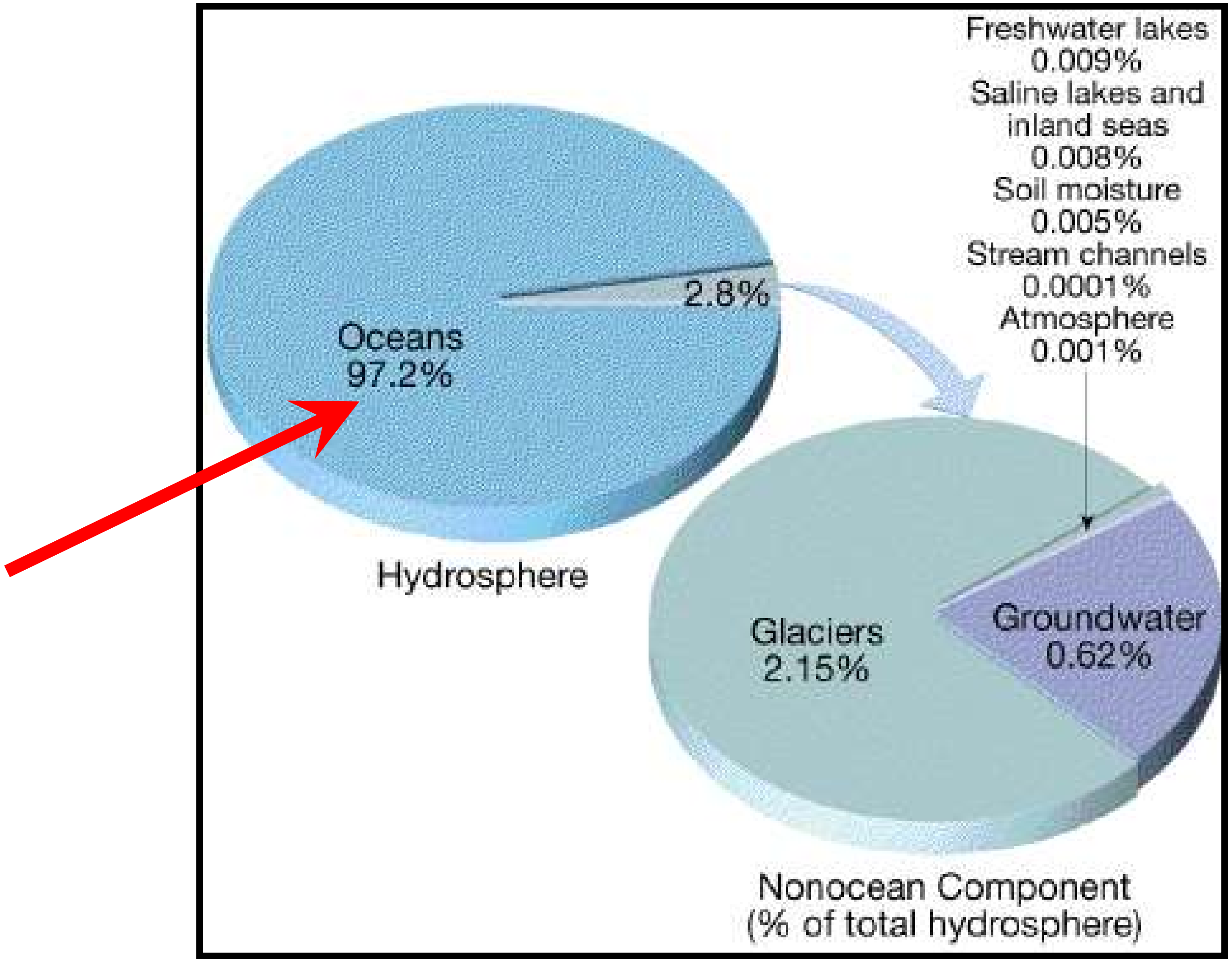
Northern Hemisphere is approximately 39% land.

The Southern Hemisphere is approximately 19% land.

Hydrologic Cycle



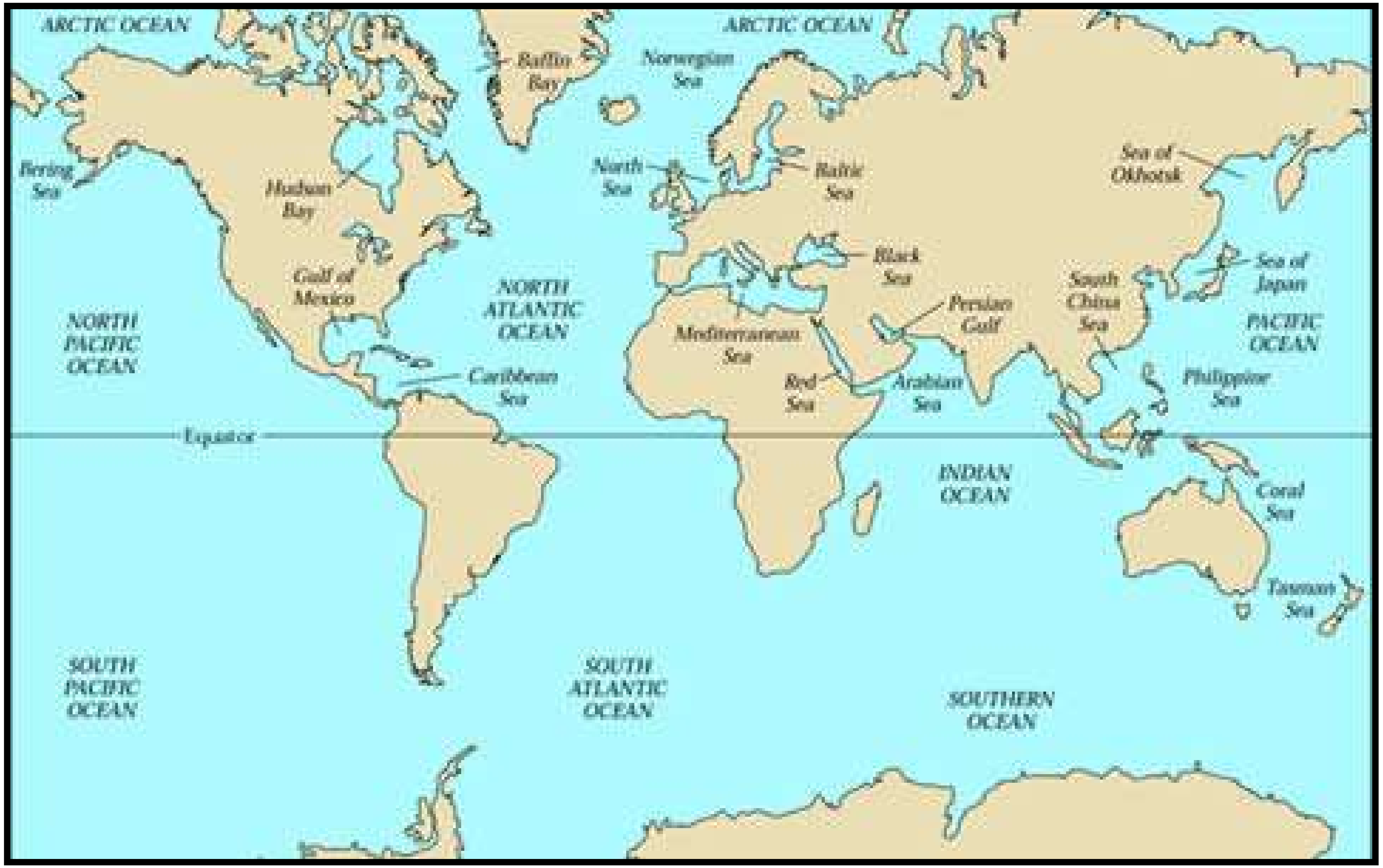
Cubic Kilometer [km^3] = 1e+12 Liters


Freshwater lakes
0.009%
Saline lakes and
inland seas
0.008%
Soil moisture
0.005%
Stream channels
0.0001%
Atmosphere
0.001%
2.8%
Oceans
97.2%
Hydrosphere
Glaciers
2.15%
Groundwater
0.62%
Nonocean Component
(% of total hydrosphere)

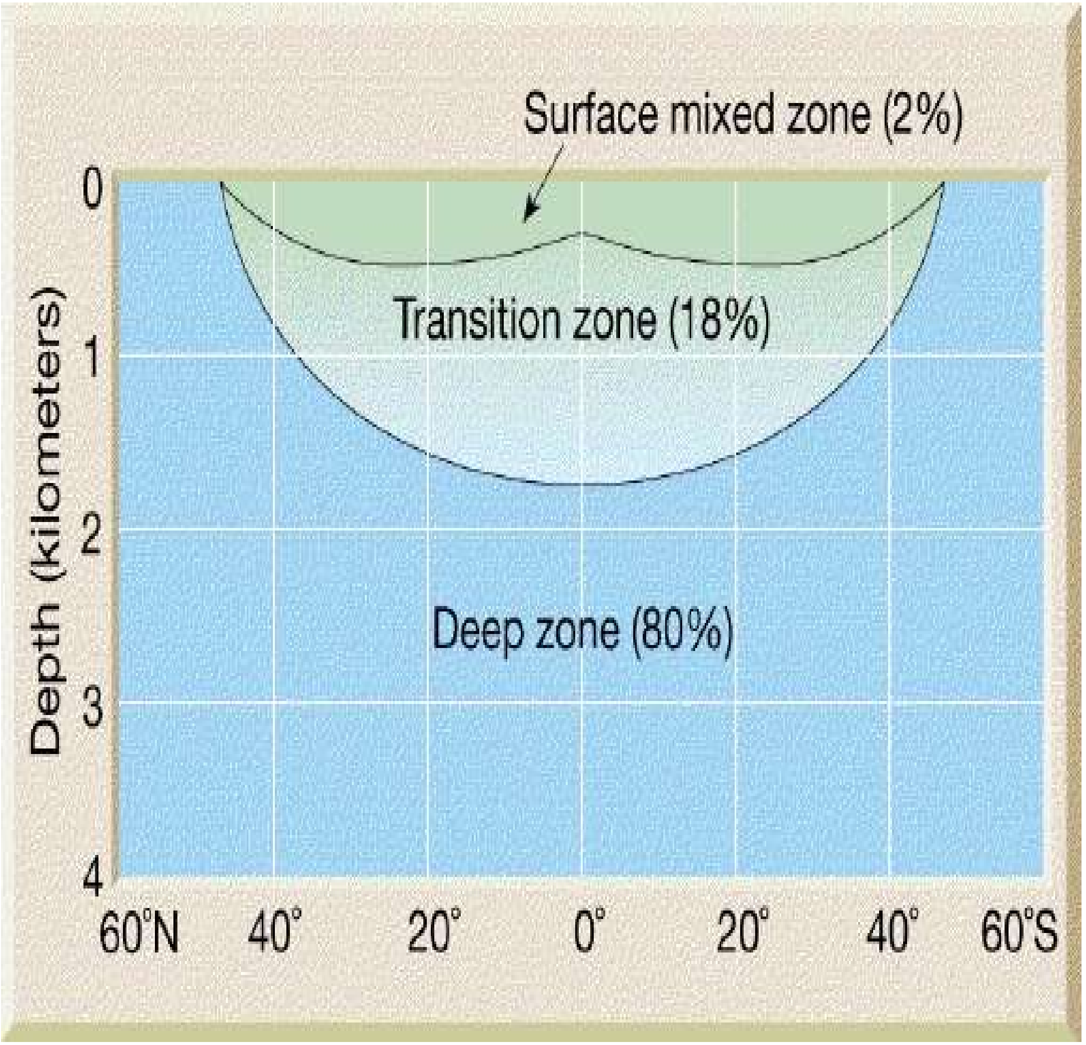
The 5 Oceans

- Pacific Ocean
  - Largest and deepest ocean
  - Mariana Trench: 11 km., 36,000 ft.
    - (Mt. Everest 29,000 ft.)
- Atlantic Ocean
  - About ½ the size of the Pacific
- Indian Ocean
  - Southern hemisphere
- Arctic Ocean
  - ¼ as deep, much smaller, sea ice
- Southern Ocean also known as the **Antarctic Ocean**
  - South of 50 deg. South latitude

Earth's Oceans and Seas



Our Layered Oceans



Surface mixing zone is warmest; saltiest near bottom of zone.

Transitional zone contains thermocline and halocline.

Deep zone coldest in temperature.

Ocean Topography:

*Oceanographers studying the oceans and ocean floor have found (3) major parts:

1. ***Continental margin***
2. Ocean basin floor
3. Mid-oceanic ridges

1. The *continental margin* includes:

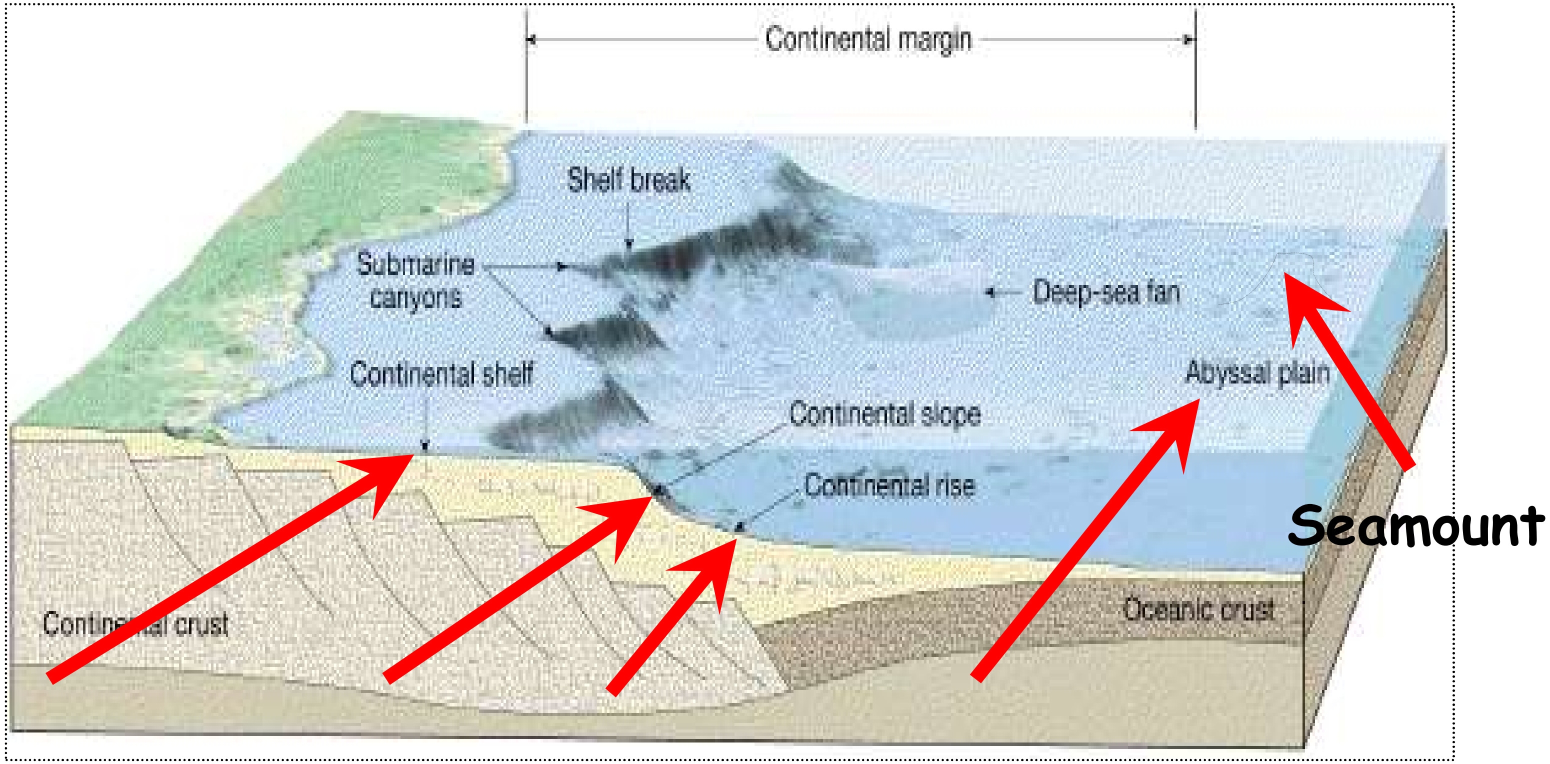
a. Continental shelf -- very gentle slope (submerged land)

b. Continental slope -- steep slope on edge of continental shelf.

c. Continental rise -- gentle slope where trenches do not exist

Surprisingly, we know very little about the mapping of our ocean floor. We probably have accurately mapped **only 5%** of the ocean floor. It is time-consuming, expensive, and our current technology only allows us to map a few miles at a stretch.

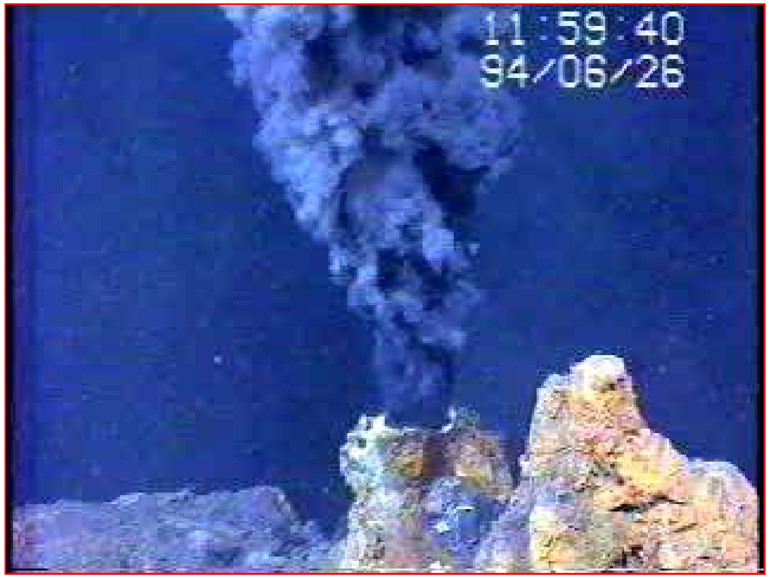
Ocean Topography



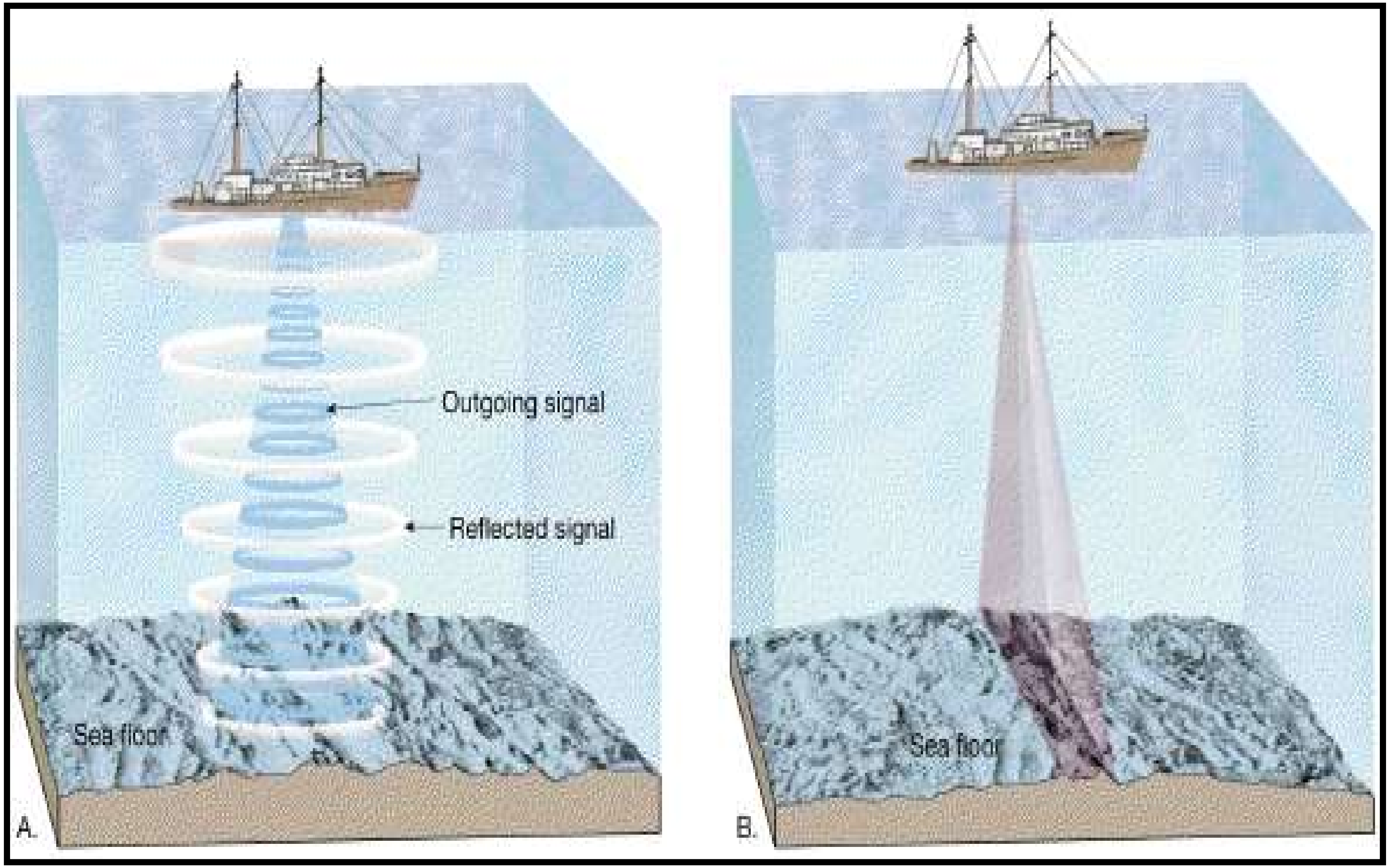
What else is at the bottom of the ocean?

