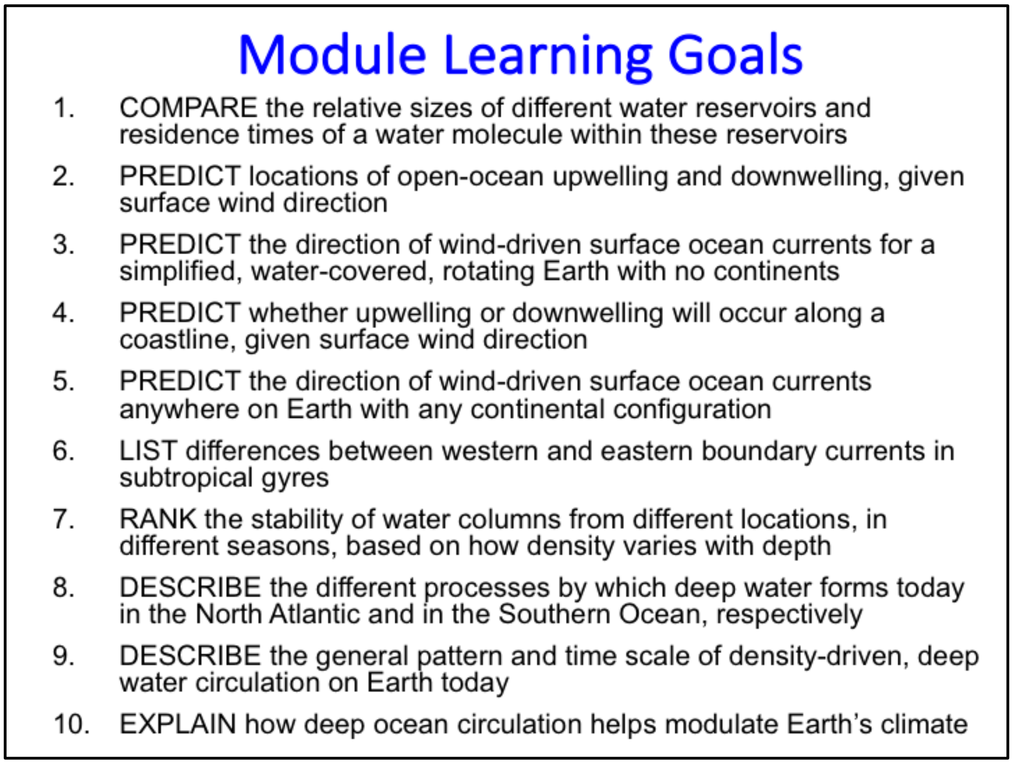
Instructor's Notes

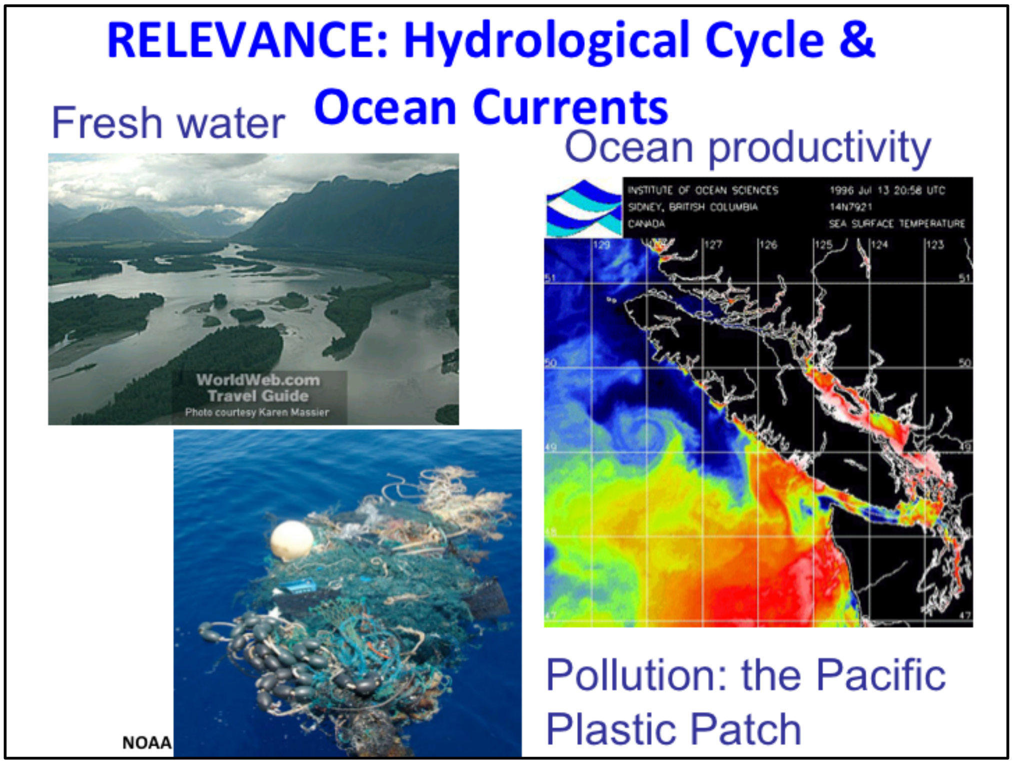
Module 3

Hydrosphere



Module Learning Goals

1. COMPARE the relative sizes of different water reservoirs and residence times of a water molecule within these reservoirs
2. PREDICT locations of open-ocean upwelling and downwelling, given surface wind direction
3. PREDICT the direction of wind-driven surface ocean currents for a simplified, water-covered, rotating Earth with no continents
4. PREDICT whether upwelling or downwelling will occur along a coastline, given surface wind direction
5. PREDICT the direction of wind-driven surface ocean currents anywhere on Earth with any continental configuration
6. LIST differences between western and eastern boundary currents in subtropical gyres
7. RANK the stability of water columns from different locations, in different seasons, based on how density varies with depth
8. DESCRIBE the different processes by which deep water forms today in the North Atlantic and in the Southern Ocean, respectively
9. DESCRIBE the general pattern and time scale of density-driven, deep water circulation on Earth today
10. EXPLAIN how deep ocean circulation helps modulate Earth's climate



RELEVANCE: Hydrological Cycle & Ocean Currents

Fresh water

Ocean productivity

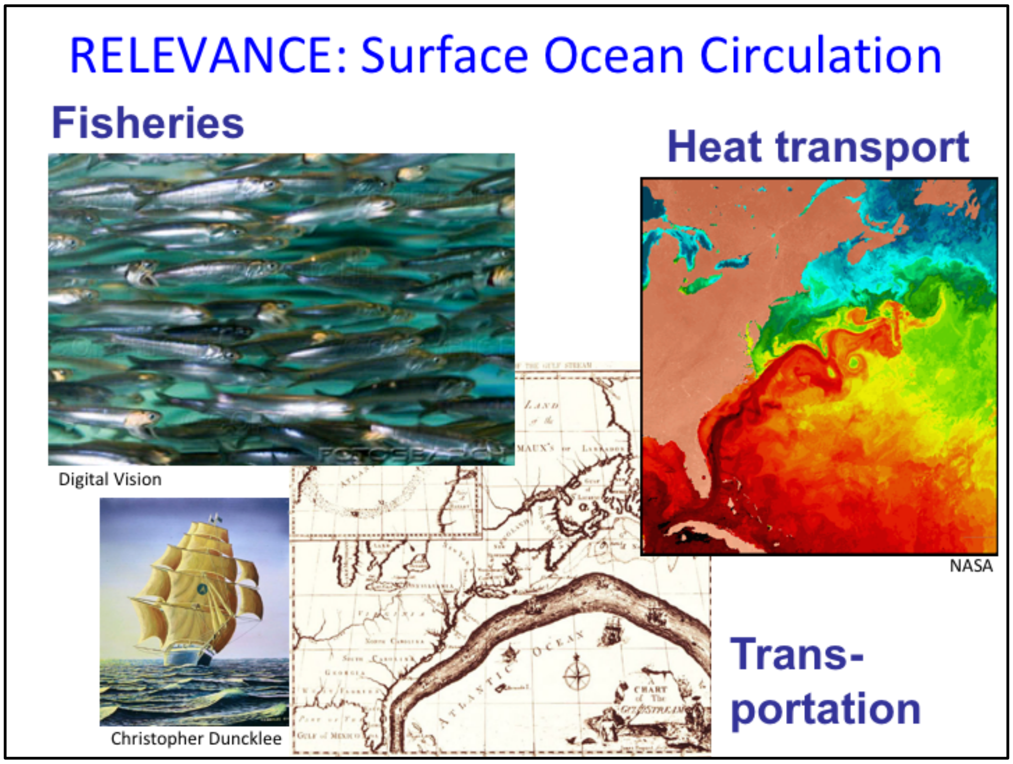
Pollution: the Pacific Plastic Patch

Why are the hydrologic cycle and surface ocean circulation relevant to human society? The three listed here are just a few of the many connections between these topics and us:

AVAILABILITY of FRESH WATER (image is an aerial view of the Fraser River): In some parts of the world, access to potable water and water for irrigation pose tremendous problems for human populations, which can lead to conflicts over water access. Many industrial processes (e.g. extracting oil from the "tar sands" in Alberta) use large amounts of fresh water, much of which is later polluted and unsuitable for other uses. Water is moved through various "reservoirs" (see next slide) on Earth via processes such as precipitation, evaporation, ice formation/melting, evapotranspiration, river flow, and flow through groundwater. The availability of water regionally depends on the storage in and transfer among these reservoirs. Global climate change can alter the hydrologic cycle, making it operate faster or slower, or changing the distribution of wet and dry regions on land.

POLLUTION, e.g. the Pacific Plastic Patch: You may have heard that out in the middle of the North Pacific floats a "patch" of plastic covering thousands of square kilometres. There's another one in the North Atlantic, and others anywhere wind-driven movement of surface water causes ocean water to converge (carrying with it anything floating). Why are these patches of trash located where they are? It's directly related to surface ocean circulation and the processes that move ocean currents.

OCEAN TEMPERATURE & PRODUCTIVITY (image is a false-color representation of sea surface temperature in the ocean in our area (note Vancouver Island) Red is warmer water, blue is colder water: Historically, here in British Columbia, marine fish have been a major source of food. Seasonal changes in sea surface temperature reflect the degree of coastal upwelling, which brings nutrients to the surface ocean and fuels productivity of tiny marine plants (phytoplankton). Fish we eat are ultimately supported by these tiny organisms at the base of the marine food web. Why is the ocean in this part of the world particularly productive? How productive is it compared to other regions? The productivity of the marine region near where we live is intimately linked to ocean circulation, the positions of continents, and (in the case of anadromous fish like salmon), is dependent on the hydrologic cycle which influences river flows.



RELEVANCE: Surface Ocean Circulation

Fisheries

Digital Vision

Heat transport

NASA

Trans-portation

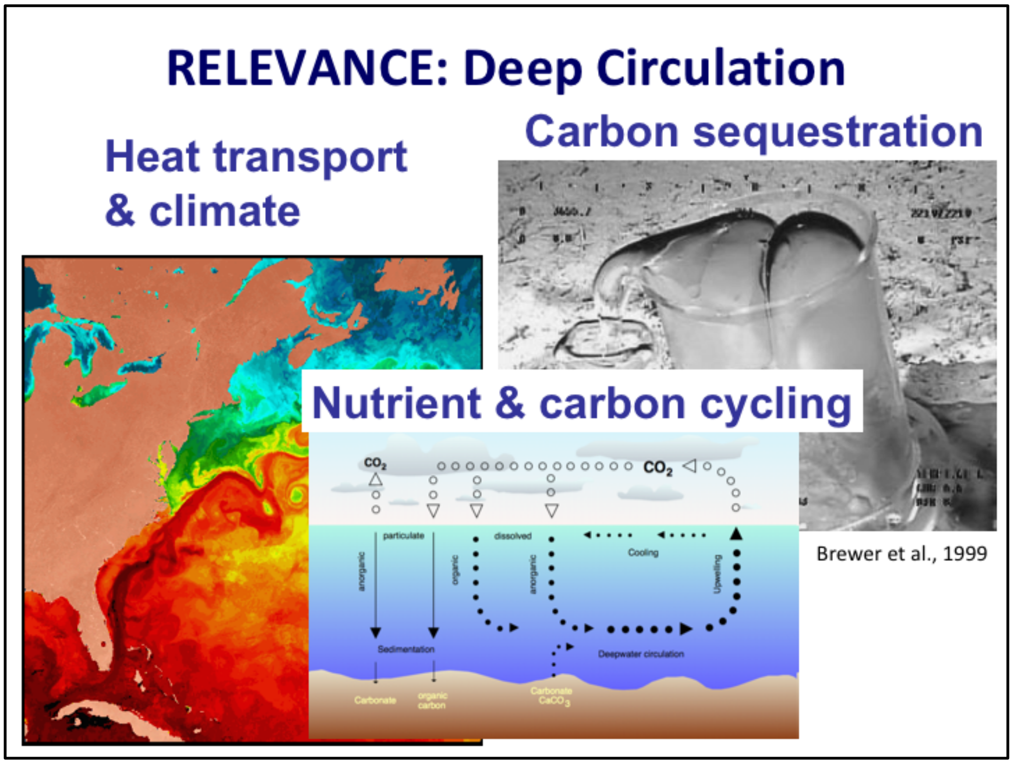
Christopher Duncklee

The physical motion of ocean currents influences marine ecosystems, the transport of heat crucial to the climate system, and the transport of goods and people across the oceans.

FISHERIES (image is a school of anchovies): Highly productive marine fisheries occur under quite specific oceanographic conditions, dictated by the physical motion of ocean water. In particular, areas of divergence where wind-driven upwelling brings nutrients to the surface layer are highly productive. These nutrients fuel productivity at the base of the food chain, on which fish depend. Historically, one of the most productive fisheries has been the anchovy fishery off the coast of Peru and Chile. This is an "eastern boundary current" and occurs along the continental margin on the east side of the South Pacific. Other similar locations include the California Current, the Canary Current and the Benguela Current (locate these on the map of surface ocean currents)

HEAT TRANSPORT, (image is false color surface temperature – see previous class for details): You may have heard that the climate in the British Isles is exceptionally mild for its latitude (about 50-60 degrees N, farther north than much of Newfoundland). This part of Europe benefits from heat transported northward in the warm Gulf Stream and transferred to the atmosphere. Cool currents carry the cooled-off ocean water back equatorward, keeping some lower-latitude coastlines cooler than one might expect. This heat transport by ocean currents is part of the system that redistributes solar energy and keeps so much of Earth habitable.

HUMAN TRANSPORTATION (image is (1) a clipper ship – one of the fastest types of sailing ships built to carry cargo, and (2) Benjamin Franklin's hand-drawn map of the Gulf Stream): Most of the goods we consume travel from somewhere else to British Columbia by ship. Chances are, nearly 100% of the clothing you're wearing was made some place other than North America. People who ship goods have an interest in making the best time possible on the voyages between continents. During the age of sail, knowledge of wind and current patterns was crucial to a successful voyage made in good time. You may have heard the story about Benjamin Franklin and the Gulf Stream. Ships carrying mail from Europe were taking two weeks longer to get to North America than ships carrying mail the opposite direction. During Franklin's own trips across the Atlantic (by sailing vessel, of course), he made measurements of surface temperatures and mapped that great "river in the ocean" that is the Gulf Stream. Knowledge about how to identify the Gulf Stream allowed captains sailing west to avoid it and make better time. Ships traveling eastward could take advantage and catch a ride on the current. Even today, with large motorized, diesel-fueled container ships and bulk carriers, knowledge of currents is important to figure out the most efficient way to cross the ocean. And who knows? Maybe the age of sail will return…



RELEVANCE: Deep Circulation

Heat transport & climate

Carbon sequestration

Nutrient & carbon cycling

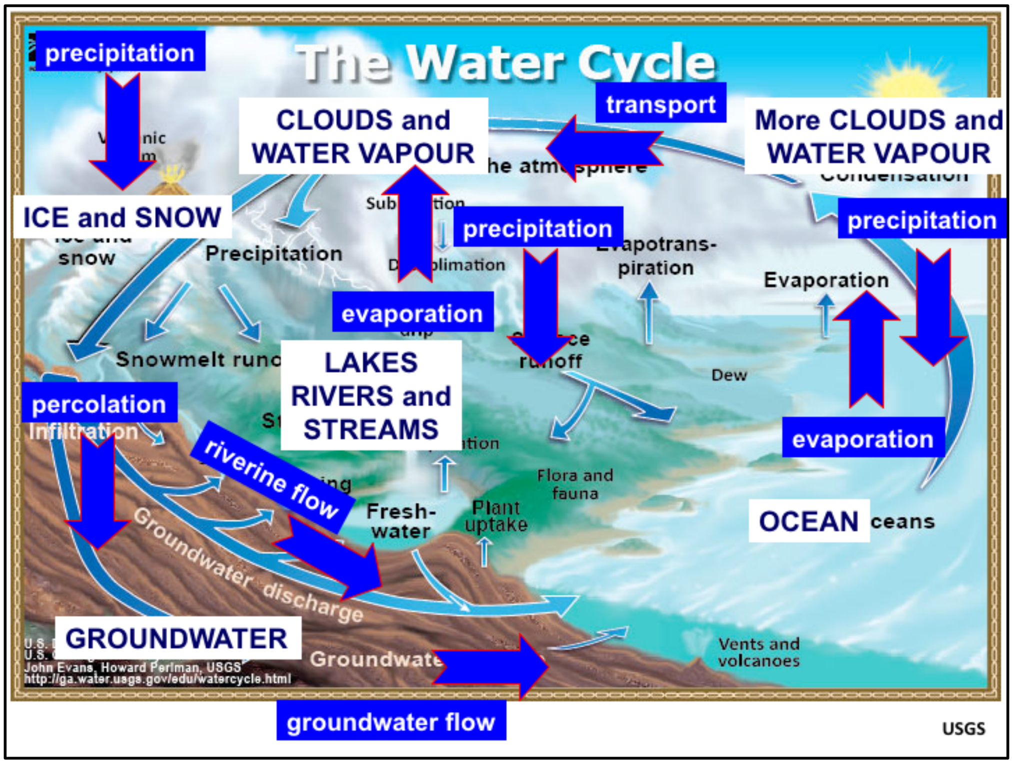
Brewer et al., 1999

Movement of water in the deep ocean is slower than the wind-driven movement at and near the surface, however, it too plays a large role in distributing energy and regulating regional climate.

HEAT TRANSPORT (image is false color surface temperature): Deep ocean circulation is intricately linked to the transport of heat poleward in surface western boundary currents. When the warm Gulf Stream reaches latitudes near Greenland, it gives up much of its heat to the atmosphere, making the surface water colder. In combination with salinity, this water often becomes dense enough to sink, which is one of the downgoing paths of the overall deep ocean circulation. Some evidence indicates that if this sinking of deep water slows or stops, the heat transport toward the poles (in surface currents like the Gulf stream) would decrease, potentially cooling regions around the North Atlantic (like northern Europe).

CARBON SEQUESTRATION IN THE DEEP OCEAN: The image above shows a beaker on the sea floor at 3650 m water depth. It's full of (and overflowing) liquid CO2. One idea for reducing the carbon dioxide concentration in the atmosphere is to deliberately inject CO2 into the deep ocean, where it will liquefy and ocean pressures might keep it there. But if we injected a lot of CO2 into the deep ocean, how long would it stay there? What impacts would it have on life that lives at great depths in the oceans, both in the water column and within the sediments and rocks? When it is released from the deep sea, will that event be slow or fast, gradual or catastrophic? Understanding deep ocean circulation helps us begin to address these questions.

NUTRIENT & CARBON CYCLING: Circulation in the deep ocean plays an important role in cycling nutrients and carbon within the marine ecosystem. Biological particles that sink from the surface to depth usually dissolve or decompose at depth, adding nutrients and carbon to the deep ocean. These nutrients are needed for productivity near the surface where light is available. Thus, part of the deep ocean circulation acts to return nutrients from the deep ocean back to the surface.



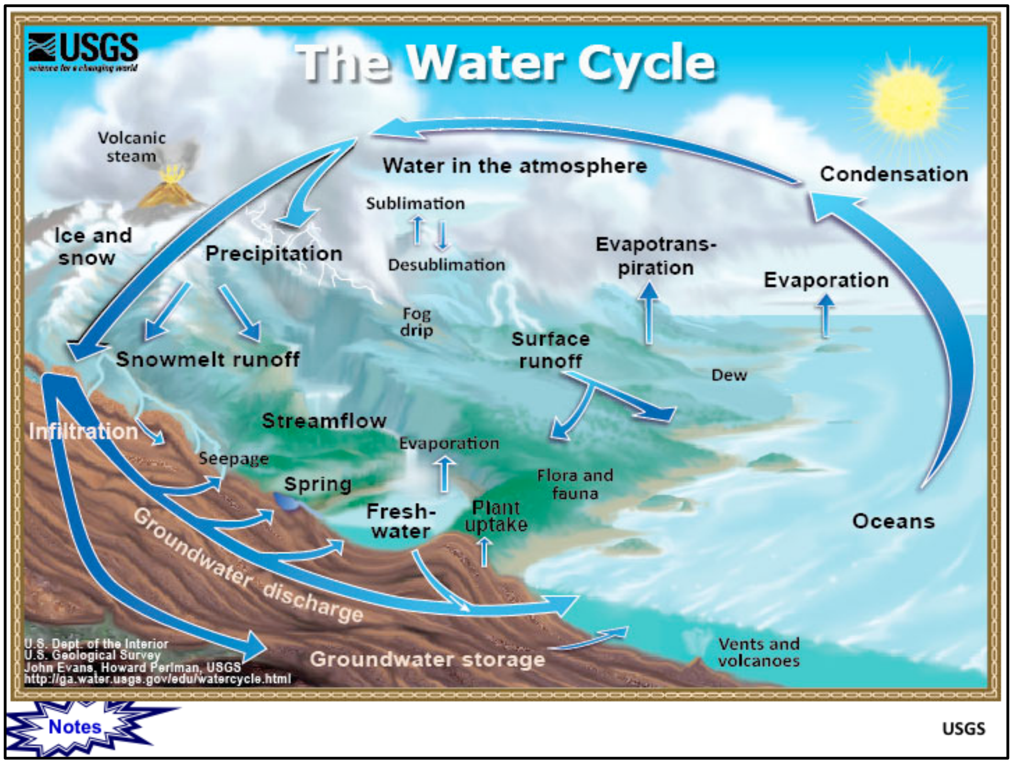
The Hydrologic Cycle (with labels):
This figure shows the generalized hydrologic (water) cycle. The key thing to learn about deciphering the hydrologic cycle is that the "cycle" describes a system made up of **RESERVOIRS** and **FLUXES**. This also applies to any other "cycle" of a specific material, like the carbon cycle, the nitrogen cycle, and the phosphorous cycle, all of which we will examine later.

Reservoirs are places where the stuff resides temporarily, in this case, places where water is temporarily stored. The reservoirs in this figure are "ocean", "ice and snow", "groundwater", "lakes, rivers & streams" (this includes all water at the surface of the continents, including puddles) and "clouds and water vapour" (which can be anywhere in the atmosphere, over land or sea).

Fluxes describe the movement of water among these reservoirs via various processes, specifically, the rate of movement (see "Reservoir Sizes and Fluxes" slide). The large blue arrows in the figure above indicate the processes by which water passes from one reservoir to another. For example, the primary process by which water leaves the ocean reservoir is by evaporation, which puts water into the atmosphere (as water vapour). That vapour can condense into droplets that form clouds, the clouds and water vapour can be transported to different areas by the wind, and the water droplets can fall to Earth as rain or snow (precipitation), over either land or sea. Water that falls onto the surface of the land can run off via rivers and streams, or percolate downward into the groundwater, or evaporate into the atmosphere again, or be taken up by vegetation, which will return the water to the atmosphere through evapotranspiration. Take a look at each of the arrows.

Where does the energy come from to evaporate water so that it may move from the ocean to the atmosphere? Ultimately, the energy source is radiation from the Sun. When water evaporates from the ocean, energy is transferred from the ocean to the atmosphere as latent heat. That heat is released to the atmosphere when the water vapour condenses. Where does the energy come from to induce streams and rivers to transfer water downhill, off the continents, into the ocean? Gravity.

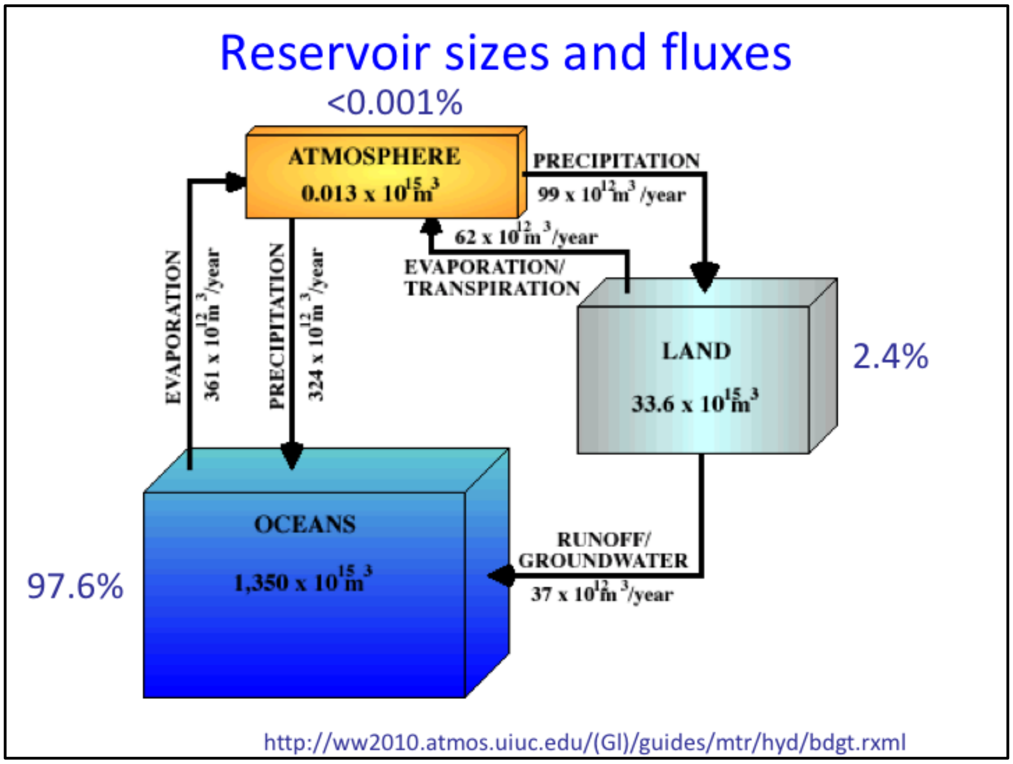
The time scales of these different processes can be very different. It may take thousands of years for water to percolate through the groundwater reservoir toward and into the ocean reservoir, whereas the full cycle of evaporation into the atmosphere and precipitation back to Earth's surface may occur within a mere several days.



U.S. Dept. of the Interior
U.S. Geological Survey
John Evans, Howard Perlman, USGS
http://ga.water.usgs.gov/edu/watercycle.html

USGS

NOTES SLIDE (not shown in class): The Hydrologic Cycle (without labels)
This figure is included to allow you to see the text information without the large labels. What processes shown here can you relate to information in the course so far? What components of this image can you relate to Earth's climate system? How are they related?



http://ww2010.atmos.uiuc.edu/(Gl)/guides/mtr/hyd/bdgt.rxml

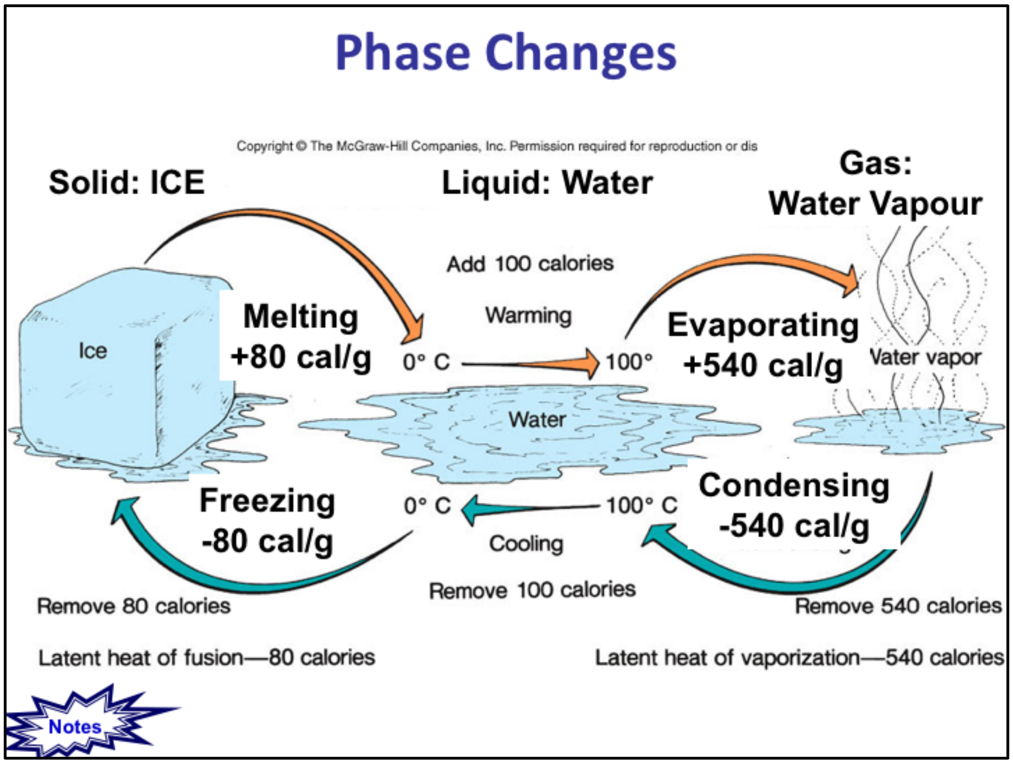
How much water and where? How fast does it cycle through?

We can simplify the near-surface hydrologic cycle to three basic reservoirs: Oceans, Land, and Atmosphere. The numbers in the boxes are the volume of water in the reservoir. Of these three reservoirs, the oceans are by far the largest holder of water, containing 1350 * 10^{15} m^3 (which is 1350 million cubic kilometres), or about 97.6% of the total. "Land" includes both surface water (lakes, rivers, glaciers) and groundwater, which together are only about 2.4% of the total. The atmosphere contains the smallest amount at less than 0.001% of the total. This might be surprising, since water vapour and rain play such an important role in weather and climate.

Take a look at the major processes by which water travels from one reservoir to another (labeled black arrows). The numbers on those arrows indicate the volume of water transferred via that pathway in cubic metres per year. Add up the arrows that go INTO the Ocean reservoir. Add up the arrows that go OUT OF the ocean box. How do these compare? (they should be equal, right? Why should they be equal?). Repeat for the Land and Atmosphere boxes.

Next, how does the total flux into the ocean every year compare to the amount of water in the reservoir itself? Examine the "OCEANS" box. The oceans contain a huge amount of water (1350*10^{15} m^3). Every year, only 361*10^{12} m^3 enters the oceans through precipitation and runoff/groundwater flow. This means that, on average, a water molecule spends about 3740 years in the "OCEANS" box. This is what we call the "**residence time**" of water in the ocean. Water cycles through the ocean fairly slowly, compared to, say, how fast it cycles through the atmosphere. Repeat for the Atmosphere and Land boxes. How do their residence times compare to the ocean's? How many years/days (approximately) would it take for all the water in the atmosphere to cycle through that box? What about the water in the "land" box?

[As an aside, a huge amount of Earth's water resides deep below the surface in in Earth's mantle rocks, but it participates in the surface water cycle very, very slowly, on tectonic time scales (millions and billions of years)].



Phase Changes

Solid: ICE

Liquid: Water

Gas: Water Vapour

Melting +80 cal/g

Add 100 calories

Warming

0° C → 100°

Evaporating +540 cal/g

Freezing -80 cal/g

0° C ← 100° C

Condensing -540 cal/g

Cooling

Remove 80 calories

Remove 100 calories

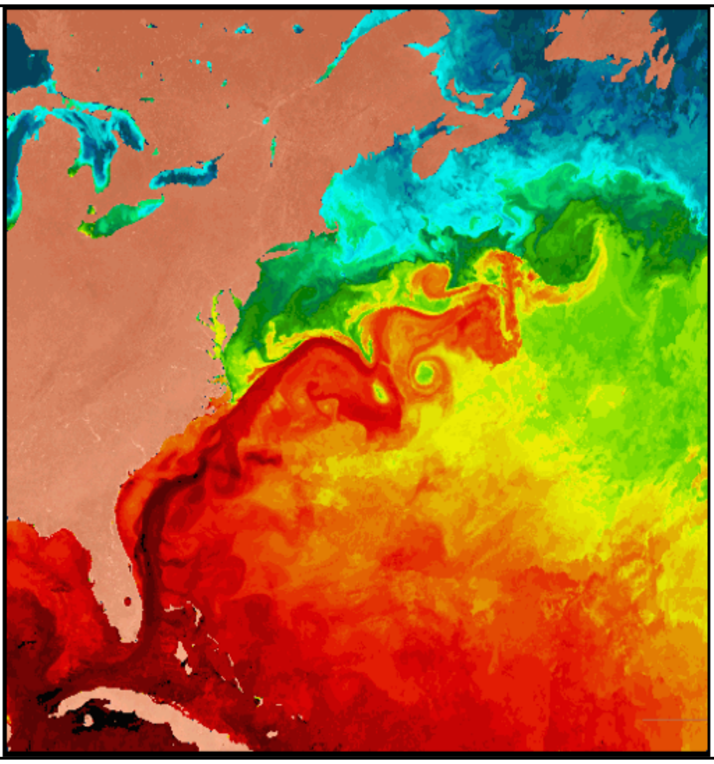
Remove 540 calories

Latent heat of fusion—80 calories

Latent heat of vaporization—540 calories

NOTES SLIDE (not shown in class): Many of the processes in the hydrologic cycle involve changing the phase (solid, liquid, or gas) of water. For water to leave the "Ice & Snow" reservoir and enter the "Lakes, Rivers, & Streams" reservoir, the ice/snow has to melt. How would you melt ice? You'd have to add energy. Specifically, melting takes 80 calories per gram of water, if the ice is at the melting temperature of water (0°C). At sea level atmospheric pressures, water exists as liquid between 0°C and 100°C. Once it reaches 100°C, it takes an additional 540 calories of energy to evaporate one gram of water and turn it into water vapour. You can follow the process in reverse with the blue arrows – go from vapour back to liquid back to ice.

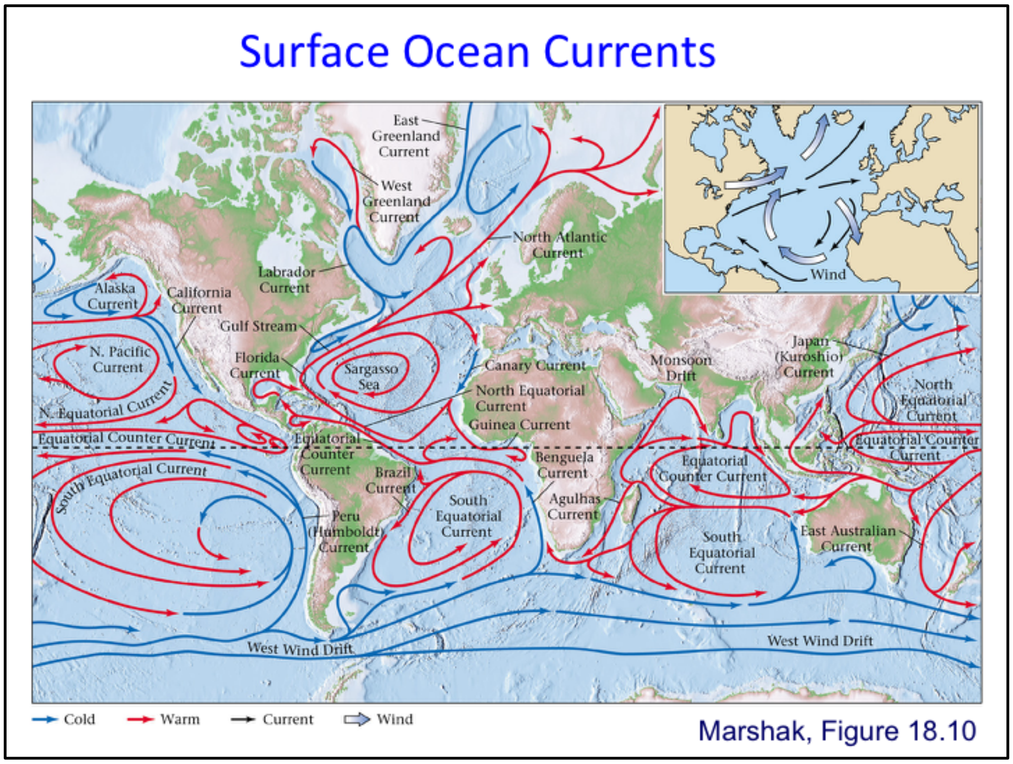
Earlier in this course, we talked about how energy from the Sun is used to evaporate water from the oceans at low latitudes, in the tropics. This water vapour made the air less dense and that moisture is one of the reasons that air rises at the ITCZ, which is why there are clouds and lots of rain in the tropics. But is water in the tropics 100°C? Is it boiling? Why would anyone go on vacation on a tropical island to swim in boiling water? The water in the tropics is not boiling (it's about 22-30°C), but it's still able to evaporate. You can convince yourself that water doesn't have to boil in order to evaporate by leaving a glass of water on your kitchen counter for a while. Do you think it takes MORE than 540 calories to evaporate surface ocean water in the tropics or LESS than 540 calories? How do you think the energy requirement varies with the temperature of the water?



The Gulf Stream

So, energy, as heat, can be transferred among the different reservoirs for water on Earth, through the processes of evaporation, condensation, ice formation, and ice melting. Heat energy can also be transported from one location to another by moving water (or air) of different temperatures around on Earth's surface, without transferring it from in or out of one of these reservoirs. We've examined the basic patterns of atmospheric circulation, which moves heat energy away from the tropics toward the poles. Next, we're going to examine how heat is moved around by the oceans. In order to do that, we need to develop the surface ocean currents.

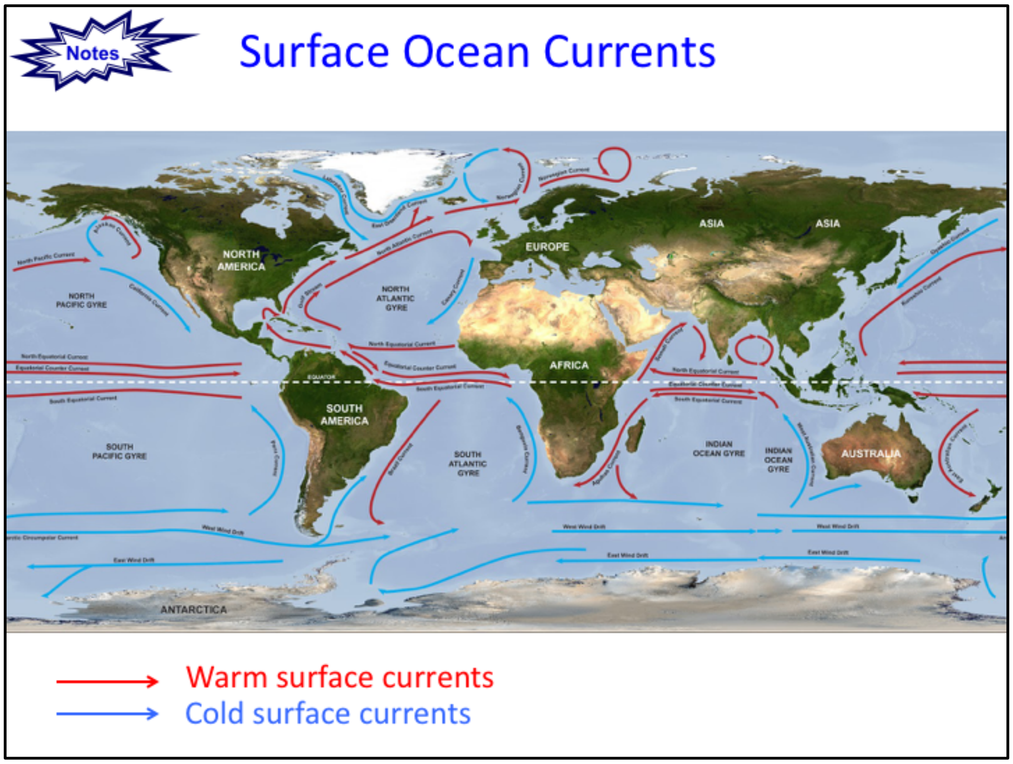
This is a satellite image of the western North Atlantic (check your west-east directions!), showing the Gulf Stream carrying warm water away from the tropics toward the north. The image is false-colored – red means warmer water, blue means colder water. The Gulf Stream is defined by the warmer water that moves up the east coast of North America then heads out away from the coast toward the northeast. This picture is complex, with large and small eddies and meanders, and complicated patterns of ocean temperature. What drives ocean currents like the Gulf Stream?



Surface Ocean Currents

Marshak, Figure 18.10

Here's the more idealized view, showing the general directions of surface ocean currents. The red arrows indicate warmer currents and the blue arrows indicate cooler currents. Note the general clockwise circulation in the North Atlantic and North Pacific (between the tropics and, say, 40-50 degrees N latitude). These are called "subtropical gyres". Find the Gulf Stream (the western arm of this clockwise circulation in the North Atlantic. Find at least three other currents that have similar characteristics to the Gulf Stream. Think about what characteristics might make a current "similar" to the Gulf Stream. Find the California Current. How does it differ from the Gulf Stream? Find at least 3 other currents that are similar to the California Current.
What directions do the equivalent circular patterns (also subtropical gyres) flow in the southern hemisphere?
In the northern hemisphere, what happens to the north of the subtropical gyres? (Look near Alaska for starters).
In the southern hemisphere, what happens south of the subtropical gyres?
What makes all this flow? Wind blowing across the surface of the water. Look at the inset in the upper right. The thick arrows represent the general wind pattern over the North Atlantic (check back to notes in the previous classes about areas of high pressure and low pressure around which the winds blow). The thinner arrows in this inset represent the surface ocean currents. They're going generally the same directions as the wind…but why? We're going to revisit geostrophic flow, this time in the ocean…
ALSO, it is important to note that this picture of the ocean currents looks this way because of the positions of the present-day continents, which present barriers and provide the boundaries of the ocean basins. It wasn't always this way, because the continents have not always been in these positions. By the end of this section, you should aim to be able to reconstruct the ocean currents for any hypothetical configuration of the continents. In fact, we're going to remove the continents for a while, as we did when developing the atmospheric circulation originally.



Notes

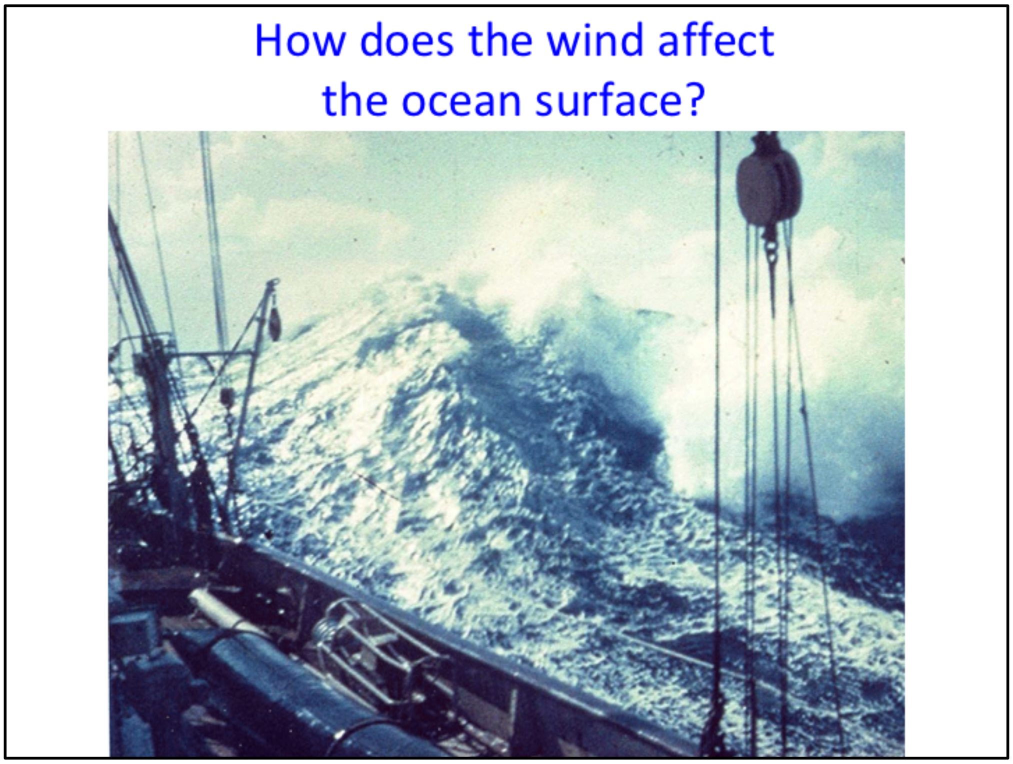
Surface Ocean Currents

Warm surface currents
Cold surface currents

NOTES SLIDE (not shown in class): Here's a simpler view of the major warm and cold currents in the oceans. This shows the major circulation and the major currents that we will discuss in this class.

For a more realistic (and complex!) view of surface ocean currents, watch these animations (links below, from NASA). See if you can pick out the main average currents shown in this image within the complex patterns of eddies in the animations.

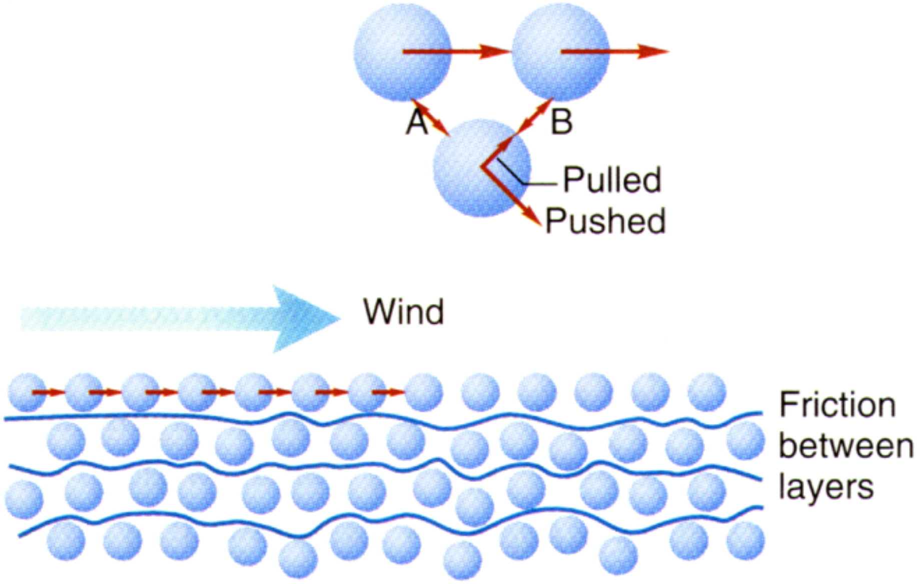
http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3821
http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3827



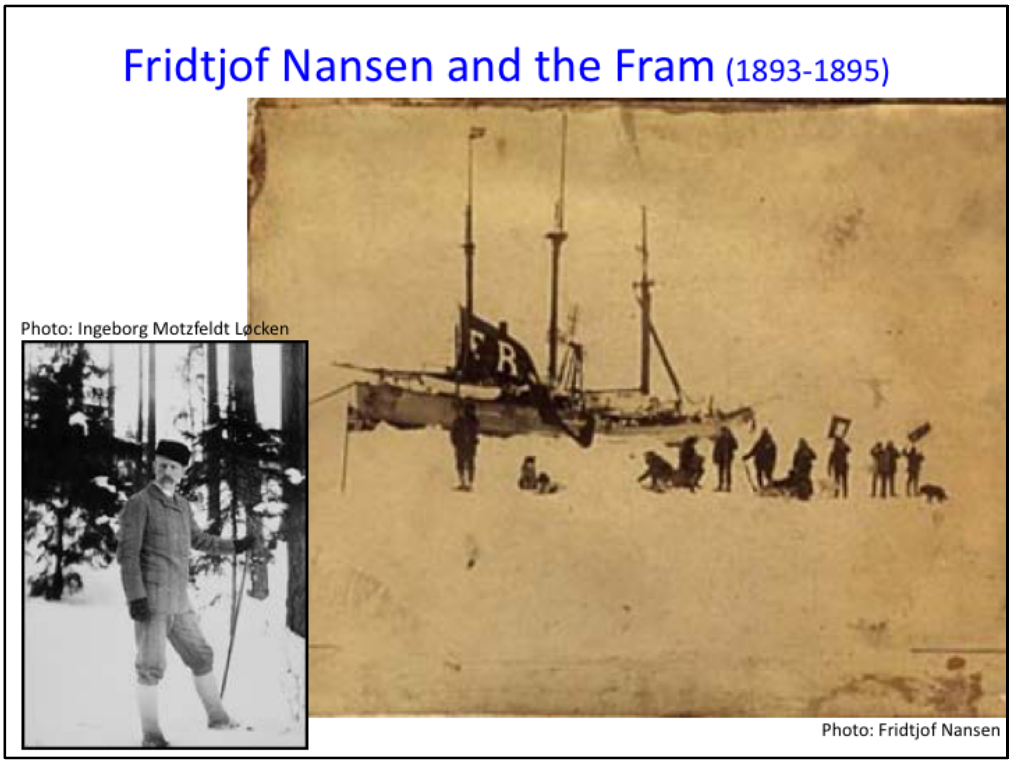
How does the wind affect the ocean surface?

Surface ocean currents are wind-driven. This means that the energy ultimately driving surface ocean circulation comes from…the Sun. Again. When wind blows over the ocean's surface, there's friction between the atmosphere and the water. Some of the energy from the wind gets transferred to the water and sets it in motion. *This might make you think that the wind drags the water along in the same direction the wind is blowing, creating the ocean currents. That's a common misconception. If you have this misconception, study the following notes to attempt to replace it in your mind!*

Air-sea frictional coupling



This figure illustrates frictional coupling between the atmosphere (in motion) and the surface ocean. As the wind blows, it influences the motion of water molecules at the surface interface between water and air. This frictional coupling transfers energy from the moving atmosphere to the ocean water. Since the very surface layer of water molecules is in contact with water molecules just below, the energy also gets transferred downward into the water column, away from the surface.
That's the gist of how wind energy gets transferred to the water and is available to move water around. What are the observed and theoretical effects on the water?

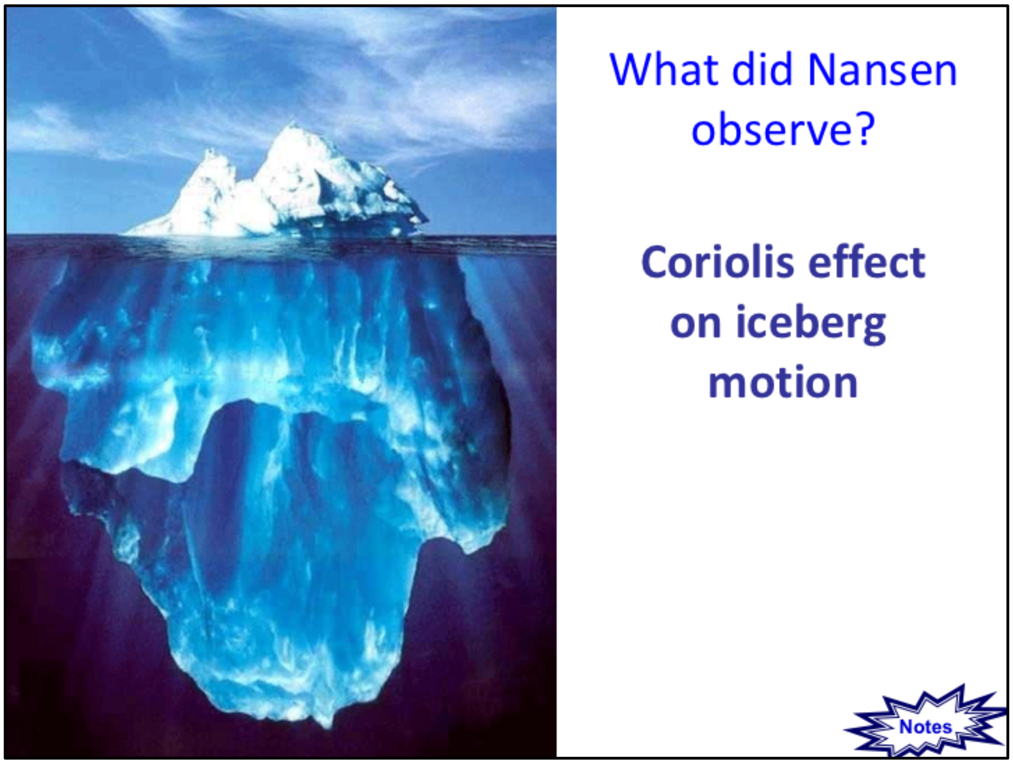


Fridtjof Nansen and the Fram (1893-1895)

Photo: Ingeborg Motzfeldt Løcken

Photo: Fridtjof Nansen

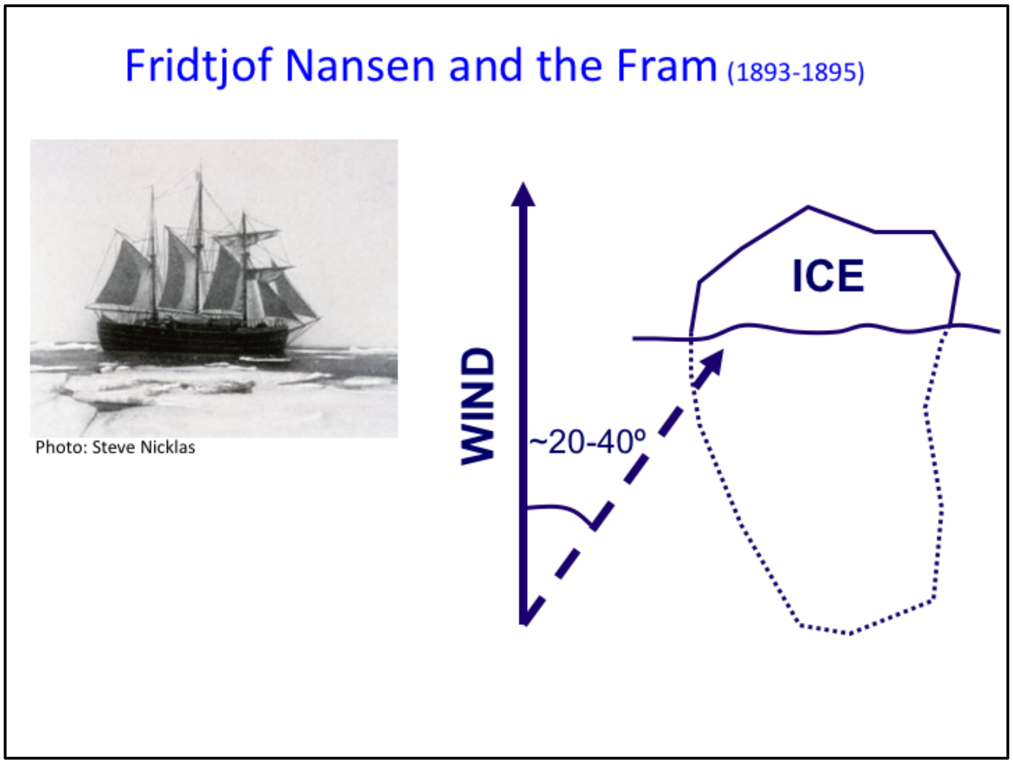
Fridtjof Nansen began to answer this question using his observations from the Arctic. Nansen was an explorer (and politician, and diplomat, and Nobel Peace Prize winner… Look him up). Probably his most famous expedition was to the Arctic Ocean. He was intrigued by observations that parts of ships that had wrecked on one side of the Arctic were found years later on the other side. He decided to investigate ocean circulation in the Arctic and he built a ship, called the Fram (after which Fram Strait is named). The Fram was designed NOT to get crushed by icebergs, but rather to be lifted up to the ice surface as the ice closed in. Nansen and his crew took the Fram up to the Arctic and froze it into the ice, and waited to see where the ice would take them (the floating ice was moving around with the ocean currents). They were up there for 3 years. (3 years! Only a few of them went insane…)



What did Nansen observe?

Coriolis effect on iceberg motion

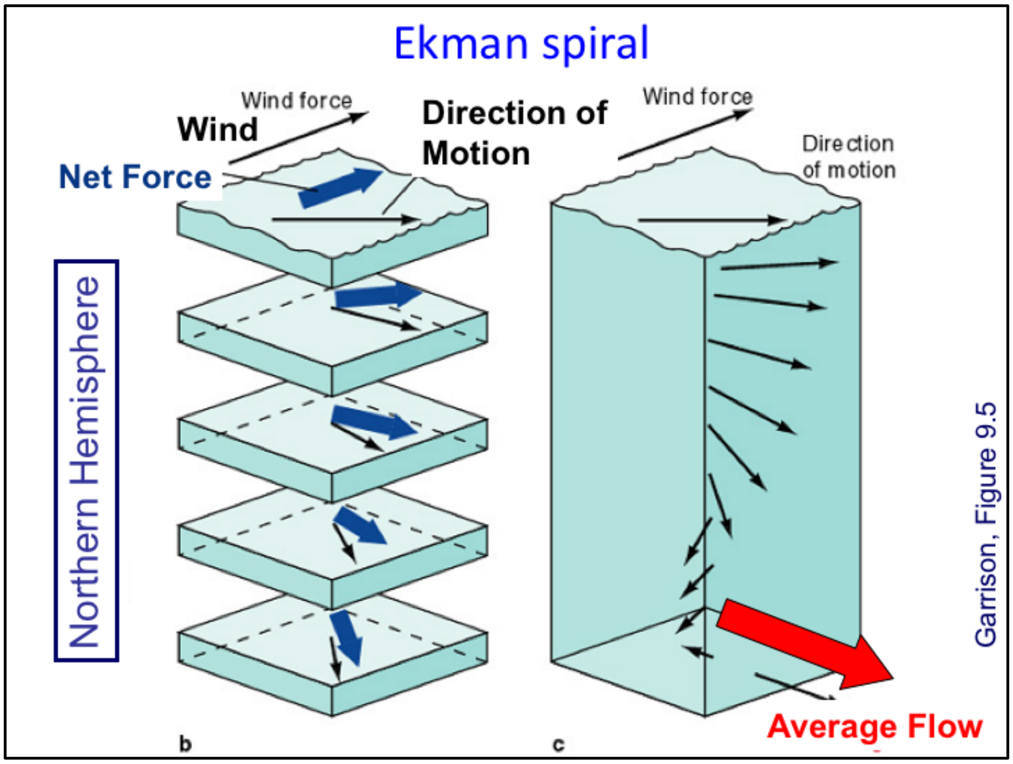
NOTES SLIDE (not shown in class): Having lots of time on his hands, Nansen made careful observations of their surroundings. The ship wasn't always stuck in the ice. Some areas of the Arctic are open water, surrounded by ice, with floating icebergs (the open water areas are called "polynyas"). Due to the relationship between the density of ice and the density of seawater, most of an iceberg is submerged with a bit sticking up above the water's surface. The motion of icebergs is therefore influenced both by the wind (above the surface) and the water currents (below the surface). In these areas of open water, Nansen observed that the motion of icebergs was not in the direction of the wind; instead, the icebergs moved off to the right of the wind direction.



Fridtjof Nansen and the Fram (1893-1895)

Photo: Steve Nicklas

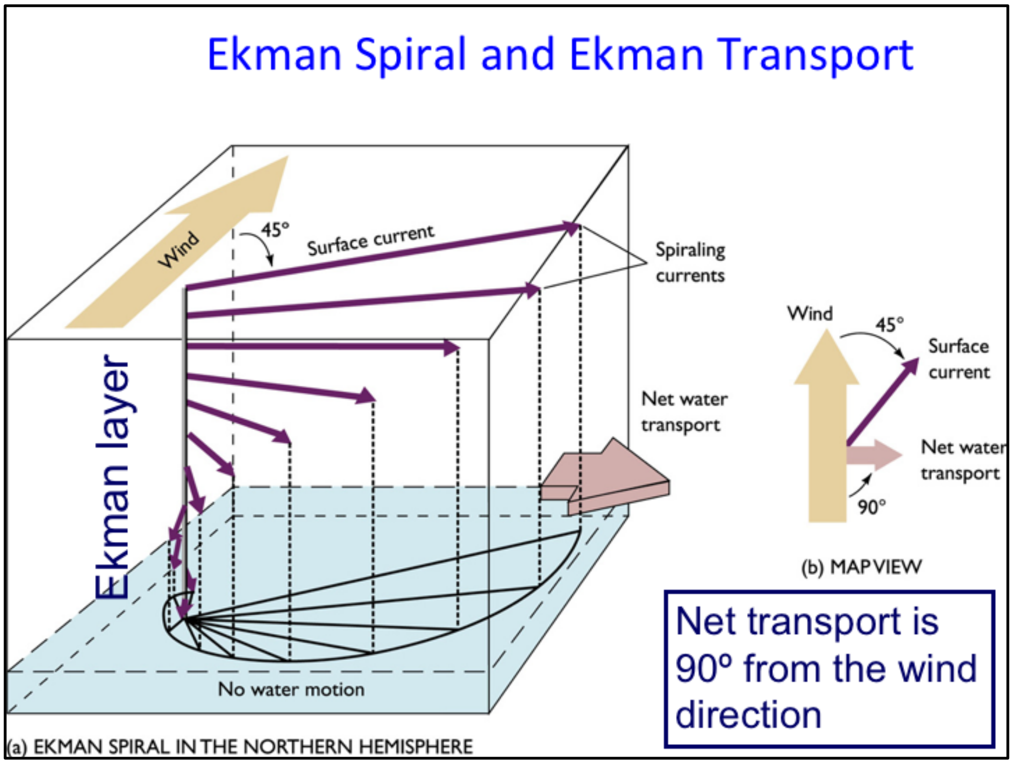
Nansen made careful observations which indicated that the iceberg were moving off to the right of the wind direction, something like 20-40 degrees to the right. He was intrigued, but Nansen was a busy guy (really, look him up). So he gave his observations to his student, Vagn Ekman and said “you figure it out”.



So Ekman did. He developed the theoretical model that explains how energy transferred from the wind to the water influences the water's motion. Imagine, first, a still water surface. No motion. Then the wind starts to blow. At the surface, the wind is frictionally coupled to the water and some of the wind's energy is transferred to the surface layer, setting it in motion. Once the water's in motion, it becomes "an object in motion on a rotating frame of reference" (the rotating Earth). Sound familiar? Yes, the water is influenced by the Coriolis force. Although initially set in motion in the direction of the wind, the Coriolis force pulls it to the right in the Northern Hemisphere (the Arctic is, of course, in the Northern Hemisphere). The result at the ocean's surface is that the water moves off about 45 degrees away from the wind direction (in the theoretical model and the ideal case. Don't get too attached to that exact number). The very surface layer is, of course, in contact with the water molecules underneath it. Once the surface is in motion, it starts to drag the lower layers along in the direction of the surface. But that next deeper layer also gets deflected a bit, farther away from the original wind direction (to the right in the Northern Hemisphere). And the next deeper layer gets dragged along and once in motion is further deflected. Etc. Etc.

The **Ekman spiral** describes this transfer of energy down through the water column, affecting deeper and deeper layers. The "spiral" refers to the pattern of motion as you go deeper. At the surface, the velocity of the water is largest and is offset to the right of the wind direction. Energy dissipates as it's transferred farther from the source, so the next layer is moving slower, but even farther off the wind direction. Etc.

Here's the punchline: If you add up all the velocity vectors for all the different water layers, ***the NET MOTION of this whole upper ocean layer is 90 degrees away from the wind direction*** (In the Northern Hemisphere, 90 degrees to the right. In the Southern Hemisphere, 90 degrees to the left).



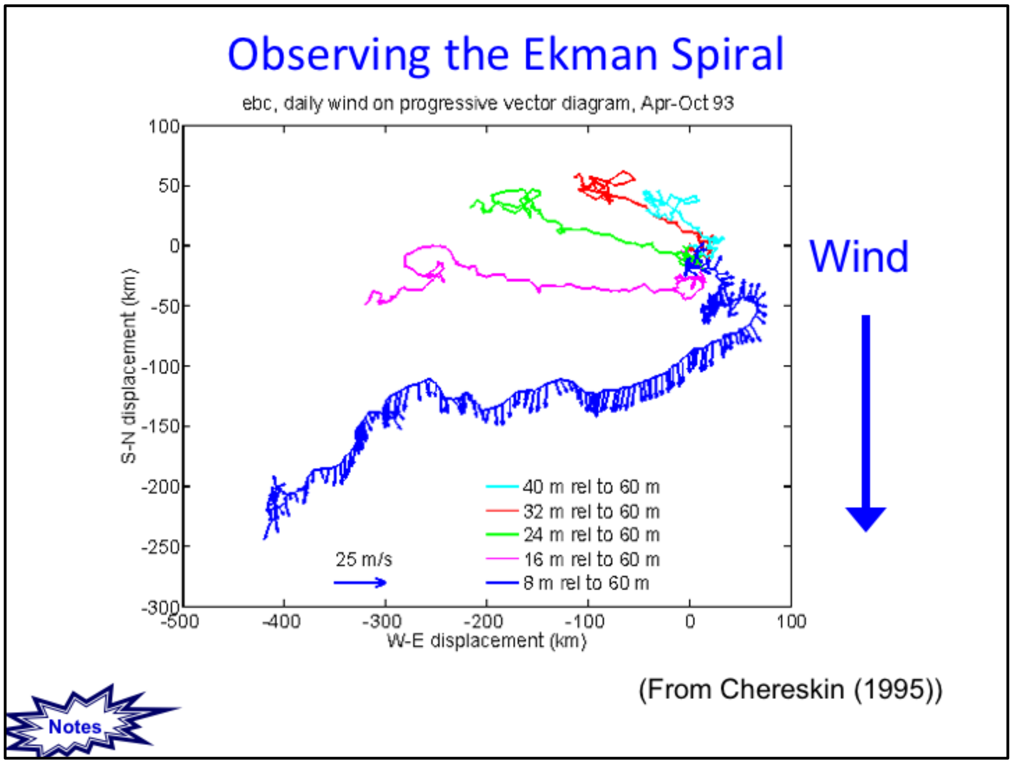
Ekman Spiral and Ekman Transport

(a) EKMAN SPIRAL IN THE NORTHERN HEMISPHERE

(b) MAPVIEW

Net transport is 90° from the wind direction

This figure illustrates the Ekman spiral, the net direction of transport, and the Ekman layer.
Ekman spiral: The pattern of water velocity vectors that gradually moves farther away from the wind direction and goes slower with increasing depth. Note that at some depth, the direction of water motion is opposite (180 degrees away from) the direction of the wind motion. This is the theoretical base of the **Ekman layer**.
Ekman layer: The layer of water near the surface that is set in motion by the wind blowing across the surface. The top of the Ekman layer is the ocean's surface. The bottom of the Ekman layer is the depth at which the water is moving exactly opposite the wind direction. You might ask, could there still be enough energy to keep the spiral going deeper? Sure. It's also possible that the energy could dissipate before the water's going exactly opposite. That's OK. The depth of the Ekman layer varies depending on the wind speed. Higher wind speeds produce a deeper spiral. Here are some ballpark numbers:
10 m/s wind speed (that's about 35 km/hr, or about 20 knots) → 50-100 m deep spiral
20 m/s wind speed (that's about 70 km/hr, or about 40 knots) → 100-200 m deep spiral
Ekman transport: This is the net transport of water within the Ekman layer. As mentioned in the previous slide, if you add up all the velocity vectors at all the different depths, the net transport is 90 degrees away from the wind direction. This is a key point that you're going to have to use later. ***Another very key point is that the Ekman transport is NOT the same as the surface current you would experience if you were out in the ocean floating in a kayak!*** We haven't yet made it to ocean currents.



Observing the Ekman Spiral

Wind

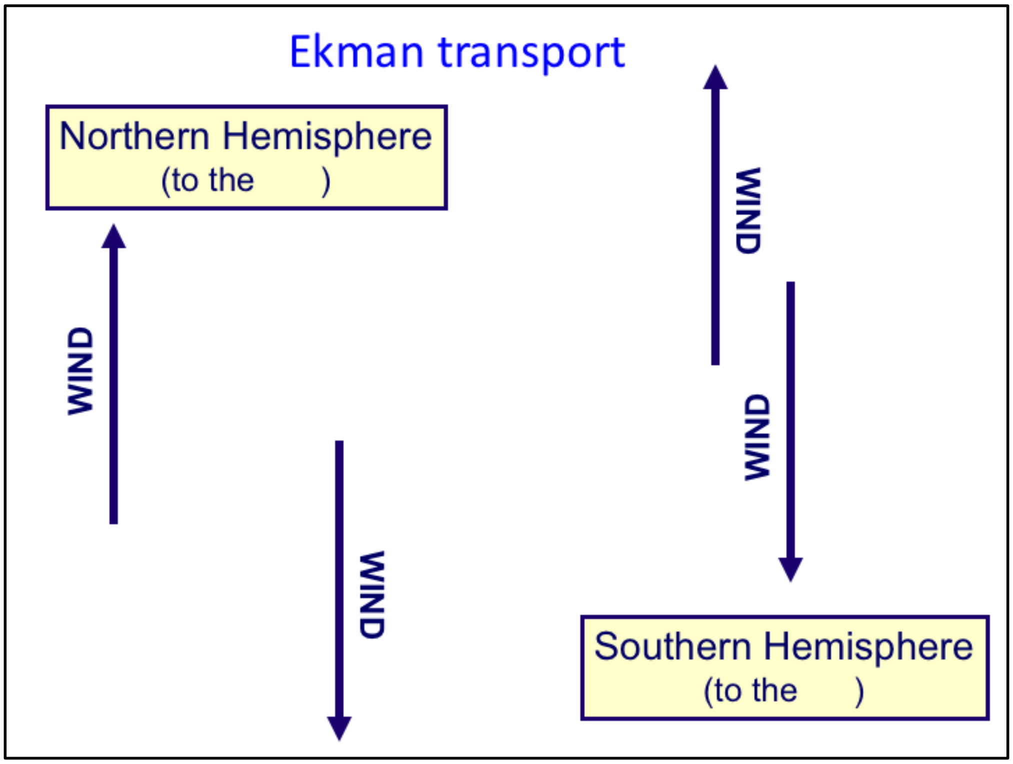
(From Chereskin (1995))

NOTES SLIDE (not shown in class): So, Ekman came up with this beautiful theoretical model of the Ekman spiral. It turns out that the Ekman spiral, with its varying velocity vectors with depth, is quite difficult to observe in action. We primarily observe the final result of Ekman transport, which piles up water in some places and removes it from other places. Here's one example of a pretty good attempt at observing the Ekman spiral itself.

The figure shows the motion of water at different depths relative to 60 metres depth, which serves as the reference depth. Each of the squiggly colored lines shows the motion of water at some depth, relative to the motion at 60 metres. Over the time period displayed in this diagram (Apr-Oct 1993), the wind in this area was mostly blowing toward the south (see big wind arrow, and also the little blue wind vectors on the blue squiggly line. The squiggly blue line indicates that the water at about 8 m depth (close to the surface) moved to the south west, compared to the water at 60 m depth. This is what one would expect given a wind blowing from north to south in the northern hemisphere. The pink, green, red, and turquoise squiggly lines indicate the relative motion at progressively deeper depths in the water column. They gradually move farther "to the right" of the wind vector with increasing depth.

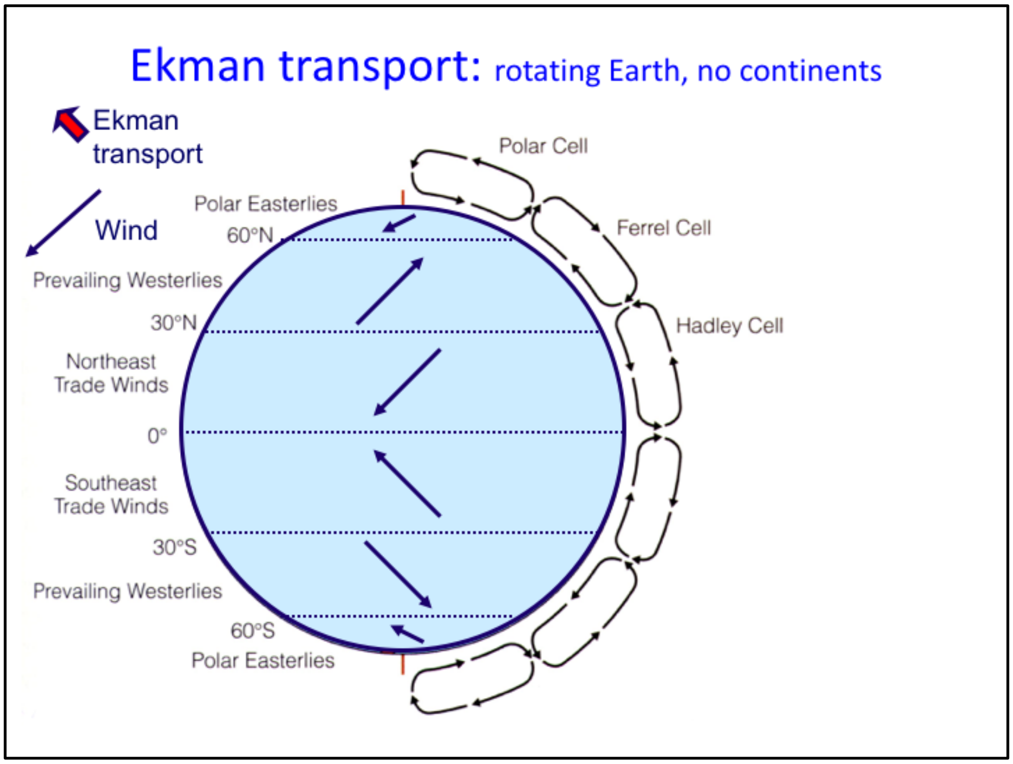
These data were collected at a subset of depths from a moored Acoustic Doppler Current Profiler at 37.1 N, 127.6 W in the California Current, deployed as part of the Eastern Boundary Currents experiment. Daily averaged wind vectors are plotted at midnight UT along the 8-m relative to 60-m displacement curve. Wind velocity scale is shown at bottom left.

Chereskin, T. K., 1995: Evidence for an Ekman balance in the California Current. J. Geophys. Res., **100**, 12727-12748.