Answer: Hydrothermal vents …a.k.a…

Black smokers!



Echo Sounding Used for Mapping Ocean Floor



Physical Characteristic of the Ocean

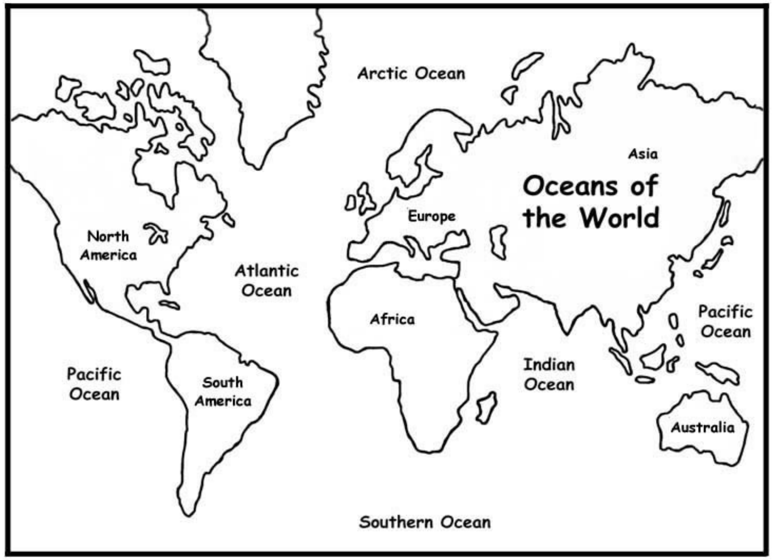
Why important

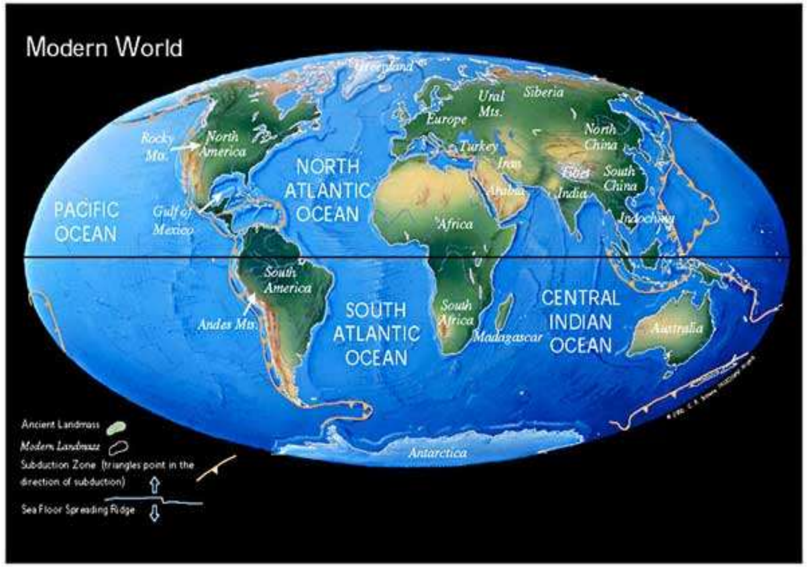
- **Because water in the ocean holds a large amount of heat, the ocean has a major effect on climate.**
- **Heat moves from warmer objects to cooler ones, until both reach the same temperature**
- **When air in contact with the ocean is at a different temperature than the sea surface, heat transfer by conduction takes place.**
- **The ocean also absorbs and stores energy from the sun, and when precipitation falls, it releases heat energy into the atmosphere.**

✓ **Many of the processes that occur in the oceans depend on the physical properties of sea water. The conduction of heat, absorption of light, transmission of sound, formation of waves, tides, ice, currents and water masses are some of the important physical features of ocean water. Sea water contains pure water as well as salts, dissolved gases, organic substances and undissolved suspended particles.**

- **The presence of salts and other substances in sea water greatly influence the various characteristics of sea water. Hence, an understanding of the physical properties of sea water is necessary to study the various processes that occur in the ocean.**
- **The forces that cause circulation of water in the ocean arise from changes in the physical properties of that water.**
- **Physical properties like temperature and salinity directly affect the density, buoyancy and stability of seawater and consequently the motion of water in the ocean basins.**
- **The physical properties of seawater also strongly influences the behaviour of heat and light in the ocean.**

<u>Oceans of the world</u>

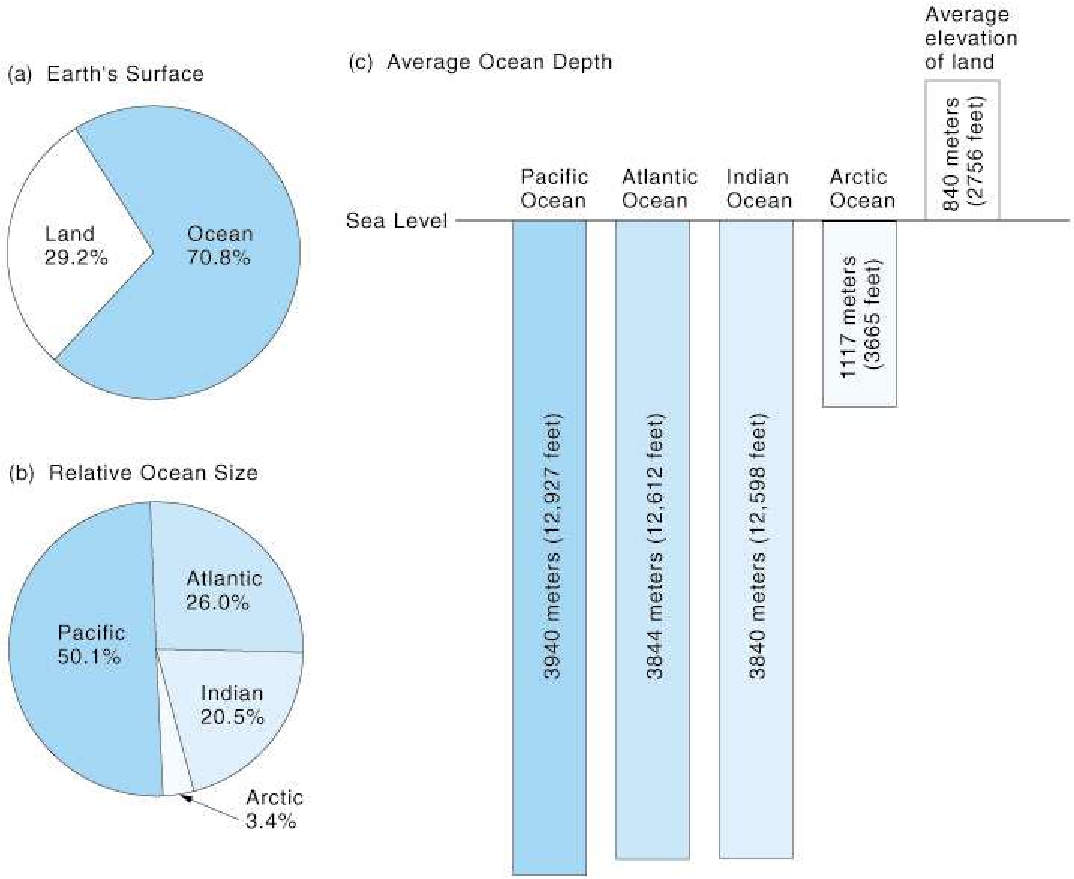




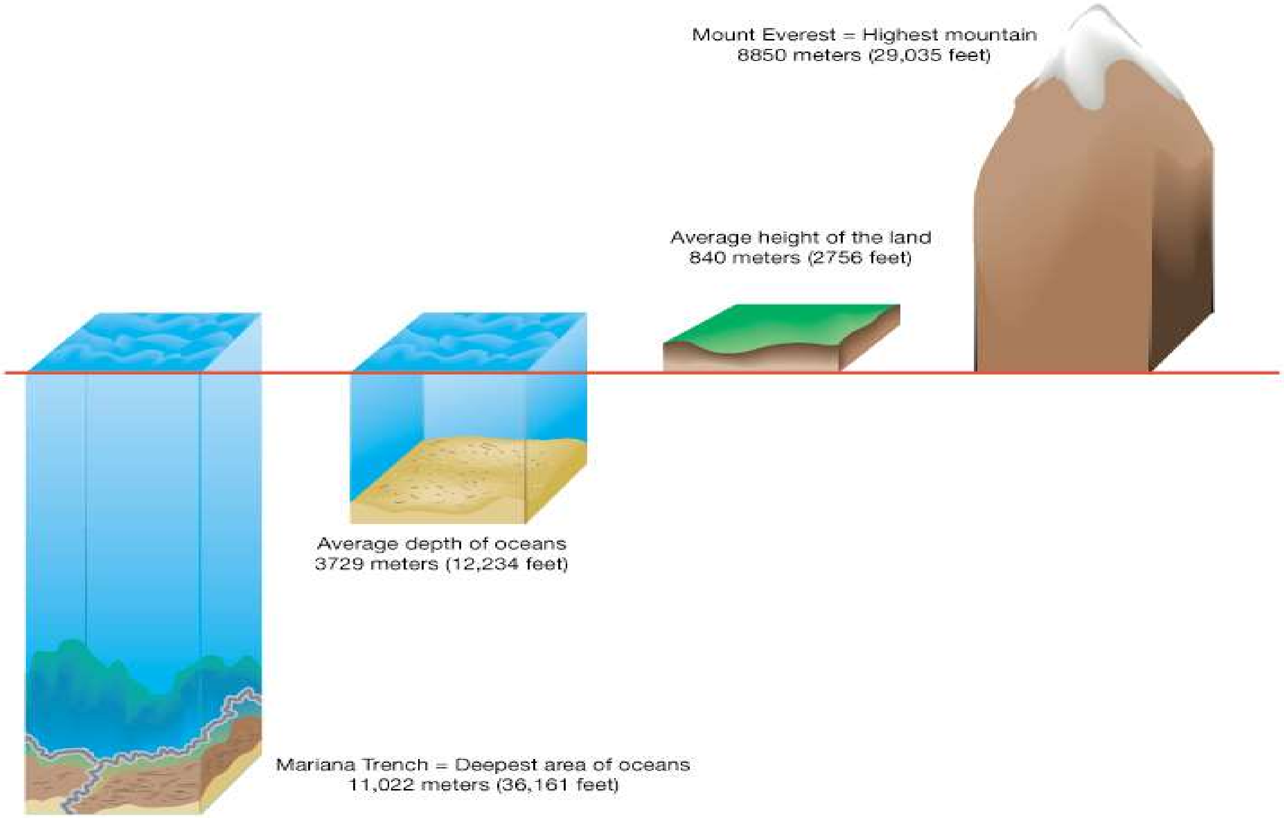
Oceans Covers ~71% of the Earth

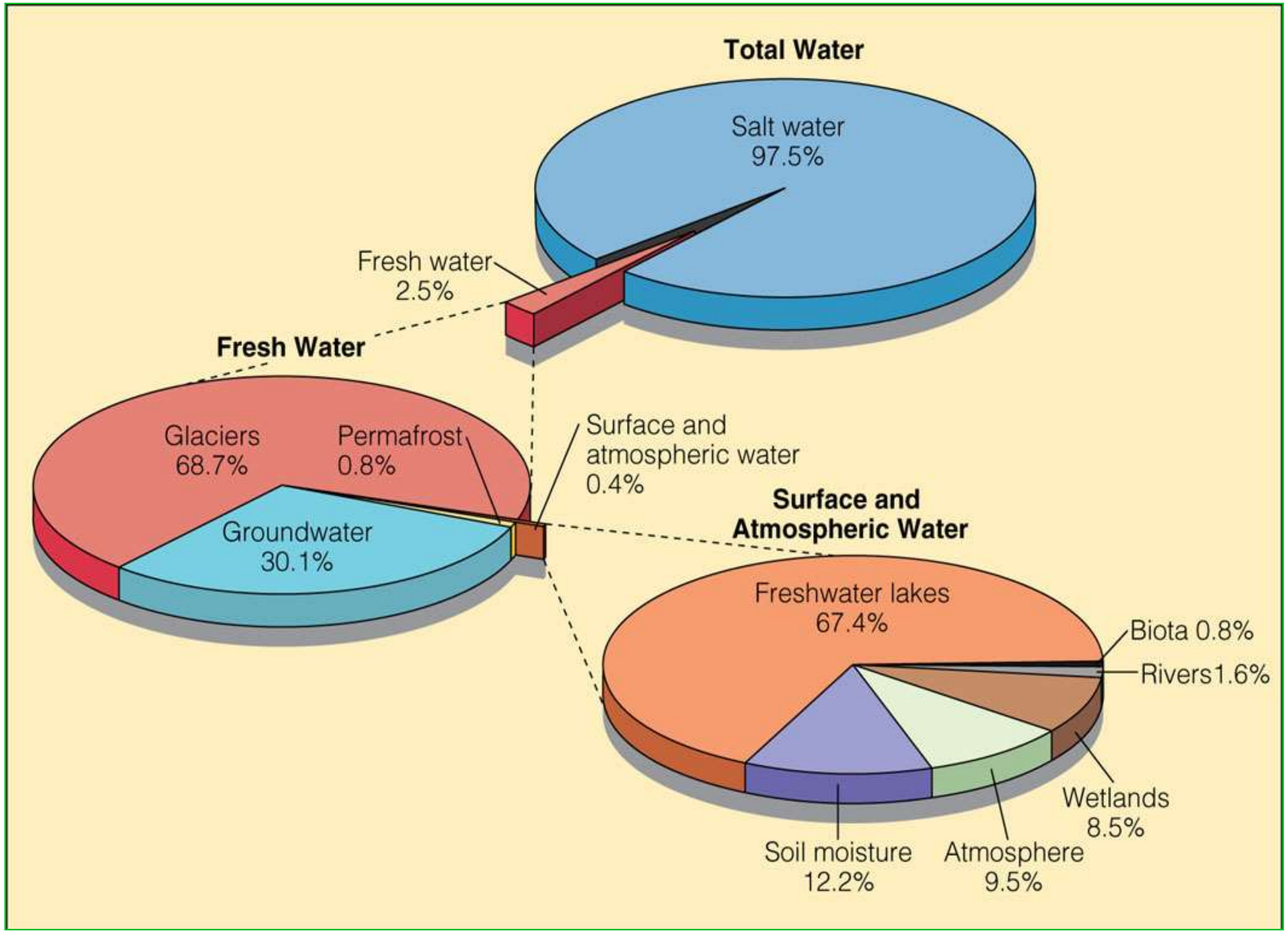
4 major basins

- Atlantic
- Pacific
- Indian
- Arctic



Depth of Ocean





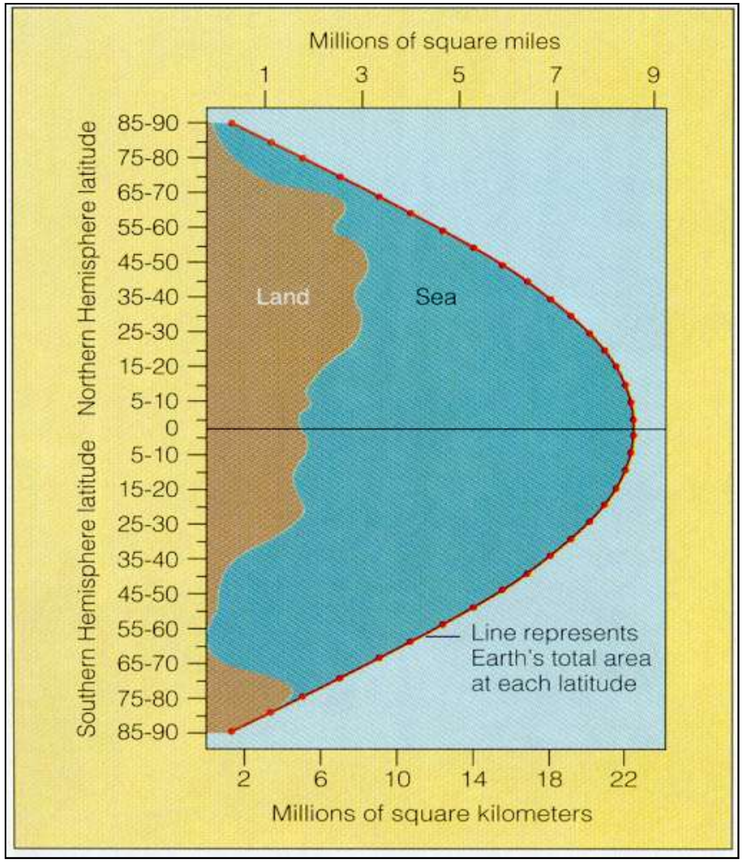


Fig. The distribution of land and water in the northern and southern hemispheres.

Permafrost: an area of land that is permanently frozen below the surface.

Biota (ecology): the plant and animal life of a region (e.g., tropical region).

Sea Water Temperature

- **Temperature**
- Temperature of surface very
- **Temperature below surface vary with**
- 1. Depth
- 2. Circulation
- 3. Turbulence
- 4. Geographic location
- 5. Heat generating
- Sources such as volcanoes
- Temperature of seawater vary from below -5^{0}C to Over 33^{0}C
- Freezing pt of saltwater is -1.9^{0}C

Heat Energy and Water

- **Heat energy produced by molecular vibration (number of molecules and how rapidly they vibrate). The calorie is the unit of heat.**

- **Temperature is only a measure of how rapidly molecules vibrate.**

- **Different substances have different temperature responses for the same amount of heat added or removed.**

- **Specific heat is the measure of how much heat is required to raise 1g of a substance by 1ºC.**

- **Specific heat of liquid water is 1.0 calories. Relative to other substances, water can absorb or release a lot of heat with little temperature change.**

- **In contrast, the specific heat of sand is about 0.1 calories. It does not resist change in temperature with gain or release of heat. Think of hot, mid-day, beach sand versus the cooler seawater; both received the same solar energy.**

Temperature: Temperature is a thermodynamic property of a fluid, and is due to the activity of molecules and atoms in the fluid. The more the activity (energy), the higher the temperature. Temperature is a measure of the heat content. Temperature units used in oceanography are degrees Celsius.