Ekman transport

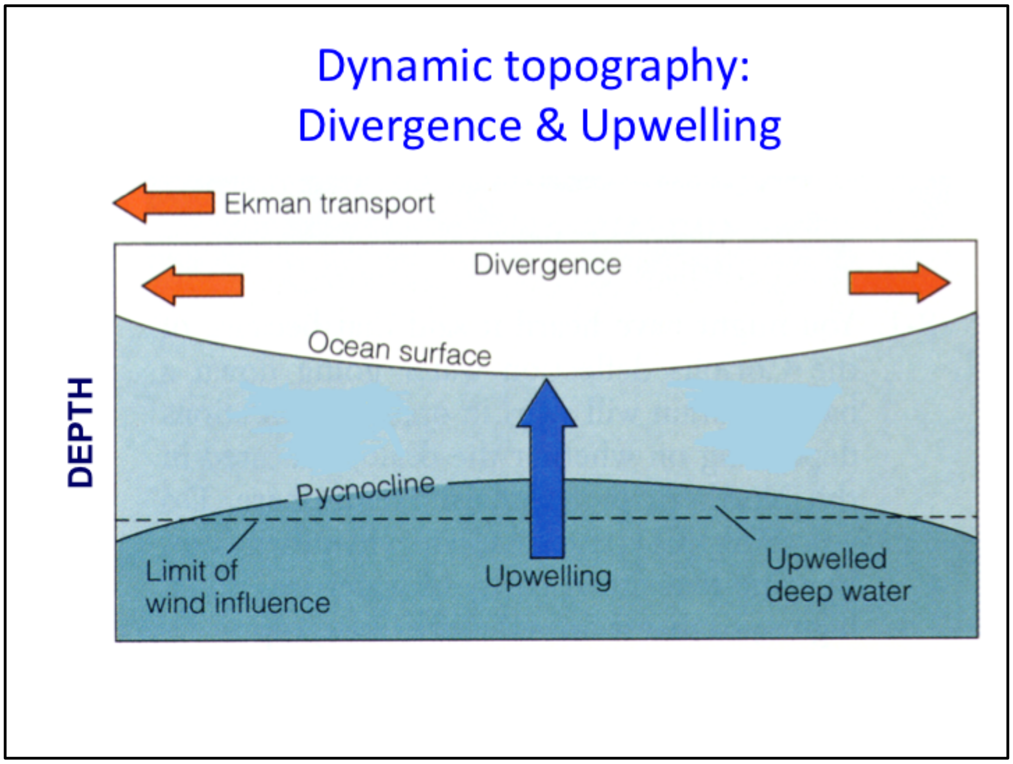
Come to the lecture to fill this in!



Ekman transport: rotating Earth, no continents

What would Ekman transport look like on an Earth with no continents? We'd need to consider the general wind patterns on such a planet. Recall the vertical circulation cells (Hadley, Ferrell, Polar). Recall the resulting surface wind directions, with Coriolis, because this planet is rotating. The blue arrows represent the generalized surface wind directions in this scenario. Starting from these surface winds, what direction is the Ekman transport in each of the main wind bands (trades, westerlies, polar easterlies)?

Once you've convinced yourself of the Ekman transport directions, can you identify place on this planet where the surface waters appear to be coming together and piling up, or moving apart?



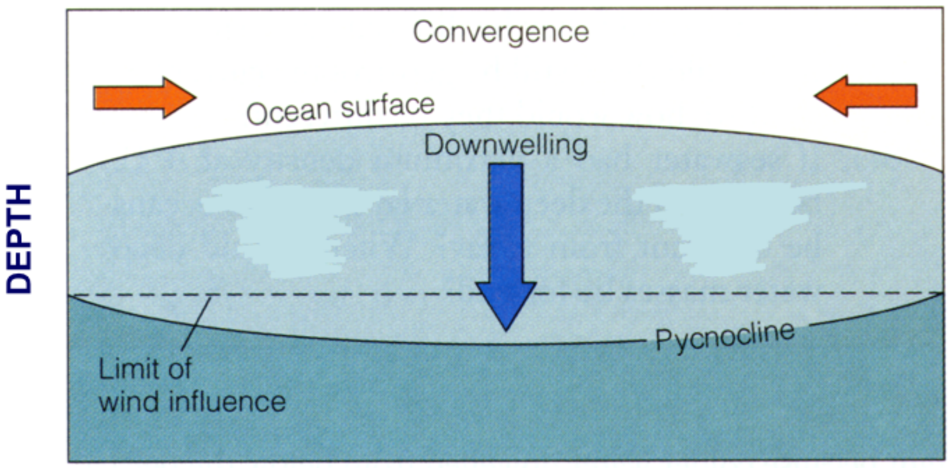
Dynamic topography: Divergence & Upwelling

This figure shows a cross-section (slice down through the ocean water) of a place where Ekman transport is causing surface water to diverge, that is, the Ekman transport on either side is “away” from the middle. This motion actually creates a little valley in the ocean surface, where sea level is a bit lower. There’s a small, but significant sea level height difference between the centre of this image and the edges. The height differences are on the order of 1-2 metres across distances of hundreds to thousands of kilometres. It’s not something you’d notice if you were at sea in a boat, but we can measure these height differences with satellites. These height differences are called “**dynamic topography**”.

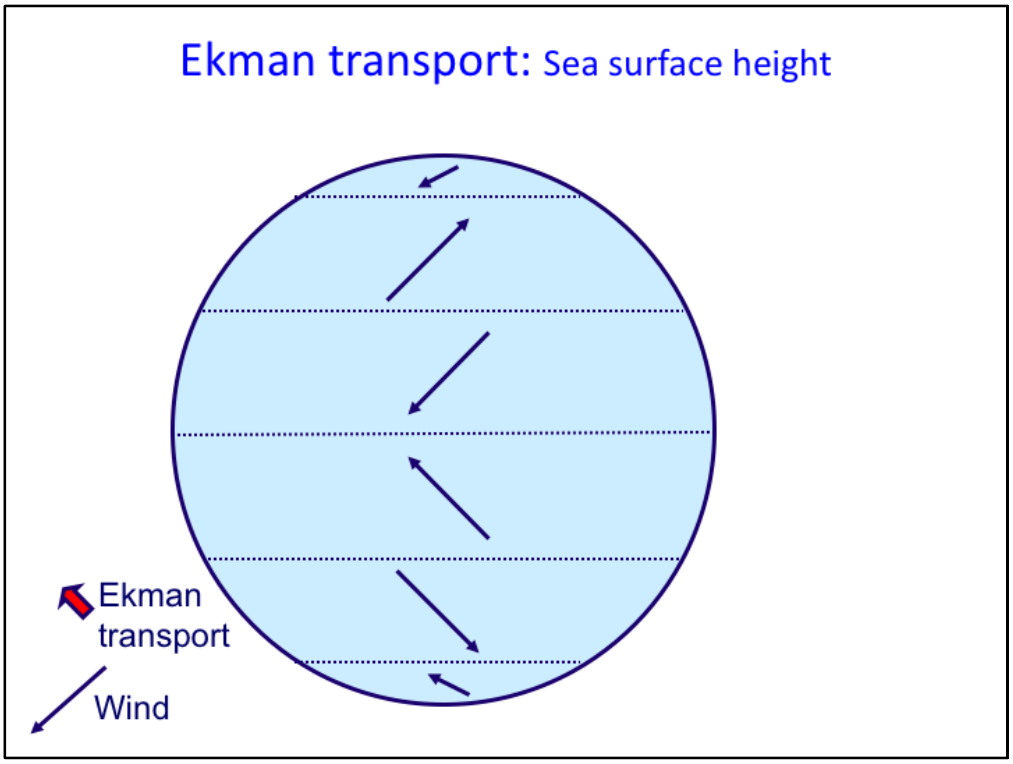
When Ekman transport creates an area of divergence, the water that’s moved away must be replaced from somewhere. This “somewhere” is typically water from deeper depths. The thick blue arrow represents water rising to the surface to “fill” the gap. This upward movement of water near the surface, driven by the wind, is called **Ekman pumping,** which causes water to **upwell** from deeper depths and move toward the surface. This **upwelling**/Ekman pumping is very important for biological productivity, as we’ll see later.

These height differences are a components of what ultimately sets up pressure gradients, which ultimately drives geostrophic flow in the ocean. In this figure, which direction does the horizontal pressure gradient go? Where’s the “high”? Where’s the “low”?

Dynamic topography: Convergence & Downwelling



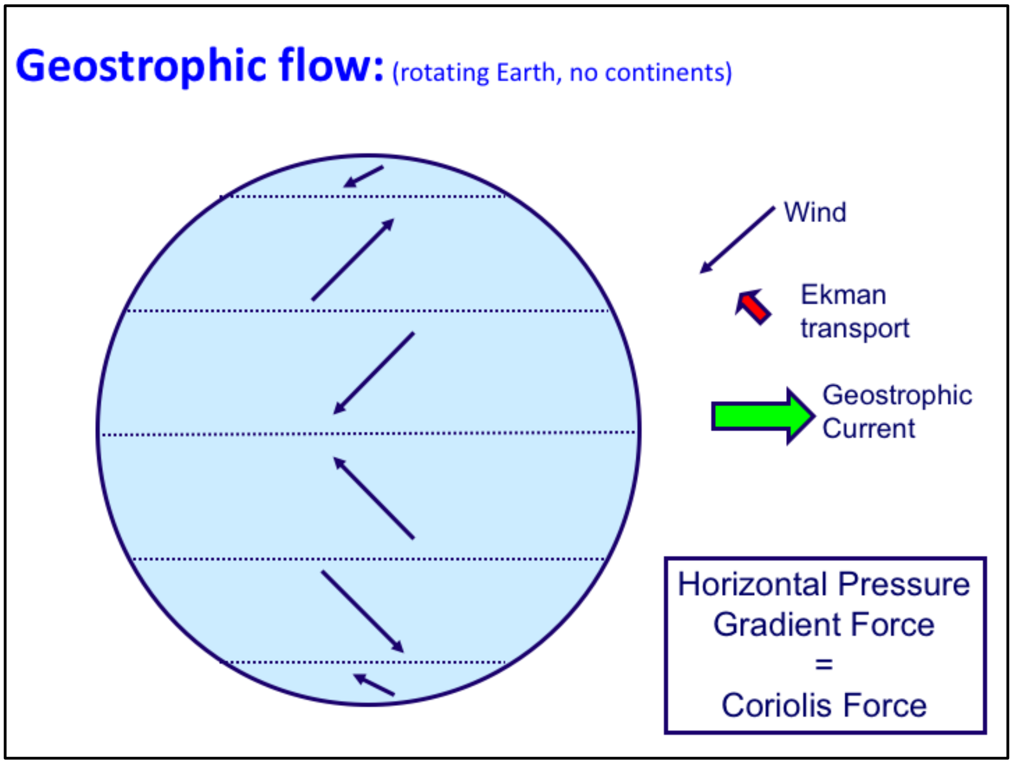
Here's an equivalent figure, but this time showing what happens in a location where Ekman transport is moving water toward the middle from either side. In this case, the sea level height increases slightly in the middle.
When Ekman transport creates an area of convergence, the "hill" of water increases the pressure below it, resulting in some movement downward from the surface toward deeper depths. The thick blue arrow represents water **downwelling** at an area of convergence.
Again, identify the pressure gradient in this figure. Which direction does the horizontal pressure gradient go? Where's the "high"? Where's the "low"?



Ekman transport: Sea surface height

Take a look at what Ekman transport does to the dynamic topography on our water-covered planet with no continents. Starting from the wind, add the Ekman transport arrows. Identify the areas of convergence and divergence. Label the places on the planet where the sea surface height is relatively high (a hill) and where it's relatively low (a valley).

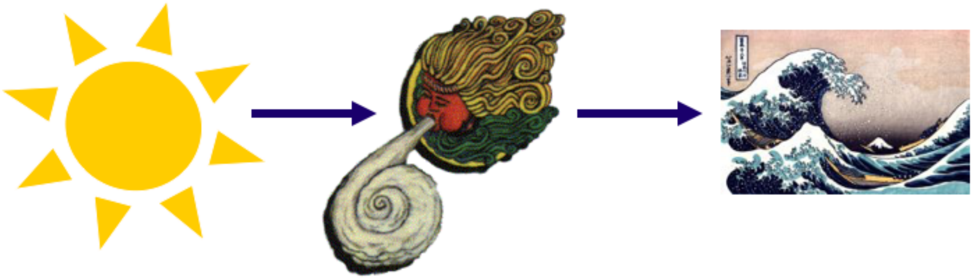
What does this mean for the directions of pressure gradients? Look back at the notes from the Atmospheres section and review how pressure gradients set up geostrophic flow (the state at which the horizontal pressure gradient force balances the Coriolis force). Based on the balance between these two forces, what direction would the geostrophic surface ocean currents flow on this water covered planet with no continents?



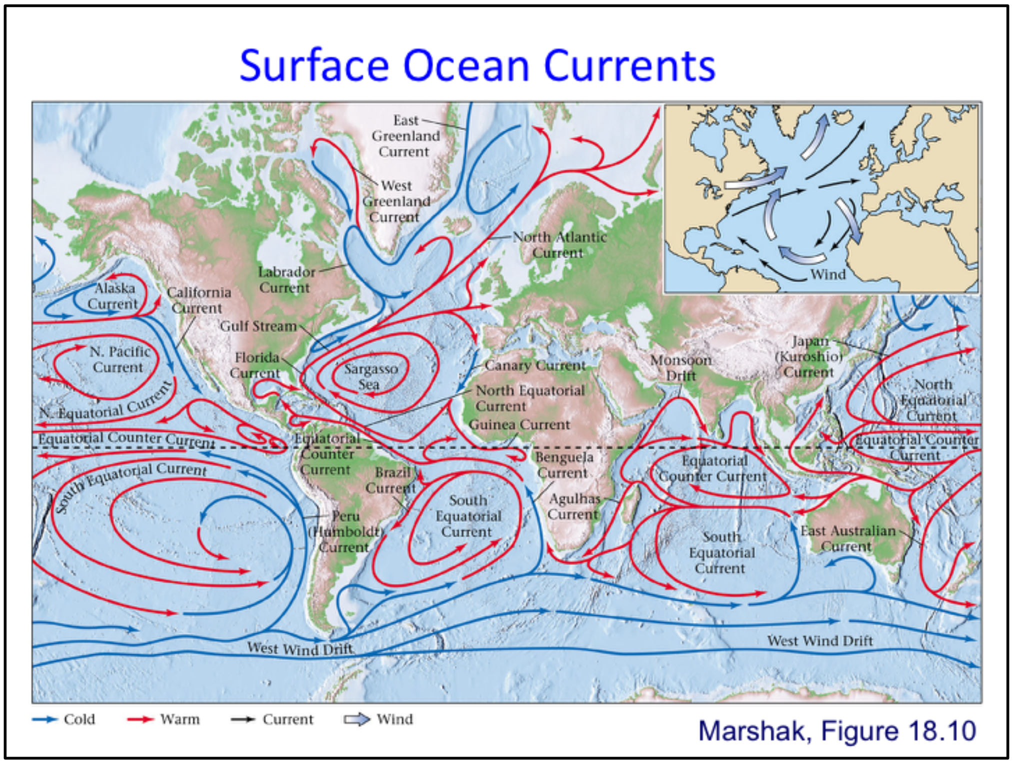
Geostrophic flow: (rotating Earth, no continents)

Horizontal Pressure Gradient Force
=
Coriolis Force

See lecture slides!



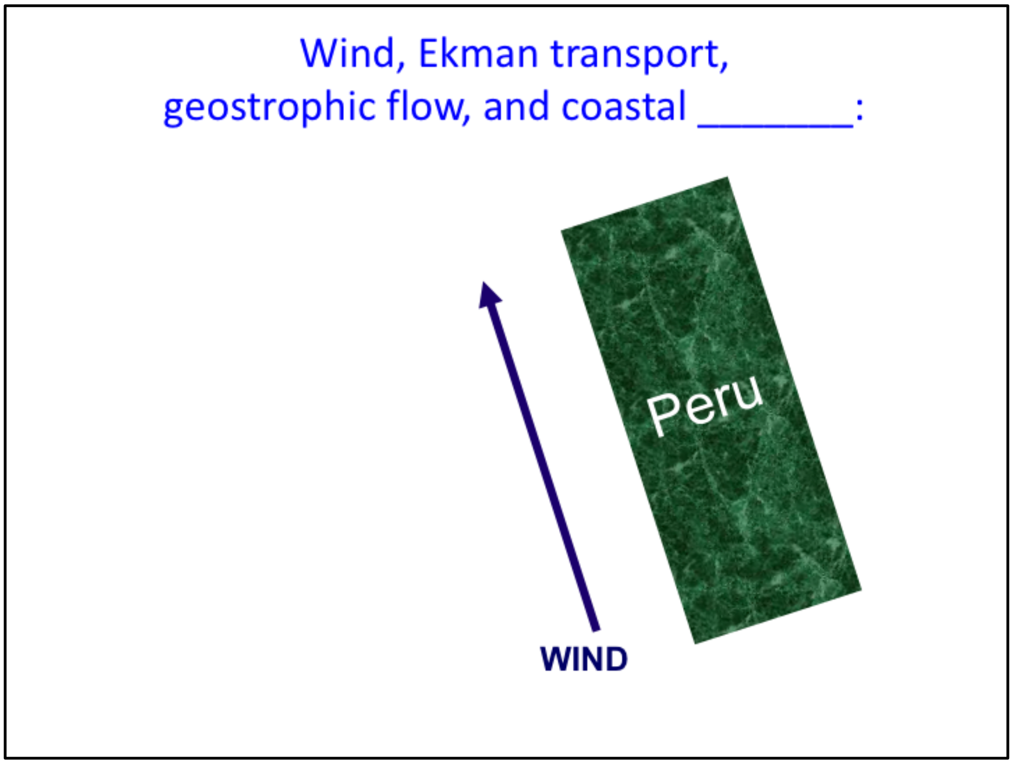
Could you logically explain the directions of flow of the geostrophic ocean currents, starting from the sun, including the atmospheric circulation, and ending with wind-driven currents? Try it on a clueless friend.



Surface Ocean Currents

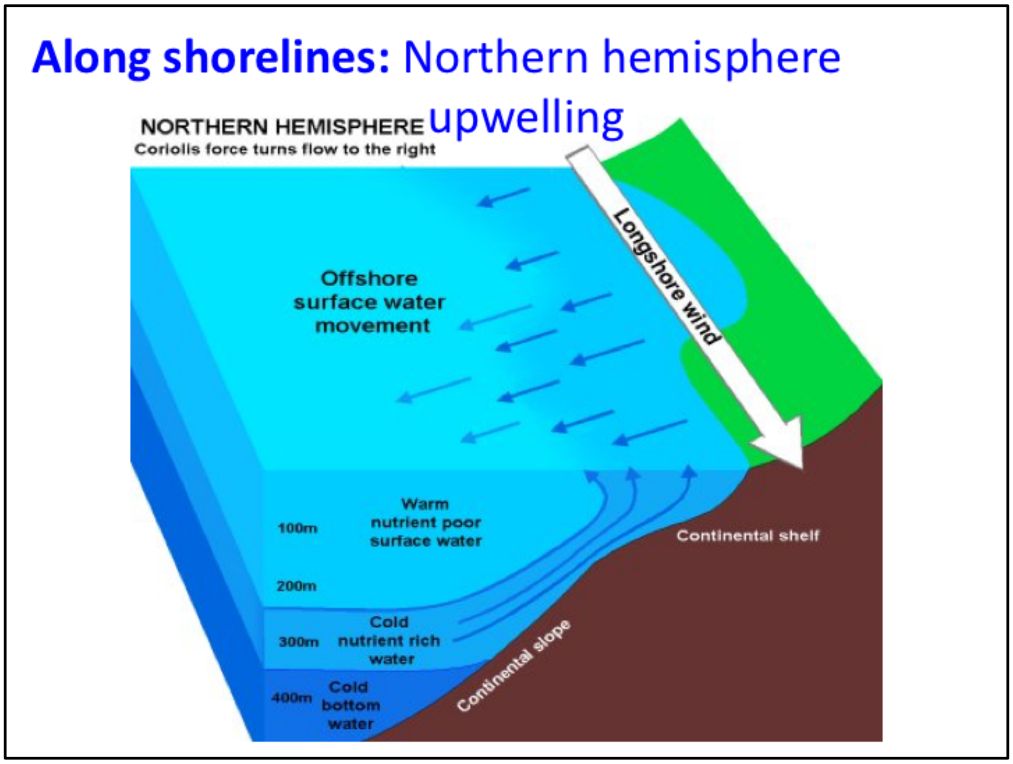
Marshak, Figure 18.10

Here it is again, the idealized view of average ocean currents, with the present-day continents in their places. First, we're going to examine what's going on along some of the coastlines, which define the edges of the ocean basins.



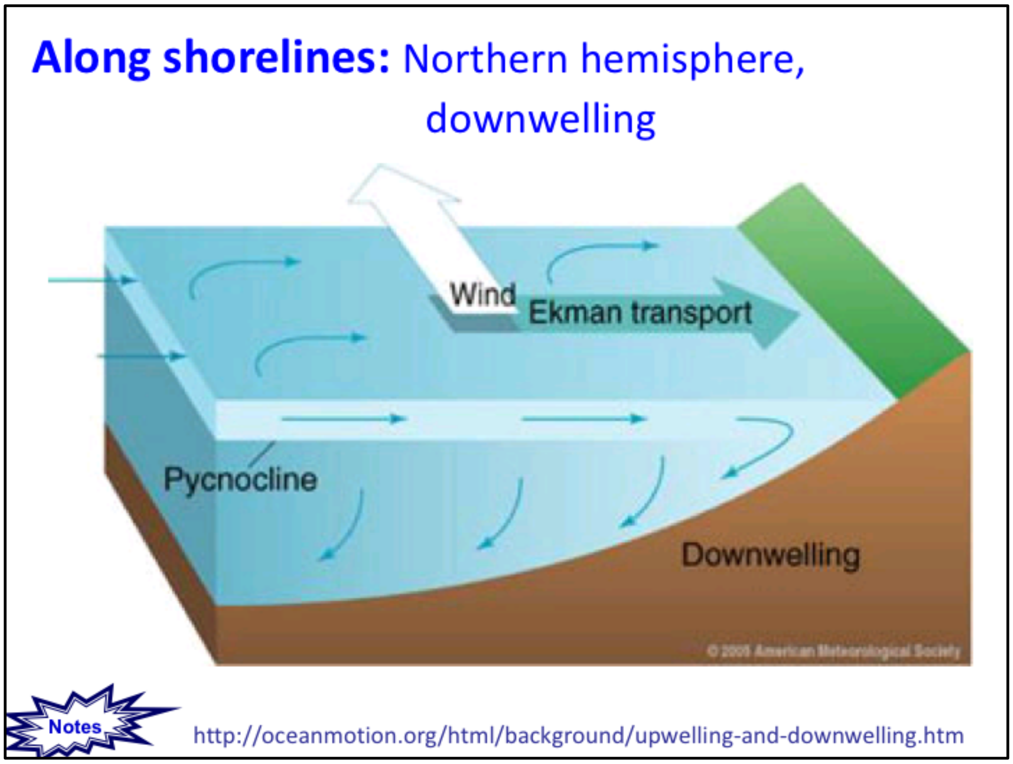
Wind, Ekman transport, geostrophic flow, and coastal ________:

Come to the lecture!



Along shorelines: Northern hemisphere upwelling

Here's a cross section showing the situation in the Northern Hemisphere along a shoreline like, say, California. In the summertime, the wind along California generally blows from north to south. The Ekman transport is 90 degrees to the right of the wind direction, or offshore. The water moved offshore is replaced by cooler, nutrient-rich water upwelling from below. The resulting geostrophic current is shown by the wide green arrow (see Lecture Slides).

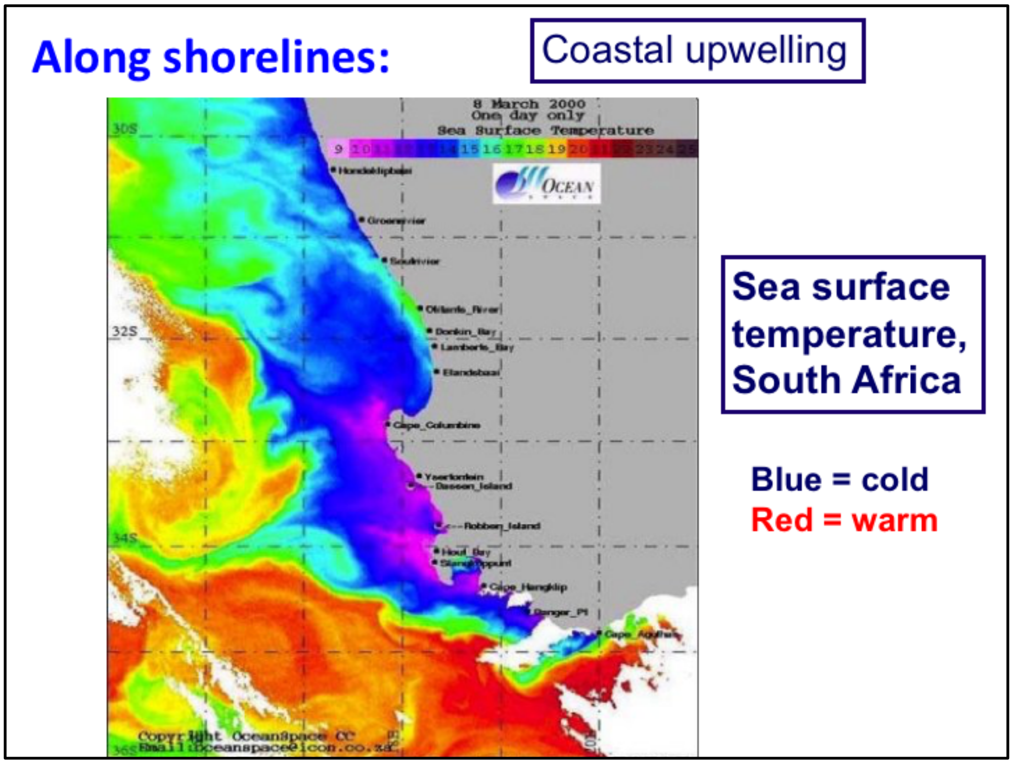


Along shorelines: Northern hemisphere, downwelling

http://oceanmotion.org/html/background/upwelling-and-downwelling.htm

NOTES SLIDE (not shown in class): Upwelling doesn’t occur on all coastlines all the time. In the winter, off the coasts of Oregon and Washington, the prevailing wind blows from the south to the north. Notice that in this scenario, the Ekman transport (northern hemisphere) is onshore, raising the sea surface height next to the continent and creating an area of downwelling. Which direction would the geostrophic current flow in this scenario?

Test yourself on the concepts that control ocean currents, upwelling, and downwelling along coastlines, in as many scenarios as you can think of.



Along shorelines:

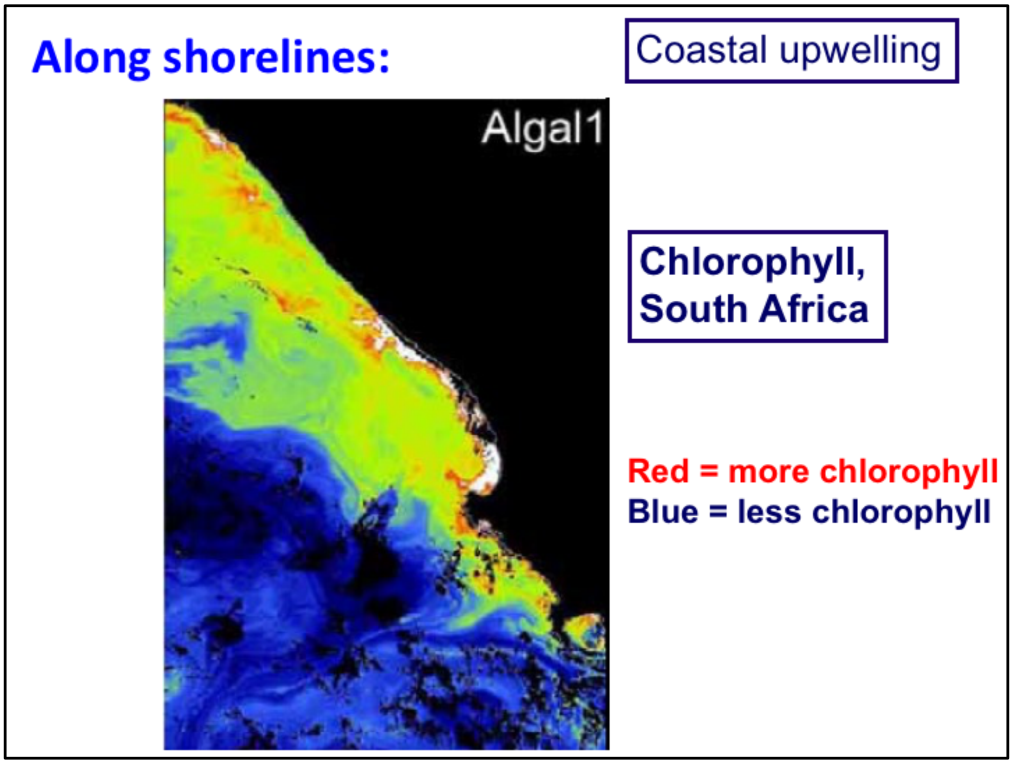
Coastal upwelling

Sea surface temperature, South Africa

Blue = cold
Red = warm

We've seen that coastal upwelling causes water from deeper depths to rise to the surface. This deeper water has different physical and chemical properties than the surface water it's replacing. It's colder than the surface water nearby and is more nutrient-rich (which we'll get into in detail in the biota section). This cool, nutrient-rich water fuels biological activity, thus *the physical motion of water (physical oceanography) has a profound effect on biology (biological oceanography).*
This figure shows a false-color satellite image of sea surface temperature for the area just west of South Africa. Blue/purple colors indicate colder temperatures and red colors indicate warmer temperatures. Cooler temperatures near the coast indicate that this is an area of upwelling. What would the sea surface temperature pattern look like if this were an area of downwelling?

Can you tell what direction the wind had been blowing, when this image was taken? Toward what direction is the Ekman transport? Likely geostrophic current direction?



Along shorelines:

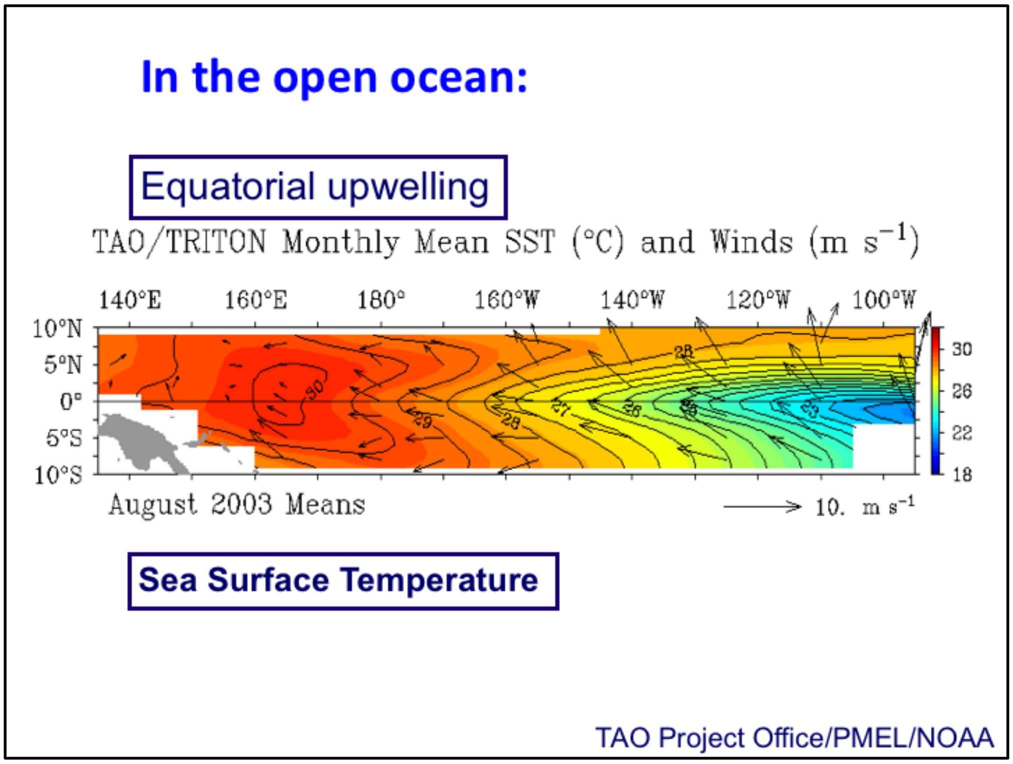
Coastal upwelling

Chlorophyll, South Africa

Red = more chlorophyll
Blue = less chlorophyll

The previous slide was sea surface temperature, showing the cool water upwelling near the coast of South Africa. This image shows the results of biological activity fueled by that upwelling. Tiny marine “plants”, called phytoplankton, utilize the upwelled nutrients and reproduce quickly. The concentration of phytoplankton in the water can be approximated by the water’s color (really green water has a lot of phytoplankton in it; clear blue tropical water has little phytoplankton in it). Chlorophyll, which is shown in this image, is a pigment in phytoplankton that they use for photosynthesis. The red colors indicate where the chlorophyll (and phytoplankton) concentration is high, and the blue indicates where it’s low. Note that it’s high close to shore, where that nutrient-rich water is upwelling. It’s low farther offshore.

Again, can you logically guess at wind direction, Ekman transport, geostrophic flow based on this image?



In the open ocean:

Equatorial upwelling

Sea Surface Temperature

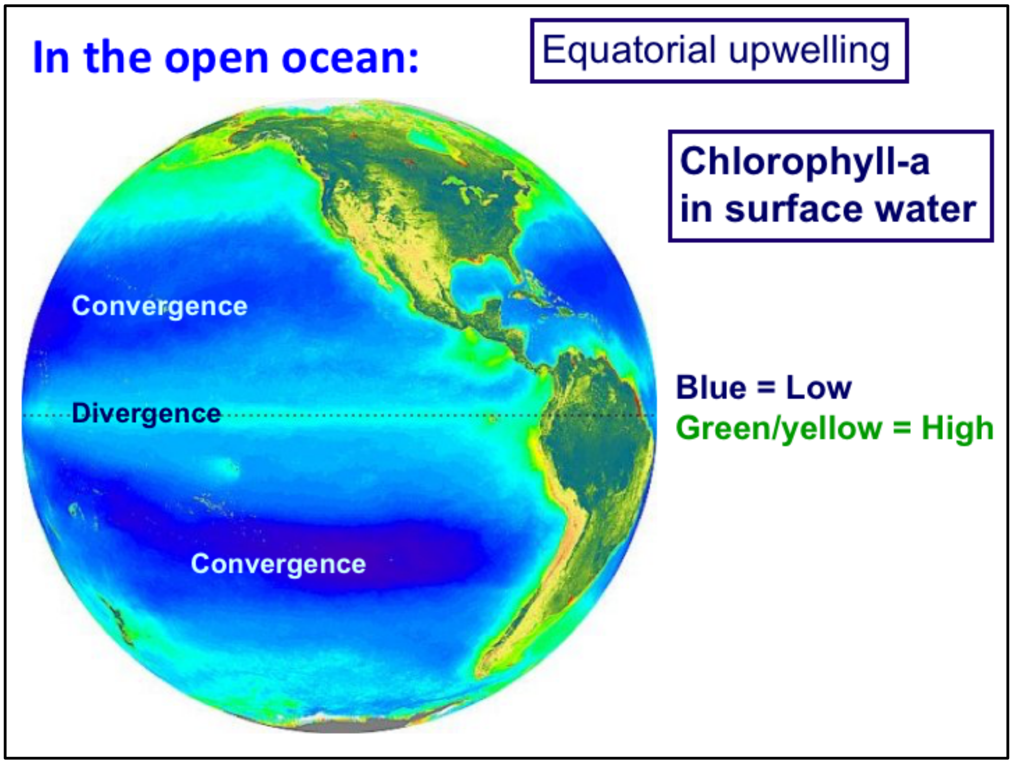
TAO Project Office/PMEL/NOAA

Upwelling doesn’t just occur along coastlines, it can also happen in the open ocean. We saw on the water-covered Earth (no continents) that there are areas of divergence where Ekman transport is carrying water away from certain regions, even without a shoreline to act as a boundary. Here’s one of the classic examples of open-ocean upwelling on Earth – **equatorial upwelling**.

This map shows sea surface temperature (degrees Celsius) in the equatorial Pacific Ocean. Note the latitude and longitude scales. We’re just looking at a strip of the ocean from 10 degrees north to 10 degrees south of the equator. The horizontal line across the middle marks the equator. The small black arrows are wind vectors, showing the direction and strength of the wind (strength is indicated by the length of the arrow).

Based on these wind arrows, what direction is the Ekman transport in this figure? Remember that the Coriolis effect changes sign (left/right) at the equator. If you were to draw Ekman transport arrows on this figure, you’d generally get picture showing Ekman transport of surface water away from the equator into both hemispheres. This divergence creates a low or a valley in the sea surface topography right along the equator. To replace the water moving away, cool water upwells from below. This equatorial upwelling occurs right along the geographic equator because of the change in sign of the Coriolis effect.

Do these arrows match your expectations of the wind pattern near the equator in the equatorial Pacific? These wind vectors seem to be generally coming from the southeast, and are the southeast trade winds. Why is it that the southeast trade winds can cross the equator?



In the open ocean:

Equatorial upwelling

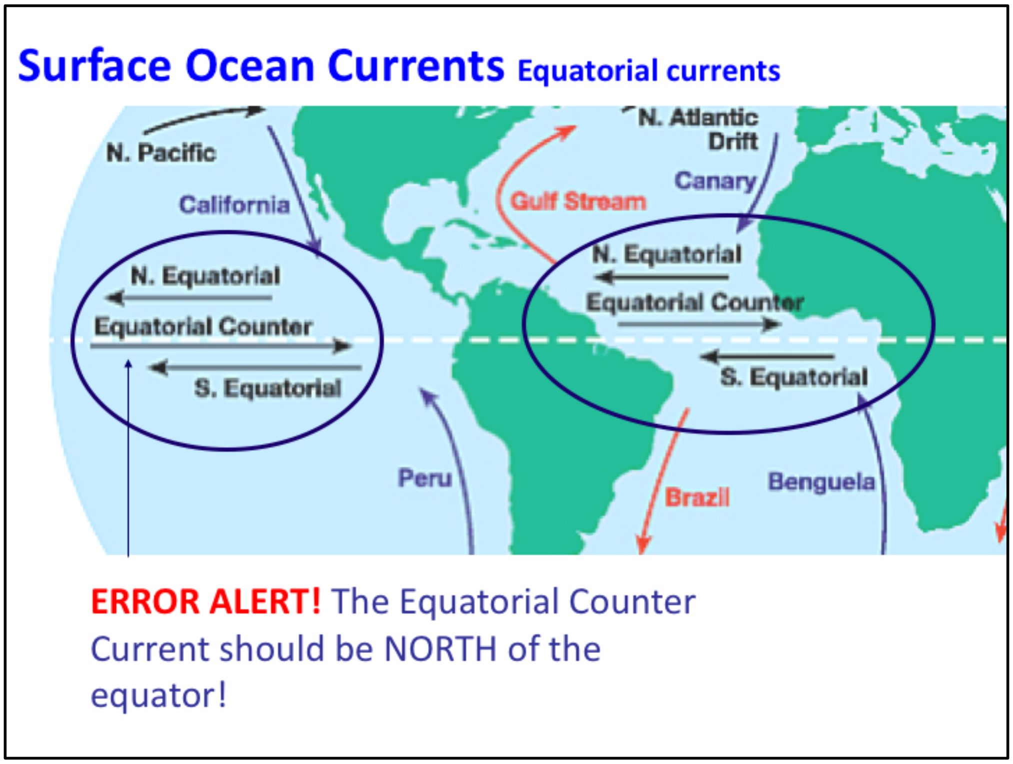
Chlorophyll-a in surface water

Blue = Low

Green/yellow = High

Here’s a larger image of the Pacific, showing the effects of areas of divergence and convergence, upwelling and downwelling in the open ocean away from the continents. The image shows chlorophyll-a concentrations in surface water, where blue = low concentration, and the green/yellow =higher concentrations. Note the band of relatively high chlorophyll right along the geographic equator. Note the areas of quite low chlorophyll concentration about 30 degrees latitude both north and south of the equator. Do these match the general patterns of convergence and divergence on the water-covered Earth with no continents? What happens at higher latitudes?