The general definition of sea surface temperature (SST) is that it is the water temperature at 1 meter below the sea surface.

Salinity: Salinity is roughly the number of grams of dissolved matter per kilogram of seawater. The dissolved matter in seawater affects its density, hence the importance of measuring salinity.

http://sam.ucsd.edu/sio210/

The total amount of salt in the world oceans does not change except on the longest geological time scales. However, the salinity does change, in response to freshwater inputs from rain and runoff, and freshwater removal through evaporation. In the original definition, salinity units were o/oo (parts per thousand). This was replaced by the "practical salinity unit" or psu.

Density: Seawater density depends on temperature, salinity and pressure. Colder water is denser. Saltier water is denser. High pressure increases density. The dependence is nonlinear. An empirical equation of state is used, based on very careful laboratory measurements. (See Gill book).

Pressure and depth

- **Pressure is the force per unit area exerted by water (or air in the atmosphere) on either side of the unit area. The force due to pressure comes from the difference in pressure from one point to another - i.e. the "pressure gradient force" since the gradient is the change over distance. In the ocean, the downward force of gravity is balanced mostly by an upward pressure gradient force. That is, the water is not accelerating. Therefore pressure increases with increasing depth.**

- **Horizontal pressure gradients drive the horizontal flows in the ocean (which are much much stronger than the vertical flows). The horizontal variation in pressure in the ocean is entirely due to variations in the mass distribution. Where the water column above a given depth is heavier because it is either heavier or thicker or both, the pressure will be greater.**

- **Note that the horizontal pressure differences which drive the ocean currents are on the order of a decibar over hundreds or thousands of kilometers, that is, much smaller than the change in pressure with depth.**

Equation of State: $\rho = \rho(T, S, p)$

T = Temperature
units: °C
ocean range: -2°C to 30°C

S = Salinity = mass of salt (gm) dissolved in 1 kg seawater
units: ppt or psu
kind of salt the same everywhere in sea
(ocean mixes up in time it takes to dissolve)
55% chlorine
31% sodium
8% sulphate
4% magnesium
1% potassium
S can go from 0 (coast) to about 40psu (Red Sea)
BUT 90% is between 34 and 35 psu

P = pressure = force/area
for ocean, use *hydrostatic* approximation:
pressure = weight of fluid above
MKS units: Newton/m^2 = Pascal
atmospheric weight $\approx 10^5$ N/m$^2 \equiv 1$ bar
ocean weight $\approx$ 1 bar every 10 m depth of water
==> ocean depth in dbar $\approx$ depth in meters
ocean pressure measured relative to surface (ignore atm)

Rules About Density

1) Density hardly changes

$\rho \approx 1000\mathrm{kg/m^3} = 1\ \mathrm{gm/cm^3}$

2) Density increases when pressure increases

z	ρ
0	1028.1
1000	1032.8
4000	1046.4

$(S = 35\mathrm{psu},\ T = 0°\mathrm{C})$

3) Density increases when salinity increases

S	ρ
0	999.8
35	1028.1

$(T = 0,\ z = 0)$

4) Density decreases as T increases

5) BUT the *amount* it changes depends on T,p

colder water: *less* sensitive to T

deeper water: *more* sensitive to T

6) Variations due to T and S are small but **very impo**

Accurate formula for $\rho(T, S, p)$ can be found in Gill appendix

My Approximate Density Formula:

$$\rho = C(p) + \beta(p)S - \alpha(T,p)T - \gamma(T,p)(35 - S)T$$

units: p in "km", S in psu, T in $^\circ$ C

$C = 999.83 + 5.053p - .048p^2$

$\beta = .808 - .0085p$

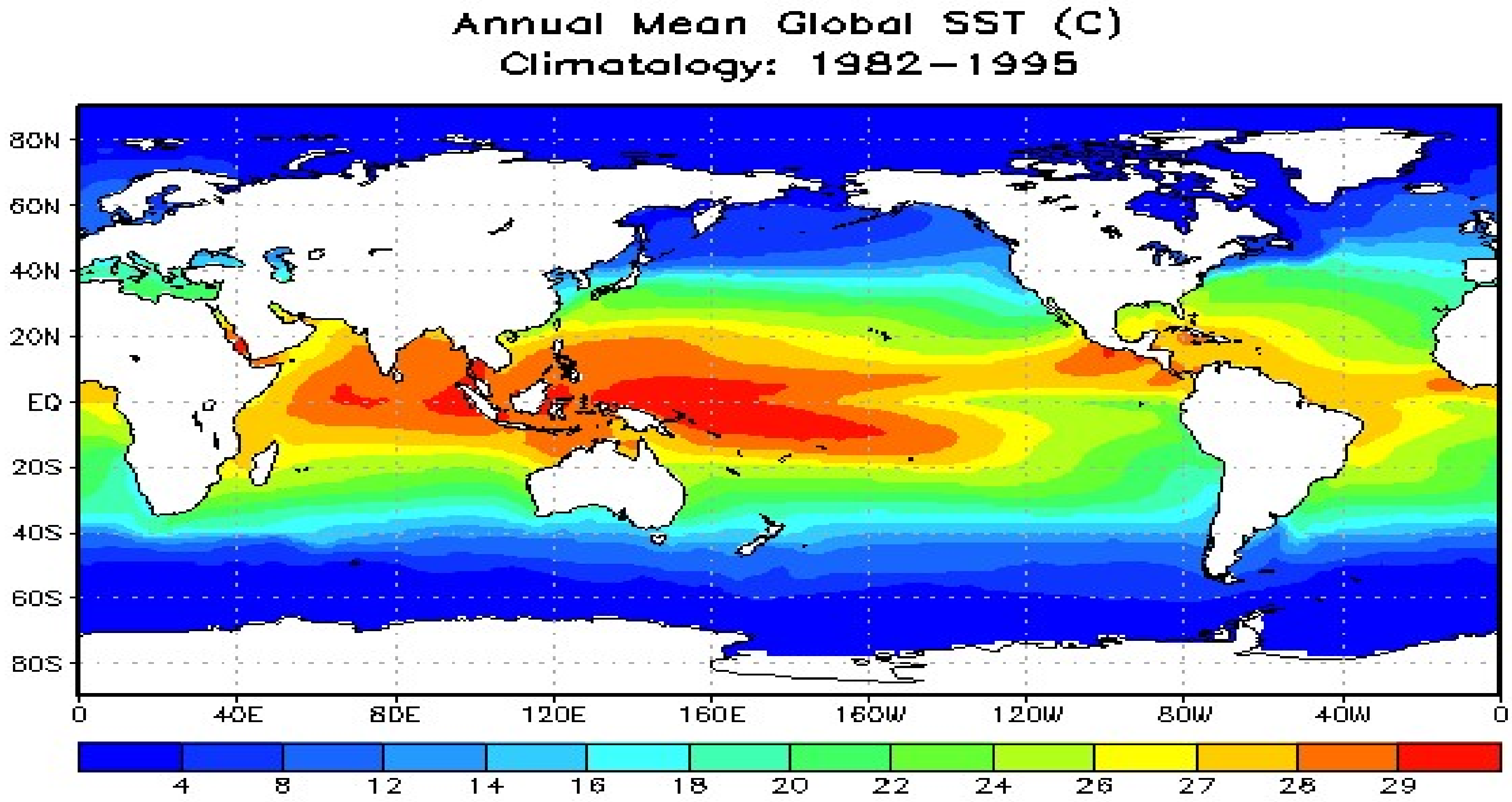
$\alpha = .0708(1 + .351p + .068(1 - .0683p)T)$

$\gamma = .003(1 - .059p - .012(1 - .064p)T)$

https://www.colorado.edu/oclab/sites/default/files/attached-files/stewart_textbook.pdf

❖ Sea Surface Temperature (SST)s are warmest in the tropics coldest in high latitudes.

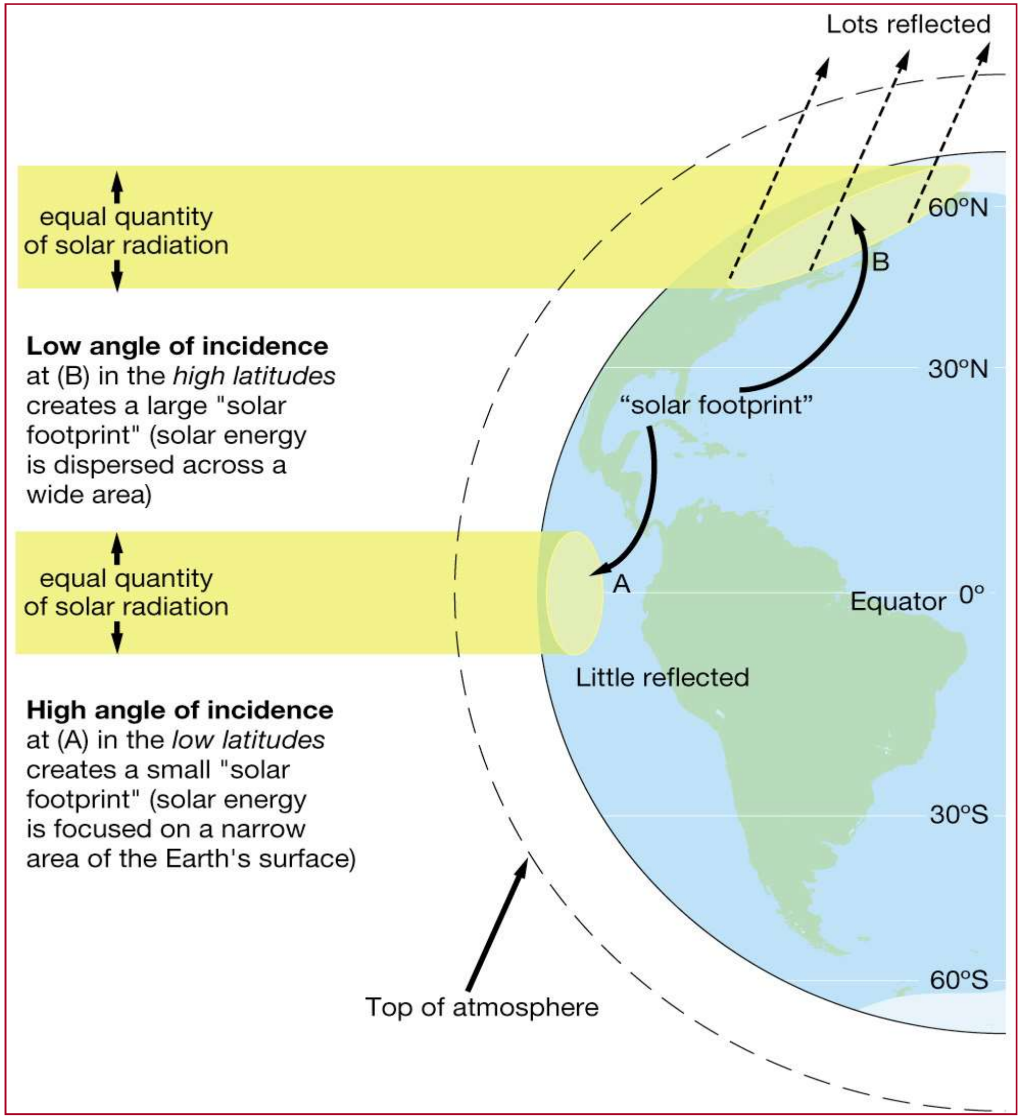
❖ The warmest water (>29◦C), follows the Sun north and south. There are also east-west variations, particularly in the tropics.



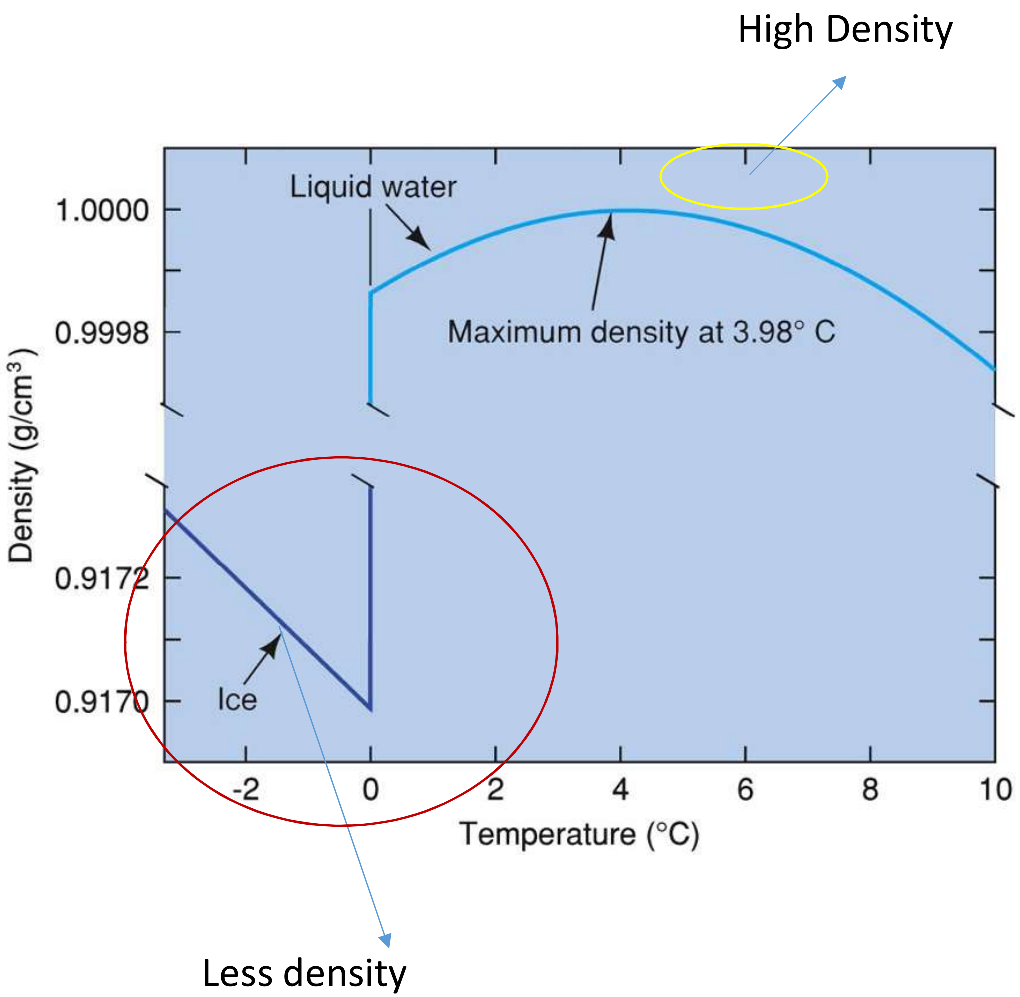
High SST in the tropics is due to net heating, and low SST at high latitudes is due to net cooling. Beyond this simple meridional variation, the more complex features of SST result from ocean circulation and spatial variations in atmospheric forcing.

Differential Solar Heating From Equator to Poles

The equator receives the most sunlight because the Sun is closer to being directly overhead year-round than it is at any other place on the Earth. This increases the amount of heat energy received and explains why areas near the equator have tropical climates.



- ✓ The polar seas (high latitude) can be as cold as -2 degrees Celsius. while the Persian Gulf (low latitude) can be as warm as 36 degrees Celsius.
- ✓ Ocean water, with an average salinity of 35 psu freezes at -1.94 degrees Celsius. That means at high latitudes sea ice can form. As salt is added to water, the salt water solution is now composed of both water molecules and dissolved salt ions. Salt water freezes more slowly than pure water because many of the water molecules that would be "crashing" into the surface of the ice in pure water are replaced by these salt ions.
- ✓ The average temperature of the ocean surface waters is about 17 degrees Celsius.
- ✓ 75% of the total volume of the ocean water has a temperature between 0 and 6C and salinity between 34 and 35 psu.
- ✓ 50% of the total volume of the oceans has properties between 1.3 and 3.8C and between 34.6 and 34.7 psu,
- ✓ The mean temperature of the world ocean is 3.5C and the mean salinity is 34.6 psu.



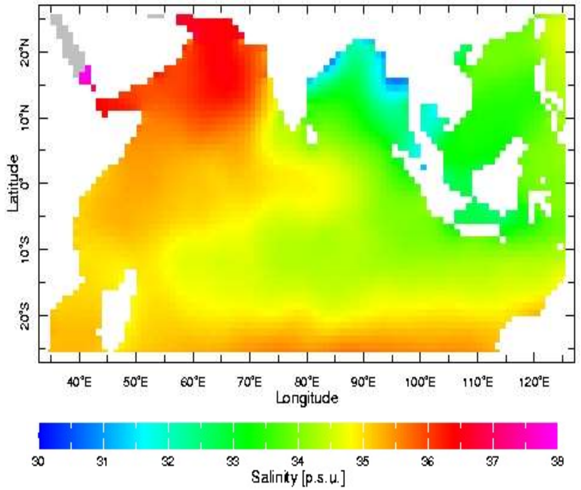
Ice floats on the water surface, so fish survive.

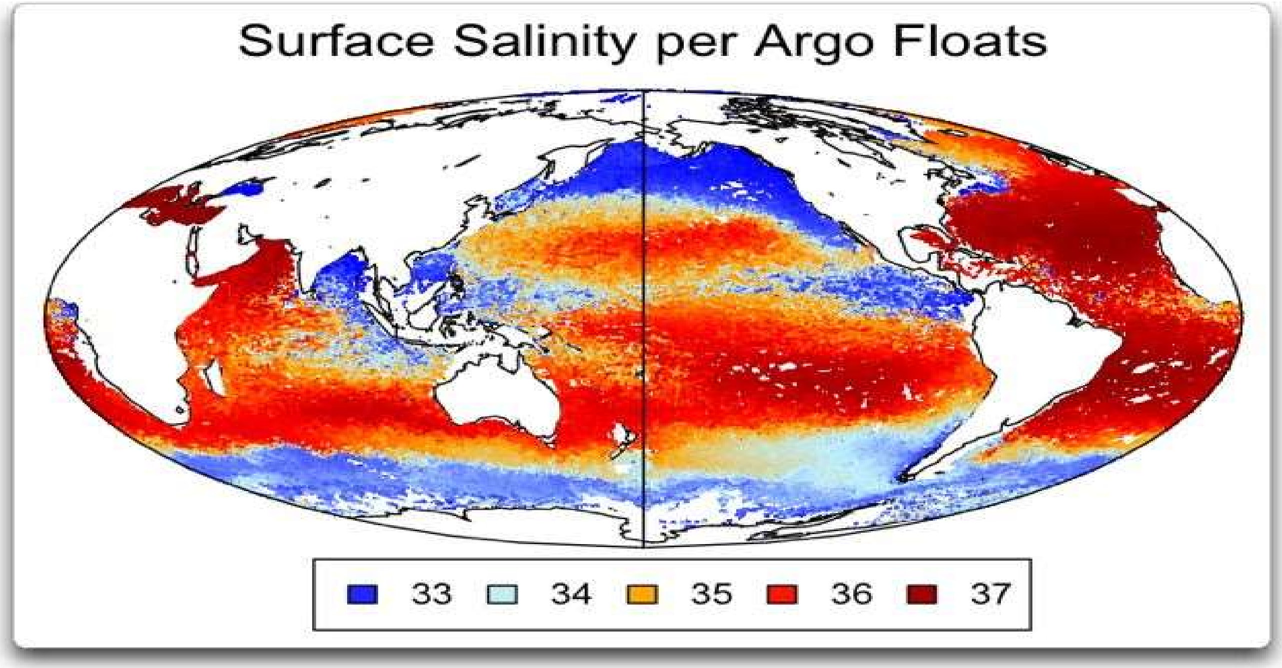
Bottom temperature of deep, cold lakes is always 4 °C.

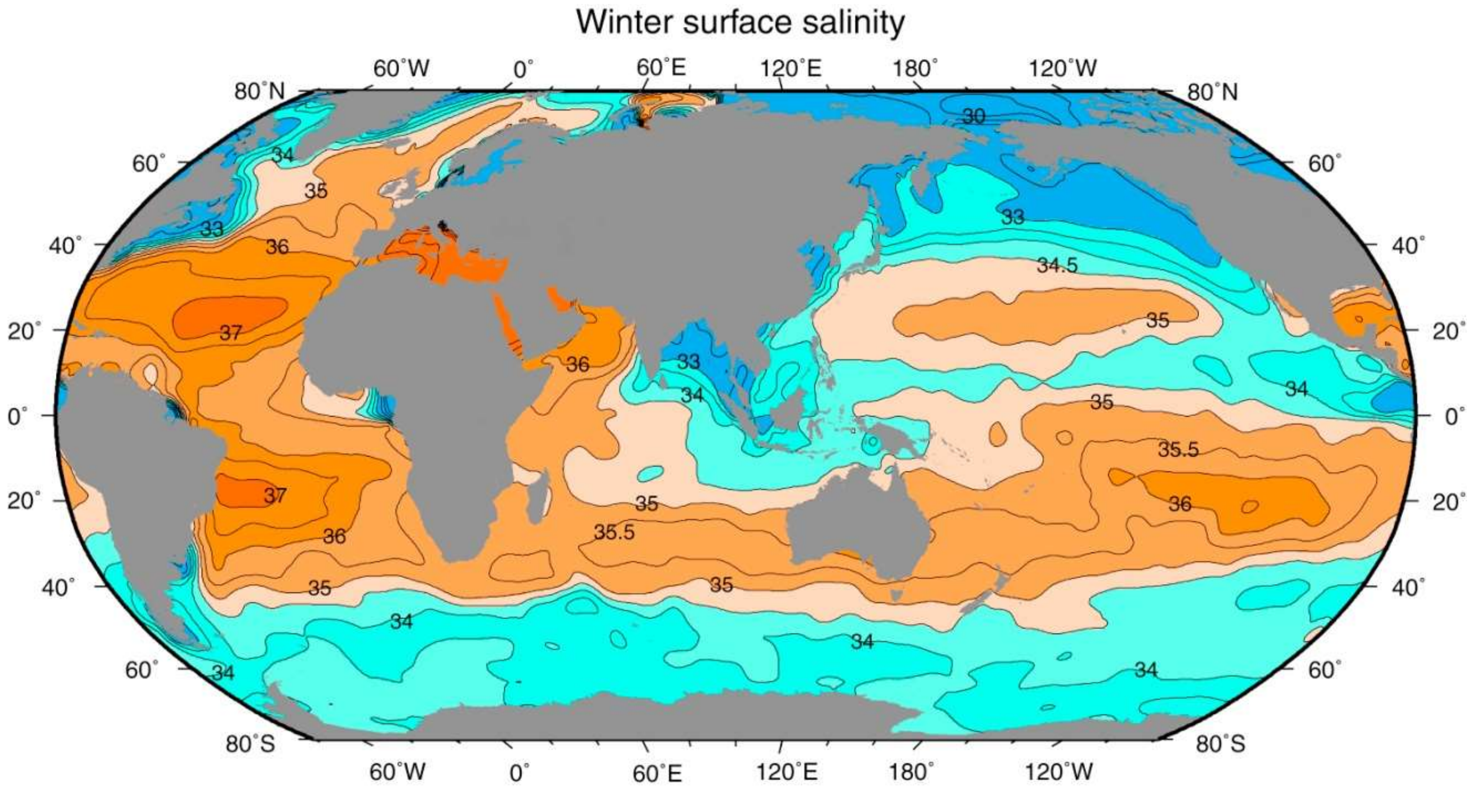
- During the fall a lake is cooled at its surface, the surface water sinks, and convective overturn proceeds as the density of the surface water increases with the decreasing temperature.
- By the time the surface water reaches 4 °C, the temperature of maximum density for fresh water, the density-driven convective overturn has reached the bottom of the lake, and overturn ceases. Further cooling of the surface produces less dense water, and the lake becomes stably stratified with regard to temperature-controlled density.
- Only a relatively shallow surface layer is cooled below 4 °C. When this surface layer is cooled to the ice point, 0 °C, ice is formed as the latent heat of fusion is extracted. In a deep lake the temperature at depth remains at 4 °C.

Deep water is a massive volume (80%) and very cold (2-5°C)

Surface Salinity







Surface salinity (psu) in winter (January, February, and March north of the equator; July, August, and September south of the equator) based on averaged (climatological) *data from Levitus et al. (1994b)*.

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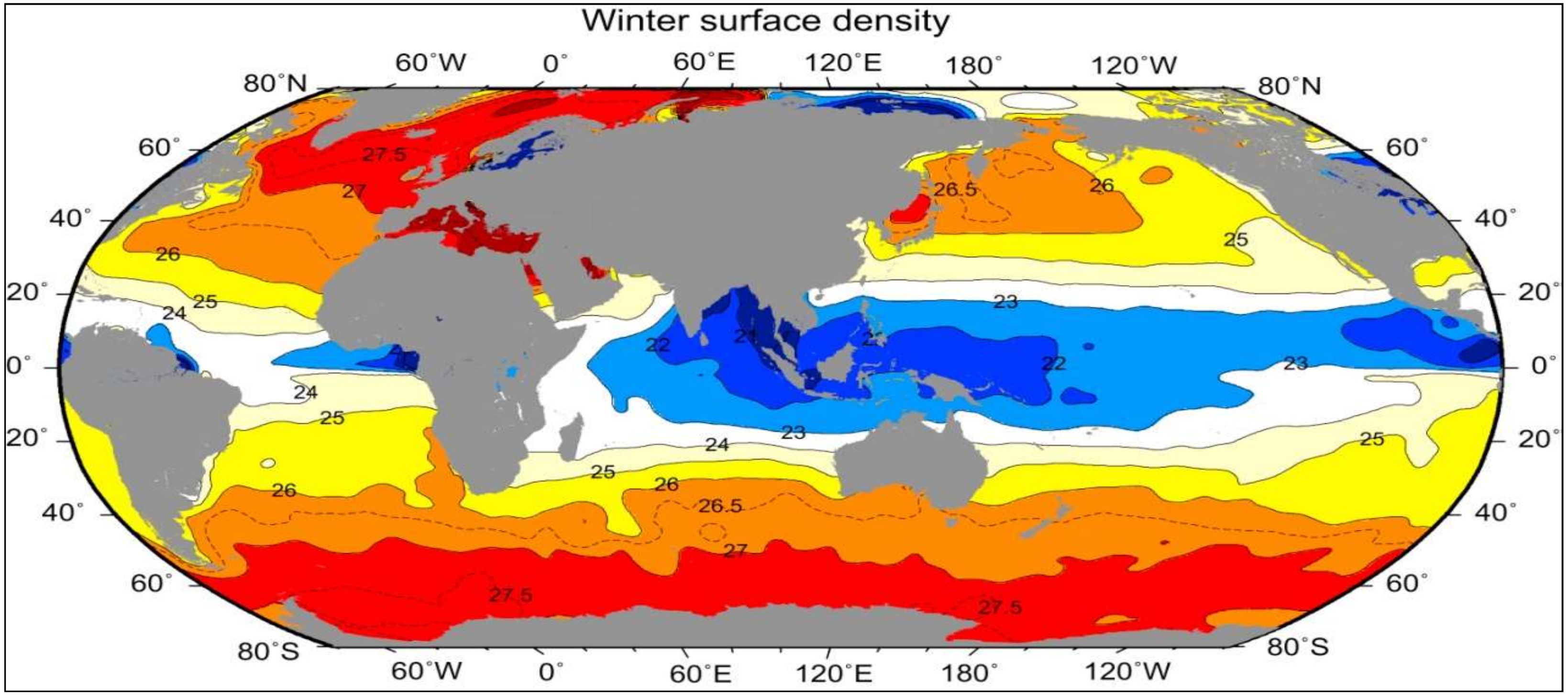

Surface density s_q (kg m^{-3}) in winter (January, February, and March north of the equator; July, August, and September south of the equator) based on averaged (climatological) *data from Levitus and Boyer (1994) and Levitus et al. (1994b)*.

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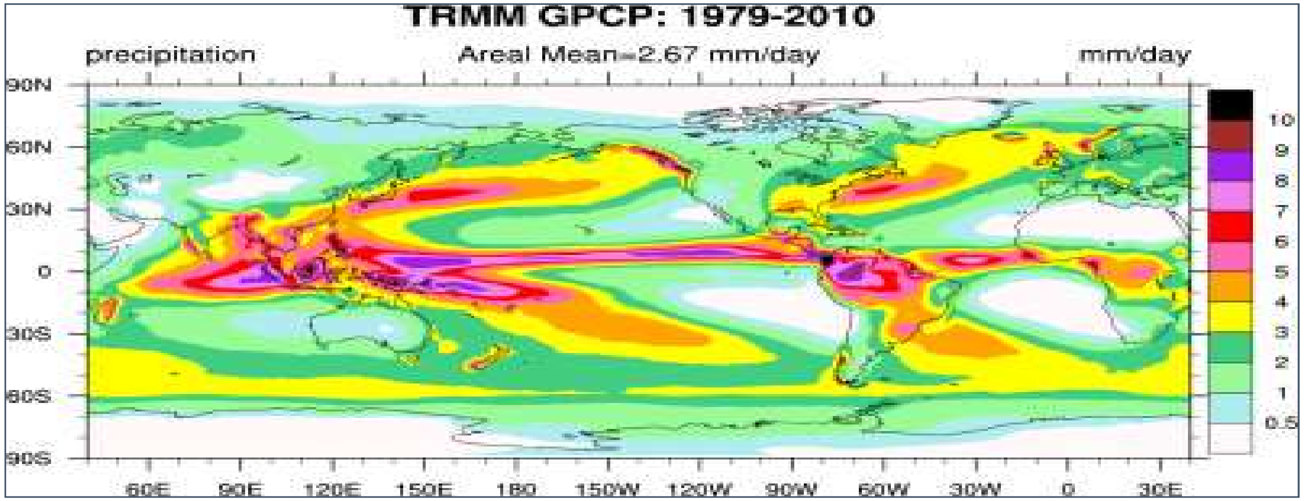
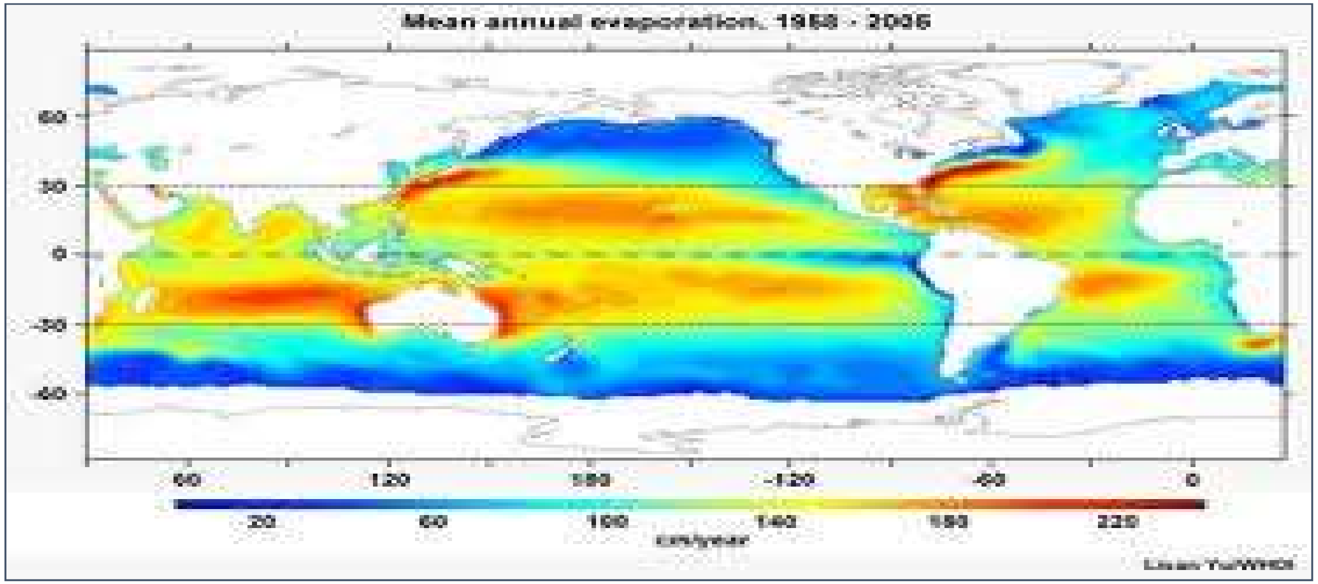
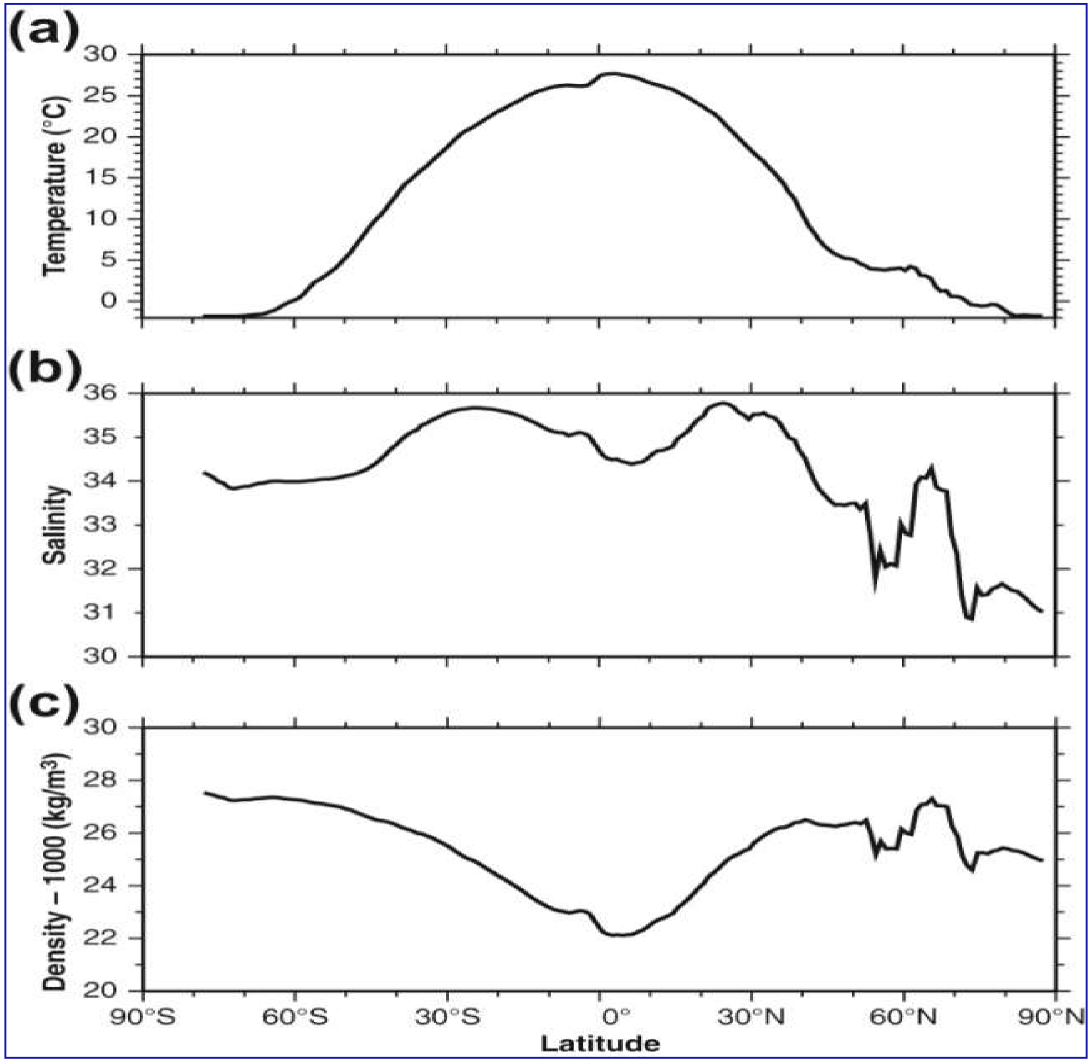

TRMM GPCP: 1979-2010
precipitation
Areal Mean=2.67 mm/day
mm/day
90N
60N
30N
0
30S
60S
90S
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
30E
10
9
8
7
6
5
4
3
2
1
0.5


Mean annual evaporation, 1958 - 2006
60
30
0
-30
-60
60
120
180
-120
-60
0
20
60
100
140
180
220
cm/year
Lisan Yu/WHOI

Variation with latitude of surface (a) temperature, (b) salinity, and (c) density averaged for all oceans for winter. North of the equator: January, February, and March. South of the equator: July, August, and September. Based on averaged (climatological) data from Levitus and Boyer (1994) and Levitus et al. (1994b).



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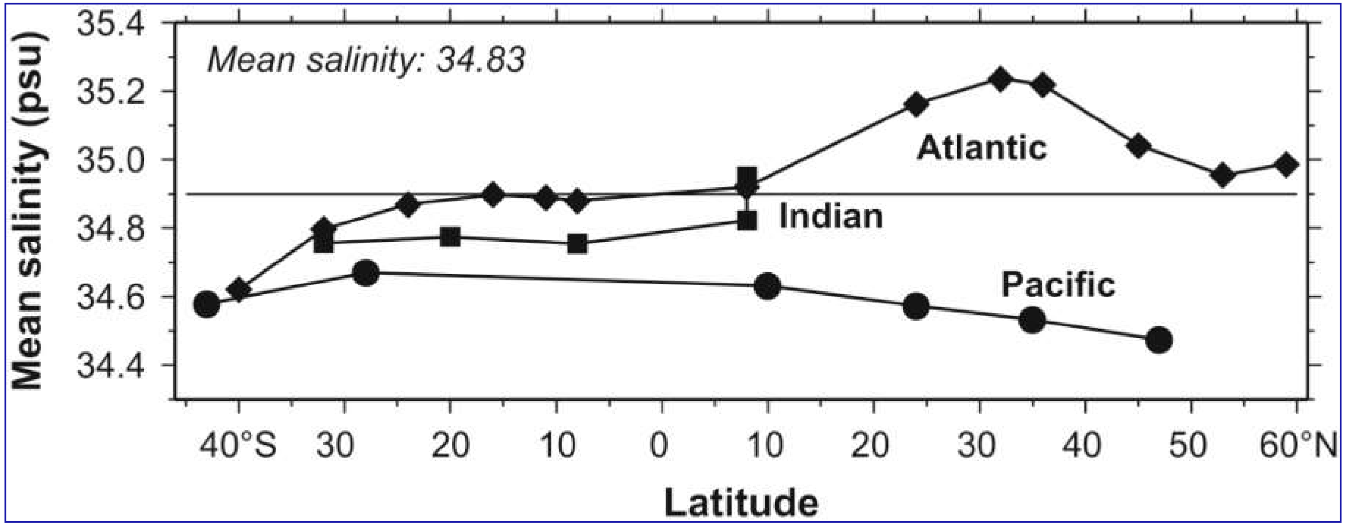

Mean salinity, zonally averaged and from top to bottom, based on hydrographic section data. The overall mean salinity is for just these sections and does not include the Arctic, Southern Ocean, or marginal seas. *Source: From Talley (2008).*