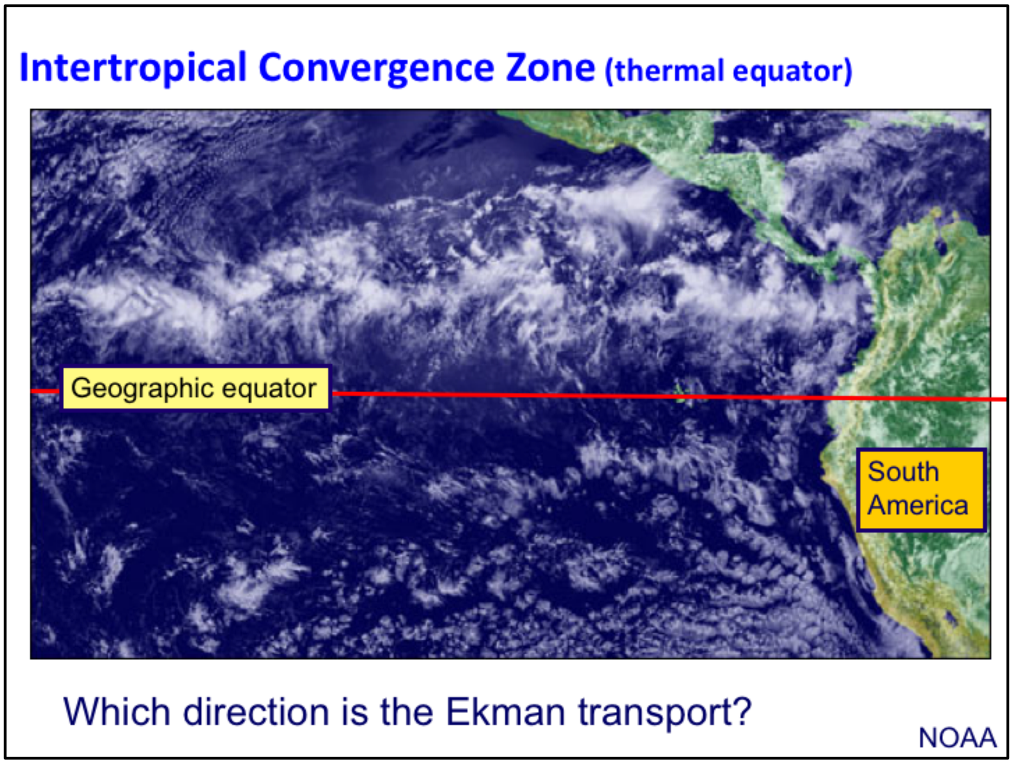
Note also, again, the areas along the coast with relatively high chlorophyll concentrations. Why is it high there?



Surface Ocean Currents Equatorial currents

ERROR ALERT! The Equatorial Counter Current should be NORTH of the equator!

We saw earlier that the global wind patterns get a little screwed up by the presence of continents, and, in particular, the fact that there's more continental land mass in the northern hemisphere at the moment than there is in the southern hemisphere. This continental imbalance means that the average position of the ITCZ is north of the equator. Like the wind patterns, the equatorial ocean currents get a little wacky too. Look back at the geostrophic currents we developed for the water-covered Earth. Compare that to the image above. For the water covered Earth, you should see equivalents of the North Equatorial and South Equatorial Currents shown here. But what's that "Equatorial Counter Current"? [Note the error on the image].
Next, we'll develop these equatorial currents. They are geostrophic, just like all the currents we've been discussing.

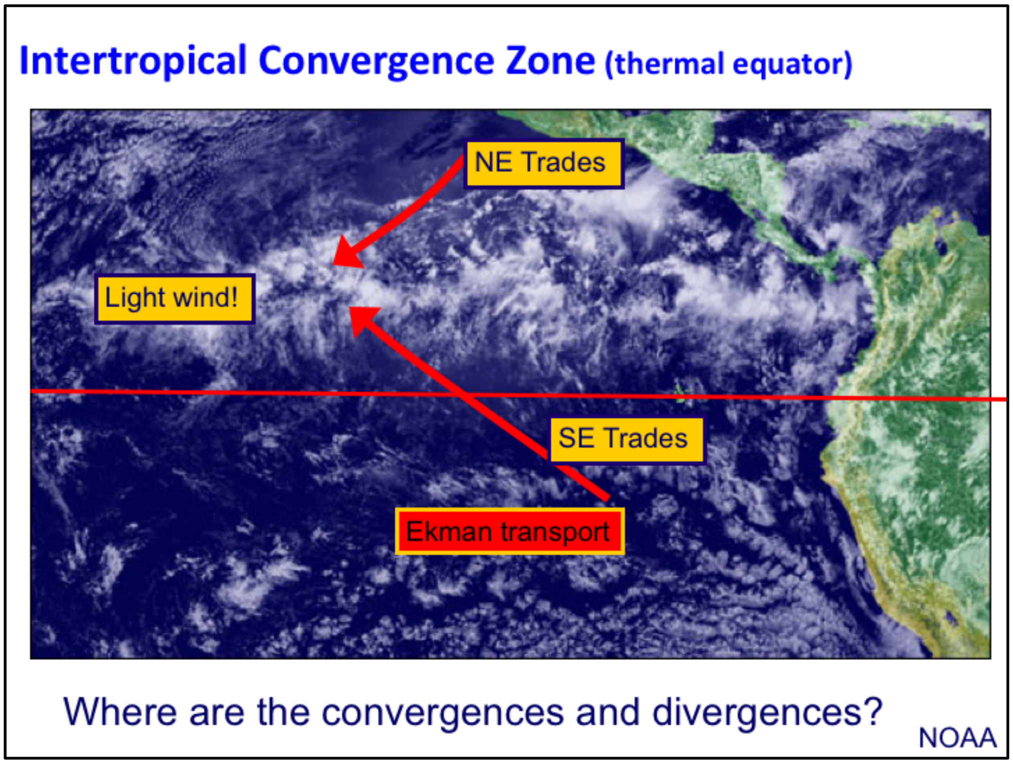


Intertropical Convergence Zone (thermal equator)

Which direction is the Ekman transport?

NOAA

Here’s a satellite image of clouds over the eastern equatorial Pacific. Where’s the ITCZ (we had a clicker question about this in an earlier class)? The ITCZ (defined by the band of clouds), is where the NE Trade Winds and the SE Trade Winds converge (“convergence zone”, right?). It’s where warm wet air is rising vertically. As we’ve discussed previously, the ITCZ is offset to the north of the geographic equator, which means that the SE Trade Winds actually cross the geographic equator in this situation. Just as in previous examples, the wind drives Ekman transport. What direction is the Ekman transport here?



Intertropical Convergence Zone (thermal equator)

Where are the convergences and divergences?

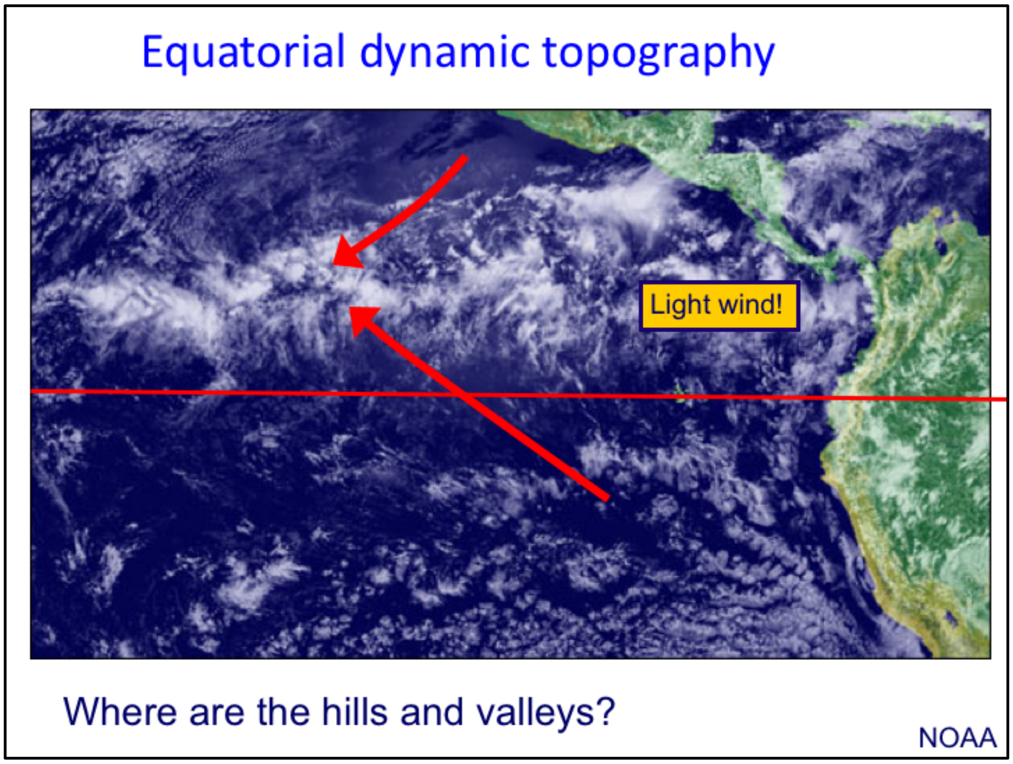
NOAA

Given this scenario, with the SE Trades crossing the equator, there are three regions in which the Ekman transport should be considered:

1. The Ekman transport from the SE Trades south of the geographic equator
2. The Ekman transport from the SE Trades north of the geographic equator
3. The Ekman transport from the NE Trades.

Draw them in.

Next question – Ekman transport produces convergences and divergences. Where are those?



Equatorial dynamic topography

Where are the hills and valleys?

NOAA

The easiest one is one we've already seen. At the geographic equator, Ekman transport is taking water away from the equator on both sides. Thus, at the geographic equator, there's a divergence, or relative low sea level (a valley in the dynamic topography)

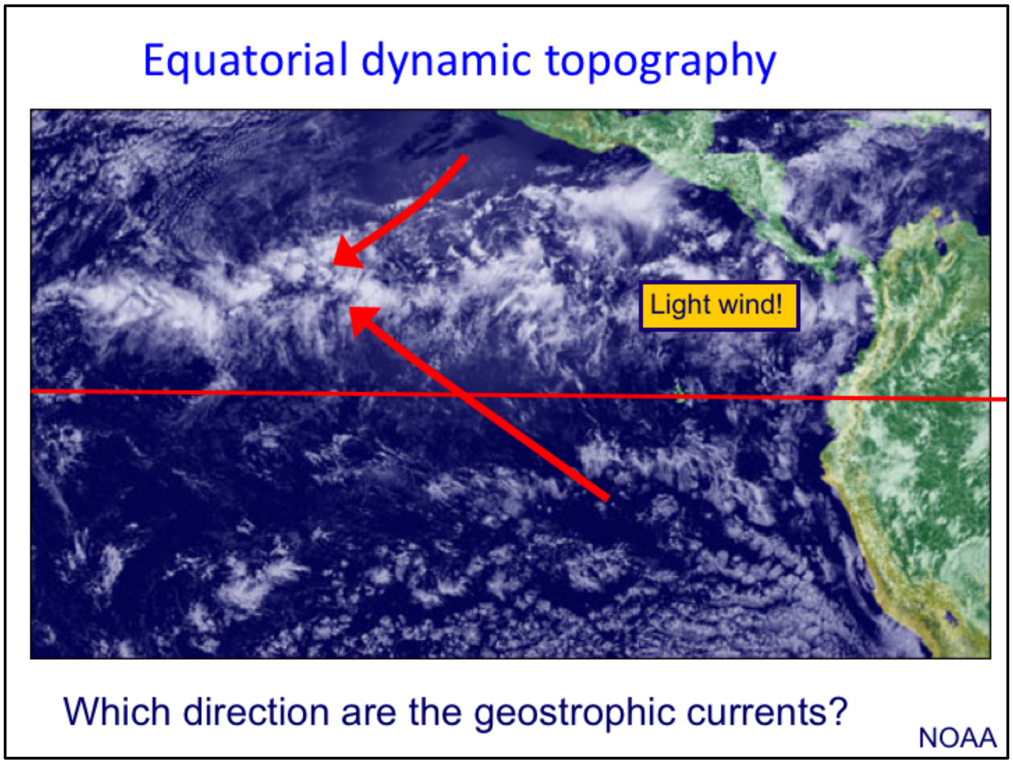
We can also assume that there is a convergence south of the equator, centred at about 30 degrees latitude. This is a feature that's similar to what happens on the water-covered Earth. Same thing at about 30 degrees north. The Ekman transport from the NE Trades shows water moving northward.

The complicated bit is between the equatorial divergence and the convergence at 30 degrees north.

At the ITCZ, the wind is weak. This makes sense because the main feature of the ITCZ is that it's a location where air is rising. The convergence of the NE and SE Trade Winds is not a violent affair, rather, the strength of both decreases as they approach the ITCZ. The surface ocean under the ITCZ is also called **the Doldrums**. The Doldrums are a place you don't want to get stuck in a sailboat with no motor. Wind is light, variable, and unreliable. Many a ship has had to row themselves out of the Doldrums to catch a breeze.

How does this information bear on the location of convergences and divergences that will set up the pressure gradients that will drive the geostrophic flow? Remember that Ekman transport is driven by the wind blowing across the water surface. Less wind, less Ekman transport. Imagine that in the Doldrums (under that cloud band) is a mass of water with very little wind blowing across it. From the south (just north of the equator), we have Ekman transport carrying water to the north. This water piles up against the water in the Doldrums (which isn't being moved much by Ekman transport since the winds are so light), creating a convergence (local "hill") a few degrees north of the equator (on average, about 4 degrees north latitude). To the north of the ITCZ, the wind strength picks up again in the NE Trade Winds, and the Ekman transport from that carries water northward AWAY from the sluggish mass in the Doldrums. That action creates a divergence (local "valley") that is located, on average, at about 10 degrees north.

Complicated!



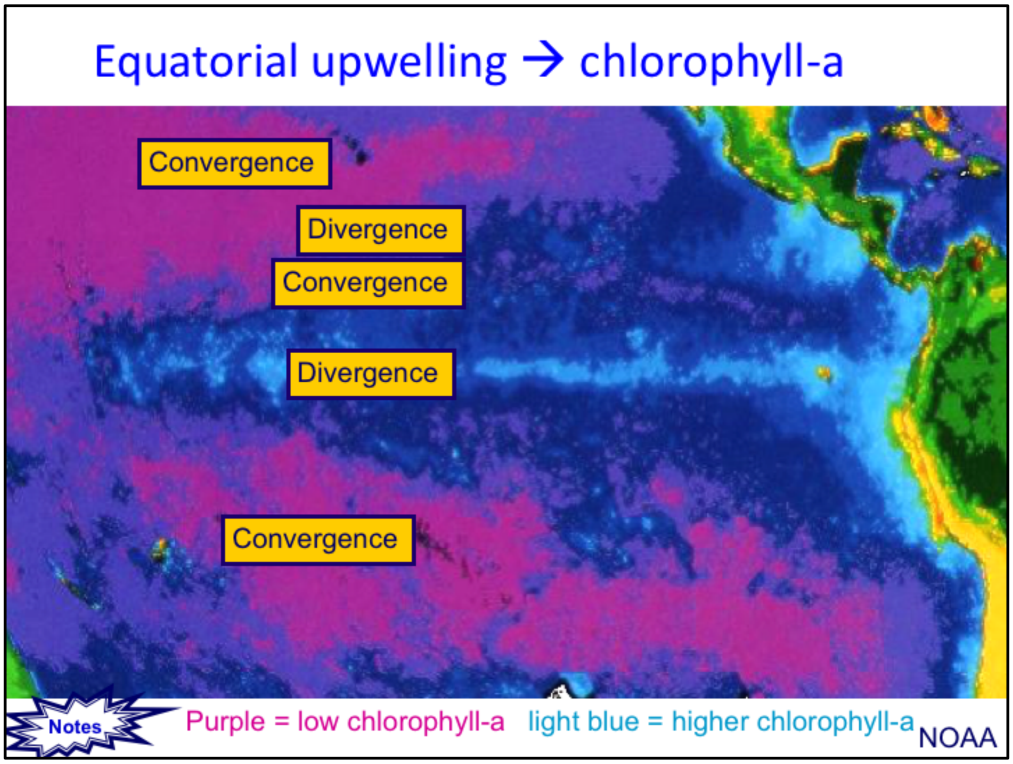
Equatorial dynamic topography

Light wind!

Which direction are the geostrophic currents?

NOAA

See lecture slides!

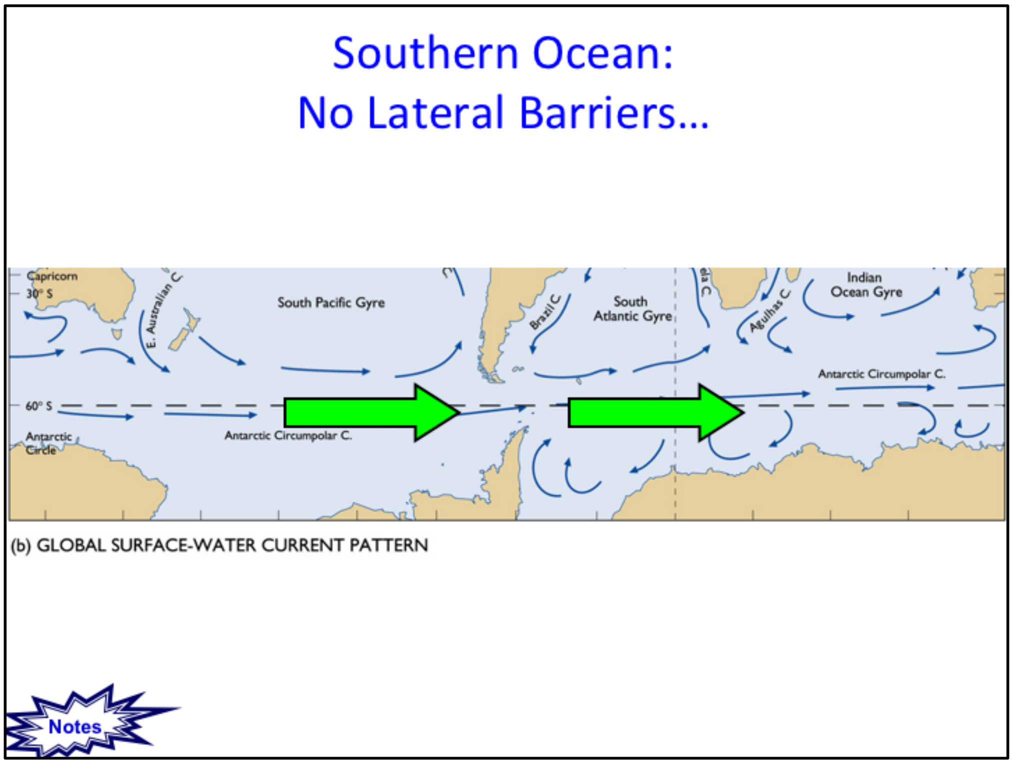


Equatorial upwelling → chlorophyll-a

Notes

Purple = low chlorophyll-a light blue = higher chlorophyll-a NOAA

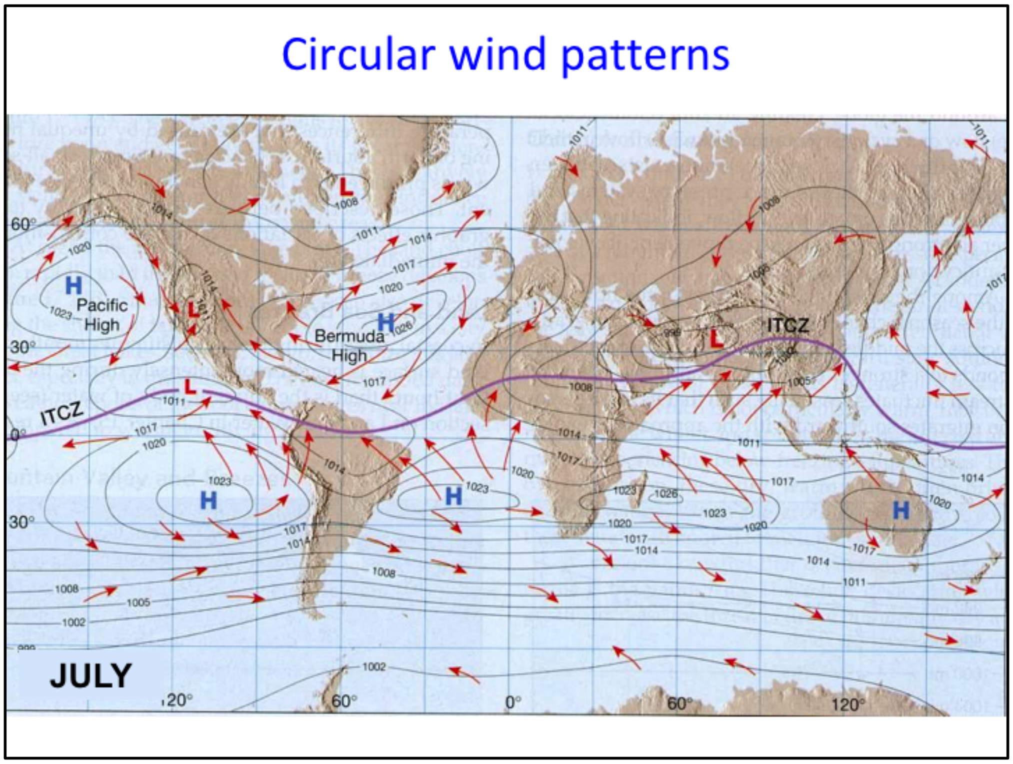
NOTES SLIDE (not shown in class): Take a closer look at the satellite image of chlorophyll in the surface ocean in the eastern Equatorial Pacific. Before, we just examined the divergence right along the geographic equator. In this image, you can also see the result of divergence (and upwelling) associated with the divergence at about 10 degrees north.



Southern Ocean:
No Lateral Barriers…

(b) GLOBAL SURFACE-WATER CURRENT PATTERN

NOTES SLIDE (not shown in class): Figure out what's going on in the Southern Ocean. This figure tells you the answer – the Antarctic Circumpolar Current flows around and around and around Antarctica from west to east (there's no land to get in the way). Can you explain the Antarctic Circumpolar Current as a geostrophic current?

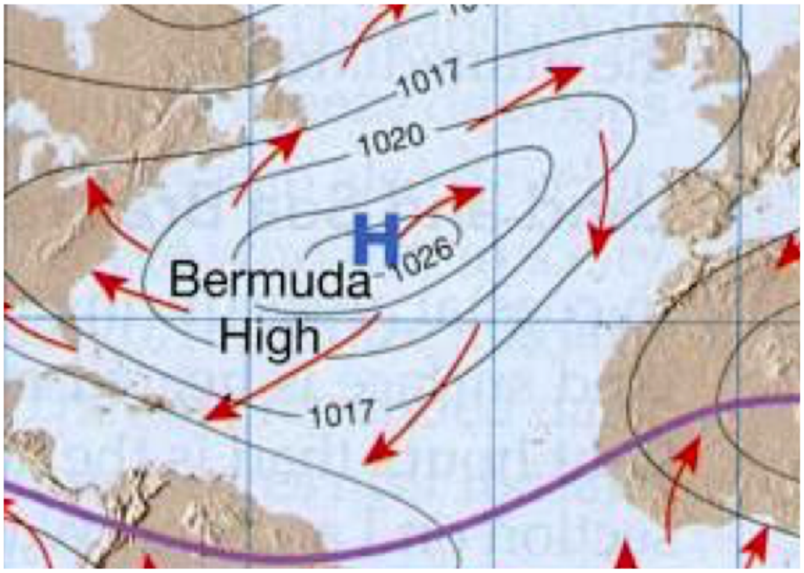


Circular wind patterns

What else happens when continents get in the way, beside coastal upwelling and downwelling? This slide is a repeat from one of the atmospheres lectures, showing generalized, broad scale, average atmospheric pressure patterns for July. Examine the locations of some of those high pressure system. For example, it looks like the wind blows around Bermuda High, in the North Atlantic basin, generally in a clockwise pattern. And this is what you can generally expect, on average, if you were in a sailboat out there (with the occasional cold front coming through). The westerlies form the northern edge of the atmospheric circulation around the Bermuda High, and the NE Trade Winds form the southern edge.

How does this circular wind pattern affect ocean circulation?

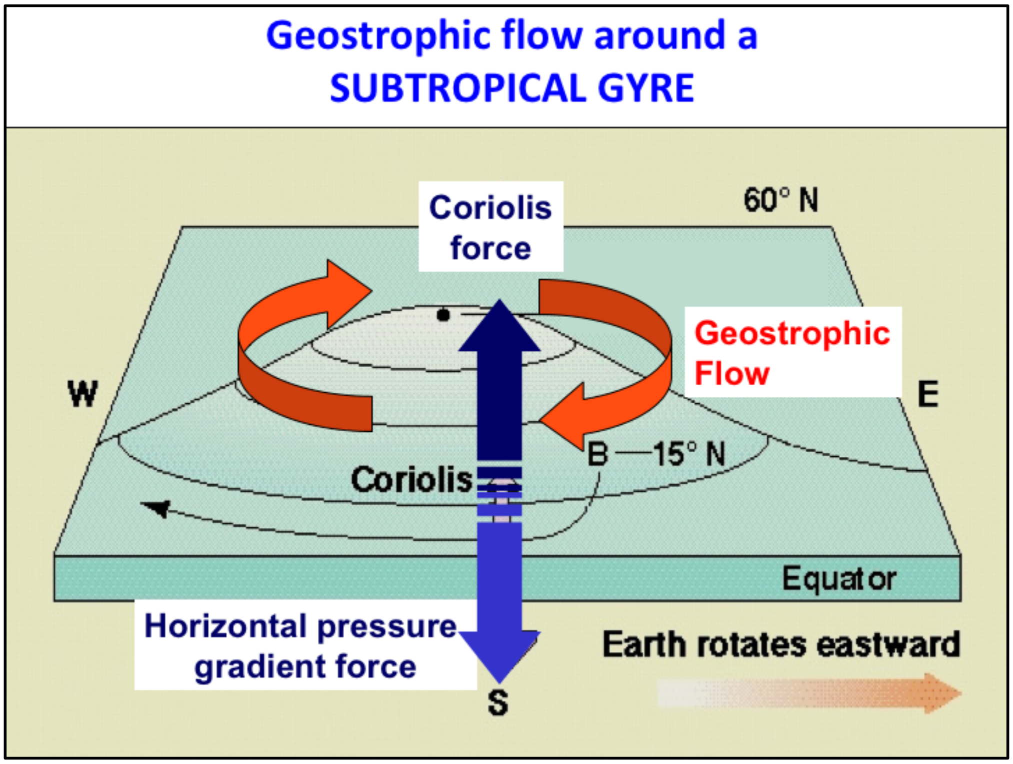
Ekman transport under the Bermuda High



Zoom in on the Bermuda High…

Given these wind vectors (red arrows), which flow clockwise around and outward from the high pressure centre (because of friction with the ground the surface winds aren't quite geostrophic), what does Ekman transport do?

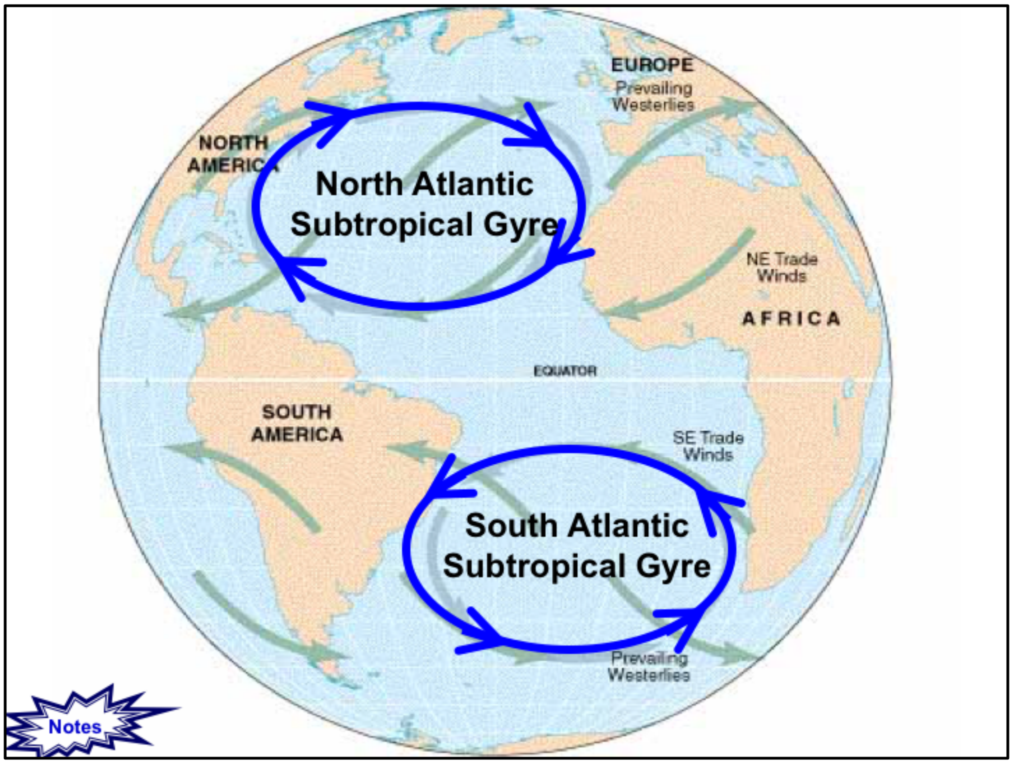
Northern Hemisphere, so Ekman transport is 90 degrees to the right of the wind direction…so the Ekman transport results in a general pileup in the middle of the North Atlantic Ocean, centred at about 30 degrees north. How does that compare with the convergence on the water-covered Earth? Where the convergence on the water-covered Earth was a ridge that ran all the way around the planet like a spare tire, the presence of the continents results in a mound bounded on either side by land. There's a mound like this in every major ocean basin that has water at about 30 degrees latitude, both north and south of the equator. These are called **subtropical gyres**. Another name you will encounter for these is **central gyres**, since these are the central features of the major ocean basins



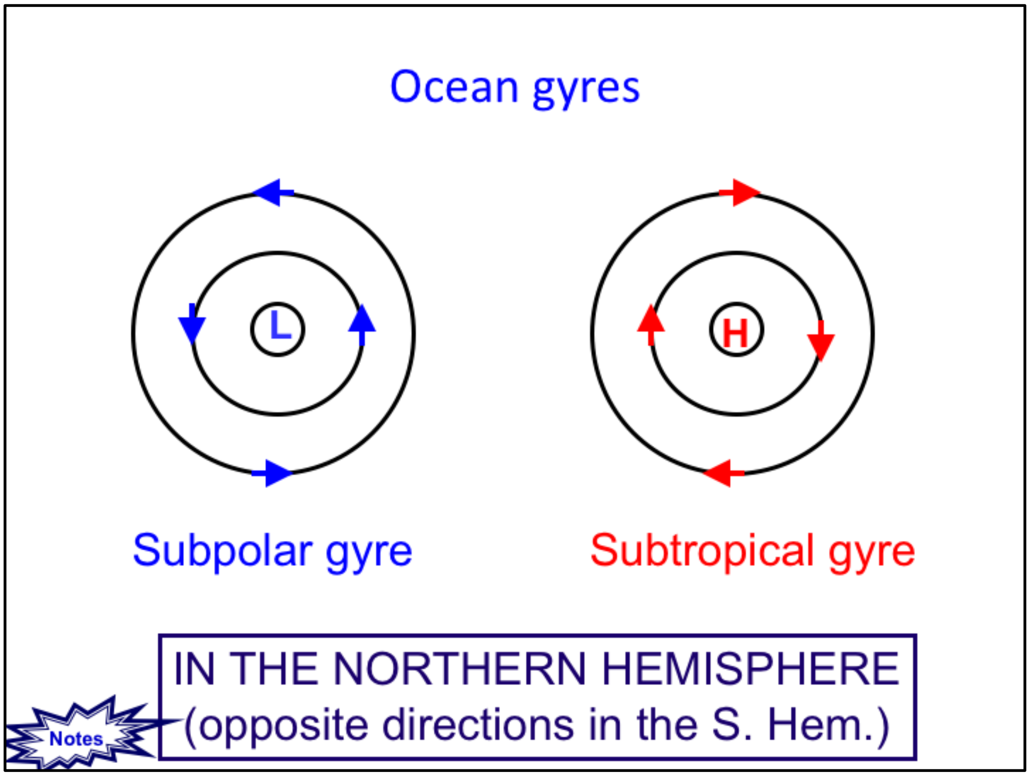
Geostrophic flow around a SUBTROPICAL GYRE

Apply the balance of the horizontal pressure gradient force and the Coriolis force to this mound of water and we get geostrophic flow around the contours of the mound. In the Northern Hemisphere, the resulting surface water flow around a subtropical gyre is clockwise, very similar to the situation in the overlying atmosphere.

What direction is the flow around a subtropical gyre in the Southern Hemisphere?



NOTES SLIDE (not shown in class): Here they are, the North Atlantic Subtropical Gyre and the South Atlantic Subtropical Gyre. Check these out in the Pacific and Indian Ocean basins too.



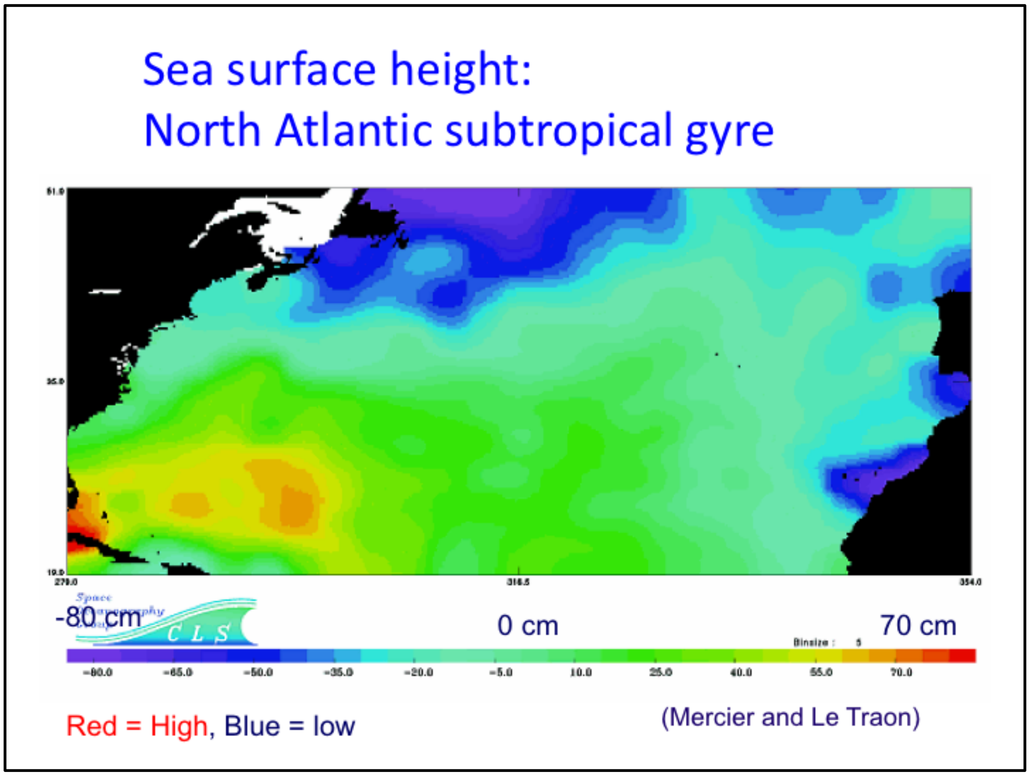
Ocean gyres

Subpolar gyre

Subtropical gyre

IN THE NORTHERN HEMISPHERE
(opposite directions in the S. Hem.)

NOTES SLIDE (not shown in class): Gyres don't have to flow around mounds/hills, with a high place in the middle (like shown on the right). Gyres can also flow in circular patterns around relative low points in the ocean's surface (also created by Ekman transport, ultimately driven by the winds). The subpolar gyres (closer to the poles than the subtropical gyres) flow around low centres. Look back at the Surface Ocean Currents slide near the beginning of this set of notes and look at what's going on near Alaska.



Sea surface height:
North Atlantic subtropical gyre

-80 cm

0 cm

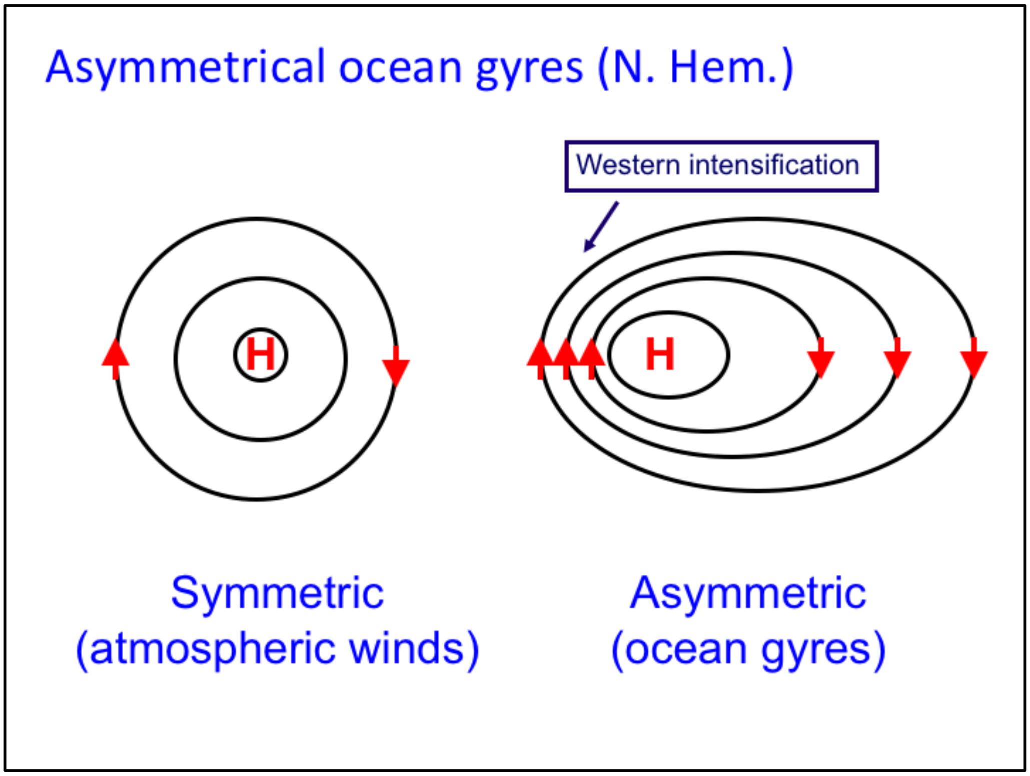
70 cm

Red = High, Blue = low

(Mercier and Le Traon)

How high are these mounds? How much difference in sea surface height are we talking about here? The figure above shows sea surface height in the North Atlantic, contoured in colors (data are from the TOPEX/POSEIDON satellite). Red is “relatively high” and blue is “relatively low”. Note the scale bar below the figure. The range of heights shown encompasses about 1.5 metres total, over distances crossing the entire Atlantic Ocean. Not something you’d notice with your eyes, but significant enough to set up a pressure gradient.

Gyres are not actually nice and symmetrical, as shown in the previous slide. Notice that the top of the mound is offset toward North America, and away from Europe and Africa. Note also that the western side of the mound is steeper than the eastern side, where the slope is more gradual. This is the result of the Earth’s rotation from west to east.



Asymmetrical ocean gyres (N. Hem.)

Symmetric
(atmospheric winds)

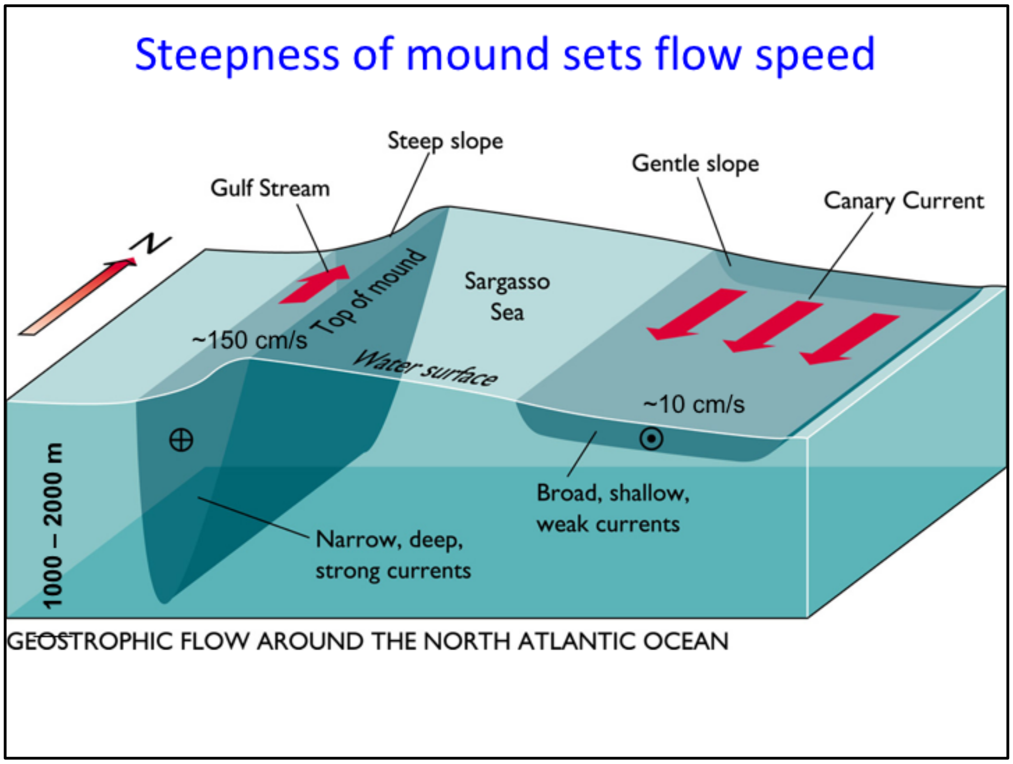
Asymmetric
(ocean gyres)

Although the overlying atmospheric circulation cells can be close to symmetrical, circulation in the ocean gyres is asymmetrical. This has to do with the conservation of vorticity, or the tendency for parcels of water to rotate, even as they flow with the main current. A discussion of vorticity is beyond our scope here. Here's a "conceptual" explanation of this asymmetry:

The Earth rotates from west to east. Since ocean water is not rigidly attached to the Earth (it's a fluid), it "lags behind" the solid rotating Earth. This "presses" the gyre up against the western boundary of the ocean basin, narrowing the space for the water to flow through. The same amount of water has to flow north on the western side of the gyre as flows south on the eastern side, so the western current must flow faster through the narrow space, while the eastern current flows more slowly through a larger space. This explanation may give you a conceptual way to visualize **"western intensification"**, but is not quite what's happening. See below for addition info (if interested).

If you're interested in investigating vorticity, there are three components to consider:

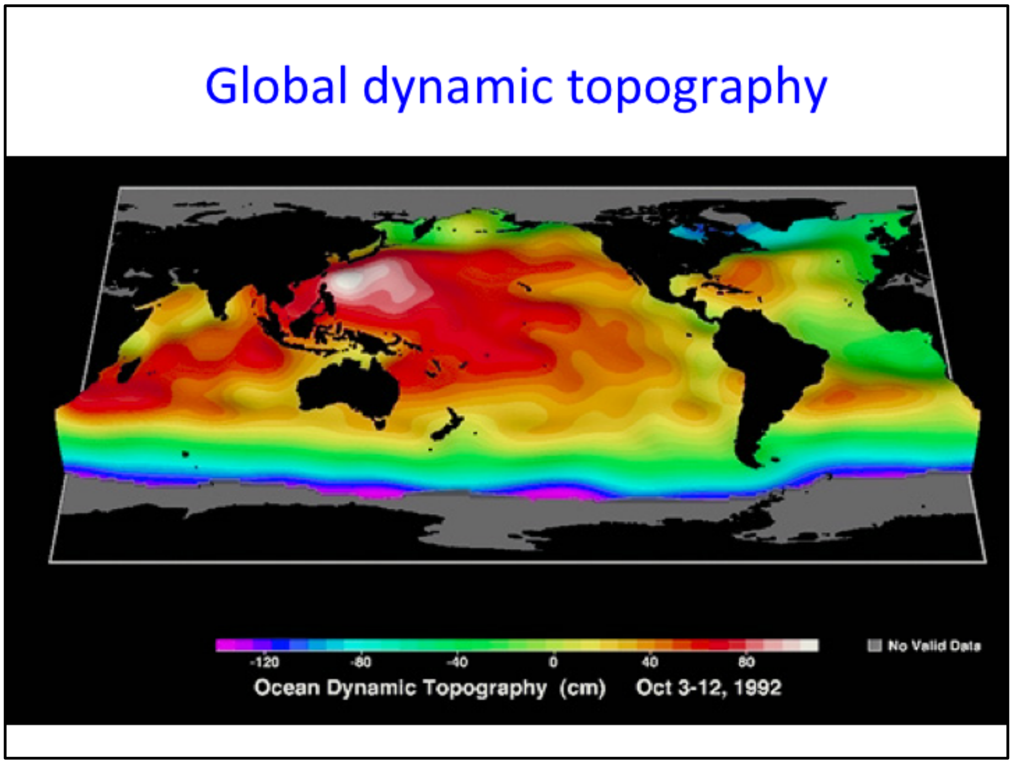
1. The vorticity induced by the overlying wind pattern, in the case of the North Atlantic subtropical gyre, the wind induces a clockwise vorticity everywhere.
2. Planetary vorticity, which changes with latitude. A parcel of water moving from the tropics northward in the northern hemisphere will acquire an additional tendency to rotate clockwise. Look at the figures above: this northward motion occurs on the western edge of the gyre. A parcel of water moving southward toward the equator in the northern hemisphere acquires a tendency to rotate counterclockwise, somewhat balancing the vorticity induced by the wind.
3. Friction with the continental boundary. On the west side of the ocean basin, factors 1 & 2 above are both acting in the same direction (clockwise in the northern hemisphere). To conserve vorticity, something must balance them and induce a counterclockwise rotation. Strong friction (and thus a strong, fast current) with the continental boundary fulfills this requirement. On the east side of the ocean basin, factors 1 & 2 above act in opposite directions and less friction is required to conserve vorticity. Thus on the eastern sides of the subtropical gyres, the current is slow and broad.



Steepness of mound sets flow speed

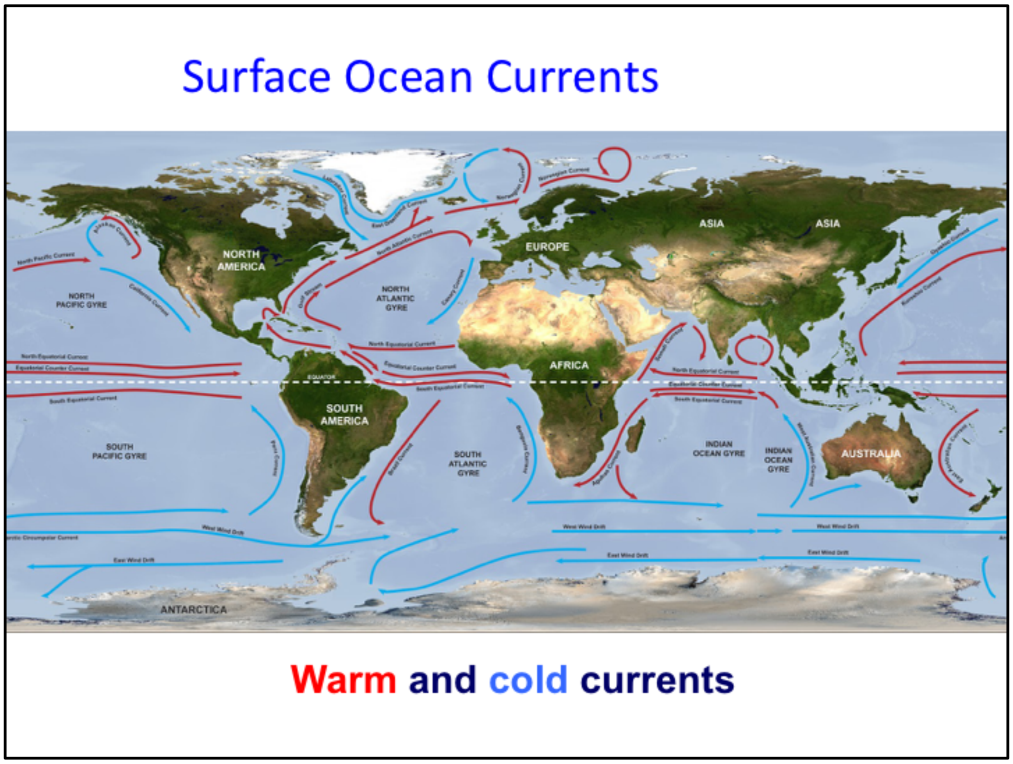
GEOSTROPHIC FLOW AROUND THE NORTH ATLANTIC OCEAN

Here's a cross section through one of these subtropical gyres (northern hemisphere still). The top of the mound is offset toward the west, and the western slope is much steeper than the eastern slope. A steep slope sets up a stronger pressure gradient. A stronger pressure gradient induces faster flow. Thus, on the western edge of subtropical gyres, the current is fast, narrow, and deep, while on the eastern side of the gyre, the current is slow, broad, and shallow. In the north Atlantic, the fast, narrow, deep **western boundary current** is the Gulf Stream. The slow, broad, shallow **eastern boundary current** is the Canary Current. Look back at the map of global surface ocean currents and identify all the western boundary currents and eastern boundary currents. What happens in the southern hemisphere? Is it what you'd expect?



Global dynamic topography

Satellites can detect very small difference in sea surface height, and have allowed scientists to construct maps of the ocean's dynamic topography. First look at the North Atlantic and South Atlantic basins. The highest point of the "mound" in each of these basins is offset to the west. Just from looking at this image, you could estimate the directions and relative speeds of the different geostrophic currents flowing around these mounds. Check out the equatorial Pacific. Can you make out the general features of the complex convergences and divergences there?



Surface Ocean Currents

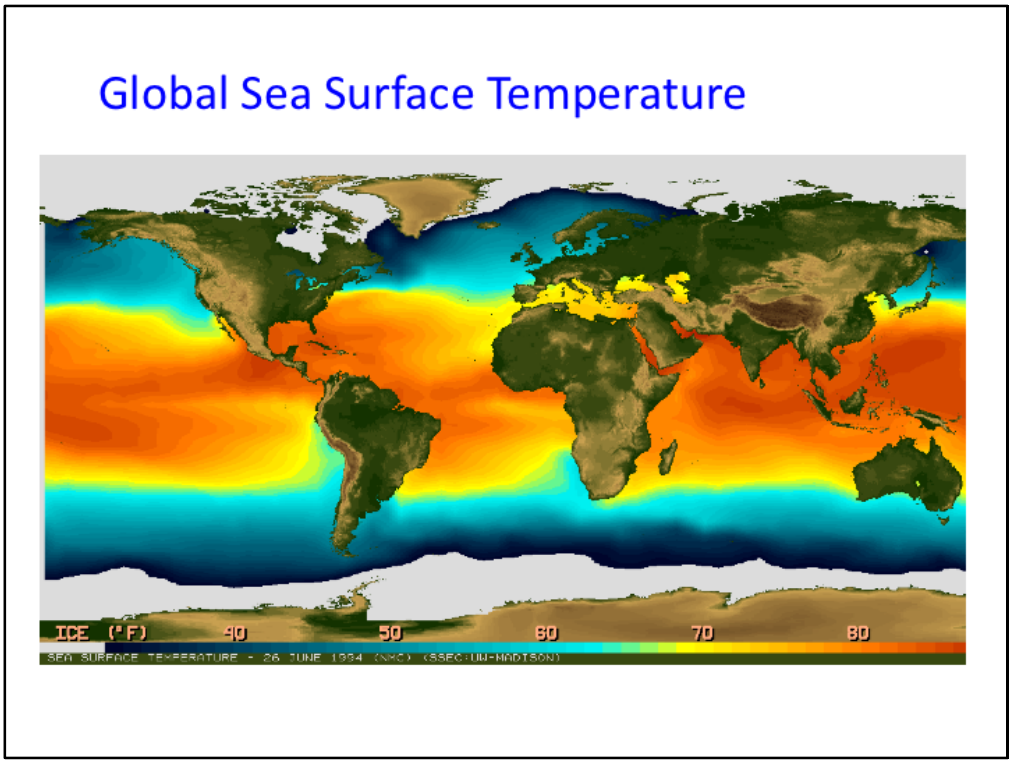
Warm and cold currents

Back to one of our broad purposes in discussing ocean circulation – how does heat get transported around by the ocean? This figure shows warm currents in red and cold currents in blue. The pattern is clear. The fast western boundary currents carry warm water from the tropics toward the poles. The broad eastern boundary currents carry cool water from high latitude back toward the tropics.

Summary of features:

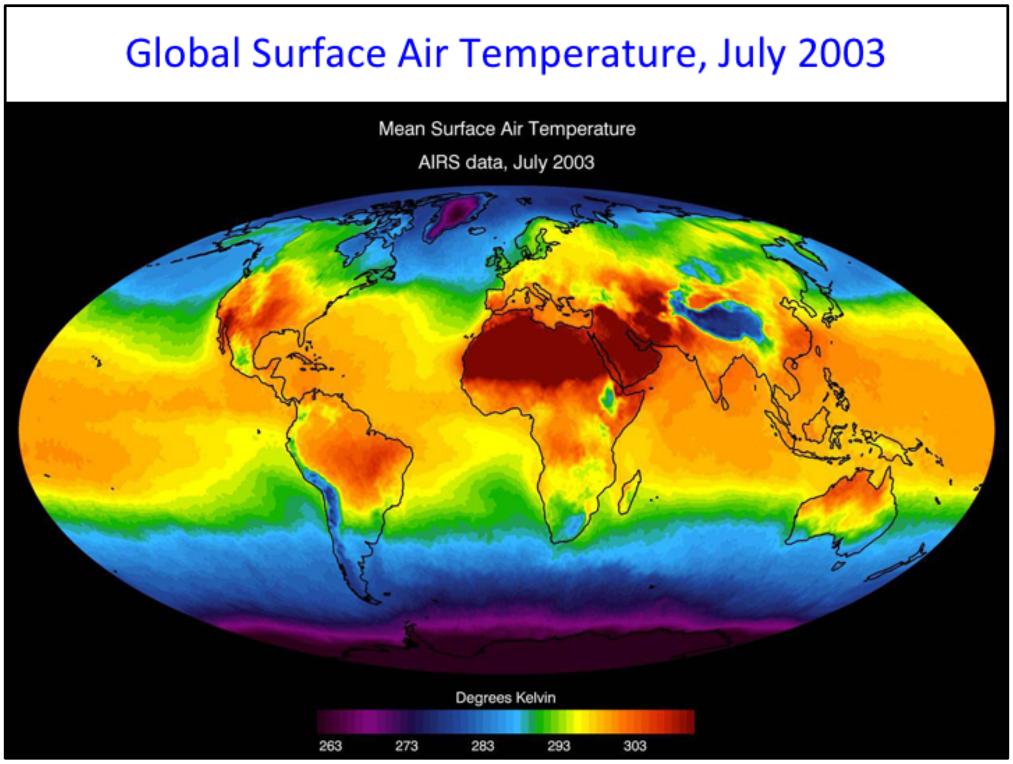
Western boundary currents: on the western sides of ocean basins; fast (up to 2 m/s), narrow (75-100 km wide), deep (up to 2000 m), warm.

Eastern boundary currents: on the eastern sides of ocean basins; slow (up to 0.3 m/s), broad (>1000 km wide), shallow (<500 m), cool.



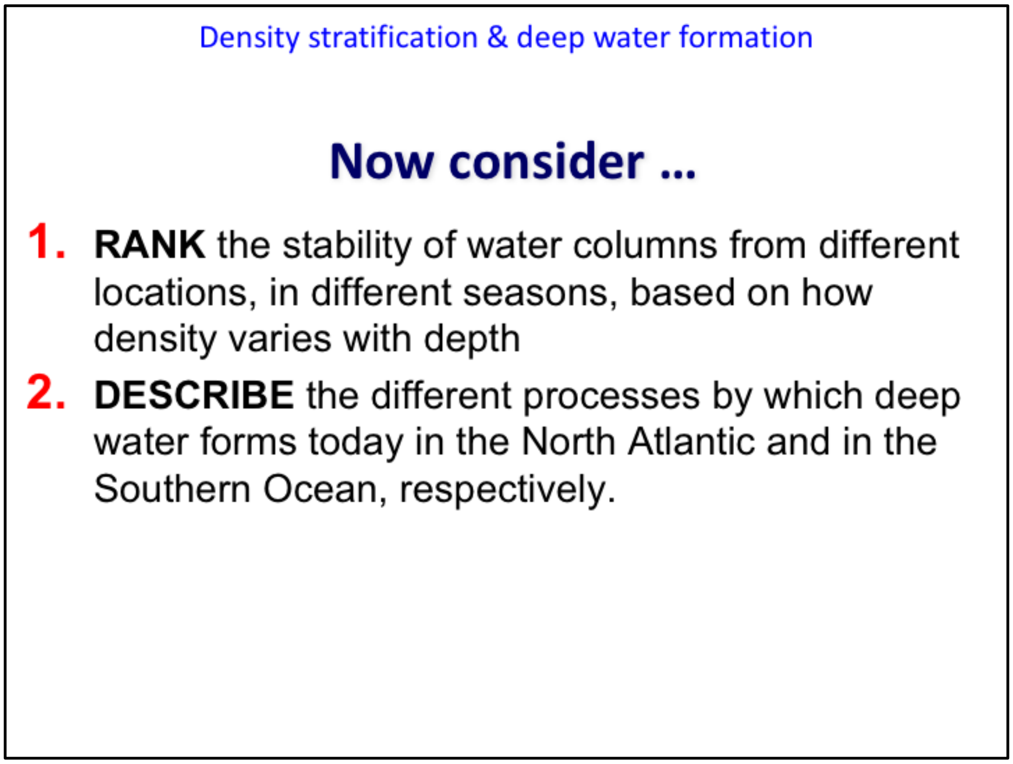
Global Sea Surface Temperature

This figure shows annual average sea surface temperature (the scale is in degrees Fahrenheit – convert). Red colors are warm, blue colors are cold. Note the warm temperatures extending poleward on the western sides of the ocean basins, and the cold temperatures extending equatorward on the eastern sides. These patterns alone give us an idea of the direction of ocean current flow!



Global Surface Air Temperature, July 2003

Here’s the surface air temperature for July 2003. Note the consistent patterns between air (this image) and sea surface temperature (previous slide). Heat is constantly being transferred between the ocean and the atmosphere. The temperature of the air affects the ocean temperature, and the ocean temperature affects the air temperature. This is one example of constant feedback between the atmosphere and ocean, which influences global and regional climate.

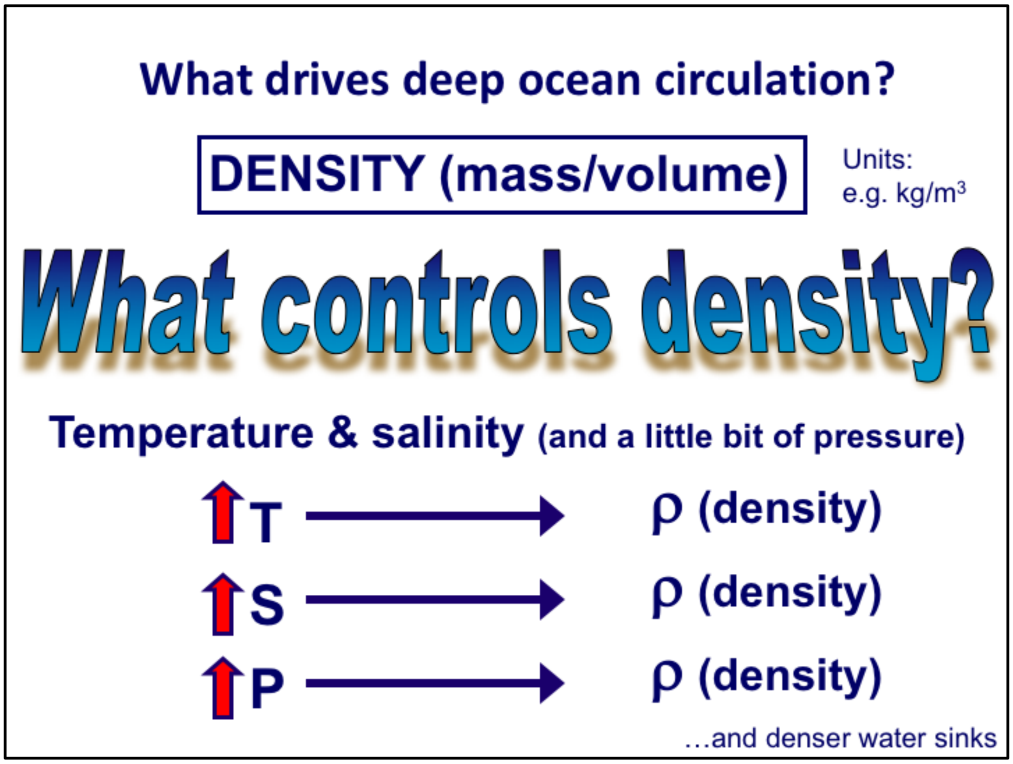


Density stratification & deep water formation

Now consider …

1. **RANK** the stability of water columns from different locations, in different seasons, based on how density varies with depth
2. **DESCRIBE** the different processes by which deep water forms today in the North Atlantic and in the Southern Ocean, respectively.

Density stratification is a key concept in all Earth-related sciences. The materials that make up the solid Earth from core to crust are stratified according to density with the denser stuff in the middle and the less dense stuff at the surface; above the solid earth, the ocean is also stratified according to density; and above the ocean, the atmosphere is stratified according to density. Within the ocean, density is controlled primarily by temperature and salinity (and, to a far lesser extent, pressure). The ocean is not homogeneous. It includes many **water masses** that have distinctive temperature and salinity characteristics (and additional characteristics too), and thus different densities. Circulation in the deep ocean is driven by the density differences among water masses. There are two primary sites of "**deep water formation**" on Earth today: The North Atlantic, and the Southern Ocean. Different processes at the surface in each of these places make the surface water become dense enough to sink.



What drives deep ocean circulation?

DENSITY (mass/volume)

Units:
e.g. kg/m^3

What controls density?

Temperature & salinity (and a little bit of pressure)

$\uparrow T \longrightarrow \rho$ (density)

$\uparrow S \longrightarrow \rho$ (density)

$\uparrow P \longrightarrow \rho$ (density)

…and denser water sinks

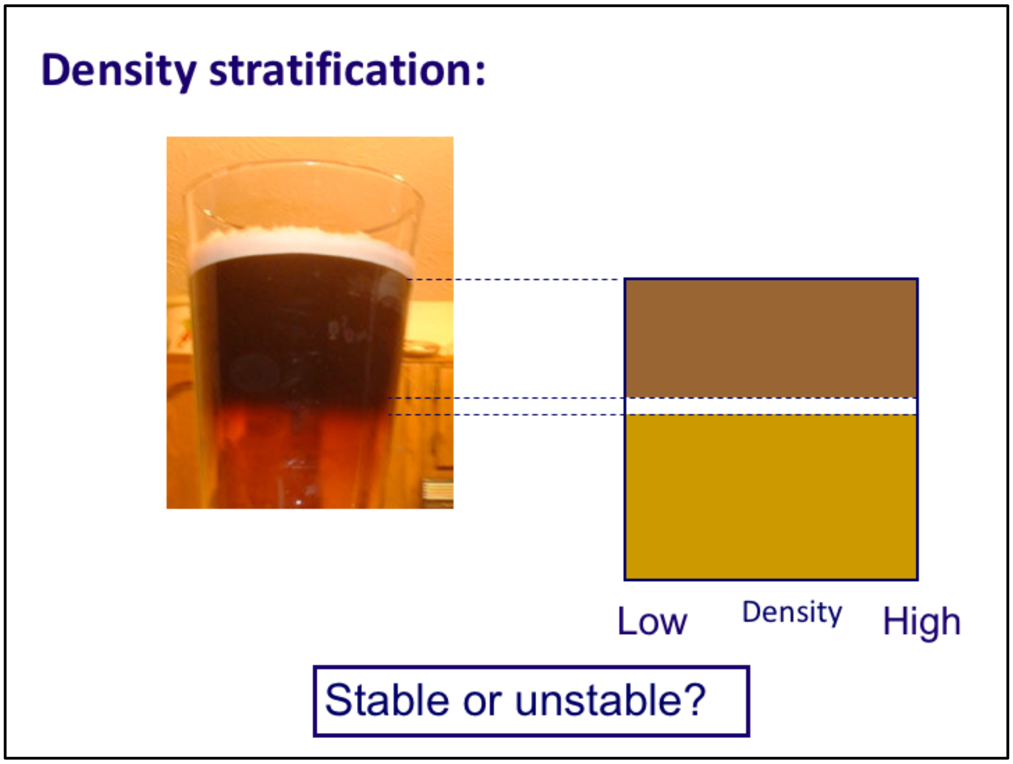
Which is more dense – lead or water? Imagine how much a cubic metre of lead would weigh (11340 kg), then imagine how much a cubic metre of water would weigh (1000 kg). Clearly, the lead has more mass per unit volume than the water. In the ocean, three properties affect water density:

Temperature. If temperature increases, what happens to density? Think back to what happens in the atmosphere when the air temperature increases.

Salinity. Salinity is the concentration of salts dissolved in water. What happens to the water's density when salt is added? Have you been swimming in both a freshwater lake and the salty ocean? In which body of water do you float more easily? Have you heard of people swimming in very saline water, like the Dead Sea? Easy to float or hard to float?

Pressure. If pressure increases, more of a substance can be packed into a smaller space. What does that do to density (mass/volume)? It's fairly difficult to compress water, but at deep depths in the ocean, pressure does influence density.

Key point: Denser water sinks.



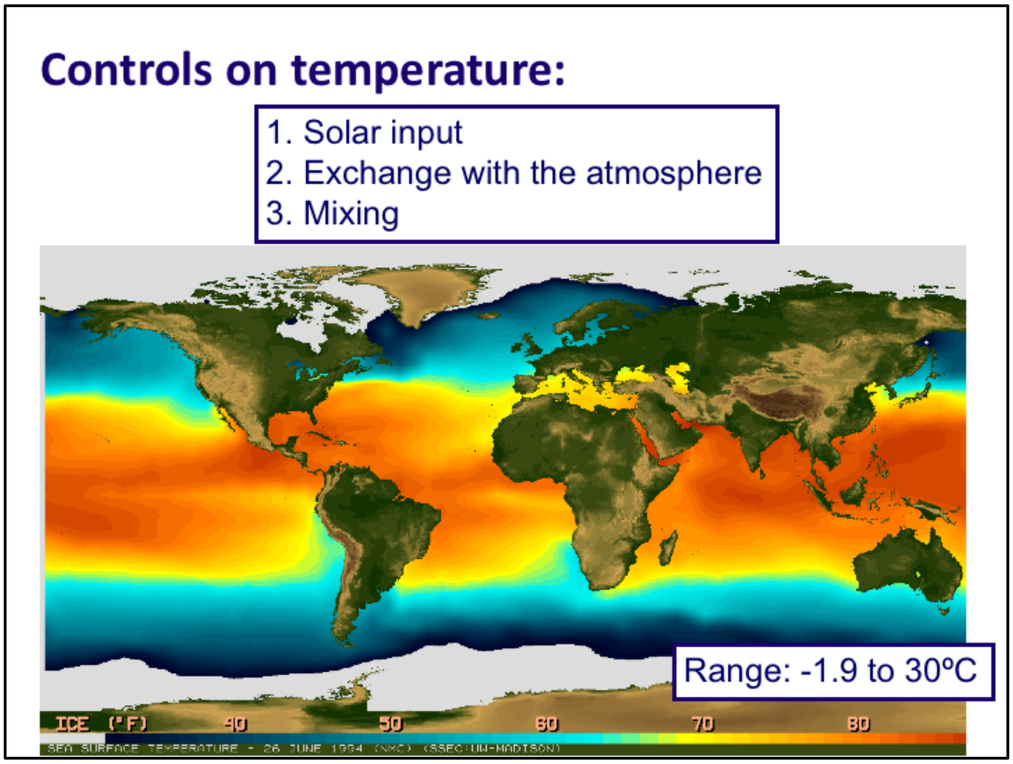
Density stratification:

Low Density High

Stable or unstable?

Density stratification is the process by which substances of different densities order themselves, with the low density substances on top and the higher density substances below. A black-and-tan illustrates this process nicely. Which beer is more dense, the “black” or the “tan”?

We can plot the density down through the beer glass (*See Lecture Slides for details*).



Controls on temperature:

1. Solar input
2. Exchange with the atmosphere
3. Mixing

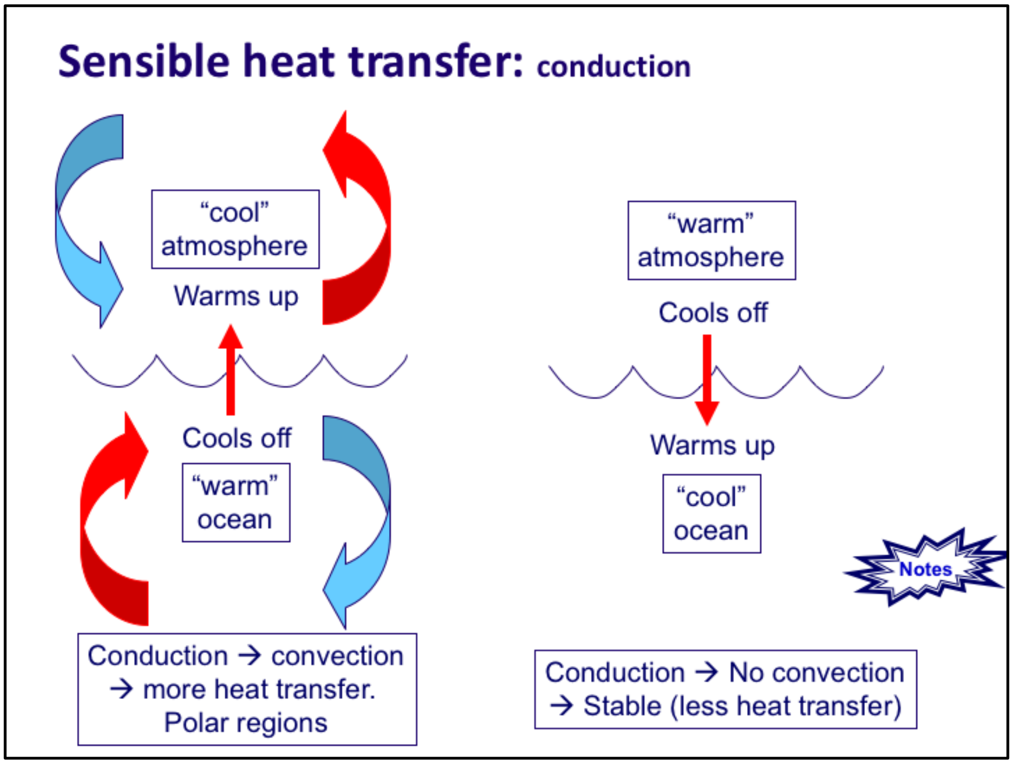
Range: -1.9 to 30ºC

In the ocean, the main controls on density are temperature (T) and salinity (S). First, a look at temperature, which ranges from about -1.9 to 30 degrees Celsius (*how can ocean water be less than zero degrees Celsius?).*

This figure shows the general pattern of sea surface temperature on Earth (same image as in previous Hydro lecture notes). We see a general pattern of higher surface temperatures at low latitudes and cooler surface temperatures at high latitudes. A slightly closer look reveals warm western boundary currents and cool eastern boundary currents on the sides of the subtropical gyres.

There are three primary controls on the temperature of ocean water:

1. **Solar input** – clearly this input of energy only occurs at and very near the surface of the ocean.
2. **Exchange with the atmosphere** – Heat energy is transferred between the ocean and atmosphere, which also clearly has to happen at the ocean's surface. **Latent heat transfer** happens during ice formation and melting, and during evaporation and precipitation. Look back to "Phase Changes" in Hydrosphere 1. For example, when water evaporates from the ocean, the process removes heat from the ocean, cooling it off. When that evaporated water vapour condenses in the atmosphere, that heat energy is released to the atmosphere. The combined process transfers energy from the ocean to the atmosphere. An analogous process is humans sweating. Why does sweating cool you off? Your body sweats out droplets of water, which then evaporate. The energy for evaporation comes from you, and the process removes heat from your skin, cooling you off. **Sensible heat transfer** occurs along a temperature gradient. Higher temperature molecules vibrate faster and cause the molecules next to them to move, etc., transferring sensible heat. A relatively "warm" ocean will give up heat to a relatively "cool" overlying atmosphere and vice versa (see next Notes Slide).
3. **Mixing.** What happens if you pour cold water into a cup of hot coffee? Mixing between the hot and cold liquids, producing a liquid of intermediate temperature. The same thing happens between water masses of different temperatures in the ocean. Mixing can happen ANYWHERE in the water column (shallow, intermediate, deep). This is the only one of these three processes that doesn't necessarily have to occur at or near the ocean's surface.