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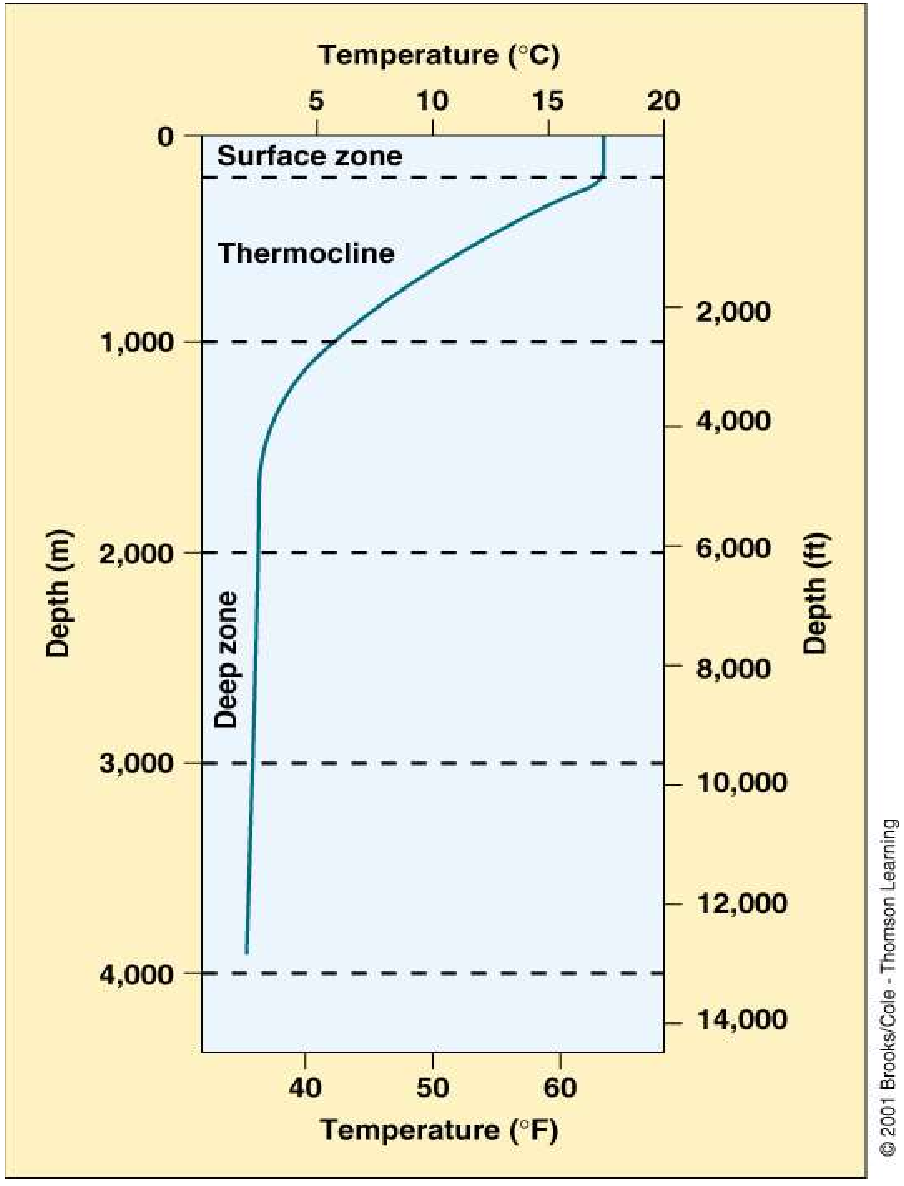
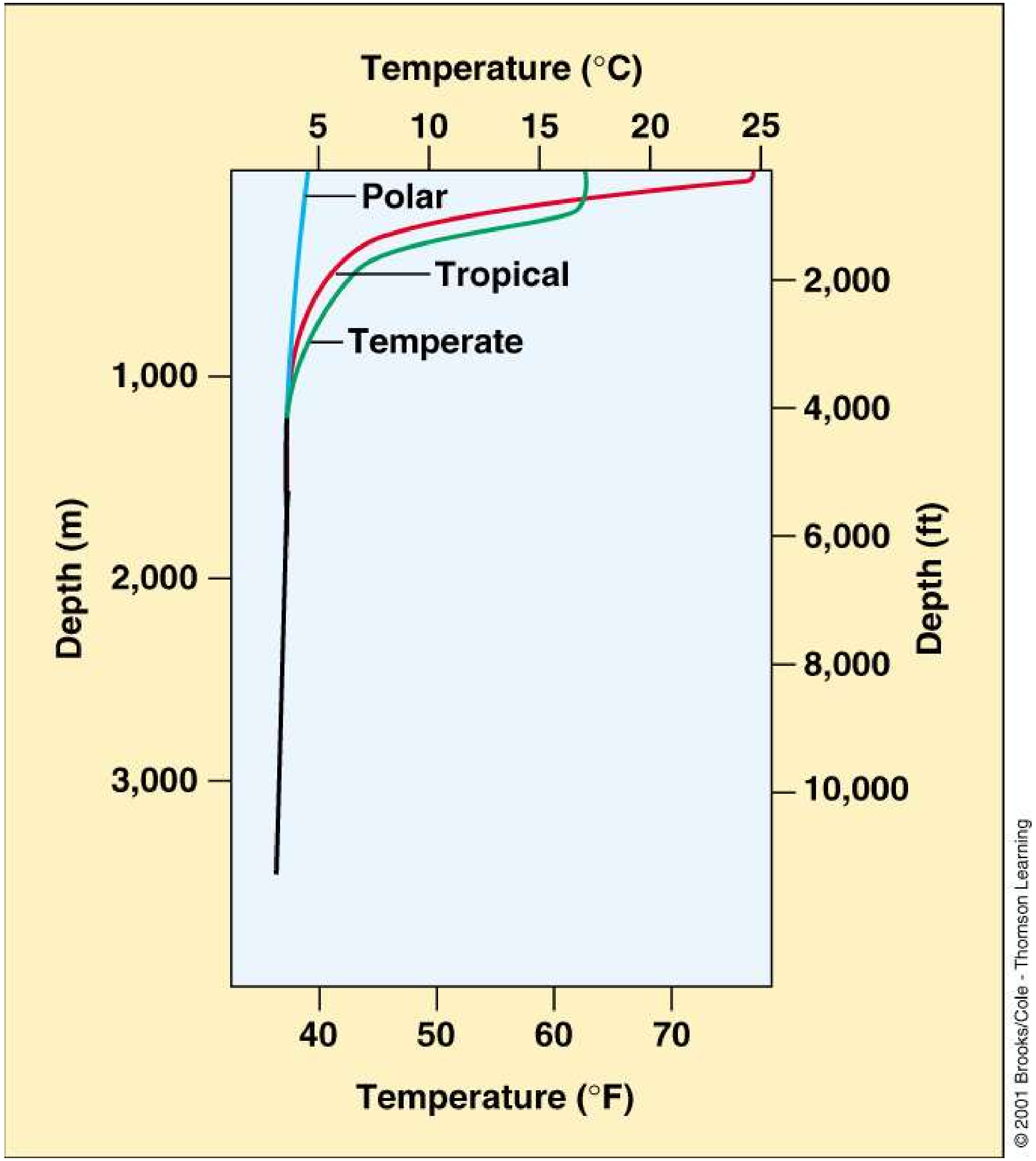
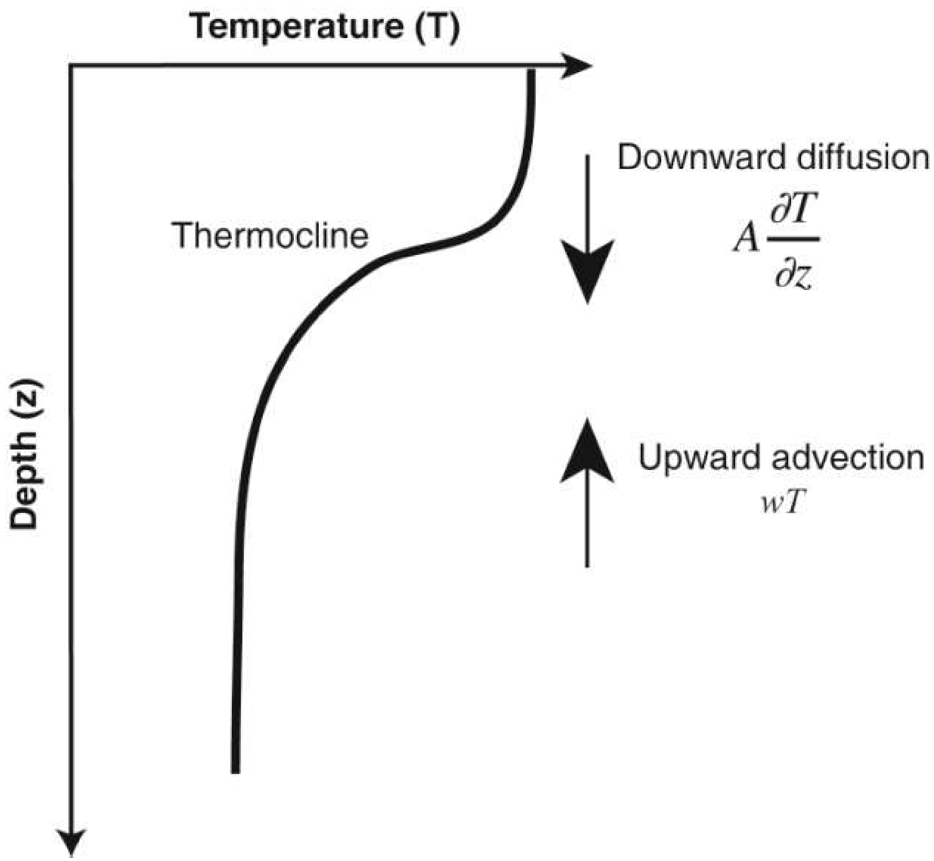
Vertical Structure:

- Temperature is the dominant factor in controlling density in the ocean, particularly when salinity does not vary dramatically.
- Surface water (<200 m) absorbs the majority of solar radiation and converts it to heat, slowly raising surface water temperature.
- A distinct layer of warmer lower density seawater forms at the surface zone when there is ample sunlight and calm conditions.
- The transition depths between warm surface zone and cold denser deep water is called the <u>thermocline</u> (*thermo* = heat; *cline* = change).



- Thermocline characteristics vary with latitude due to differences in solar radiation inputs with latitude.
- Weak to no thermocline is seen at the poles due to cold surface water being mixed by sinking and mixing by storms.
- When a thermocline does exists, we refer to the water as being <u>stratified</u> (layered).





Vertical processes that can maintain the thermocline in a simplified one-dimensional model.

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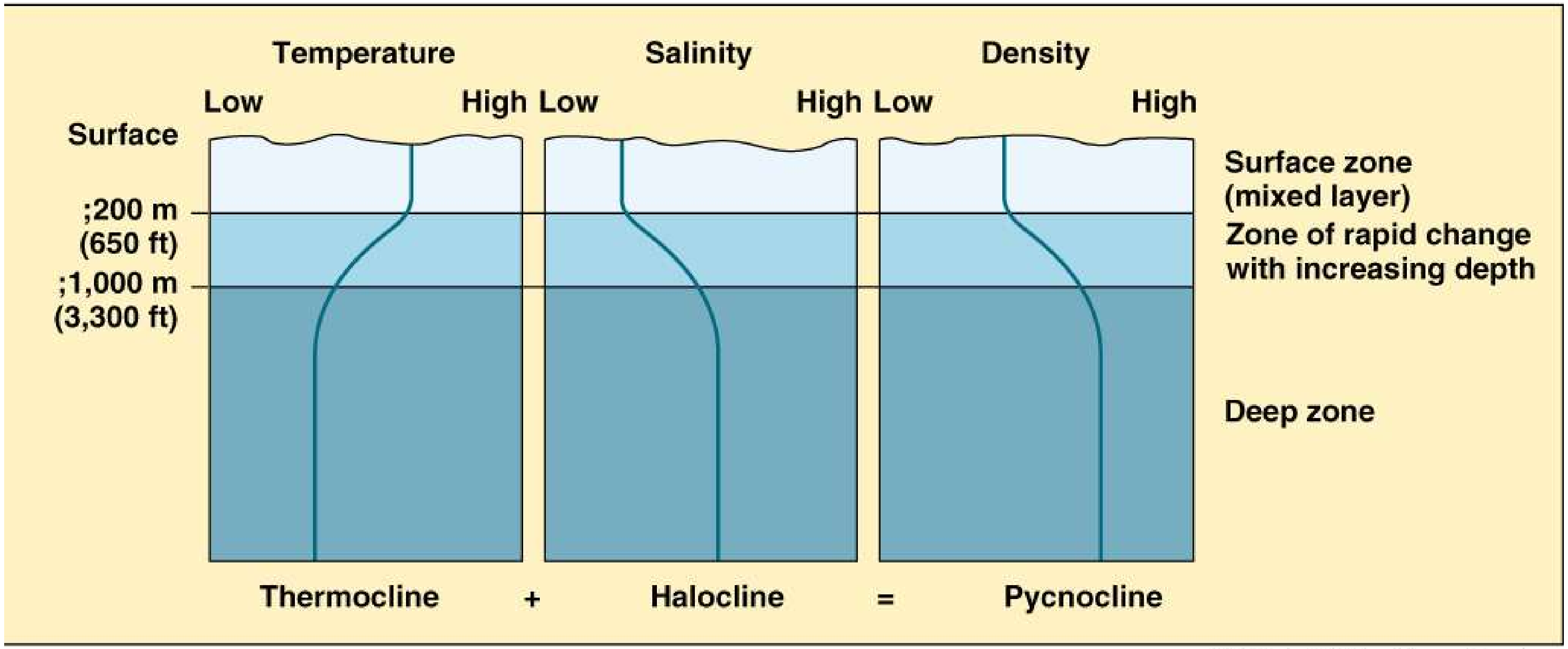
- Seawater can also be stratified due to density differences related to salinity. The depth of rapid salinity change is called a <u>halocline</u> (*halo* = salt).
- The combination of temperature and salinity determines overall density; the depth of rapid density change is called a <u>pycnocline</u> (*pycno* = density).



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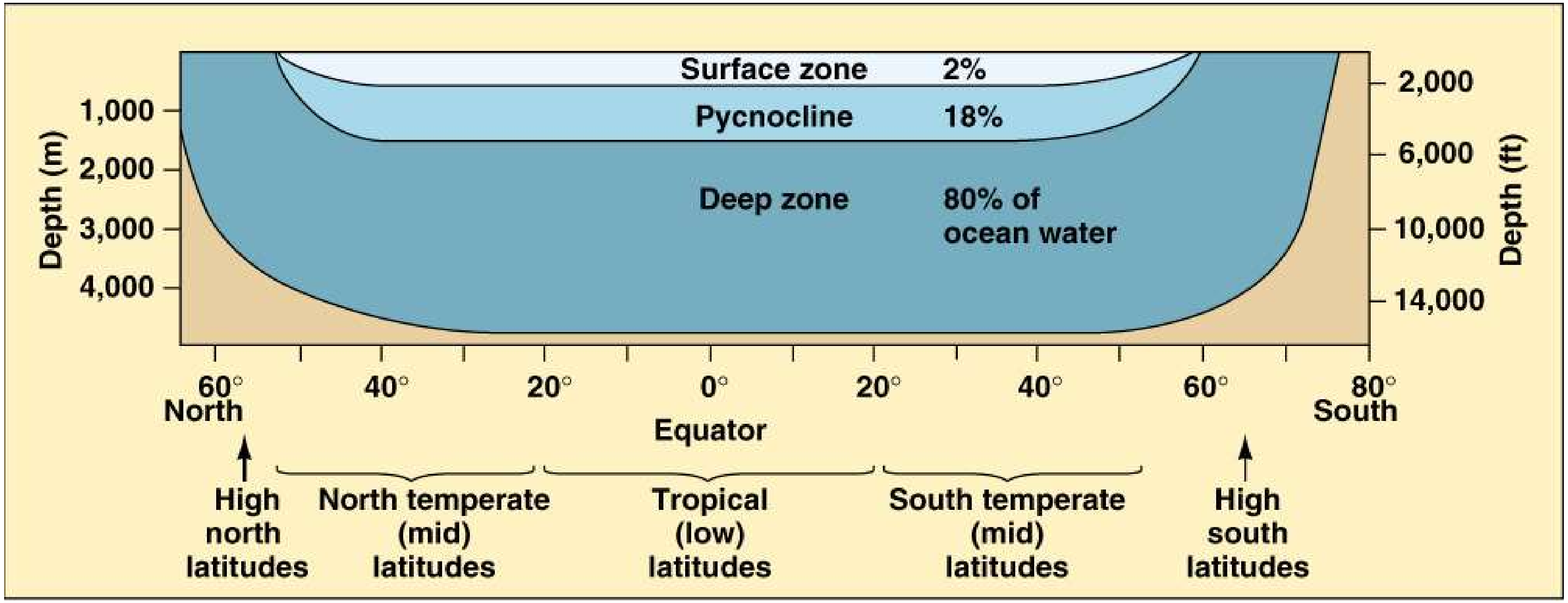
- Largely due to the temperature influence on density, pycnoclines are greatest (deepest) at the equator, and shallow to non-existent above 60º North of South latitude.
- Winds generate waves to keep the thin surface zone mixed to the top of the thermocline. Deep water is a massive volume (80%) and very cold (2-5ºC)



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Points to be noted

Density: 1034-1035 kg/m^3 (Pure water: 1000 kg/m^3) over 90% of the ocean. Depends on temperature and salinity.

Cold water → high density

Loss of water by evaporation → increase salinity → high density

Precipitation and river discharge → decrease salinity → low density

Heat capacity: high compared to land

Temperature: less variable than in the atmosphere

Freezing point: – 1.9°C, not at 0°C because of salinity

Two main forms of circulation:

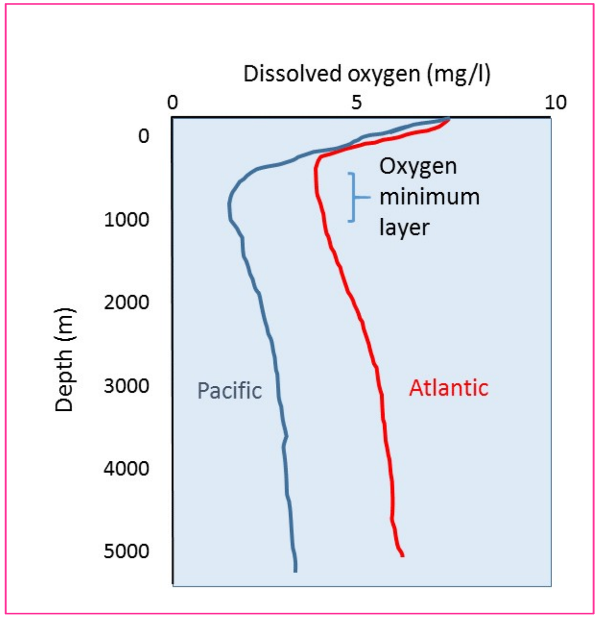
- wind-driven circulation (horizontal, surface waters, fast)
- thermohaline circulation (vertical, deep waters, slow)

Dissolved Gases: Oxygen

- **The oceans also contain dissolved gases that are very important to living organisms, particularly oxygen (O2), carbon dioxide (CO2), and nitrogen (N2).**
- **Oxygen is required for respiration in marine plants, algae, and phytoplankton (the primary producers) and animals.**
- **Carbon dioxide is utilized by the primary producers to power photosynthesis, a byproduct of which is oxygen.**
- **Nitrogen gas dissolved in the ocean is fixed by bacteria and converted into the forms required for primary production, such as nitrate and nitrite.**

Percentage of total gas in each compartment

	Air	Total Ocean	Surface Ocean
N2	78%	11%	48%
O2	21%	6%	36%
CO2	0.04%	83%	15%



Typical oceanic dissolved oxygen profiles are shown in Figure. The shape of the profile is determined by the various processes that add or remove oxygen from the water at different depths.