Sensible heat transfer: conduction

"cool" atmosphere

Warms up

Cools off

"warm" ocean

Conduction → convection → more heat transfer. Polar regions

"warm" atmosphere

Cools off

Warms up

"cool" ocean

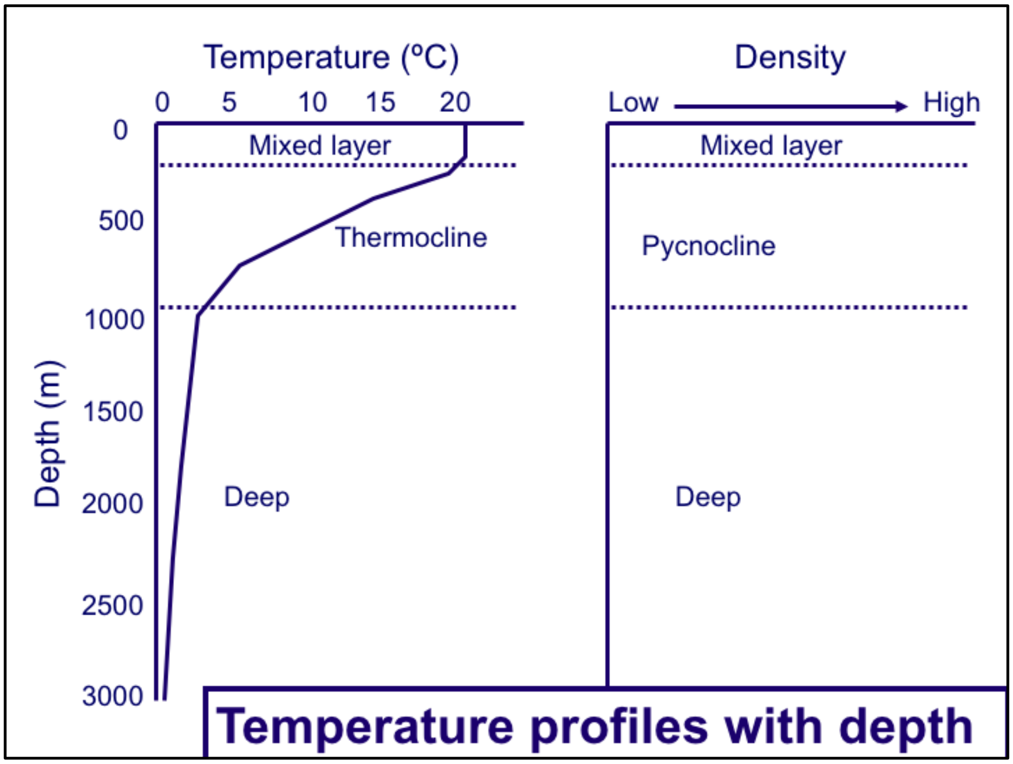
Conduction → No convection → Stable (less heat transfer)

NOTES SLIDE (not shown in class): illustrating sensible heat transfer, which, combined with density-driven convection, works best in the situation on the left, with a "relatively cool" atmosphere overlying a "relatively warm" ocean.

On the left: a "warm" ocean underneath a "cool" atmosphere. This means that there's a temperature gradient that promotes sensible heat transfer from the ocean to the atmosphere. Imagine that some heat energy crosses that boundary, warming the lower atmosphere and cooling the upper ocean. The warmed air will be less dense than the cooler air above it, and the warm air will rise, setting up a little vertical circulation cell in the atmosphere. The cooled upper ocean water will be more dense than the water below it and will sink, setting up a little convection mixing cell in the upper ocean. These convection cells perpetuate the temperature gradient and promote more sensible heat transfer from ocean to atmosphere.

On the right: a "warm" atmosphere overlying a "cool" ocean. In this case, the temperature gradient promotes sensible heat transfer from atmosphere to ocean, cooling the lower atmosphere and warming the upper ocean. What does this do to density stratification in the atmosphere and in the ocean? Nothing. This perpetuates and already stable situation, no convection occurs, and the sensible heat transfer is less than in the case on the left.

Think about where on Earth these two scenarios might happen.

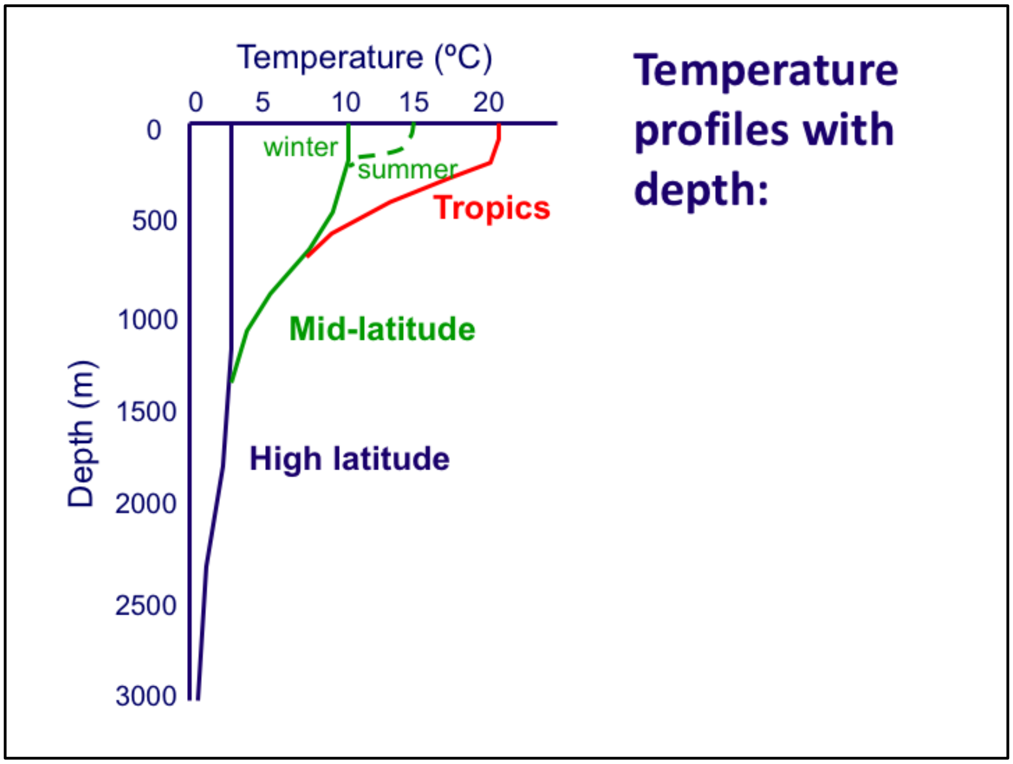


We've seen the distribution of sea surface temperatures. Next, how does temperature vary with depth?

On the left, a standard, generalized depth profile of temperature in the ocean. The mixed layer at the top is warmest (is this stable or unstable?). Note that the temperature remains pretty much constant throughout the mixed layer. The deep ocean is the coldest part and also makes up by far the greatest volume of water. In between the mixed layer and the "deep ocean" is the **thermocline** (*thermo-* for temperature, *-cline* for gradient) where temperature decreases rapidly with increasing depth.

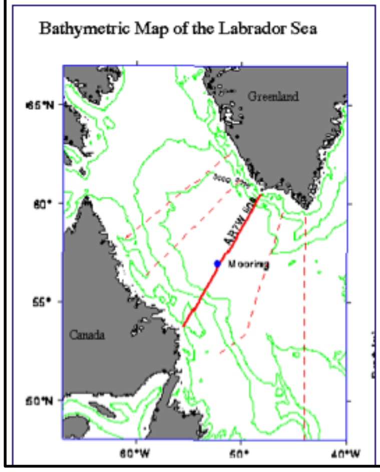
If we consider only the effects of this temperature profile on the density of the water column, we get the figure on the right. The density of the warm water in the mixed layer is lower than the density of the cold water in the "deep" box. The change in temperature within the thermocline causes the density to also change rapidly with depth, producing the **pycnocline**. In many cases, the pycnocline is largely defined by the thermocline.

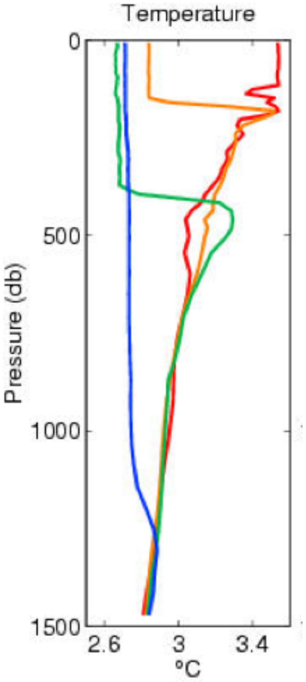
Note that the two depth profiles of temperature and density are mirror images.

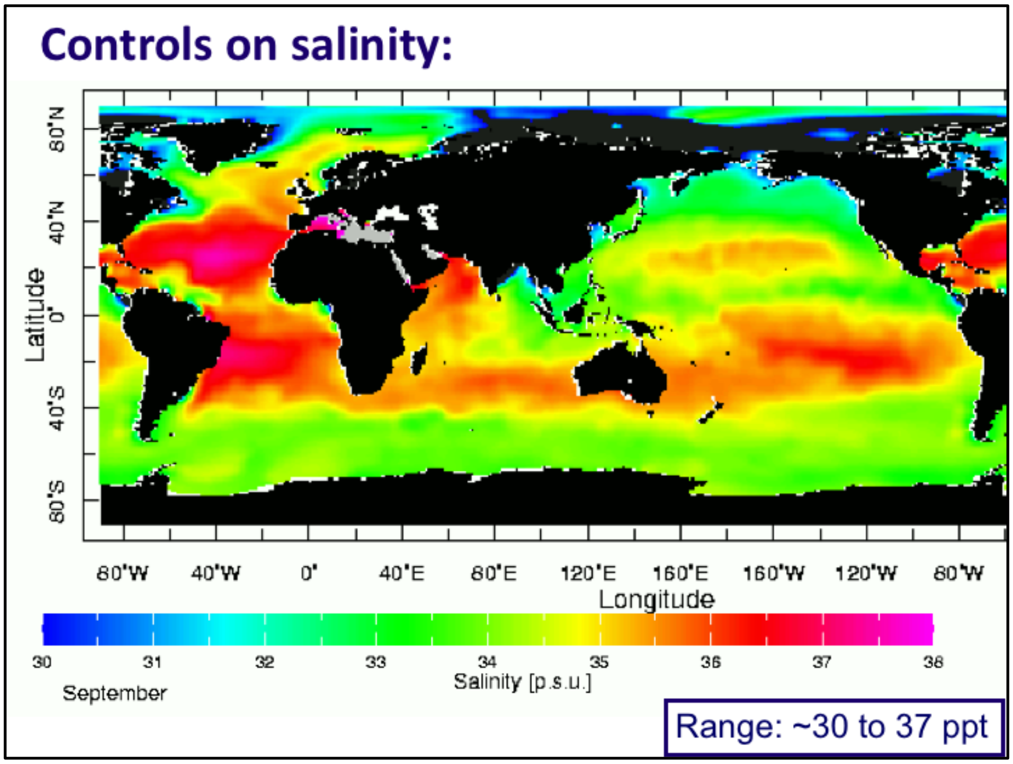


Temperature profiles with depth:

Temperature profiles in the Labrador Sea







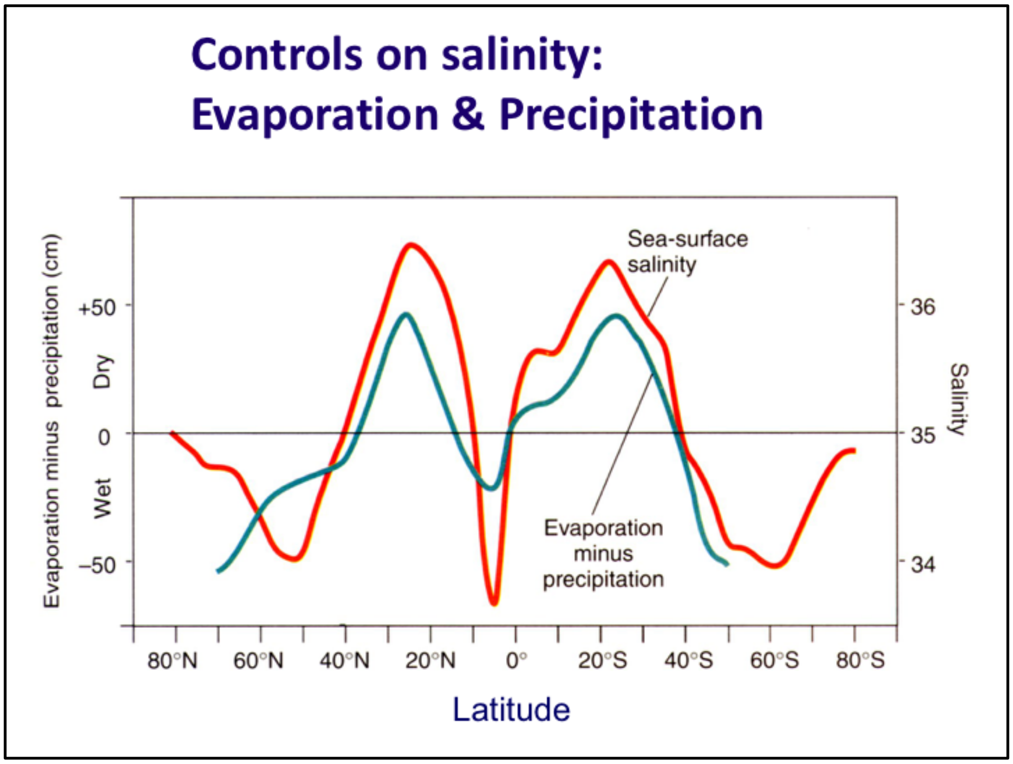
Controls on salinity:

Range: ~30 to 37 ppt

So that was temperature. Note that the controls on temperature are heating at the surface, exchange of heat with the atmosphere, and mixing of water at different depths.

What about salinity, the other major factor that controls ocean water density? Salinity in the oceans ranges from about 30 to 37 parts per thousand. That means that every kilogram (1000 grams) of seawater contains 30-37 grams of salt. This image shows sea surface salinity in “practical salinity units”, which, for our purposes, are essentially equivalent to parts per thousand.

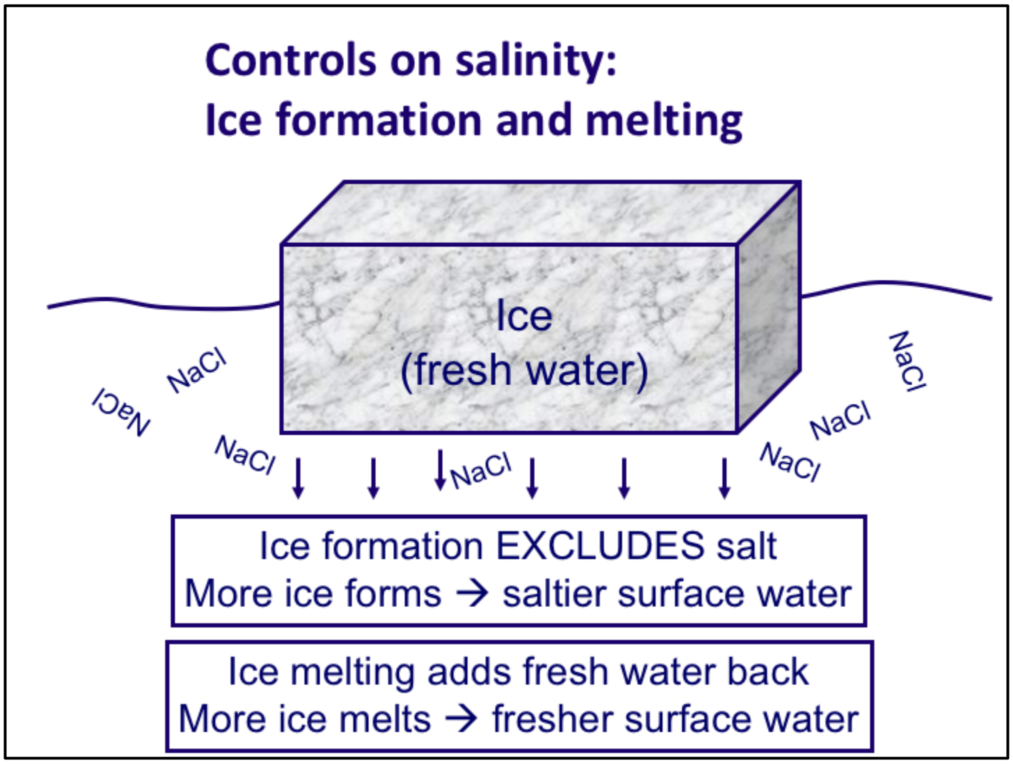
1. What patterns do you see in this image?
2. Where is salinity high? Low?
3. Can you make comparisons with latitude? Between ocean basins? Based on proximity to land? Other ways of examining these data?
4. Does this pattern reflect any patterns you’ve seen previously in this class?



Controls on salinity:
Evaporation & Precipitation

One of the controls on sea surface salinity is evaporation and precipitation. The blue line in the figure shows the values for “evaporation minus precipitation” (left axis) as it varies with latitude. Note the latitudes where the peaks/highs are. Note the latitudes where the lows are. Why is the low in the middle offset to the north of the equator?

The red line in the figure is the sea-surface salinity (right-hand axis) with latitude. Note peaks and valleys. Do these two curves look similar to one another?



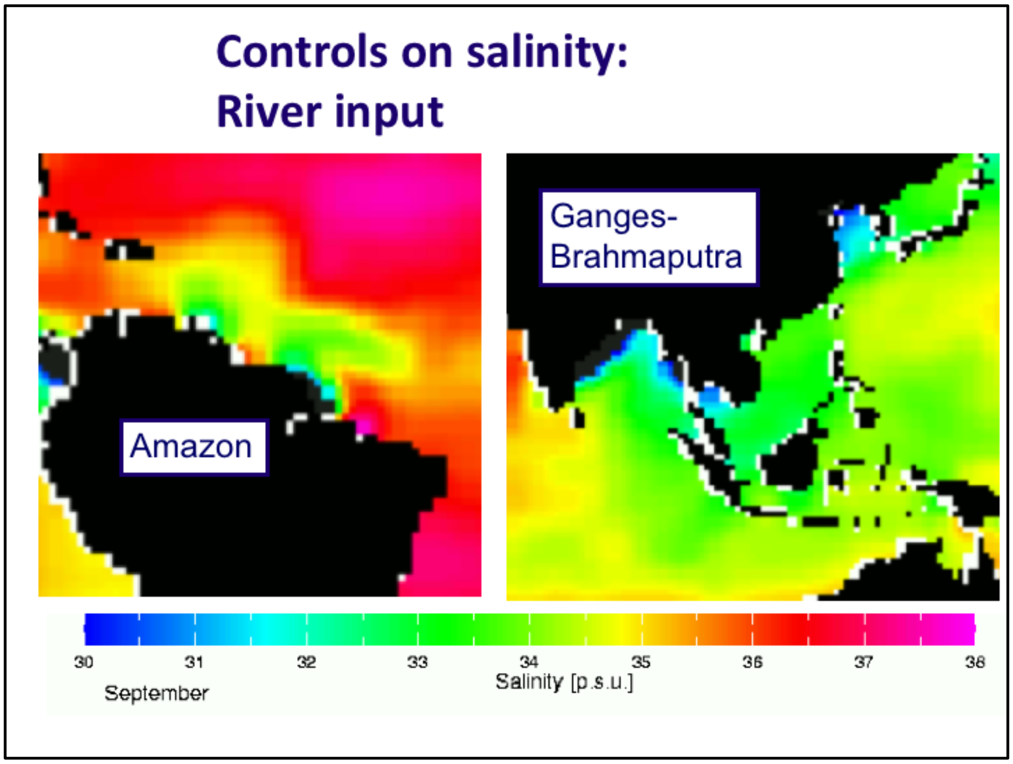
Controls on salinity:
Ice formation and melting

Ice formation EXCLUDES salt
More ice forms → saltier surface water

Ice melting adds fresh water back
More ice melts → fresher surface water

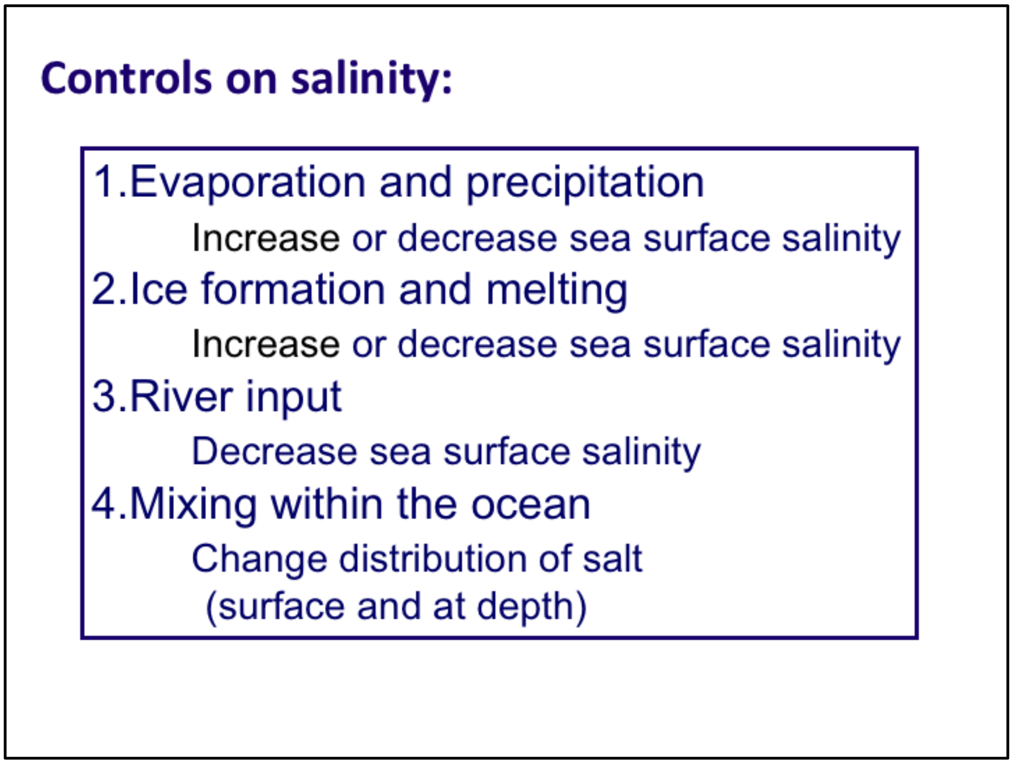
Another control on sea surface salinity is ice formation and melting. When seawater freezes at the ocean's surface, the crystal structure of the solid ice leaves out the salt molecules and incorporates just the water molecules (mostly). So, in places where sea ice is forming, the surface water around the ice is getting saltier. What would adding salt to the surface water do to the stability of the water column? In some high latitude locations, the formation of ice is an important process driving deep water formation.

What about when ice melts? The ice is primarily fresh water, and it floats, so melting ice adds fresh water to the ocean's surface. What does that do to density stratification and water column stability?



Controls on salinity:
River input

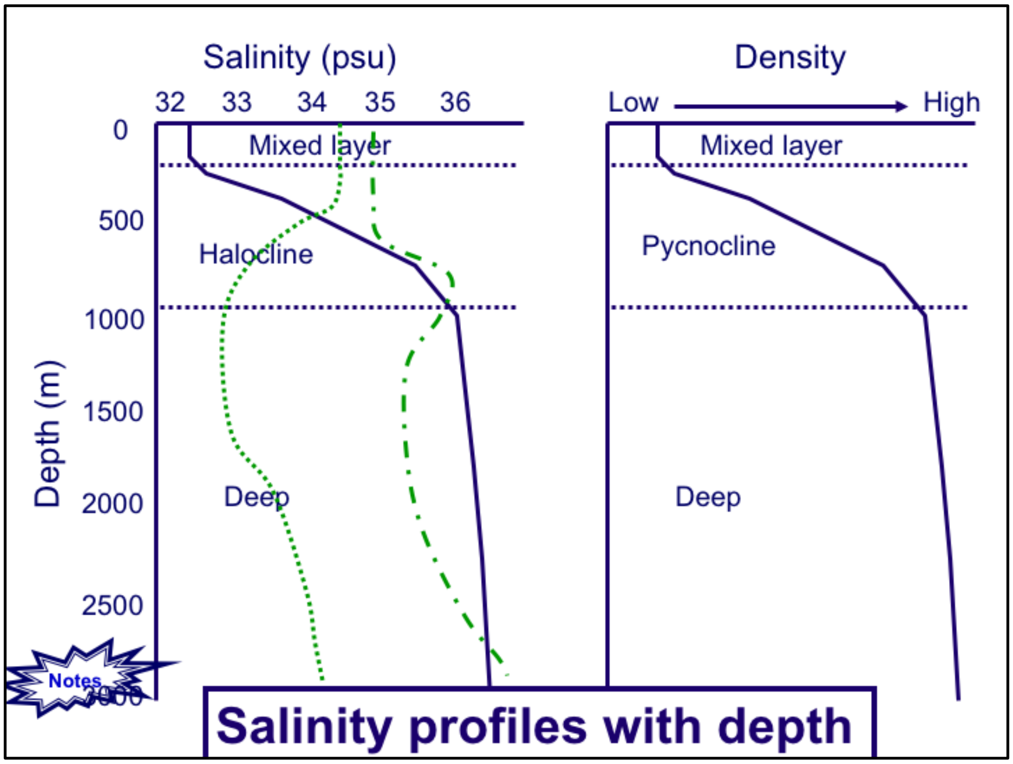
Rivers input fresh water to the oceans. In regions near where major rivers flow into the ocean, the surface ocean water is slightly less saline, due to those inputs of fresh water. These two are examples from South America and India/SE Asia. Where near Canada would you expect to find plumes of fresh water in the ocean that are associated with river input?



Controls on salinity:

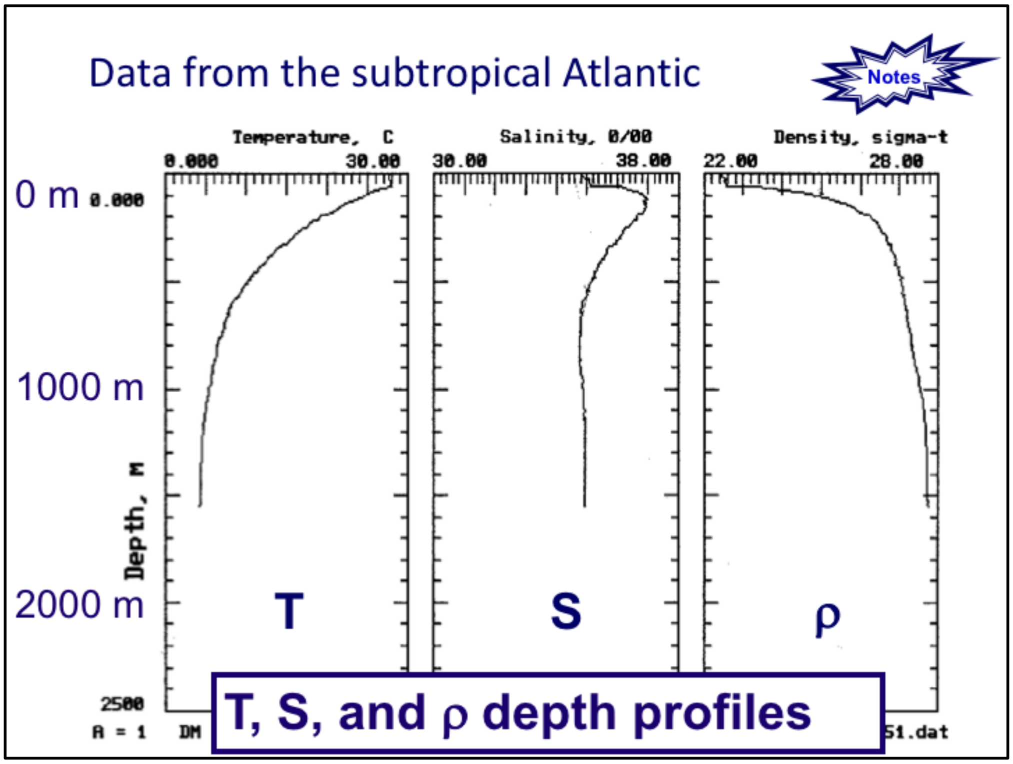
1. Evaporation and precipitation
    - Increase or decrease sea surface salinity
2. Ice formation and melting
    - Increase or decrease sea surface salinity
3. River input
    - Decrease sea surface salinity
4. Mixing within the ocean
    - Change distribution of salt (surface and at depth)

Summary of controls on salinity. The first three are explained in previous slides. Fourth, **mixing** water masses of different salinities will produce a new water mass with intermediate salinity. Note that, like temperature, all the processes that control salinity happen at the surface, *except* mixing, which can happen anywhere in the water column.



Salinity profiles with depth

NOTES SLIDES (not shown in class): Salinity profiles with depth have much more variability than temperature profiles. On the left, the blue solid line shows one possible generalized salinity profile, with low salinity in the surface, higher salinity at depth, and a **halocline** in between (*halo-* for salt, *-cline* for gradient). On the right is the generalized density profile that would result from this standard salinity profile. Is this stable? (yes).
Unlike temperature, however, salinity profiles can vary widely. The two green dashed and dotted profiles on the left show two other possibilities. In the dash-dot profile, there appears to be a subsurface salinity maximum. In the dotted profile, there appears to be a subsurface salinity minimum. These changes in salinity can act as markers for different subsurface water masses and can help oceanographers trace where different water masses go in the ocean.

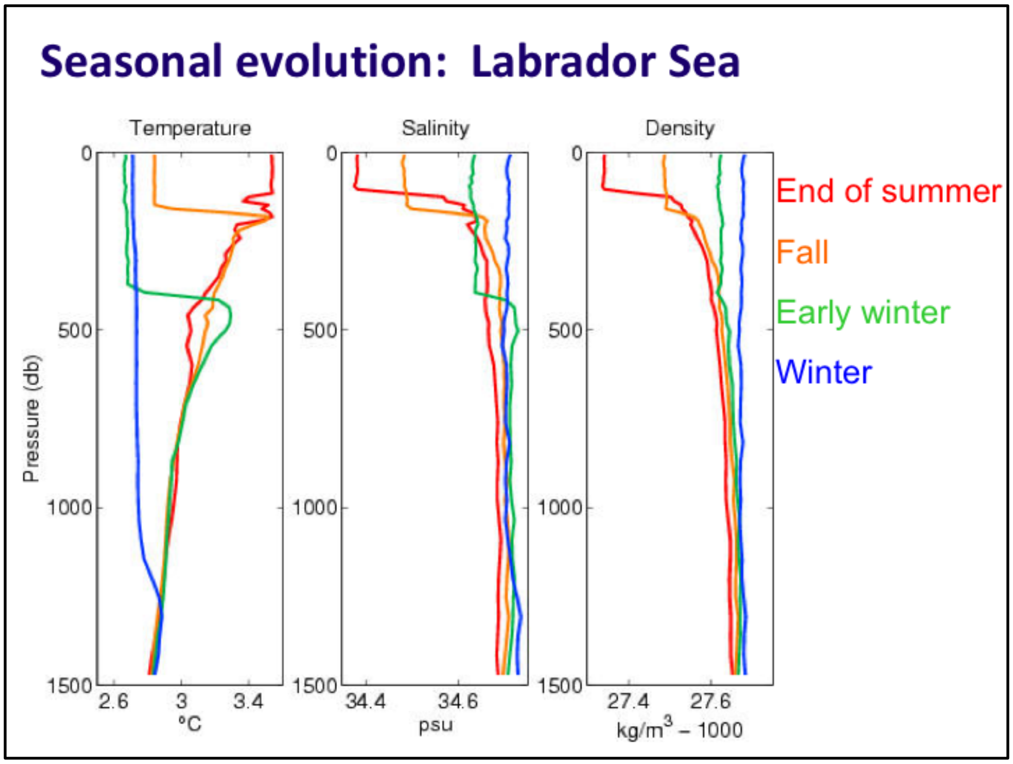


Data from the subtropical Atlantic

Notes

T, S, and ρ depth profiles

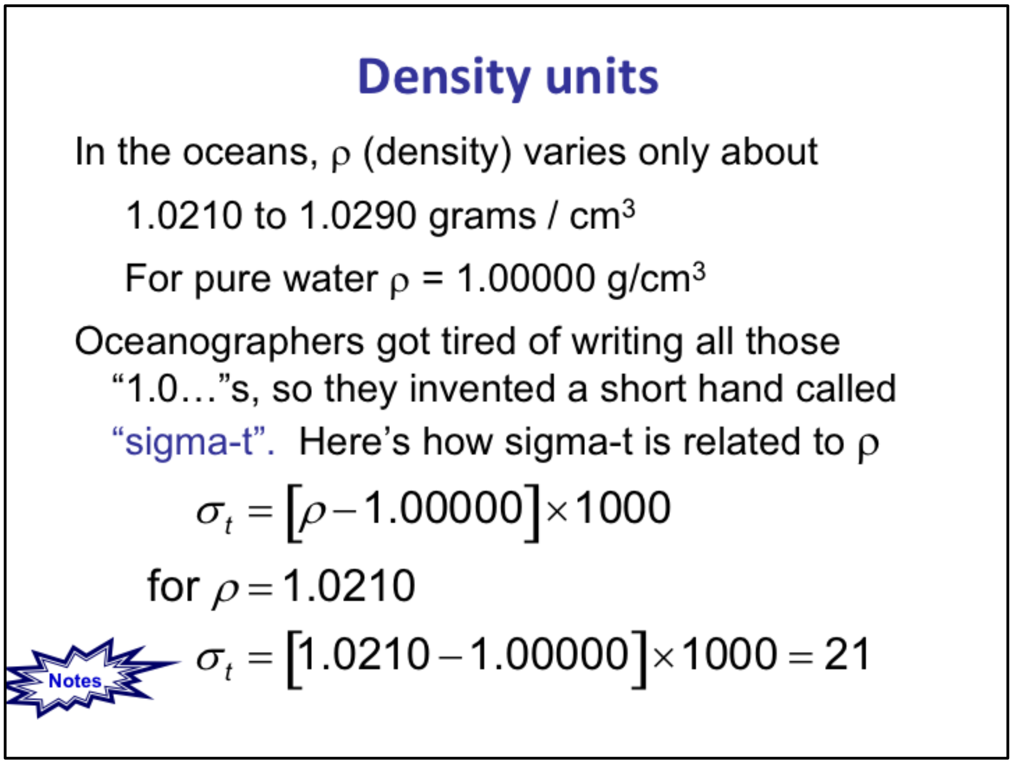
NOTES SLIDE (not shown in class): Regardless of what the temperature and salinity profiles look like independently, it's the combination of T and S that produce the density profile. Here's an example from the subtropical Atlantic Ocean, showing data from the surface down to about 1500 m depth. Temperature, on the left, shows a standard profile – warm at the surface, a mixed layer about 75 m deep, a thermocline that extends below the mixed layer, with the profile getting nearly vertical at the deepest depths shown. In the middle, an interesting salinity profile showing a subsurface salinity maximum, a bulge of water that's higher salinity than that either at the surface or at deeper depths. The combination of these two, temperature and salinity, yield the density profile on the right. Notice that in this profile, density always increases with depth, indicating that the water column is stratified and stable in this location. Rates of vertical motion in a stratified situation are much slower than horizontal motion.



Seasonal evolution: Labrador Sea

Now let’s return to the Labrador Sea and add some information. Temperature, salinity, and density profiles all vary seasonally here. What are the processes, involving the atmosphere, ocean, and ice, that influence temperature and salinity through these seasons?

Notice the density profiles. At what point during the year is the water column most stable? At what point is it least stable? When the water column is LEAST stable, there’s the possibility for deep water formation – in this case the winter density profile shows the least stability.



Density units

In the oceans, ρ (density) varies only about

1.0210 to 1.0290 grams / cm^3

For pure water ρ = 1.00000 g/cm^3

Oceanographers got tired of writing all those "1.0…"s, so they invented a short hand called "sigma-t". Here's how sigma-t is related to ρ

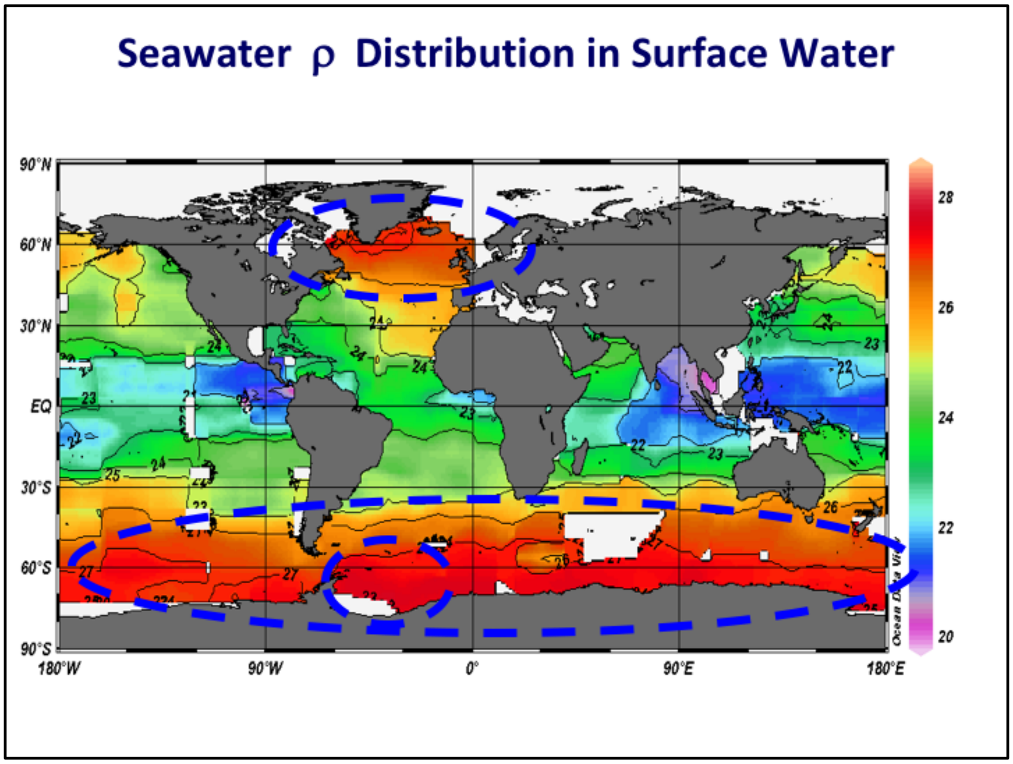
$$\sigma_t = [\rho - 1.00000] \times 1000$$

for $\rho = 1.0210$

$$\sigma_t = [1.0210 - 1.00000] \times 1000 = 21$$

Notes

NOTES SLIDE (not shown in class): Short hand for seawater density units - Sigma-t: recognizes that density difference is only within 3-4 decimal points. Sometimes you'll see density plotted, sometimes sigma-t.



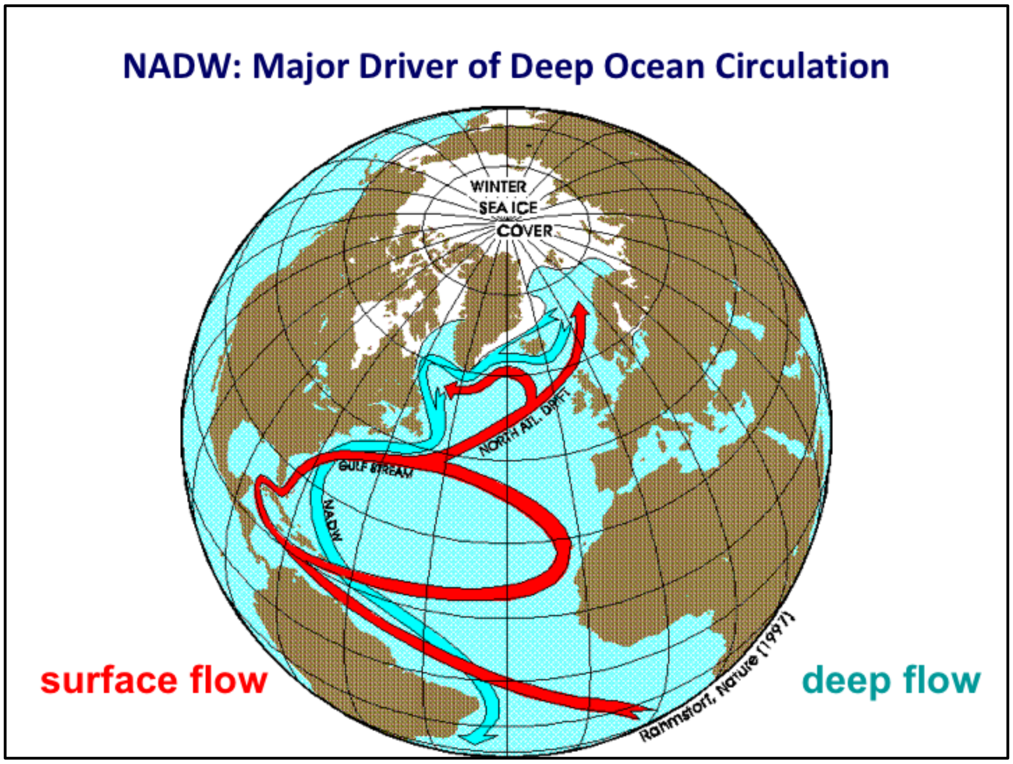
Seawater ρ Distribution in Surface Water

Where in the world’s oceans is the surface water most likely to sink? Where is the surface water the most dense?

In this image, surface water density (actually “sigma-t” – see prior explanatory notes slide) is plotted, with red color indicating higher density and blue colors indicating lower density. Note that higher density surface water is at high latitude in the North Atlantic and in the Southern Ocean around Antarctica.

Compare the North Atlantic to the North Pacific. Which is a more likely spot for dense surface water to sink? Why do you think there’s this difference between the North Atlantic and North Pacific? What could change today’s situation (fresher Pacific, saltier Atlantic) to something different?

Are there other patterns in density distribution that you might be able to deduce, based on what you know about temperature and salinity patterns?

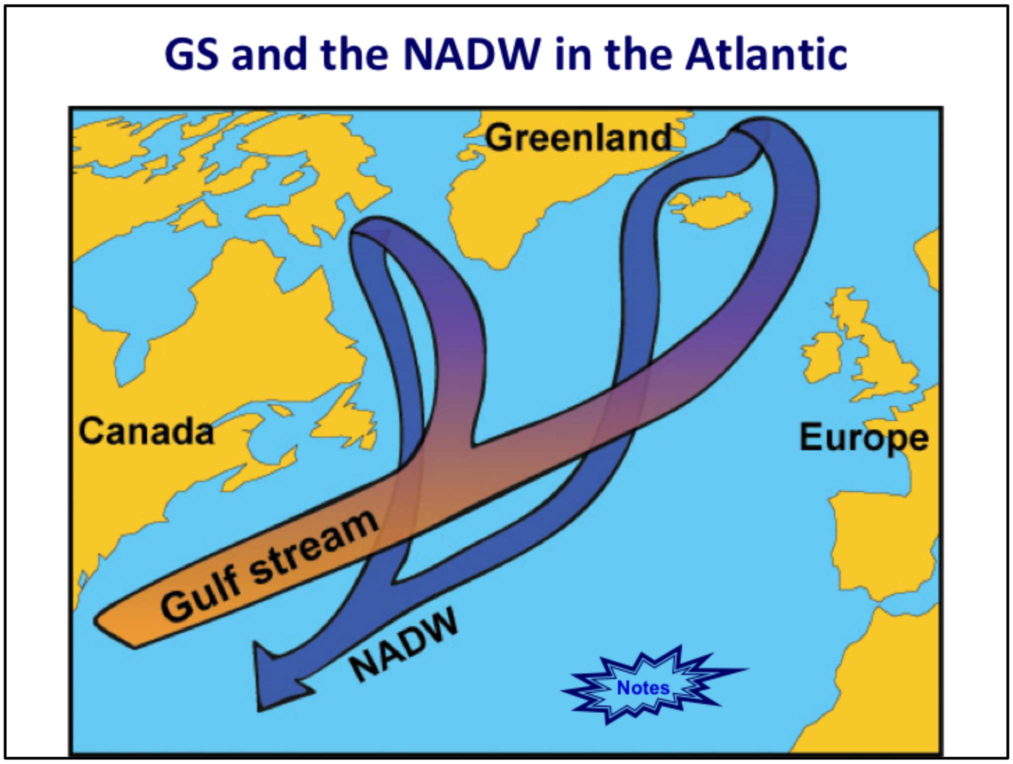


NADW: Major Driver of Deep Ocean Circulation

Rahmstorf, Nature (1997)

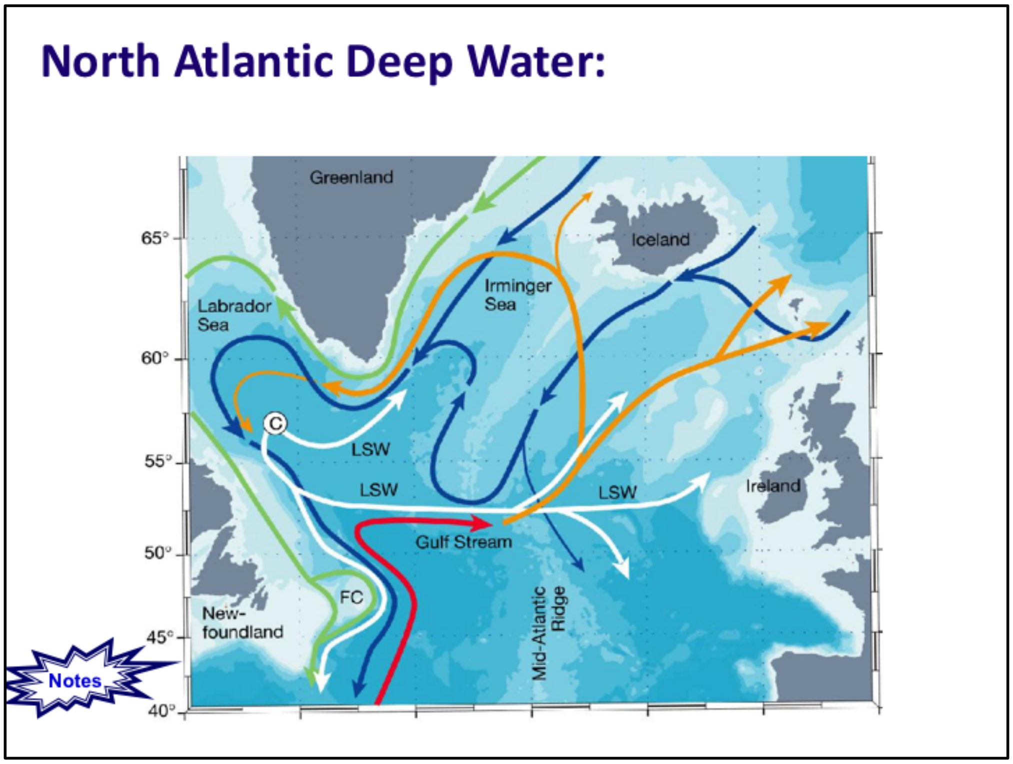
Let's take a look at the situation in the North Atlantic. As we've seen, the Gulf Stream flows northward from Florida up the western boundary of the North Atlantic basin, carrying warm and relatively salty water northward. A branch of this current heads northward from the subtropical gyre in what's called the "North Atlantic Drift". As this water heads north, it progressively loses its heat to the overlying atmosphere, primarily through latent heat transfer. Once it reaches latitudes up by Greenland, Norway, and Iceland, the water has become cold enough and is salty enough to be dense enough to sink. As we saw for the Labrador Sea, when the thermocline and density stratification break down in the winter months, the surface water can be the same or greater density than the water below.

This water sinking in the North Atlantic is creatively named **"North Atlantic Deep Water" or NADW**. It's typically cool (3-4 deg C) and fairly salty (about 34.9 ppt). On average, about 20 million cubic metres of water per second sink in the North Atlantic.



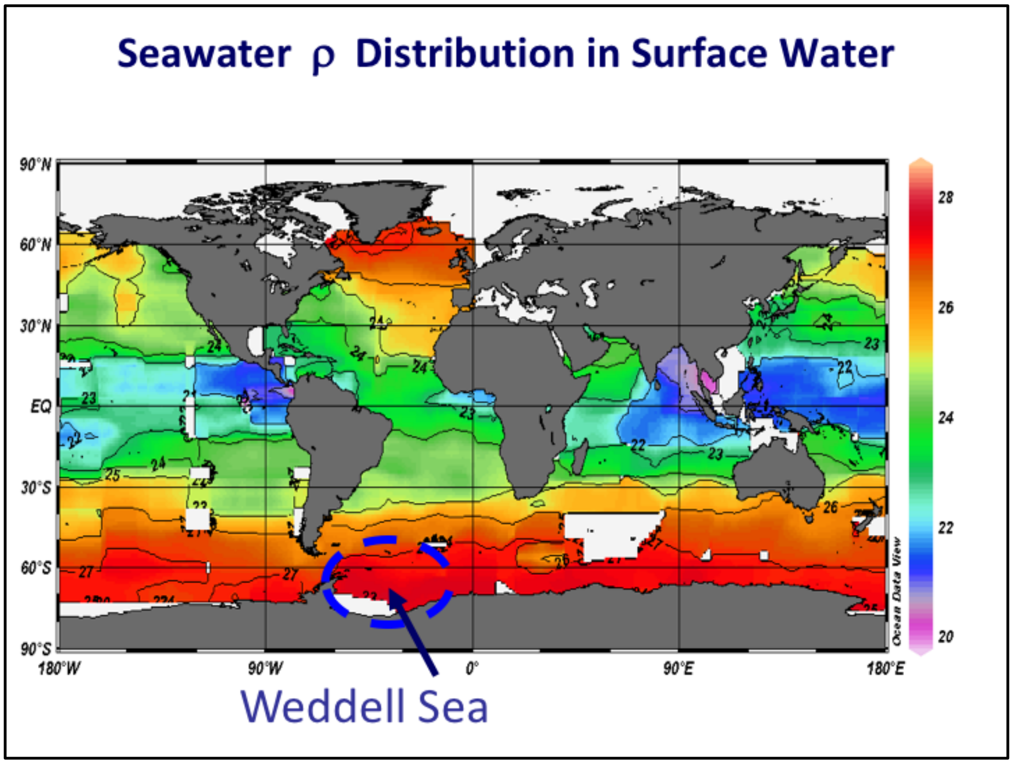
GS and the NADW in the Atlantic

NOTES SLIDE (not shown in class): Here's a closer, generalized look at the North Atlantic. The surface current heads north, the water loses heat and cools, becomes dense enough to sink, forming NADW, which heads back southward, at depth. Note that the Gulf Stream plays a key role in the large-scale deep ocean circulation, which we'll return to later.



North Atlantic Deep Water:

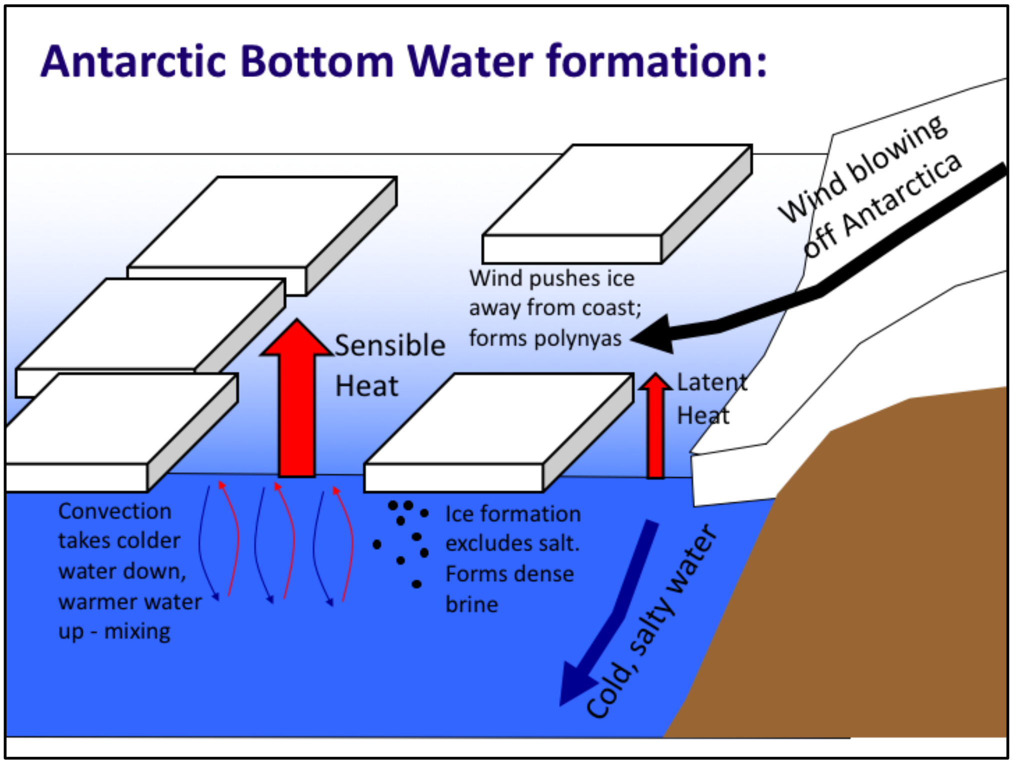
NOTES SLIDE (not shown in class): And here's a more detailed look. NADW actually forms in various locations – the Labrador Sea, the Greenland SEA, and Norwegian Sea. Water sinking in all locations in the North Atlantic flows back southward, mostly along the western boundary of the ocean basin, underneath the Gulf Stream.



Seawater ρ Distribution in Surface Water

Weddell Sea

Let's take a look at the processes going on in the other location where surface ocean water gets dense enough to sink into the deep ocean. Surface water is quite dense all around the Antarctic continent. However, the Weddell Sea has the conditions most suitable for forming really dense water. This is the place that the densest water in the world's oceans forms – **Antarctic Bottom Water, or AABW**.



Antarctic Bottom Water formation:

Wind blowing off Antarctica

Wind pushes ice away from coast; forms polynyas

Sensible Heat

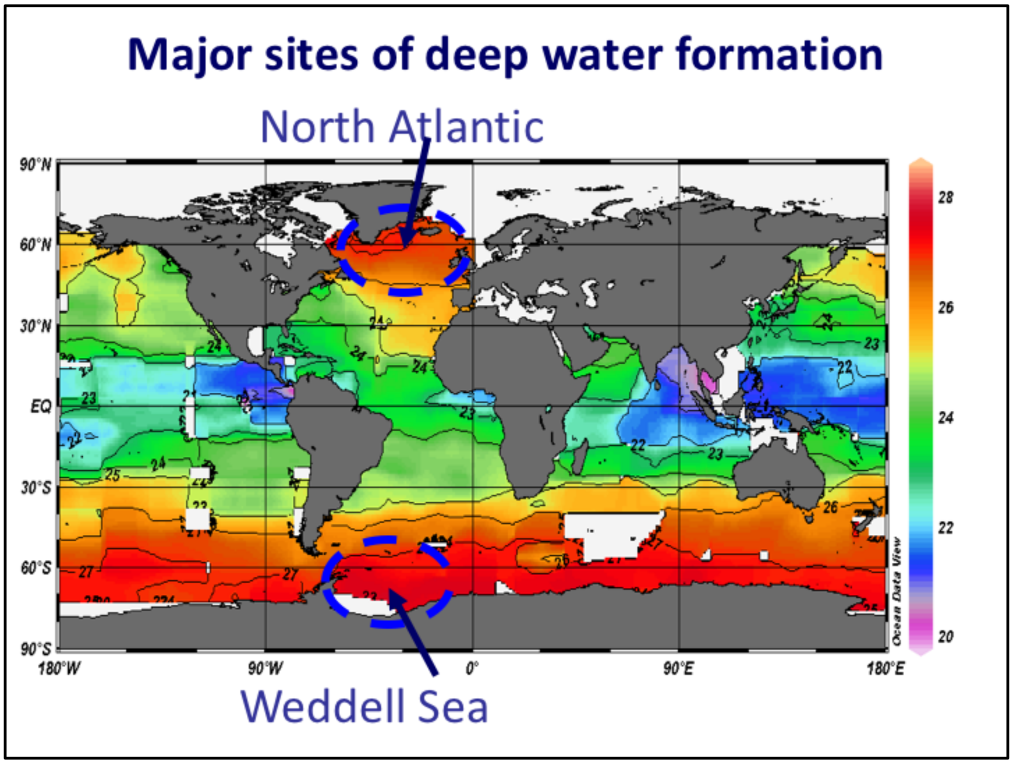
Latent Heat

Convection takes colder water down, warmer water up - mixing

Ice formation excludes salt. Forms dense brine

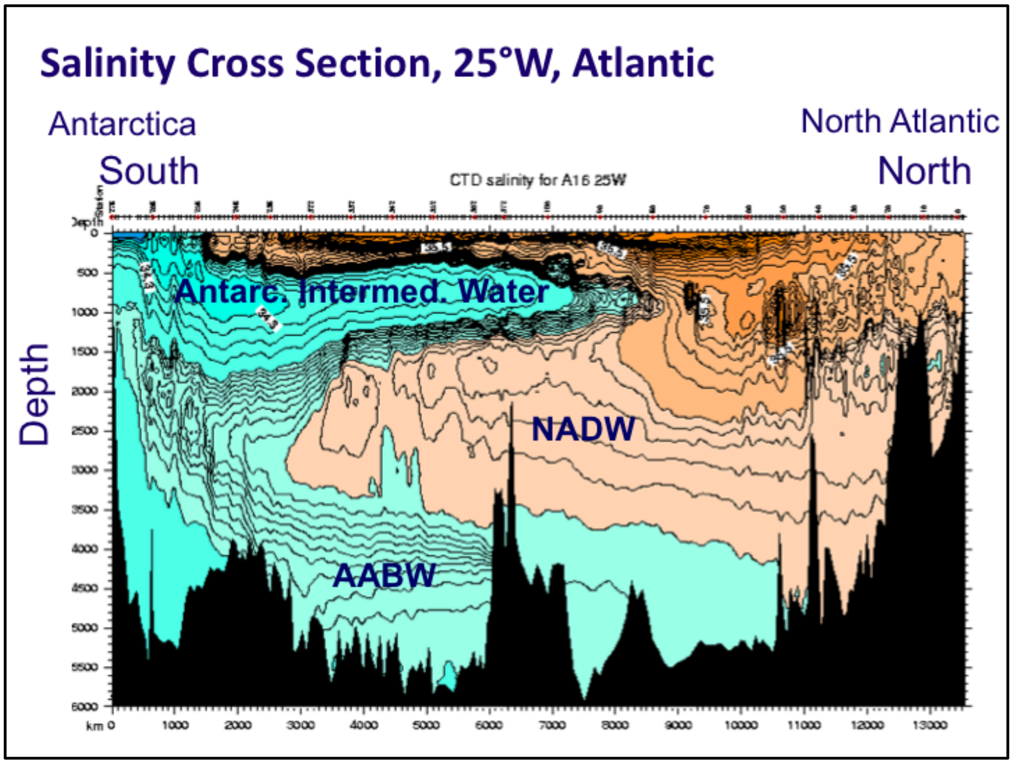
Cold, salty water

Antarctic Bottom Water (**AABW**) forms in the Weddell Sea in the winter, over the shallow continental shelf. Strong winds blow off the Antarctic continent in the winter, opening up polynyas (areas of open water). Sensible heat (look back in these notes) is transferred from the “relatively warm” ocean to the “relatively cool” overlying atmosphere in these polynyas. Some latent heat transfer also occurs, evaporating fresh water. This cooling of the surface water encourages sea ice to form, which excludes salt from the ice crystal lattice. The salt is left behind in the liquid water, which is the lowest temperature it can be – at the freezing point. This freezing cold, salty water forms AABW, which sinks and flows off the continental shelf into the deep ocean. It is aptly named “bottom water” since it is the water right along the bottom of the ocean basin (at least in some places).
The wind blowing off the continent keeps pushing the sea ice and opening up areas of open water, keeping the process going.
AABW’s temperature is typically about -1.9 degC and its salinity is about 34.7 ppt. It is denser than NADW.



Major sites of deep water formation

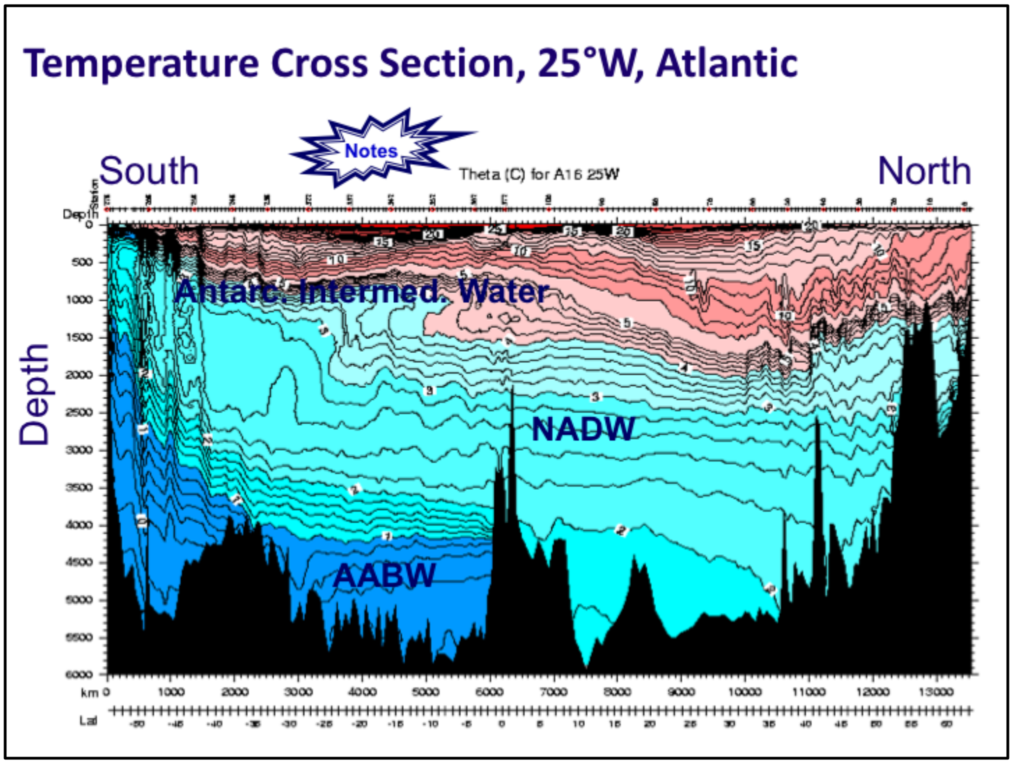
The two major sites of deep water formation on Earth at present – the North Atlantic and the Weddell Sea.



Salinity Cross Section, 25°W, Atlantic

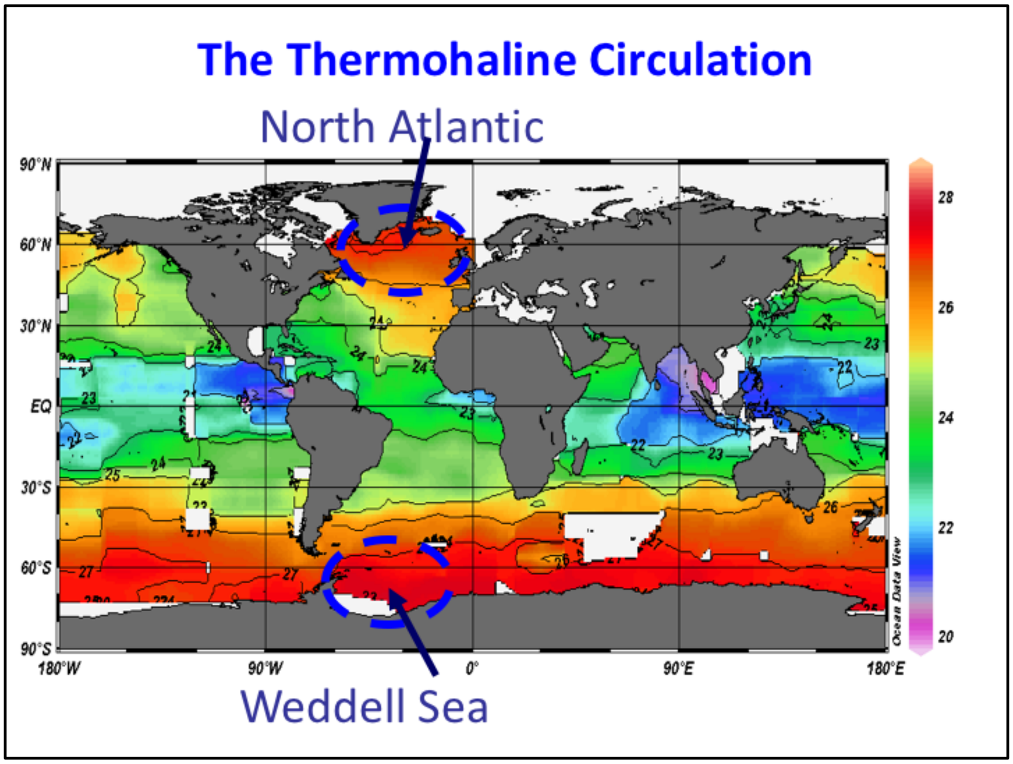
So we have two major sites of deep water formation. How do these two water masses interact? This is a cross section through the Atlantic Ocean going from the South Atlantic on the left to the North Atlantic on the right. The vertical axis is water depth, extending to 6000 m. (Imagine yourself standing on the west coast of Africa and looking at the wall of water that would be exposed if you could slice the Atlantic Ocean and look at the inside, like a layer cake). The data that are plotted here are salinity. The blue is slightly lower salinity and the red is higher salinity. These patterns of salinity reveal the flow at depth of NADW and AABW. AABW flows off the continental shelf from Antarctica (on the left) and fills the deepest parts of the ocean basin (it’s the most dense). NADW sinks in the North Atlantic and flows southward. Where AABW and NADW meet, the NADW flows above AABW (density stratification). These two water masses are clearly in contact with one another and there is mixing along the boundary.

The other “tongue” of water visible in this plot is called Antarctic Intermediate Water. We are not going to discuss intermediate water masses in detail in this course.



Temperature Cross Section, 25°W, Atlantic

NOTES SLIDE (not shown in class): Here's the temperature data for that same cross section through the Atlantic. NADW is warmer than AABW, which is the primary reason it's less dense (recall that NADW is slightly more saline than AABW). It's much more difficult to determine the water mass boundaries based on temperature alone. One can pick out the small tongue of Antarctic Intermediate Water closer to the surface.

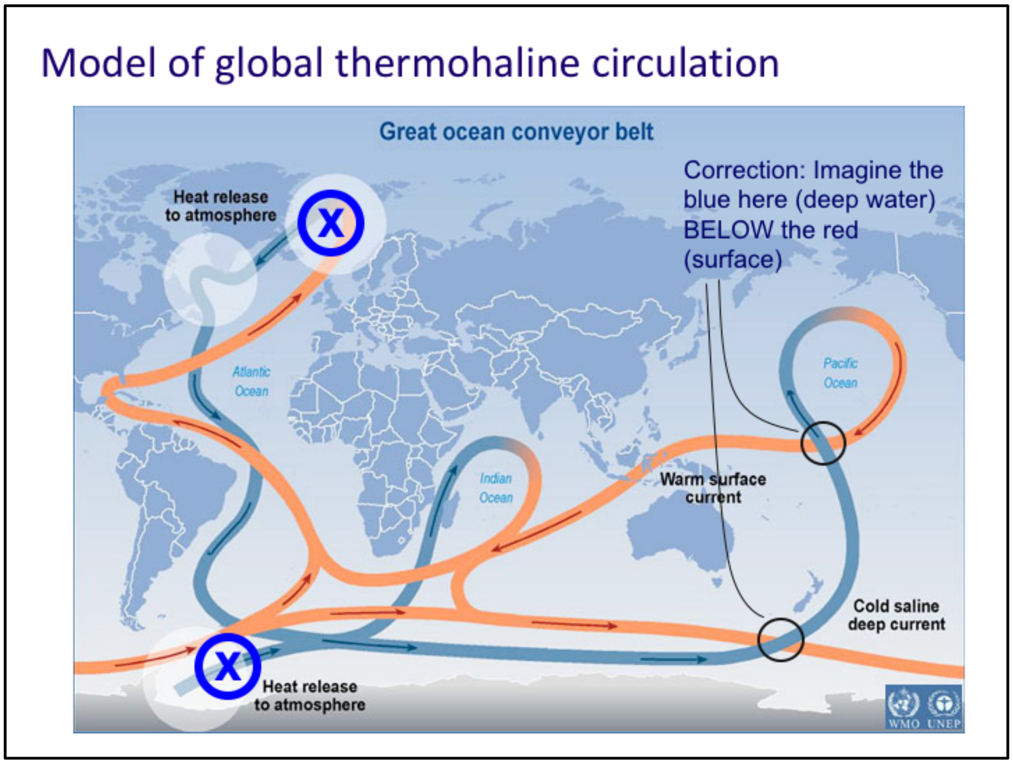


The Thermohaline Circulation

North Atlantic

Weddell Sea

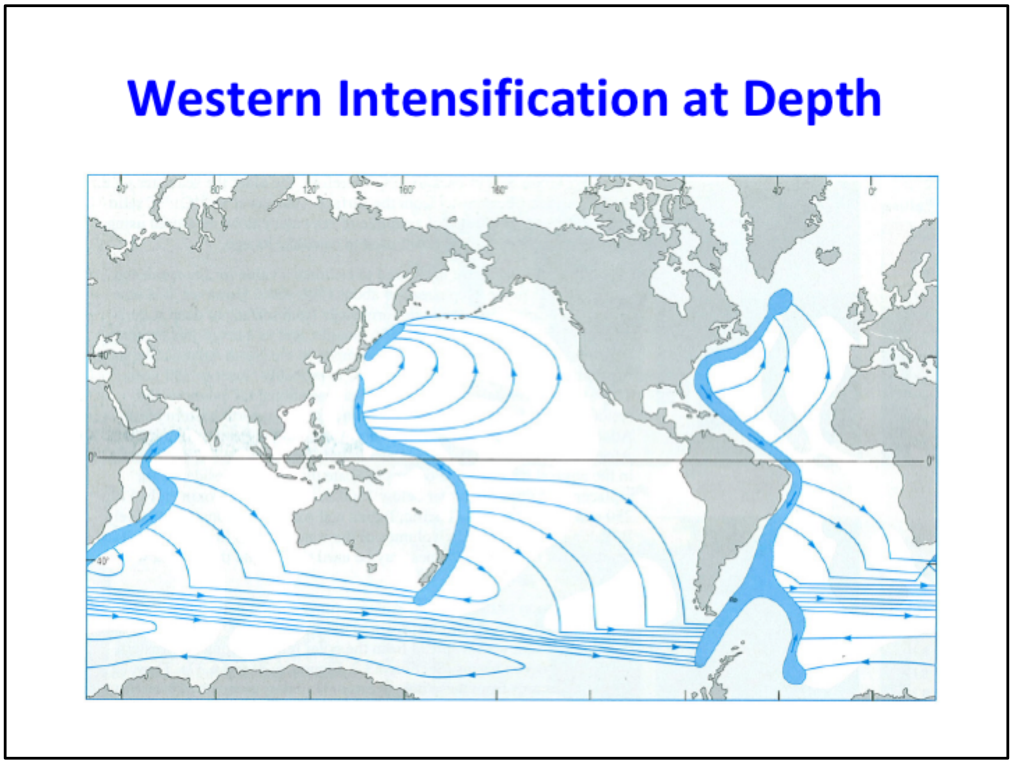
The basic idea of thermohaline circulation is that water is made cold and/or salty enough at the sea surface by heat loss to the atmosphere or freshwater loss due to evaporation/ice formation, becomes more dense and sinks toward the ocean bottom. We have seen that there are two major sites of deep water formation on Earth at present – the North Atlantic and the Weddell Sea. These are places where surface water becomes dense enough to sink.



Model of global thermohaline circulation

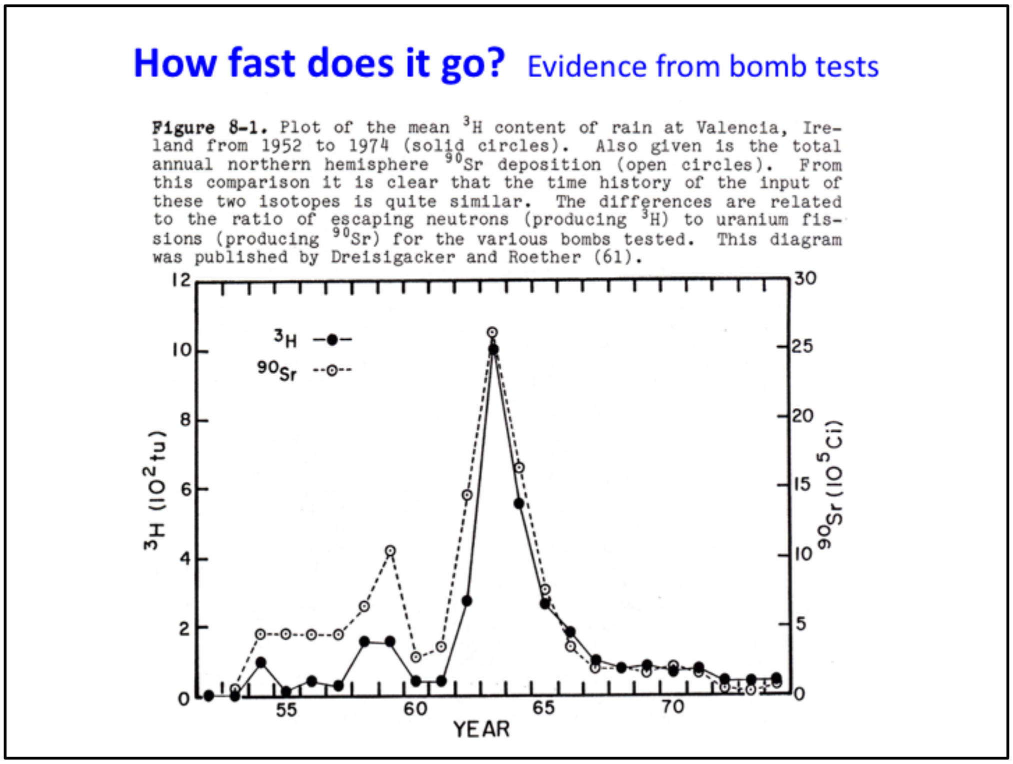
Correction: Imagine the blue here (deep water) BELOW the red (surface)

After sinking from the surface, where does the deep water go? Here's a generalized model, originally proposed by Wally Broecker, called "The Conveyor Belt". Water sinks in the North Atlantic, travels southward across the equator, all the way to the Southern Ocean around Antarctica, where it joins Antarctic Bottom Water, then travels eastward, into both the Indian Ocean Basin and the Pacific Ocean Basin. Due to mixing across the pycnocline by tidal energy, the deep water upwells back to the surface (regions not well-defined), where it is incorporated into the surface ocean circulation, eventually making its way back to the North Atlantic where it sinks again.



Western Intensification at Depth

Note that the Atlantic is now on the right side of the figure, unlike the previous map. The pattern of circulation at depth is more complex than implied by the conveyor belt. Similar to the western intensification of ocean currents at the surface (e.g. The Gulf Stream), bottom currents also display intensification on the western sides of ocean basins. After sinking in the North Atlantic, NADW flows southward, mostly in the Deep Western Boundary Current which hugs the east coast of the Americas in the western Atlantic. Some of the water returns northward in the central and eastern parts of the North Atlantic Basin and some continues south. Similar western intensification at depth occurs in the Indian and Pacific Ocean basins. Note the flow around Antarctica.

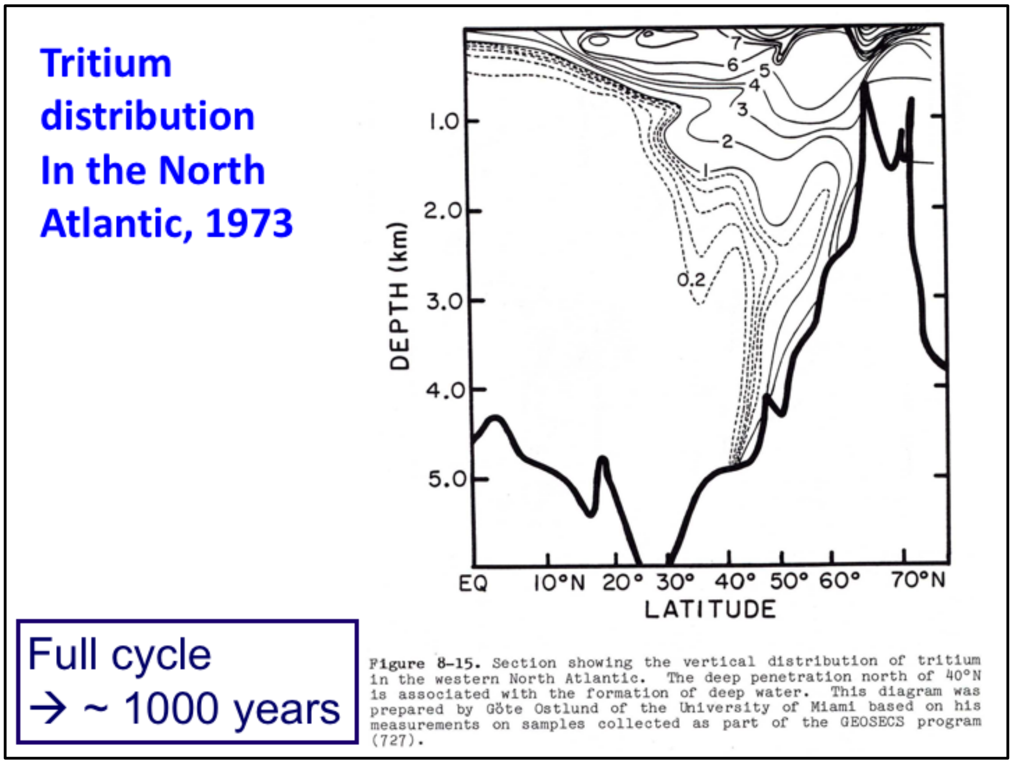


How fast does it go? Evidence from bomb tests

Figure 8-1. Plot of the mean ^3H content of rain at Valencia, Ireland from 1952 to 1974 (solid circles). Also given is the total annual northern hemisphere ^{90}Sr deposition (open circles). From this comparison it is clear that the time history of the input of these two isotopes is quite similar. The differences are related to the ratio of escaping neutrons (producing ^3H) to uranium fissions (producing ^{90}Sr) for the various bombs tested. This diagram was published by Dreisigacker and Roether (61).