Representative dissolved oxygen profiles for the Pacific and Atlantic oceans. *https://rwu.pressbooks.pub/webboceanography/chapter/5-4-dissolved-gases-oxygen/*

- Oxygen content is highest at the surface for two main reasons; this is where oxygen dissolves into the ocean from the atmosphere, and the surface water is where oxygen is produced by phytoplankton through photosynthesis.
- As depth increases, dissolved oxygen declines, reaching a minimum between a few hundred meters and 1000 m deep, the aptly-named oxygen minimum layer.
- At these depths and below, the water is too far removed from the surface for any atmospheric exchange, and there is not enough light to support photosynthesis, so there is little if any oxygen added to the water.
- Below the oxygen minimum layer there is often an increase in dissolved oxygen at the greatest depths (Figures).
- In polar regions, the cold surface water absorbs lots of oxygen. This cold, oxygen-rich water sinks to the bottom due to its high density, taking the oxygen with it. The oxygen-rich bottom water will then spend the next thousand years or so moving over the seafloor throughout the major ocean basins. https://rwu.pressbooks.pub/webboceanography/chapter/5-4-dissolved-gases-oxygen/

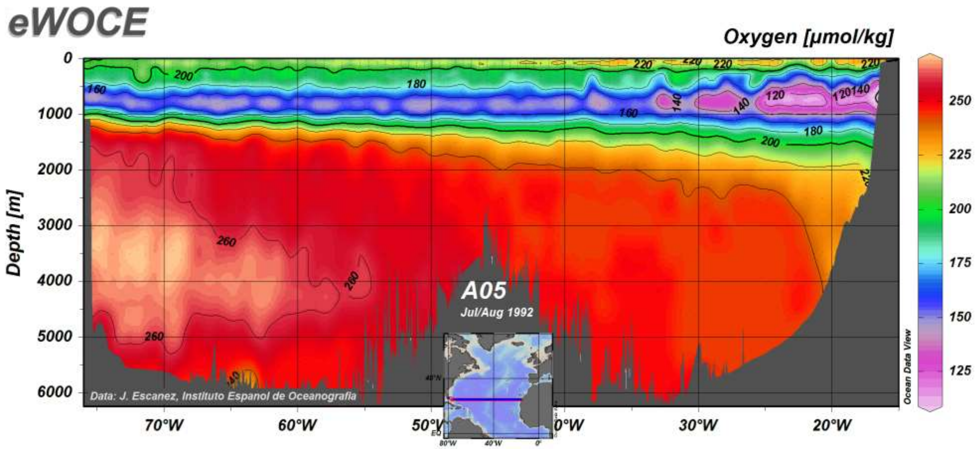


***Figure** Dissolved oxygen profile from a transect across the Atlantic Ocean from Florida to the coast of Africa (inset). The oxygen minimum layer is visible between 500-1000 m (eWOCE, http://www.ewoce.org/gallery/eWOCE_Tables.html#Atlantic).*

Sound (acoustical)

- Sound is a form of energy transmitted through pressure waves; longitudinal or compressional waves.
- With ocean sounds, the energy is transmitted via water molecules vibrating back and forth parallel to the direction of the sound wave, and passing on the energy to adjacent molecules.
- In other words, sound travels faster through denser materials. Since water is much denser than air, the speed of sound in water (about 1500 m/s) is approximately five times faster than the speed in air (around 330 m/s).
- At the surface, the pressure is low, but the temperature is at its highest point in the water column.
- The temperature effects dominate at the surface, so the speed of sound is fast in surface waters. As depth increases, the temperature and the speed of sound decline. Near the bottom, the extreme pressure dominates, and even though temperatures are low, the speed of sound increases with depth.

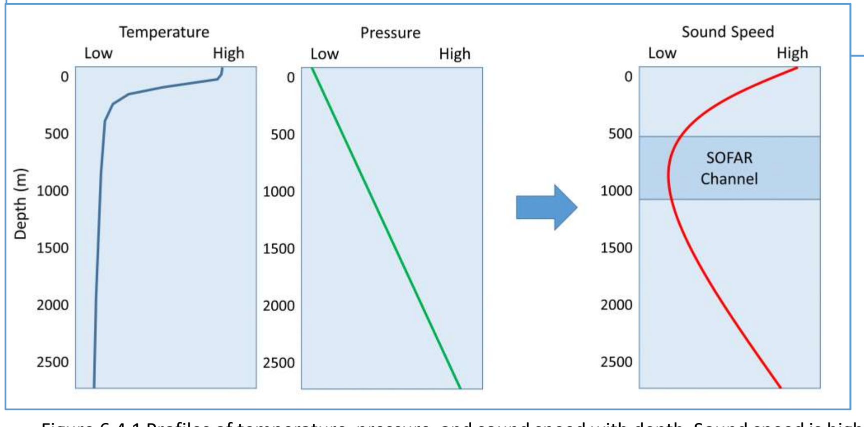


Figure 6.4.1 Profiles of temperature, pressure, and sound speed with depth. Sound speed is high at the surface due to the high temperatures, and is high at depth because of the high pressure. At moderate depths lies the SOFAR channel, the region of slowest sound speed (PW).

- At moderate depths (between a few hundred and one thousand meters) there is a zone where both temperature and pressure are relatively low, so the speed of sound is at a minimum. This zone of minimum speed is called the SOFAR channel (Sound Fixing And Ranging) or the Deep Sound Channel.

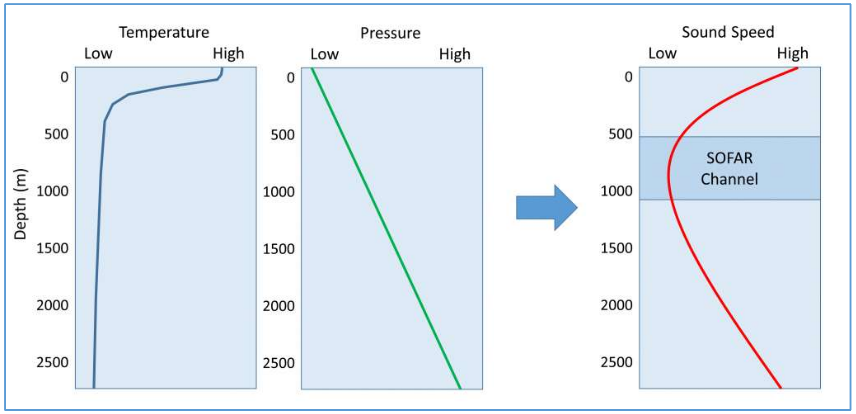


Figure 6.4.1 Profiles of temperature, pressure, and sound speed with depth. Sound speed is high at the surface due to the high temperatures, and is high at depth because of the high pressure. At moderate depths lies the SOFAR channel, the region of slowest sound speed (PW).

- The SOFAR channel is important because sounds produced in that region can be propagated over very long distances with little attenuation (loss of energy).
- Baleen whales are thought to use the SOFAR channel to communicate with each other over long distances of hundreds to thousands of kilometers. Their vocalizations are very loud and are low frequency calls, which travel farther than high frequency sounds in the oceans.
- The military has been able to track submarines using the SOFAR channel, and during World War II.

Optical or Light

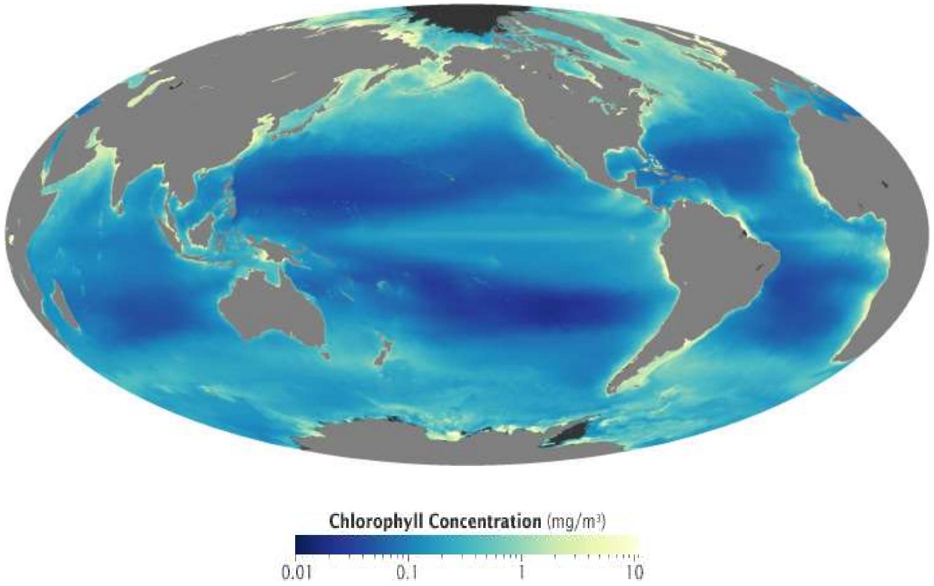
- **Solar Radiation** - initial source of energy to the Earth. It can be absorbed, reflected and reradiated. The redistribution of this energy controls the structure and dynamics of the Atmosphere and Oceans.

- **Solar energy is the primary heat source of the earth system. It not only provides energy to drive the atmospheric circulation but also can penetrate to a certain depth of ocean to provide energy for phytoplankton's photosynthesis.**

Phytoplankton: a flora of freely floating, often minute organisms (mostly plants) that drift with water currents. Like land vegetation, phytoplankton uses carbon dioxide, releases oxygen, and converts minerals to a form animals can use.

In fresh water, large numbers of green algae often colour lakes and ponds, and cyanobacteria may affect the taste of drinking water. Oceanic phytoplankton is the primary food source, directly or indirectly, of nearly all sea organisms.

https://www.britannica.com/science/phytoplankton



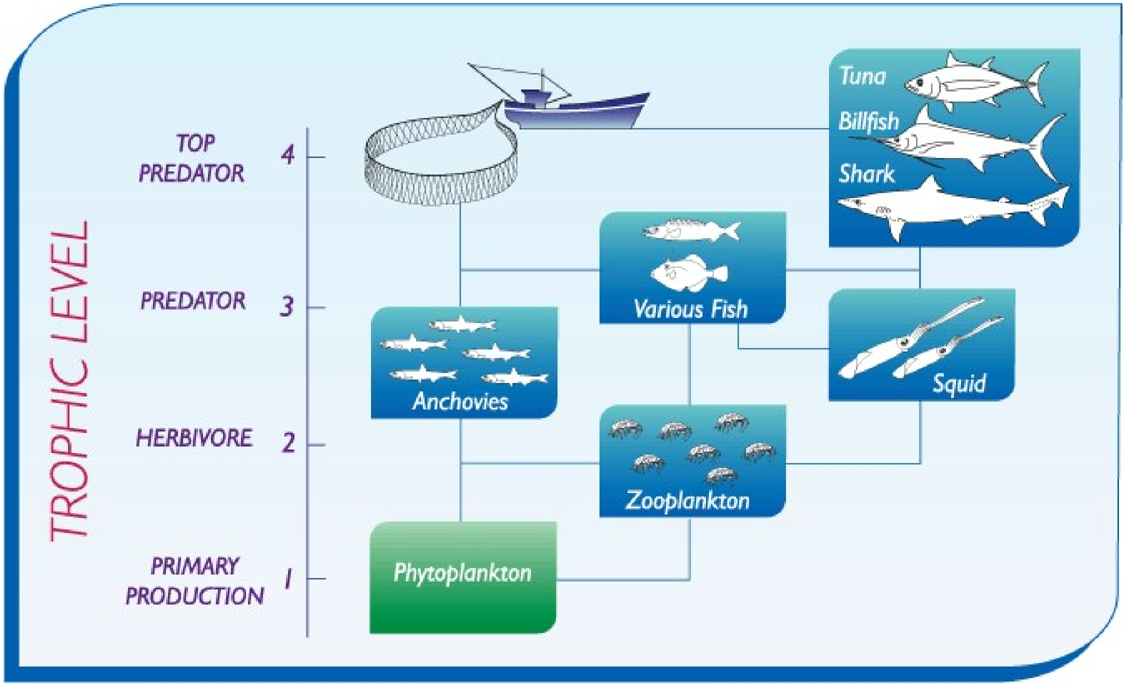
https://earthobservatory.nasa.gov/features/Phytoplankton

Individual phytoplankton are tiny, but when they bloom by the billions, the high concentrations of chlorophyll and other light-catching pigments change the way the surface reflects light.

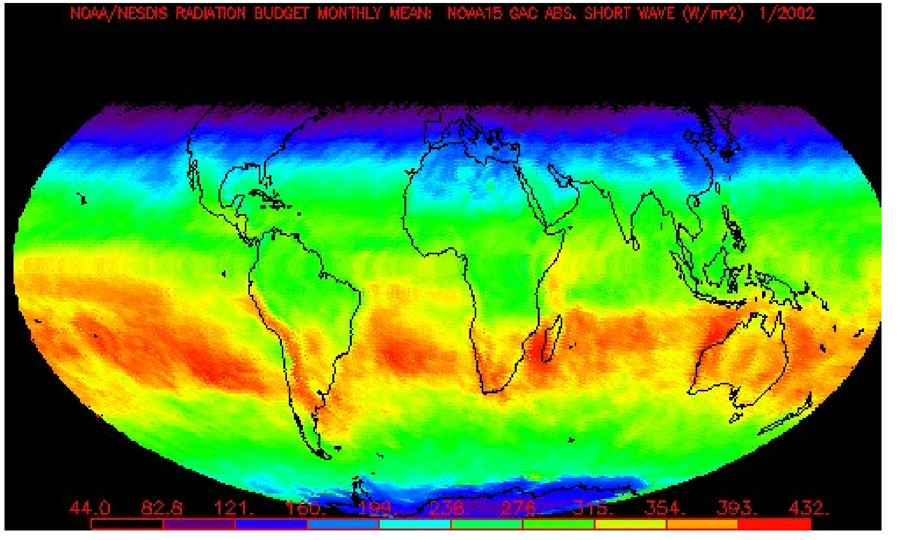
Sun Light is important : Primary production

Primary production refers to the amount of inorganic C (mainly carbon dioxide) converted to organic C (e.g. simple sugars) by microscopic algae in a process known as photosynthesis (photo – (sun) light; synthesis = to make something). Land plants also do a similar thing

Primary producers represent the base of the oceanic food chain and their abundance is critical to the abundance of animals higher in the chain

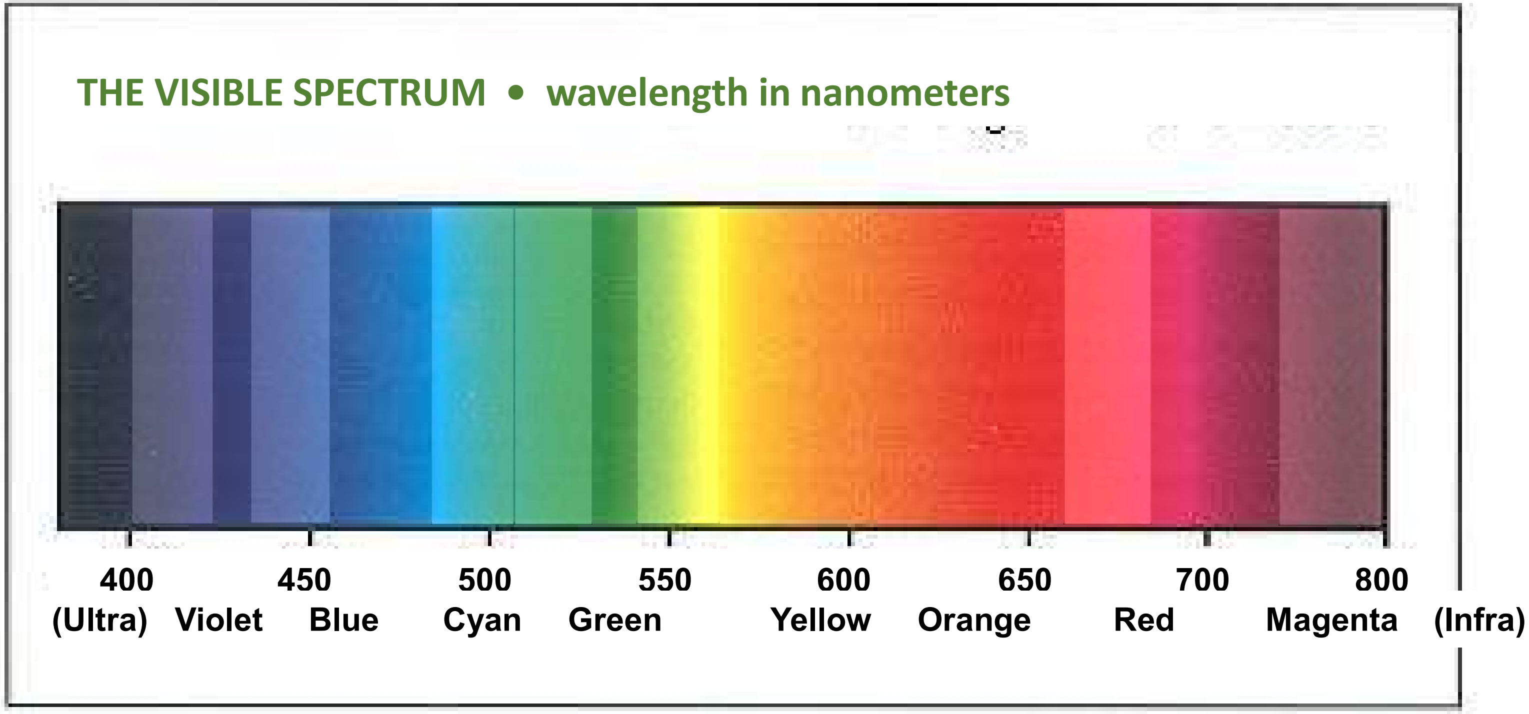


Absorbed Shortwave Radiation



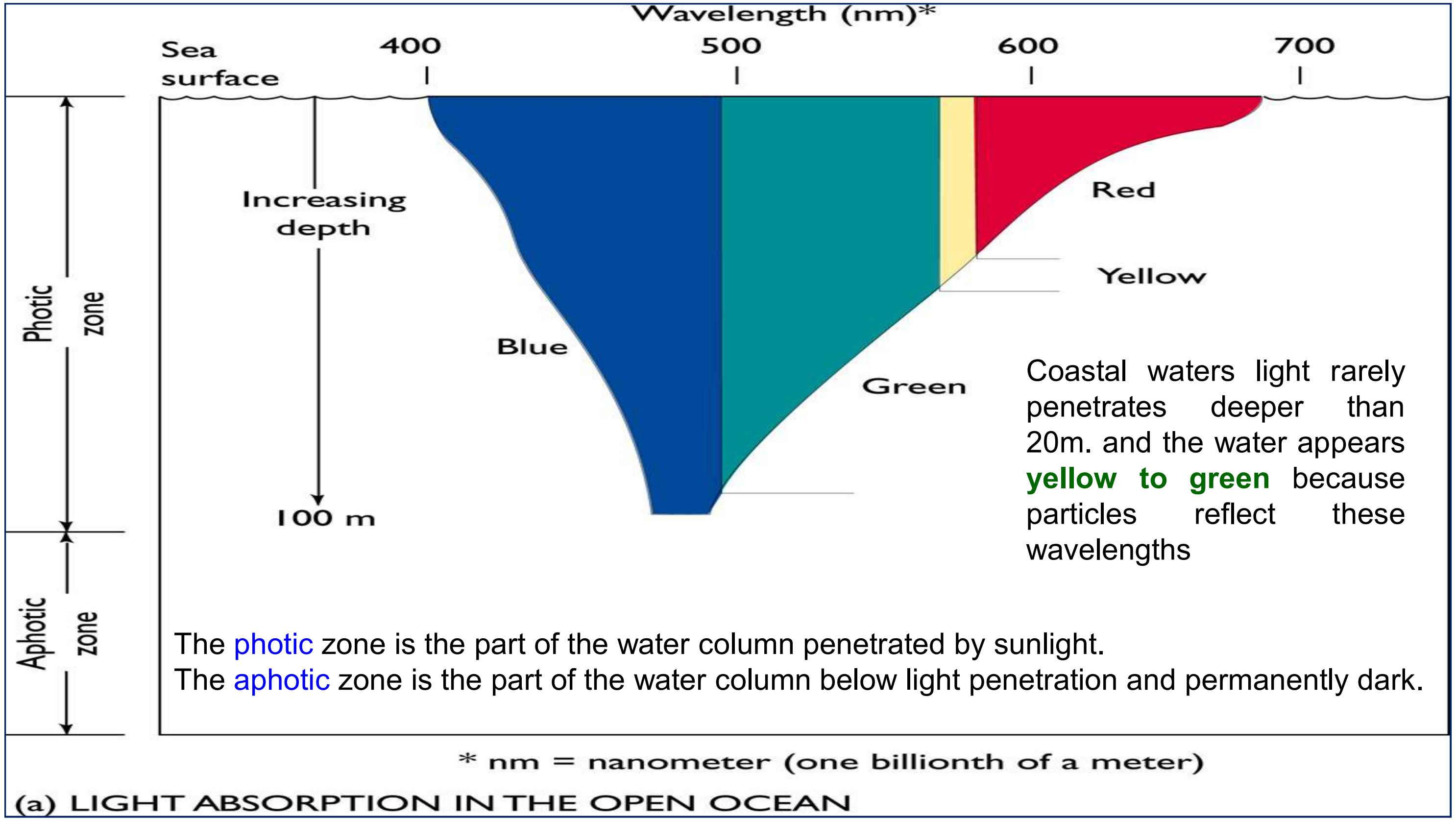
More solar radiation is absorbed by the oceans than adjacent lands about the equator due to clouds on land