How fast does it go? Surface currents can flow fairly fast – up to about 1.5 m/s (about 5.5 km/hr). Deep ocean currents are much slower. Fast motion down there would be about 0.05-0.15 m/s. Upwelling back to the surface happens even slower, maybe about 3 cm/day.

The deep ocean is difficult to measure, so one technique to estimate flow velocities is to use chemical "tracers". Imagine you could add some strange and traceable substance to the water sinking in the North Atlantic, then track its motion over time as the water sinks and flows southward. The nuclear bomb tests of the 1950s and 1960s provide just such a "tracer". Among other things, these bomb tests released tritium into the atmosphere. Tritium is a radioactive isotope of hydrogen with a short half-life (12.26 years). Since it's a form of hydrogen, it is rapidly incorporated into water in the atmosphere and rains out quickly (within days). Thus, because we know when the bomb tests took place, we know when an unusually large amount of tritium was added to the atmosphere, and thus to rainwater, some of it falling over the North Atlantic.



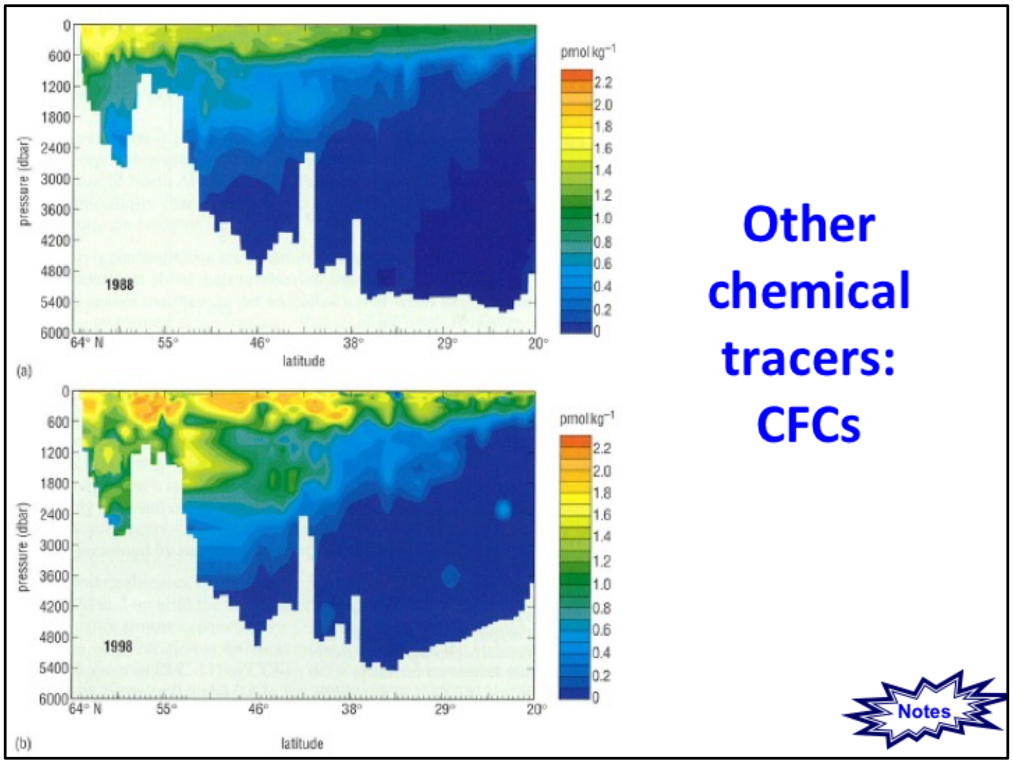
Tritium distribution In the North Atlantic, 1973

Figure 8-15. Section showing the vertical distribution of tritium in the western North Atlantic. The deep penetration north of 40°N is associated with the formation of deep water. This diagram was prepared by Göte Ostlund of the University of Miami based on his measurements on samples collected as part of the GEOSECS program (727).

Full cycle
→ ~ 1000 years

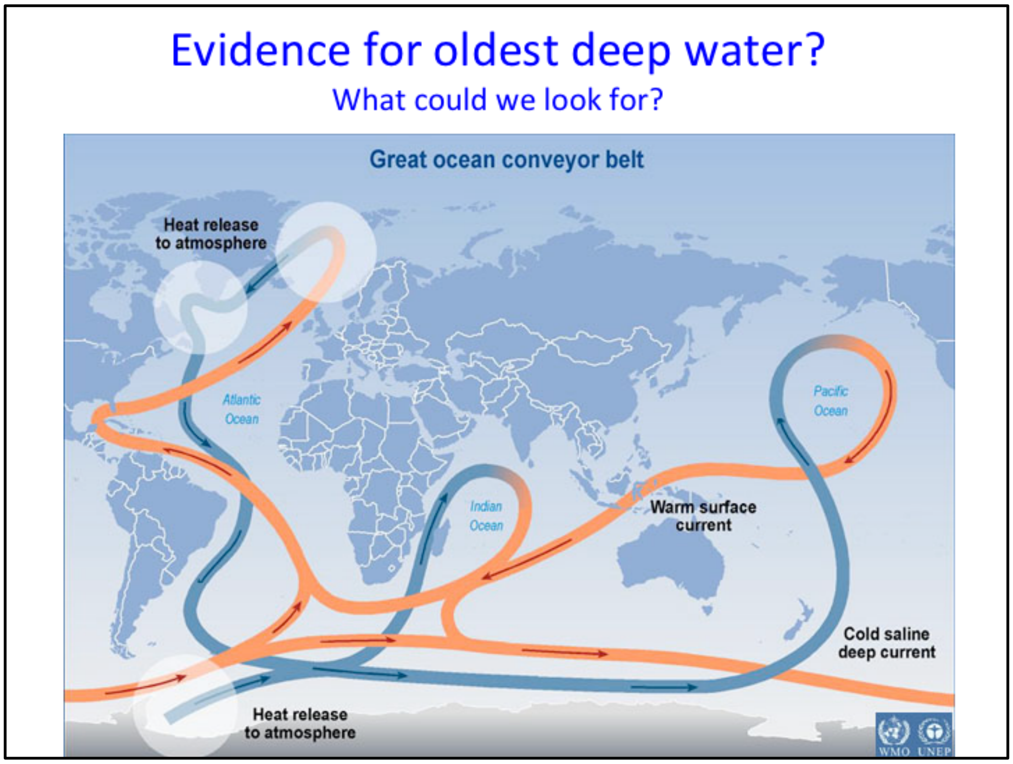
By sampling water at various depths and in various locations, and analyzing it for tritium, we can track the progression of this tracer as it travels with NADW, sinking from the surface and starting on its journey at depth. This figure shows the tritium distribution in the North Atlantic in 1973, in which you can see the progress of tritium-laced water from the surface down into the water column. People have traced this tritium southward in the deep western boundary current, and based on its rate of motion, estimated the speed at which the whole conveyor belt cycles. Result? About 1000 years for a full overturning.

This rate of overturning is, of course, an average, ballpark number, and varies regionally. However, it does give us a useful “order-of-magnitude” to consider when we discuss the roles deep ocean overturning plays in climate change.



Other chemical tracers: CFCs

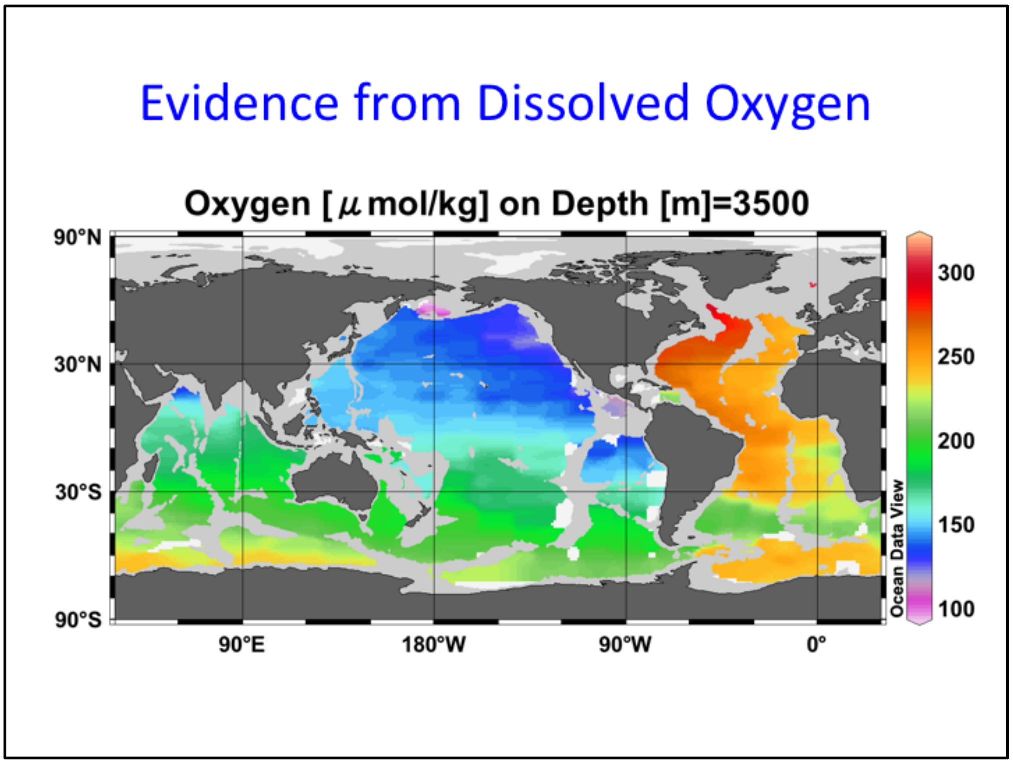
NOTES SLIDE (not shown in class):
Other chemical tracers have also been used to track the motion of deep water. The top panel above shows the distribution of CFC-12 concentration in the North Atlantic in 1988. The bottom panel shows the same, but for 1998. In 10 years, surface water has mixed to deeper depths, to varying degrees. The high concentrations of CFC-12 at 1000-2000 m depth at 50-55 degrees North latitude are tracers of deep water that formed in the Labrador Sea and sank.



Evidence for oldest deep water?

What could we look for?

Where would we find the “oldest” deep water, that is, the deep water that’s been down there for the longest time? What kind of evidence could we look for to help determine how long the water had been down there (how long since the last time it was at the surface)?



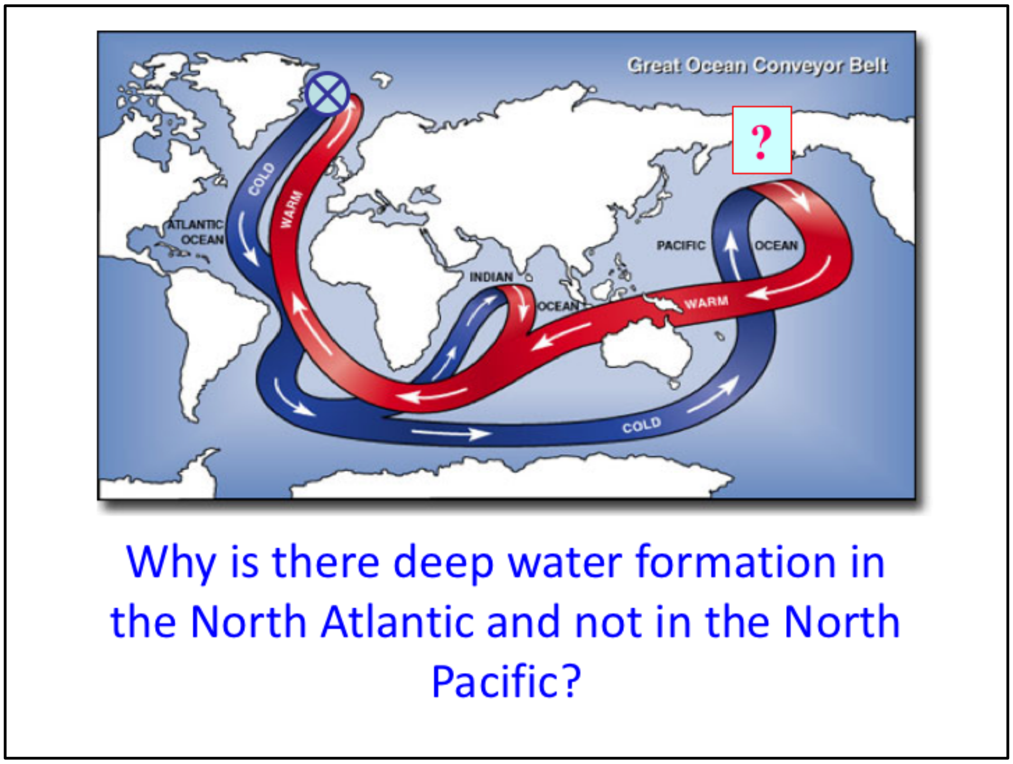
Evidence from Dissolved Oxygen

Examine this pattern of O2 in deep water. Where is it high, where is it low?

Oxygen concentrations are related to nutrient concentrations. NADW and AABW dissolve high concentrations of oxygen at the surface where the water can exchange gases with the atmosphere. This oxygen sinks with the deep water masses and is transported around the global oceans with the thermohaline circulation. As water masses get "older" they lose their oxygen as it is used to decompose organic matter. Thus, oxygen is a tracer for the "age" of a water mass.

High O2 - "young water", NADW and AABW
Low O2 - "old water", deep Pacific

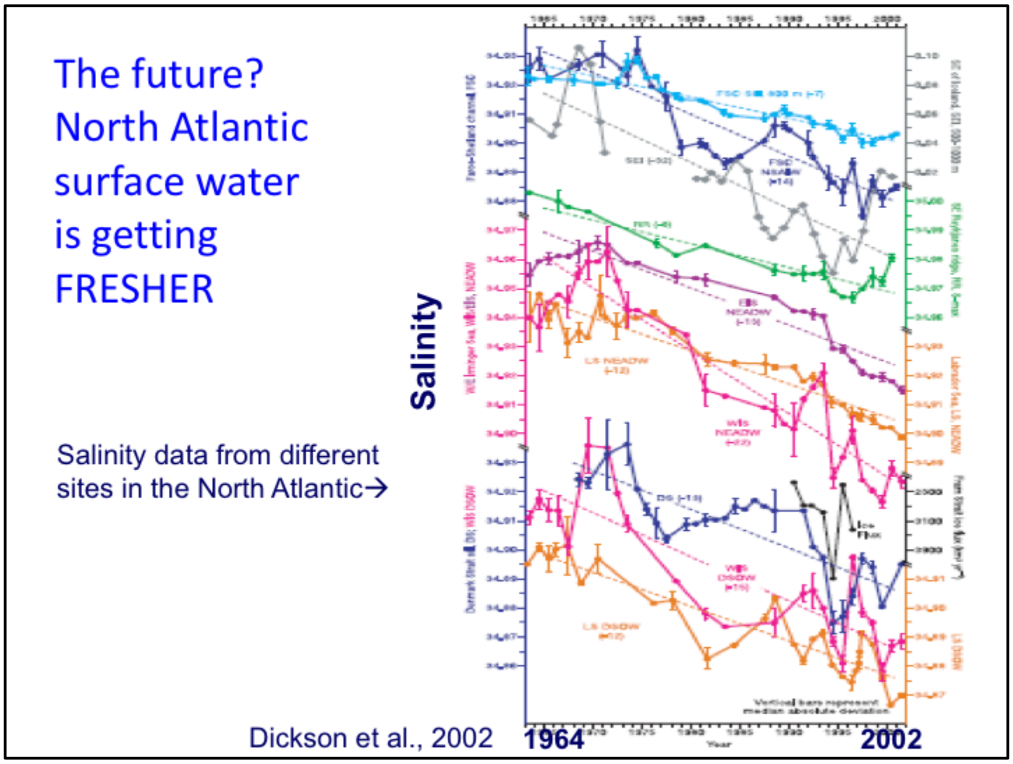
What spatial pattern would you expect for concentrations of carbon dioxide in the deep ocean?



Why is there deep water formation in the North Atlantic and not in the North Pacific?

NOTES SLIDE (not shown in class):
One could wonder why there is deep water formation in the North Atlantic and not in the North Pacific.
Things to consider: latitude, surface ocean salinity patterns, transport of water vapour, dominant wind directions…

Image: Argonne National Laboratory, via NASA.

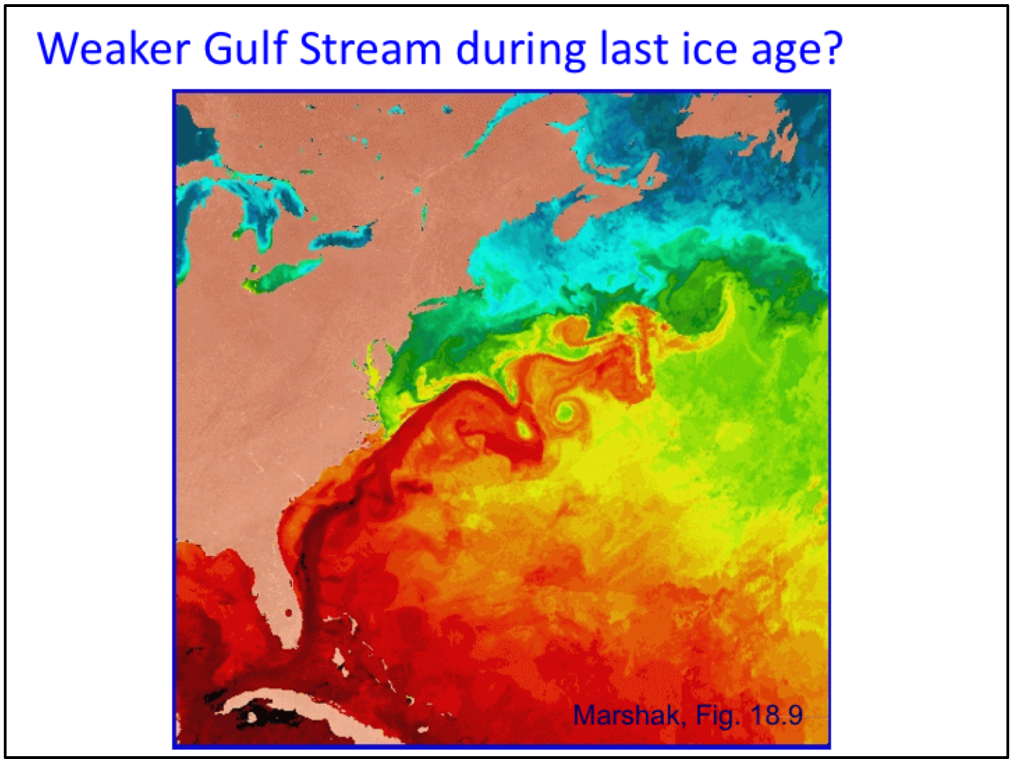


The future?
North Atlantic
surface water
is getting
FRESHER

Salinity data from different
sites in the North Atlantic→

Dickson et al., 2002

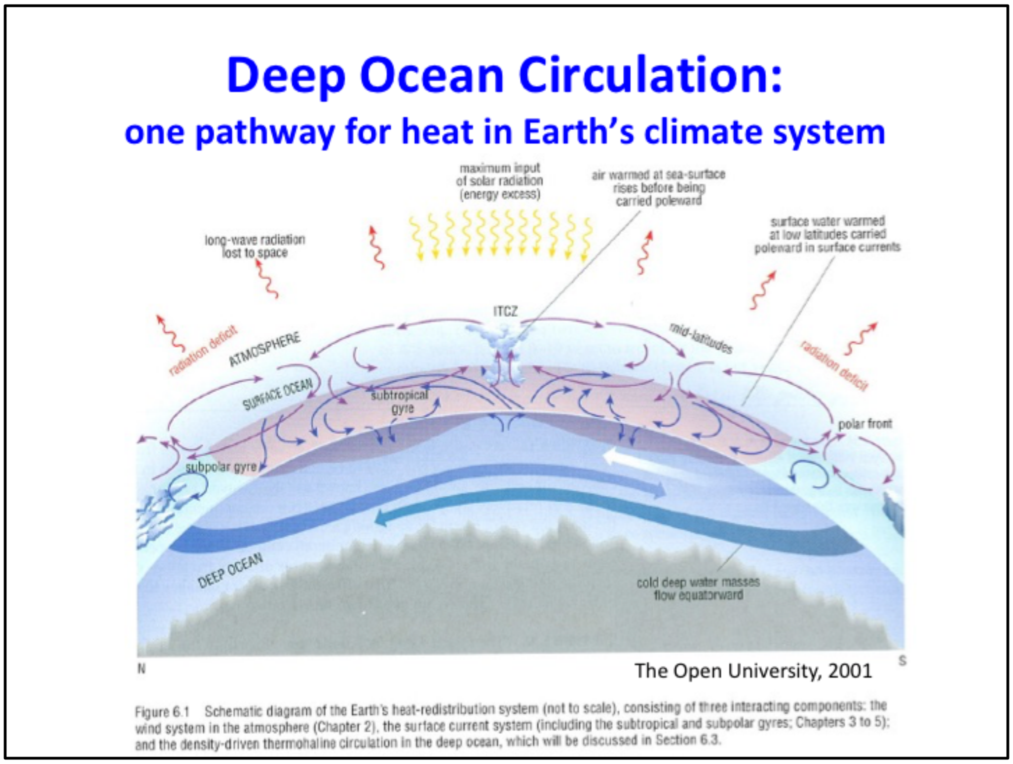
What might happen to the thermohaline circulation in the future? Recent measurements of salinity from several places in the North Atlantic indicate that the surface water is getting less salty. What impact might that have on deep water formation?



Weaker Gulf Stream during last ice age?

Marshak, Fig. 18.9

There is some evidence that the Gulf Stream was weaker during the last ice age, and evidence that the conveyor belt circulation was slower. How might these features be linked?



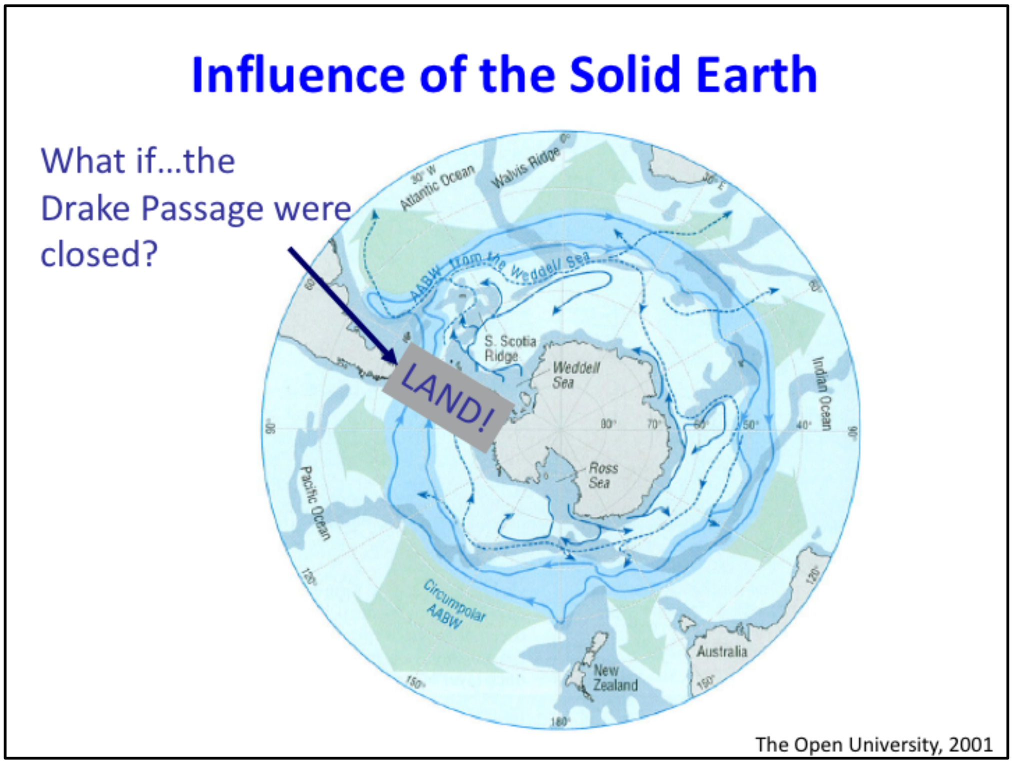
Deep Ocean Circulation:

one pathway for heat in Earth's climate system

The Open University, 2001

Figure 6.1 Schematic diagram of the Earth's heat-redistribution system (not to scale), consisting of three interacting components: the wind system in the atmosphere (Chapter 2), the surface current system (including the subtropical and subpolar gyres; Chapters 3 to 5); and the density-driven thermohaline circulation in the deep ocean, which will be discussed in Section 6.3.

We began this course discussing the Earth's radiation balance. Where does the energy come from to drive the Earth's climate system? We've now added processes in the atmosphere, the upper ocean, and the deep ocean to the picture. All of these play roles in moving heat energy around on the planet – each with its own time scale and via different processes. Have a look at all the components illustrated in this figure.
Figure: The Open University. "Ocean Circulation", 2nd edition, 2001. Butterworth-Heinemann .



Influence of the Solid Earth

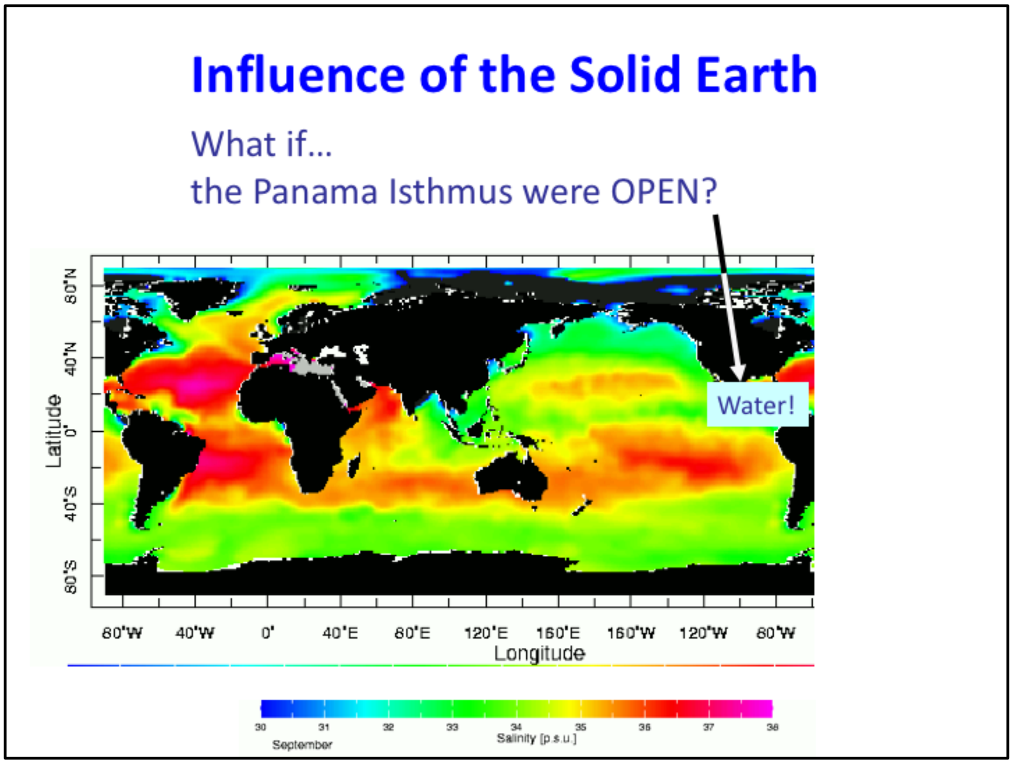
What if…the Drake Passage were closed?

LAND!

The Open University, 2001

The continents define the edges of the ocean basins and block water from flowing in some places. Until about 41 million years ago, the Drake Passage was closed, that is, there was land connecting the southern tip of South America with Antarctica. What kind of influence would this have on the flow of both surface water AND deep water? Think about the surface flow today (look back at a map of the surface currents). Both the surface currents and deep water flow around and around and around Antarctica with no barriers today.

Figure: The Open University. “Ocean Circulation”, 2nd edition, 2001. Butterworth-Heinemann

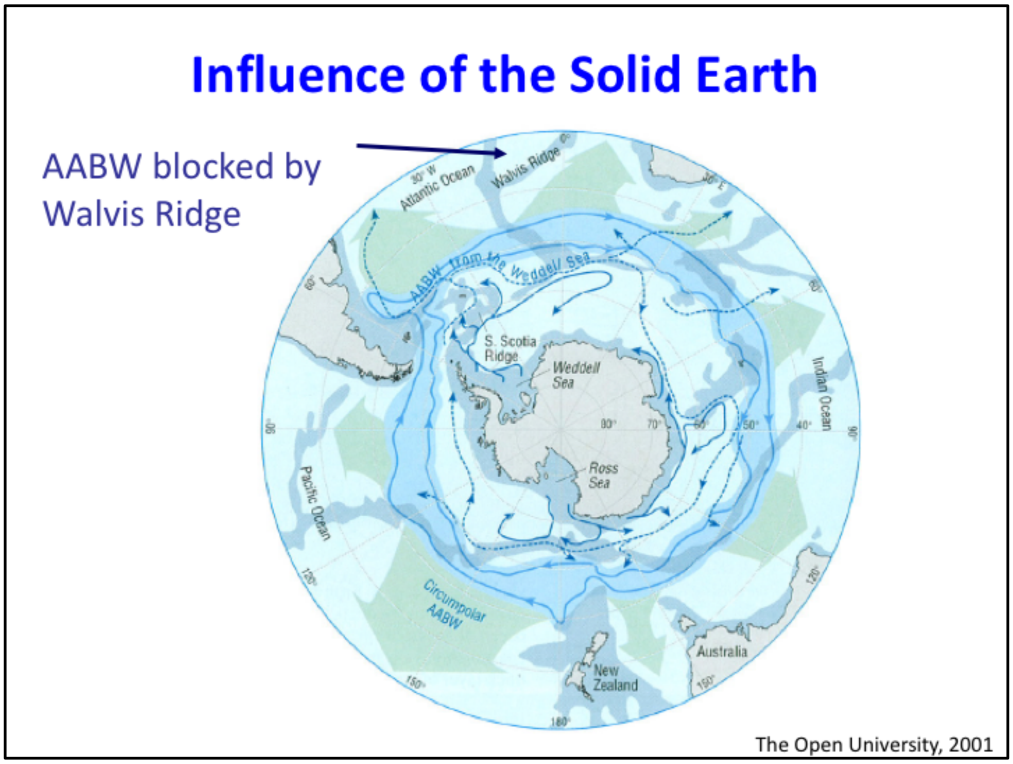


Influence of the Solid Earth

What if…
the Panama Isthmus were OPEN?

Water!

The continents define the edges of the ocean basins and block water from flowing in some places. Until about 5-6 million years ago, the Isthmus of Panama did NOT connect North and South America, that is, there was water connecting the Atlantic Ocean and the Pacific Ocean at low latitude. What kind of influence would this have on the flow of both surface water AND deep water? One thing to think about is the salinity difference between the Atlantic and Pacific that exists today. That salinity difference is largely because of the positions of the continents, e.g. water evaporates from the Atlantic, the clouds blow over the Isthmus of Panama, then it rains in the Pacific. That's one of the reasons that deep water forms in the Atlantic rather than the Pacific (the Atlantic's saltier). OK, so what if that barrier were removed and water was free to flow between the two basins at low latitude? How would that influence the salinity difference between the Atlantic and Pacific?



Influence of the Solid Earth

AABW blocked by Walvis Ridge

The Open University, 2001

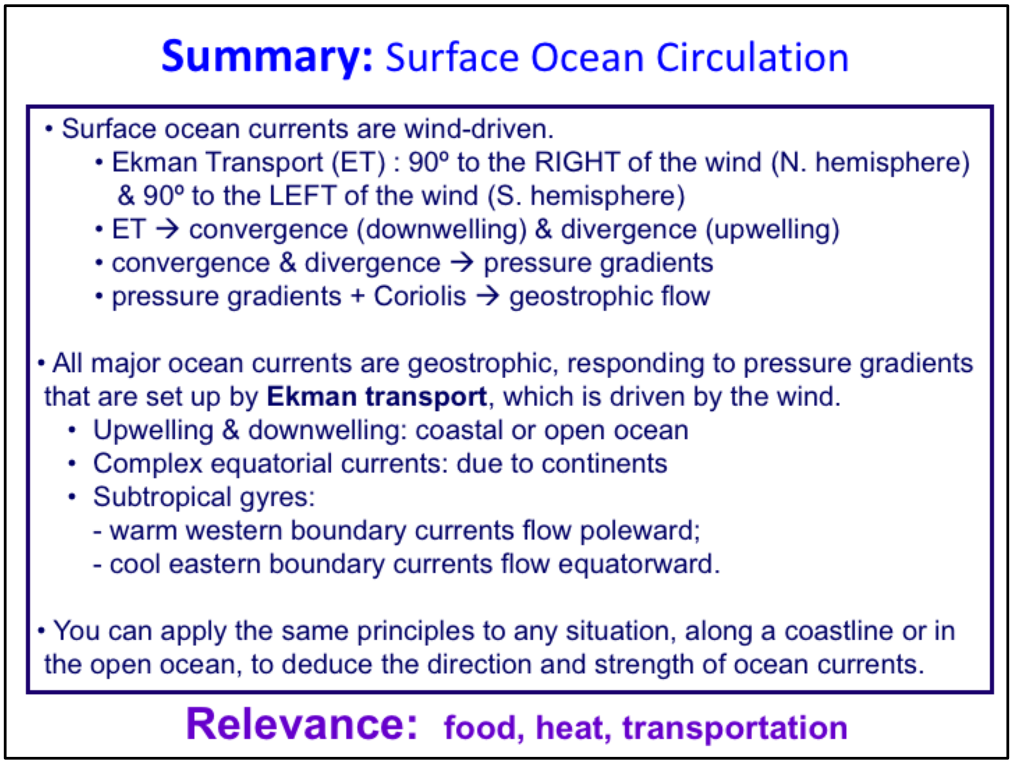
Again, the continents define the edges of the ocean basins and block water from flowing in some places. Likewise, at depth, the bathymetry of the ocean floor plays a role in where deep water can go. The ridges on the ocean floor prevent deep and bottom water from flowing everywhere. For example, in the eastern South Atlantic, Antarctic Bottom Water, flowing northward from Antarctica, gets blocked by the Walvis Ridge. This blockage results in quite different bottom water composition on the north and south sides of that ridge. Examine the wide arrows indicating the paths followed by AABW as it flows away from its areas of formation, and note how it is limited to the deepest basins.

Figure: The Open University. "Ocean Circulation", 2nd edition, 2001. Butterworth-Heinemann

Summary: Hydrologic Cycle

- The **hydrologic cycle** describes the movement of water among different **reservoirs**, including the rates of transfer and **residence times**. Water in all its forms plays crucial roles in Earth's climate system.

Relevance: **fresh water, ocean productivity, pollution**



Summary: Surface Ocean Circulation

- Surface ocean currents are wind-driven.
  - Ekman Transport (ET) : 90° to the RIGHT of the wind (N. hemisphere) & 90° to the LEFT of the wind (S. hemisphere)
  - ET → convergence (downwelling) & divergence (upwelling)
  - convergence & divergence → pressure gradients
  - pressure gradients + Coriolis → geostrophic flow

- All major ocean currents are geostrophic, responding to pressure gradients that are set up by **Ekman transport**, which is driven by the wind.
  - Upwelling & downwelling: coastal or open ocean
  - Complex equatorial currents: due to continents
  - Subtropical gyres:
    - warm western boundary currents flow poleward;
    - cool eastern boundary currents flow equatorward.

- You can apply the same principles to any situation, along a coastline or in the open ocean, to deduce the direction and strength of ocean currents.

Relevance: food, heat, transportation

Summary: Density stratification & deep water form.

- Ocean water is stratified according to density, which is controlled by the combination of T & S.
- Ocean water masses acquire their T & S characteristics primarily at the surface, and change those characteristics through mixing.
- Vertical profiles of T, S, and ρ show variations in density stratification with location and season.
- Deep water formation occurs in the North Atlantic (NADW) and the Southern Ocean (AABW), where various processes make the water cold and salty enough to sink. AABW is the densest water and flows under NADW in the locations where they meet.

Relevance: CO2 storage in the deep ocean, climate

Summary: Thermohaline Circulation

- Surface water gets dense enough to sink in two major regions – the North Atlantic and around Antarctica. This sinking water is the start of the "ocean conveyor belt", which describes water circulation through the deep ocean basins. On average, the deep ocean circulation takes about 1000 years for a full cycle.
- Deep ocean circulation transports heat, just like the atmosphere and surface ocean, but on a different time scale. It also interacts with surface currents to influence global and regional climate.
- The position of continents changes over time. The opening or closing of passageways can have major effects on ocean circulation (and thus heat transport)

Relevance: **CO2 storage in the deep ocean, climate**