Less solar radiation is absorbed at the poles than at the equator (in general)


THE VISIBLE SPECTRUM • wavelength in nanometers
400
450
500
550
600
650
700
800
(Ultra)
Violet
Blue
Cyan
Green
Yellow
Orange
Red
Magenta
(Infra)

- **Amount of light entering the ocean depends upon the height of the sun above the horizon and the smoothness of sea surface.**
- **65% of light entering the ocean is absorbed within the first meter and converted into heat. Only 1% of light entering the ocean reaches 100m. .**
- **Solar radiation consists of various wavelengths from 150 to 4000 nm. The heating due to infrared radiations with wavelengths from 700 to 4000 nm, which accounts for 40%–60% of the total downwelling surface ocean irradiance [*Mobley*, 1994], is almost absorbed totally in the top 2 m of ocean. The heating due to ultraviolet and visible light with wavelengths from 150 to 700 nm can penetrate much deeper than infrared radiations.**

Light Absorption, open ocean

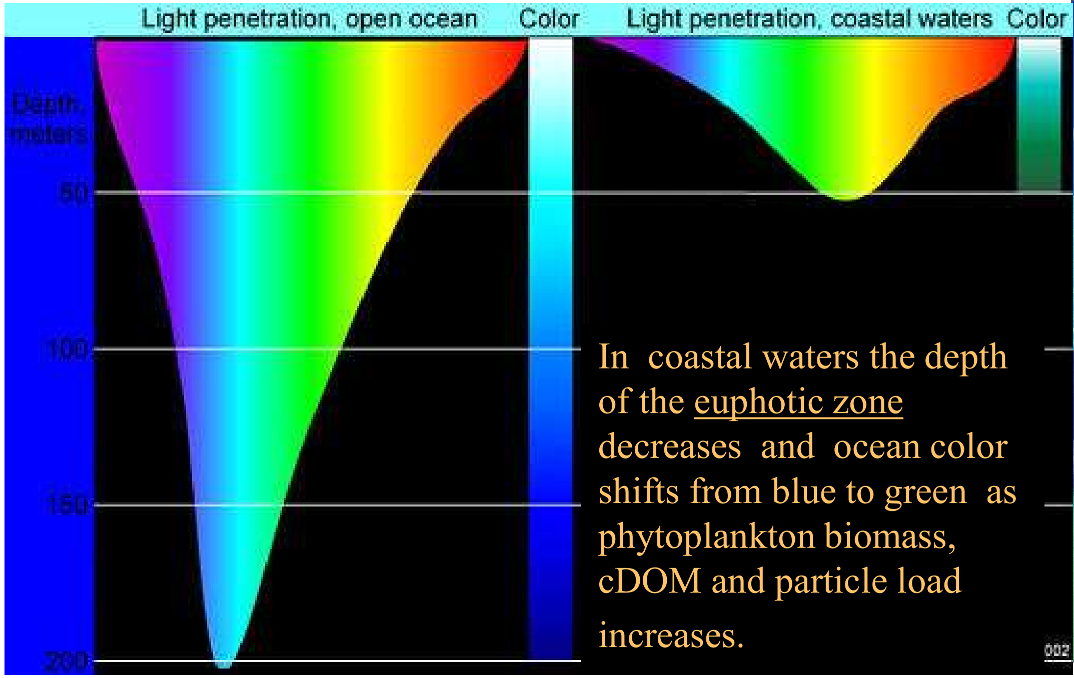


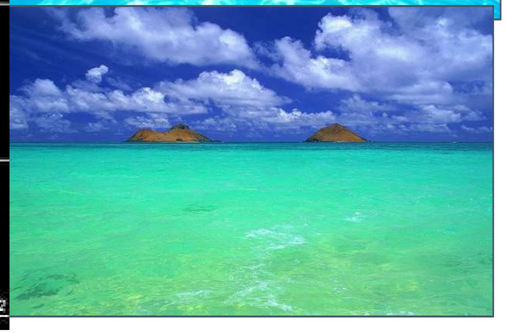
In the open ocean, blue light penetrates the deepest. Water displays the selective absorption of light with long wavelengths absorbed first and short wavelengths absorbed last.

Spectral properties of UWL vary widely

Case I: Open Ocean

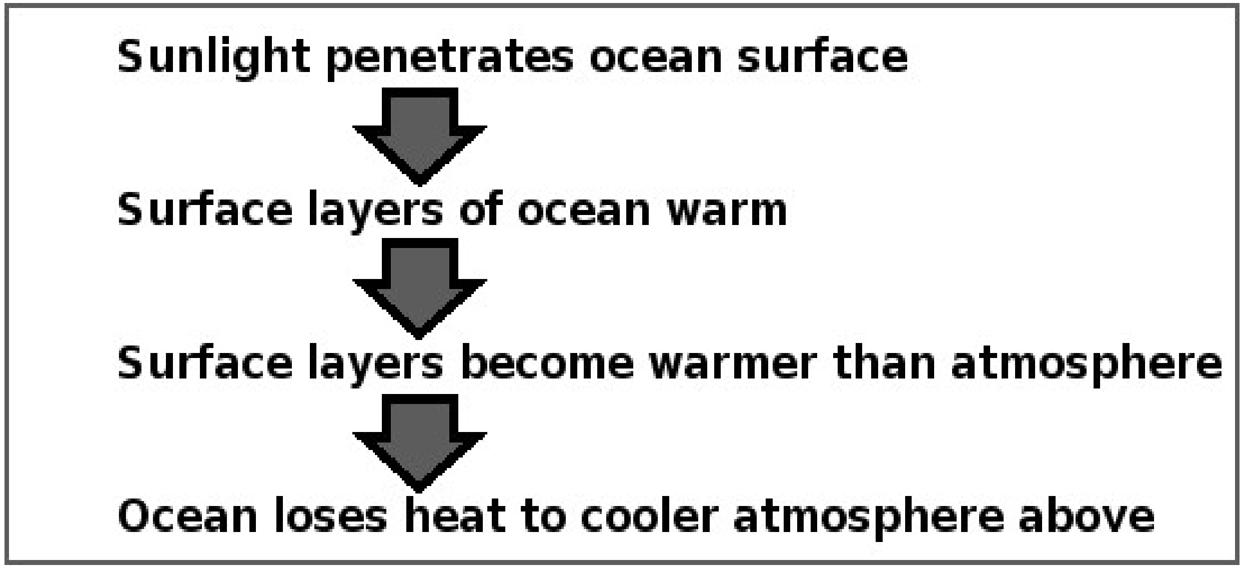
Case II: Coastal and Inland waters





Euphotic zone = depths where phytoplankton grow ~1% of surface Io

The ocean looks blue because red, orange and yellow (long wavelength light) are absorbed more strongly by water than is blue (short wavelength light). So when white light from the sun enters the ocean, it is mostly the blue that gets returned.



- **Ocean surface is directly warmed by solar radiation - loses heat to atmosphere.**
- **Air temperature a few meters above the surface tends to be slightly colder than the surface temperature.**

Neelin, 2011. *Climate Change and Climate Modeling,* Cambridge UP

1. Over half of the solar radiation reaching the Earth's surface is absorbed by the oceans.
2. The primary heat source for the oceans is solar radiation entering through the ocean surface. Almost all this insolation (incoming solar radiation) is absorbed in the top 100 metres.
3. Turbulent mixing in the surface layer is promoted by the interaction of wind and waves.
4. In the mixed layer of the ocean, convection and turbulence are so effective that the temperature and salinity are almost uniform (constant) with depth.
5. The global average thickness of the mixed layer is 70-100 metres.
6. The base of the mixed layer is marked by a horizon where the water properties change rapidly with depth – this is called the thermocline layer.

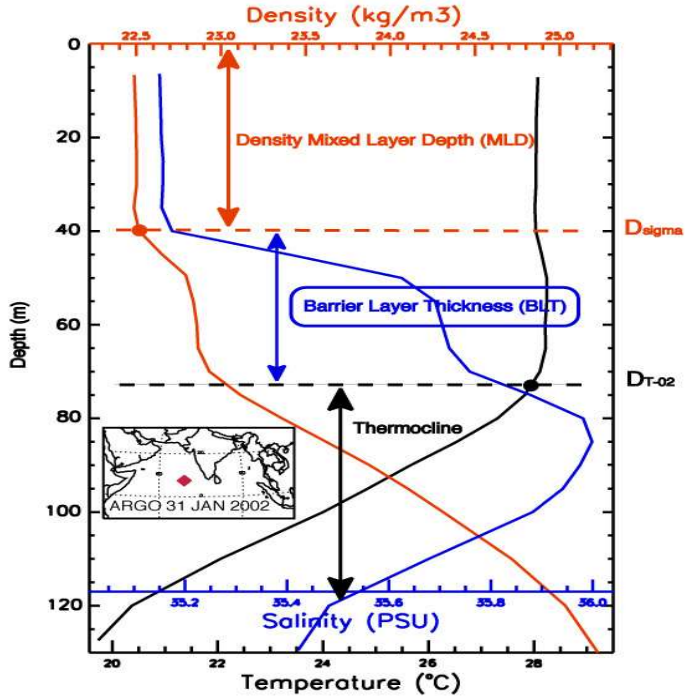
The ocean mixed layer (OML), the ocean region adjacent to the air–sea interface, is typically tens of meters deep, and due to the fact that it is well mixed, the temperature and salinity (and therefore the density) are fairly uniform. The rapidly changing regions below these uniform regions of temperature, salinity, and density are called the thermocline, halocline, and pycnocline, respectively.

An *isothermal layer* is defined as a vertical column having a constant temperature with depth.

Barrier Layer

When the top of the halocline is shallower than the top of the thermocline, the surface layer of the ocean, above the thermocline, is separated into two layers: the surface mixed layer, and the subsurface so called Barrier Layer

This BL have strong consequences on air-sea interactions as it thermodynamically insulates the deep cold ocean from the surface layer interacting with the atmosphere. Their thickness is a proxy of the amplitude of their thermodynamic barrier effect.

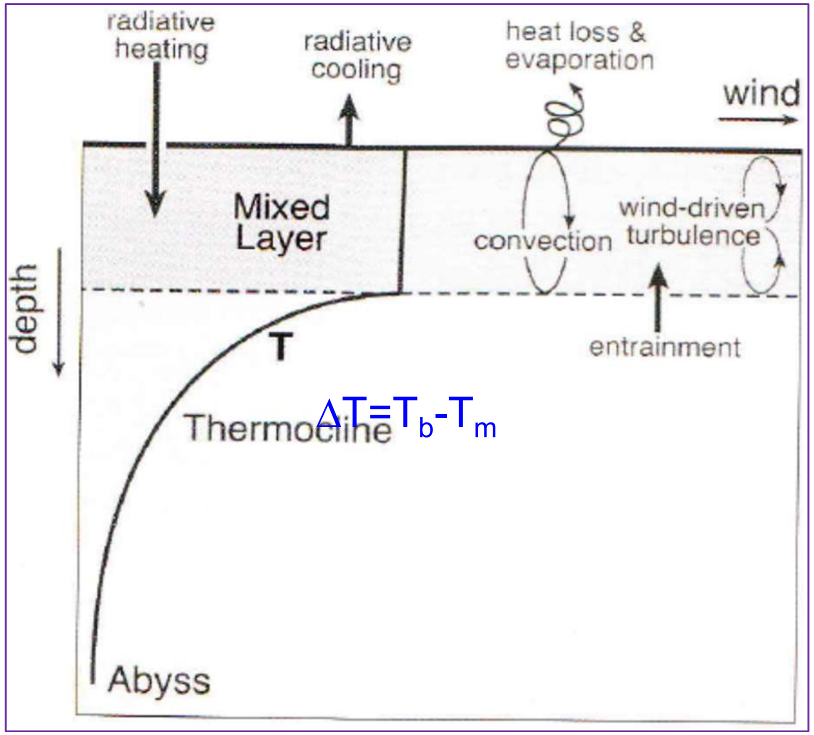


http://www.ifremer.fr/cerweb/deboyer/mld/Subsurface_Barrier_Layer_Thickness.php

What determines the mixed layer depth?

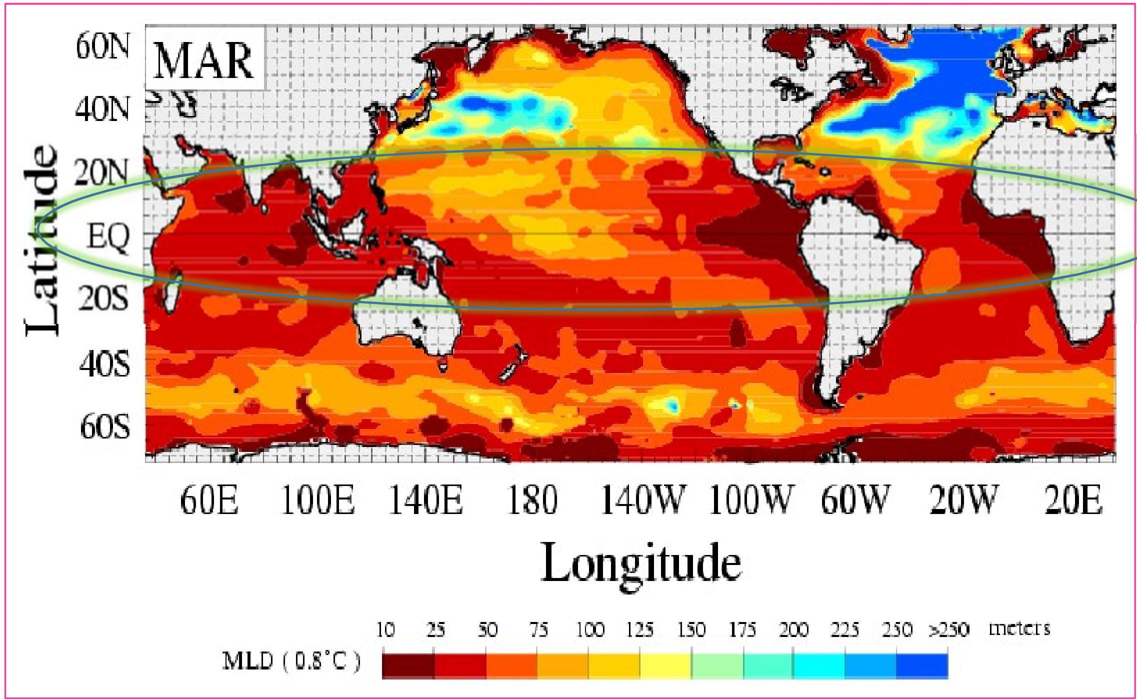
- ❑ **Mixing = vertical movement of particles**
- ❑ **Competition between kinetic energy of particle and stabilizing effect of environment**

- Turbulence creates a well mixed surface layer where temperature (T), salinity (S) and density (ρ) are nearly uniform with depth
- Primarily driven by vertical processes (assumed here) but can interact with 3-D circulation
- Density jump usually controlled by temperature but sometimes by salinity (especially in high latitudes)
- Often " measured" by the depth at which T is some value less than SST (e.g. $\Delta T = 0.5$)
- Under goes large seasonal cycle
- This impacts the evolution of ocean temperature anomalies and has important biological consequences

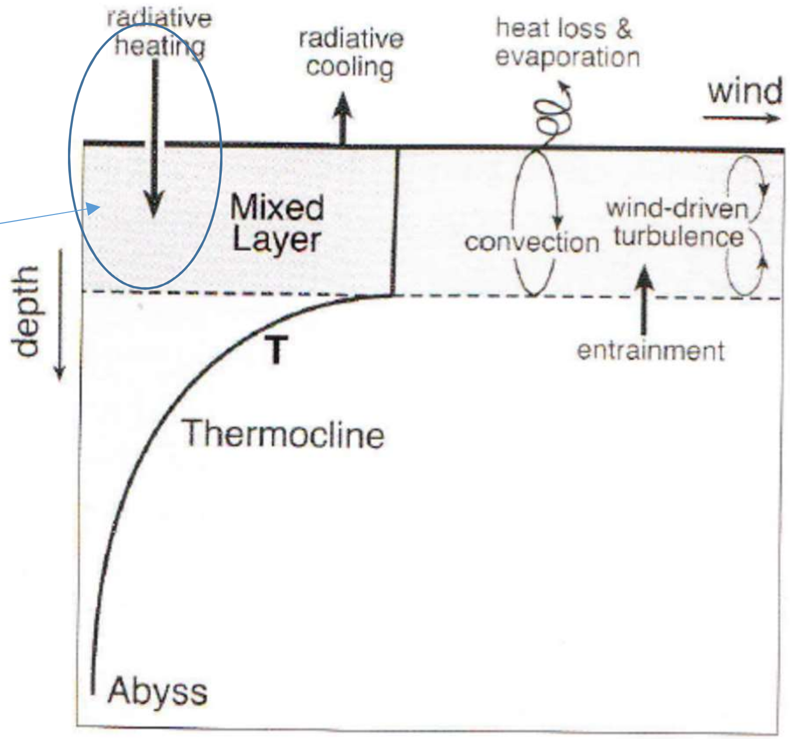


What can make the mixed layer shallower?

• **Positive buoyancy fluxes (positive heat fluxes and/or rainfall) => stabilizes mixed layer**



Kara et al., (2003)



When Shoaling:

$w_e = 0$ (no detrainment, h reforms closer to the surface)

$h = M / (B - D)$

What causes deep the mixed layer?

- **Wind => increases kinetic energy of upper ocean particles and thus easier to overcome stratification**
- **Negative buoyancy fluxes (negative heat fluxes and/or evaporation) => destabilize mixed layer**

Entrainment "To pull or draw along after itself"
MLD – Mixed Layer Depth or h

When deepening:

$dh/dt = w_e$

$w_e = M + B - D / (\Delta\rho - S)$

Where

M - Mechanical Turbulence (wind stirring)
B - Buoyancy Forcing
Net surface heating/cooling (Q_{net})
Precipitation – Evaporation (P-E)
D - Dissipation (εh)
$\Delta\rho$ - Density jump at base of the ML
S - Shear across ML

$B = \rho_o [a (\rho_o C_p)^{-1} Q_{net} - b S_o (E - P)]$

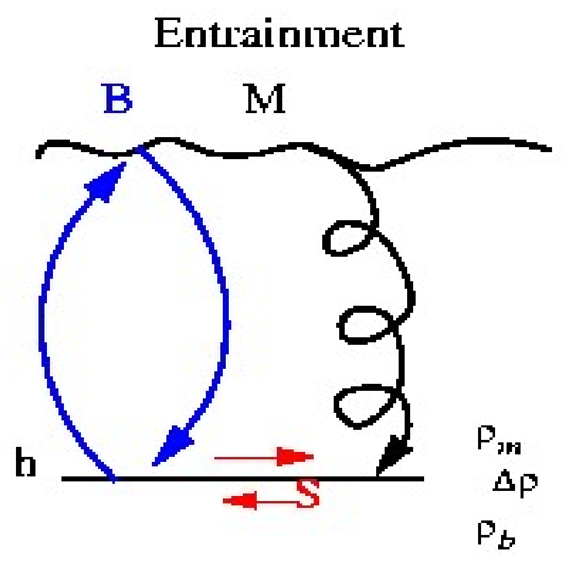
ρ_o = surface density

S_o = surface salinity

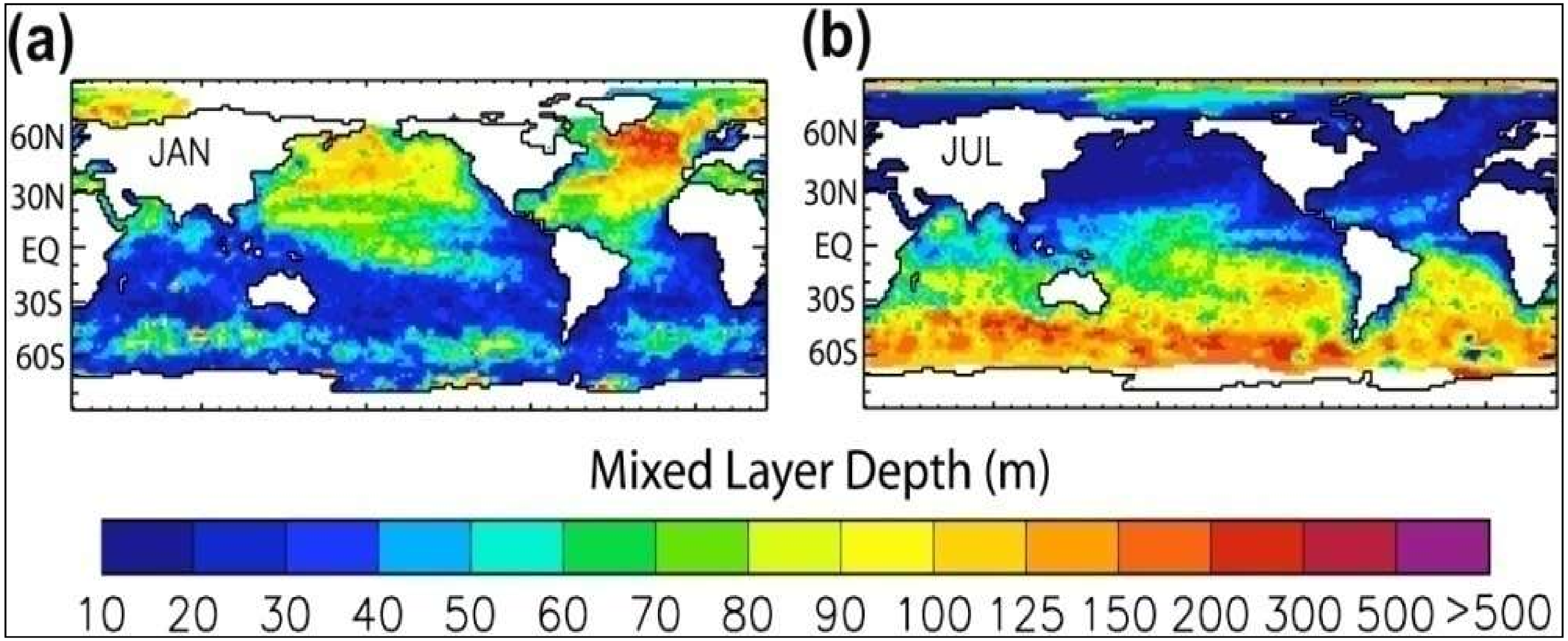
a, b = Expansion coefficients for heat and salt

C_p= heat capacity

Positive buoyancy flux is stabilizing



- **dh/dt: entrainment (when mixed layer deepens, it incorporates deeper colder water so this cools the mixed layer)**
- **Even when dh/dt = 0, turbulent movements near the bottom of the mixed layer also bring cold water into the mixed layer**
- **Those two processes are favoured by strong winds and/or negative buoyancy fluxes (i.e. cooling and/or evaporation)**



Mixed layer depth in (a) January and (b) July, based on a temperature difference of 0.2°C from the near-surface temperature. *Source: From deBoyer Montégut et al. (2004).*

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Summary MLD

1) Mixed layer: homogeneous layer (T, S, other properties as oxygen, etc…) that exchanges properties with atmosphere.

2) Existing stratification controls mixed layer (hard to mix through thermocline)

3) Mixed layer can be deepened by strong wind and/or negative heat fluxes/evaporation

4) Mixed layer can become shallower because of weak wind and/or positive heat fluxes/rainfall

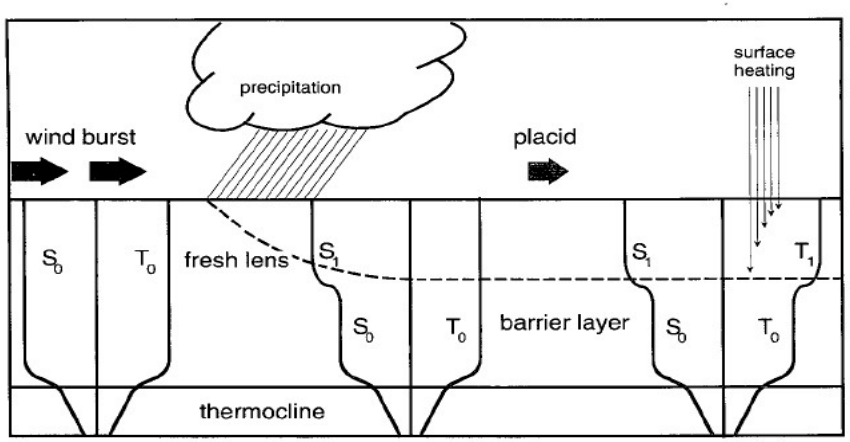
Functional definition: depth at which the water is 0.125 denser than the sigma-theta at the sea surface.

MLD estimation based on density variation (σt) determined from the corresponding temperature change T (0.8 ◦C) using the equation of state (Kara et al., 2000).

Ocean Barrier Layer

When the ocean is stratified by salinity, there is a difference between isothermal layer depth (ILD) and mixed layer depth (MLD). The ILD is typically determined by a temperature criterion while the MLD is obtained using the density criterion. The barrier layer thickness (BLT) is then defined as the difference between the ILD and MLD.

Say fresh water from rivers in Bay : Less density in upper few meters and high salinity water below that (high density) …so stratification is stronger ….Salinity plays an important role here…..



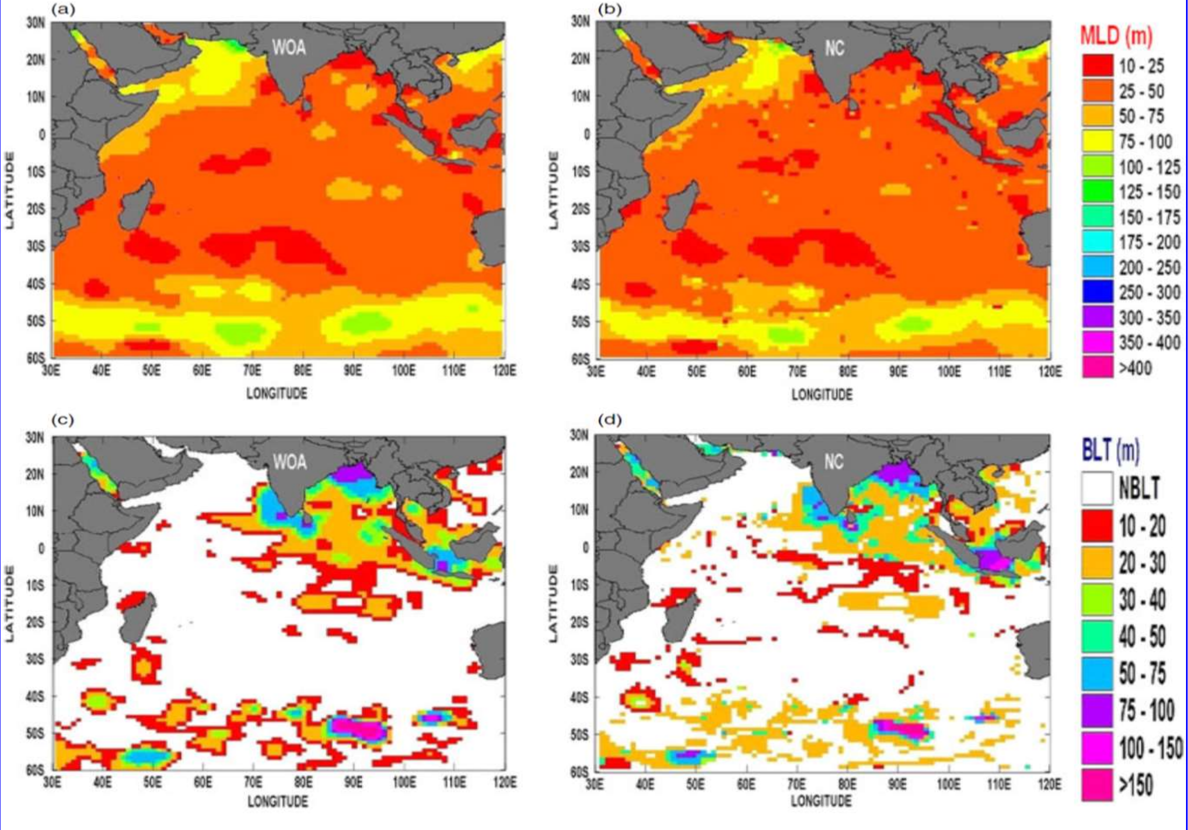


Figure 3. MLD for January using (a) WOA and (b) NC; BLT for January (c) WOA and (d) NC.

Vissa et al. 2013

In the tropical belt intense precipitation, wind, and circulation patterns along with river runoff can result in the formation of thick and persistent BL (Mignot *et al.*, 2007).

Presence of BL can have significant impact on mixed layer dynamics and heat budget within the MLD (Sprintall and Tomczak, 1992).

Over the north Indian Ocean high SSTs in Bay of Bengal along with large pool of fresh water cap by river runoff and open ocean precipitation produces 'BLs' (e.g., McPhaden *et al.* 2009).

As such this phenomenon isolates the surface from cooling of sub-surface waters which can energize tropical storms in the Bay of Bengal.

Barrier layer thickness (BLT) can influence the sea-surface temperature (SST).

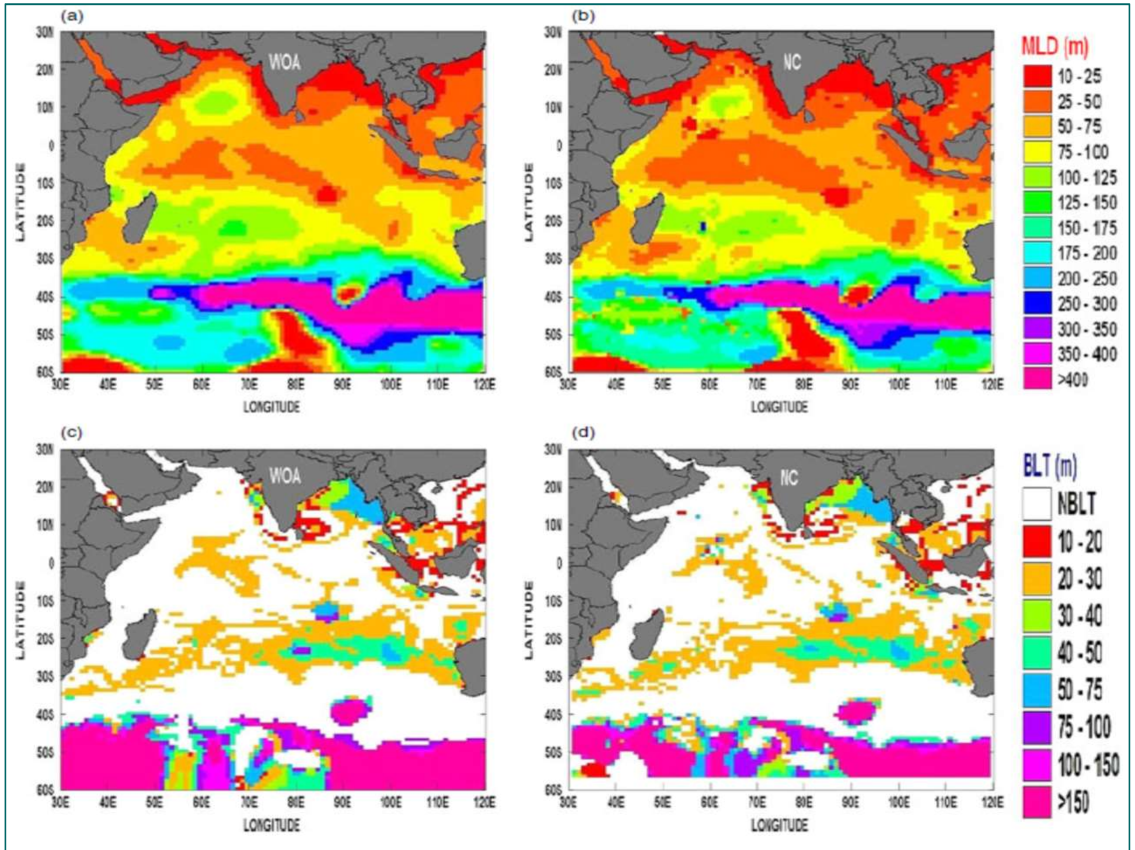
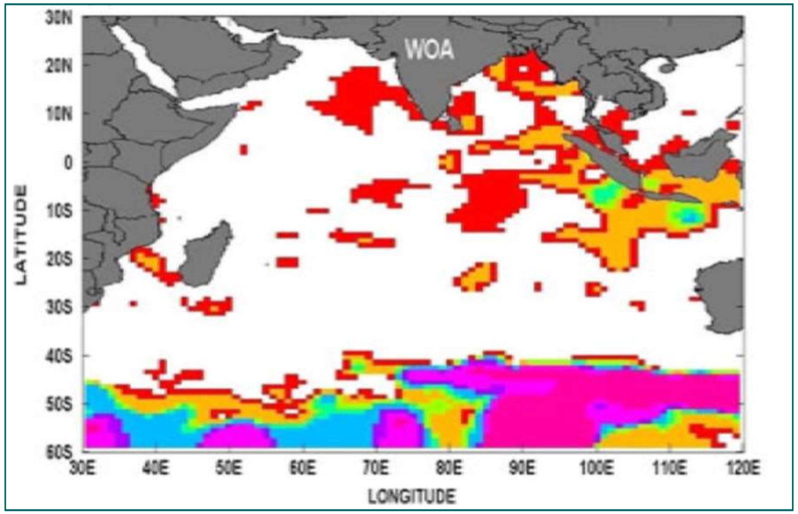


Figure 10. MLD for August using (a) WOA and (b) NC; BLT for August (c) WOA and (d) NC.

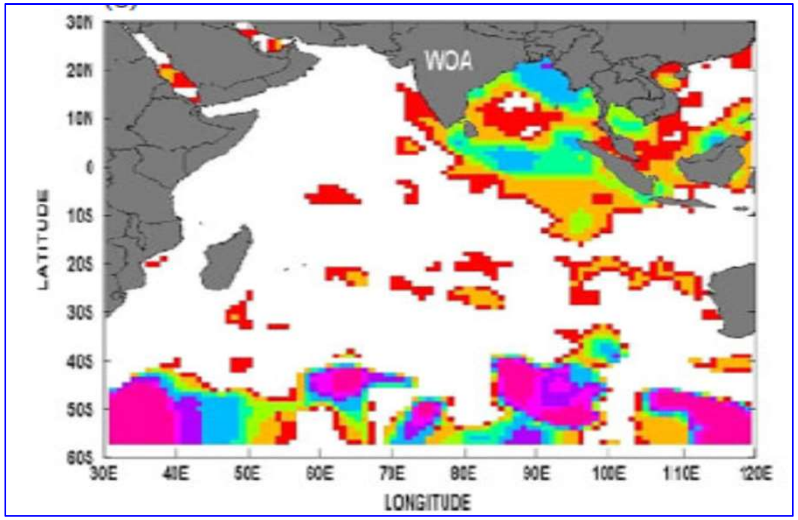
BLs may also contribute to the heat build-up necessary for El Niño development (Maes et al., 2005) and therefore play an important role in the onset of El Niño Southern Oscillation events (Maes et al., 2002, Maes et al., 2004).

In the southeastern Arabian Sea, Masson et al. (2005) show that the BL enhances spring SST warming and leads to a statistically significant increase in precipitation in May linked to an early monsoon onset.

In the tropical Atlantic Ocean, Foltz and McPhaden (2009) find that seasonal variations in BL thickness exert a considerable influence on SSTs through the modulation of vertical heat flux at the base of the mixed layer.



May



November

- ✓ **Seawater is almost incompressible; since at enormous pressures in the interior ocean compressibility effects are not always negligible.**
- ✓ **Fresh water ($S = 0$) *has a maximum* density at about 4◦C: fresh water that is colder than this is less dense. This is why ice forms on the top of freshwater lakes.**
- ✓ **Range of temperatures and salinities found in the open ocean (0–30◦C and 33–36 psu).**
- ✓ **Temperature typically influences density more than salinity.**
- ✓ **Below the thermocline layer, in the deep ocean, there exist slow circulations driven primarily by density gradients. These currents are quite weak.**
- ✓ **The mixed layer responds quickly to changes in the surface climate, whereas the deep ocean layer does not.**
- ✓ **The thermal properties of the deep ocean constitute a time lag in the climate system on the scale of 1000 years.**

Ocean atmosphere similarity and dissimilarity

- **The ocean, like the atmosphere, is a stratified fluid on the rotating Earth. The two fluids have many similarities in their behavior and, especially, in their fluid dynamics.**
- **The fluids are physically different. Water is (almost) incompressible and ocean thermodynamics has no counterpart to atmospheric moisture (as a source of latent heat).**
- **Unlike the atmosphere, all oceans are laterally bounded by continents except in the Southern Ocean where the ocean extends all the way around the globe and fluid can pass**
- **The ocean circulation is forced in a different way than the atmosphere. Atmosphere is largely transparent to solar radiation and is heated from below by convection. The ocean exchanges heat and moisture with the atmosphere at its upper surface; convection in the ocean is driven by buoyancy loss *from above*.**

- **Forcing the ocean circulation that has no counterpart in the atmosphere. Winds blowing over the ocean surface exert a *stress on it. The wind is a major* driver of ocean circulation, particularly in the upper kilometer or so.**
- **Abyssal ocean currents are, in the mean, weak, and temperature changes very slight, so the erosion of submarine relief by ocean currents occurs at a much slower rate than that of the mountains on land.**

Properties of seawater; equation

Physical properties of liquid water

- Specific heat c_w $4.18 \times 10^3\ J\ kg^{-1}\ K^{-1}$ (Heat capacity, 1000 times than atmosphere).
- Mean density 1.035×10^3 kgm^{-3}
- Latent heat of fusion L_f $3.33 \times 10^5\ J\ kg^{-1}$
- Latent heat of evaporation L_e $2.25 \times 10^6\ J\ kg^{-1}$
- Density of fresh water ρ_{fresh} $0.999 \times 10^3\ kg\ m^{-3}$
- Viscosity μ *water* $10^{-3}\ kg\ m^{-1}\ s^{-1}$
- Kinematic viscosity $\nu = \mu_{water} / \rho =$ $10^{-6}\ m^2\ s^{-1}$
- Thermal diffusivity k $1.4 \times 10^{-7}\ m^2\ s^{-1}$
- Water has an albedo of around 10%

- The density of pure water at 4◦C is 0.999×10^3 kgm−3. The mean density of seawater is only slightly greater, 1.035×10^3 kgm^{-3}.

- Unlike air, the density of seawater varies rather little, by only a few %,

- Cold water is denser than warm water; salty water is denser than fresh water; pressure increases the density of water.

- Density depends on temperature *T, salinity S, and* pressure *p in a rather complicated, nonlinear* way, $\rho = \rho(T, S, p)$.