Ocean circulation III

Reading: GPC Ch 7

Outline:
- Thermohaline circulation
- Deep water formation
- Climate changes that occurred in the past and that are thought to be caused by changes to it.
- Energy transports by the ocean circulation.

Thermohaline circulation

The other way to drive ocean circulation is through density changes as a result of T or S changes - hence **thermohaline** circulation.
It is not separated from wind driven circulation. The ocean circulation is not a linear superposition of the two circulations. They are coupled.

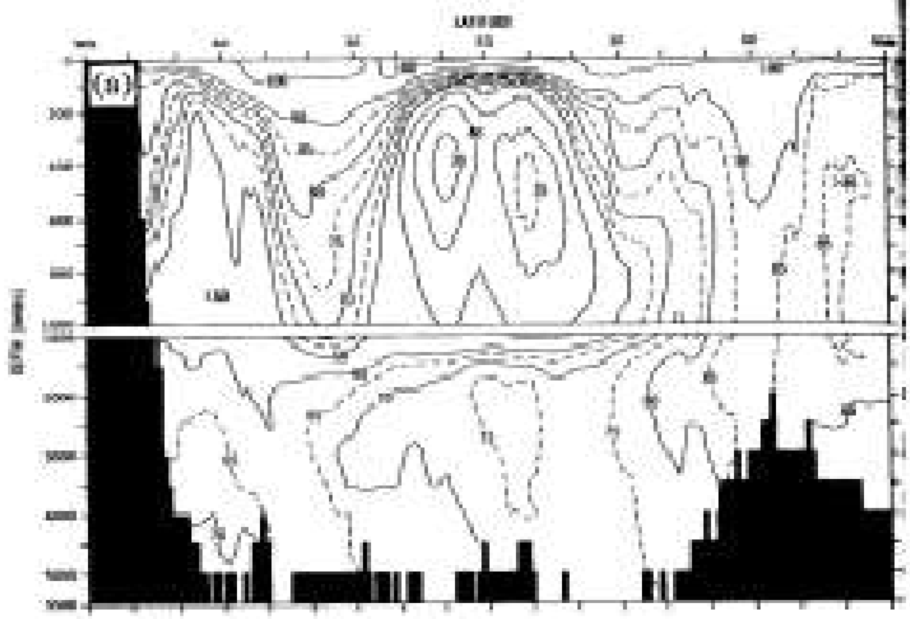
Below the thermocline there exists slow circulations driven by such density changes - ‘deep thermohaline circulation’. They are difficult to detect as they move very slowly, and the circulation has to be inferred by other means. One way to do this is to look at the distribution of trace constituents of seawater. Away from the surface, T and S of water masses change very slowly, so that the water masses and their origins can be inferred from the particular combination of T and S that characterizes them.

Another way is to look at the oxygen concentration in seawater – at the surface, the oxygen concentration is at (and actually slightly over) saturation*, since it is in contact with the air (mixing of bubbles, production by photosynthesis). When surface water sinks into the deeper levels of the ocean its source of oxygen is cut off and the oxygen is slowly consumed by bacteria as they feed on organic matter.
One may therefore use the depletion of the oxygen concentration below its saturation value as a measure of the time since the water has been at the surface: in other words, the oxygen saturation is a measure for the ‘*age*’ of the water.

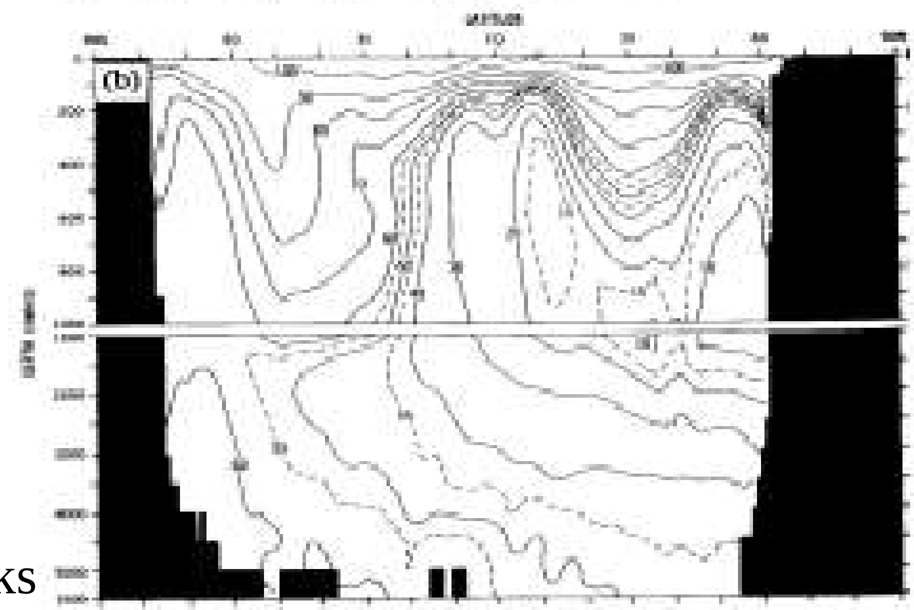
*Saturation conc. of a gas in seawater=amount that would exist in solution in equilibrium, if seawater at a given T and S were exposed to the gas.
Increases as water gets colder.

Oxygen saturation in % versus depth and latitude.

- In the N Atlantic high values extend to great depths, and these high values extend toward the SH at depths below ~ 1500 m.
- In the N Pacific the O_2 at depth is severely depleted with saturations about 10-15% at latitudes and depths where the saturaion is about 85% in the N Atlantic.



Atlantic



Pacific

From these measurements alone it may be inferred that water sinks relatively quickly in the N Atlantic and then spreads southwards, but this does not occur in the Pacific.

From the oxygen measurements we cannot infer the full circulation of the deep ocean, nor can we directly infer the subsidence rate, since the O_2 depletion depends on the biological activity at depth, which in turn depends on the rate at which nutrients are supplied to them by deposition from above. However, we may conclude that

- water sinks relatively quickly in the N Atlantic, and spreads Southwards;
- in the Pacific, deep water moves northwards, and the oldest waters are found in the North Pacific;
- the location of the oldest north Pacific water is at relatively shallow depths (compared to the deep water locations), suggesting that the deep water gradually rises to the surface.

In practice, we need to combine this information with that coming from particular associations of T and S, from the concentrations of other tracers (e.g. bomb C14, CFCs…), from measurements of the age of twater through ^{14}C dating, etc… to get a good picture of the deep circulation.

The conclusion is that there are are two locations of deep water formation:

- **North Atlantic** (in the Laborador sea, and also the Greenland-Iceland-Norwegian seas (otherwise known as the 'Gin' seas)
- **South Atlantic** (primarily in the Weddell sea)

The deep water formation mechanisms are thought to be different in the two source regions.

In the North Atlantic, the Gulf Stream circulation brings up relatively salty water that becomes dense through cooling, and then sinks.

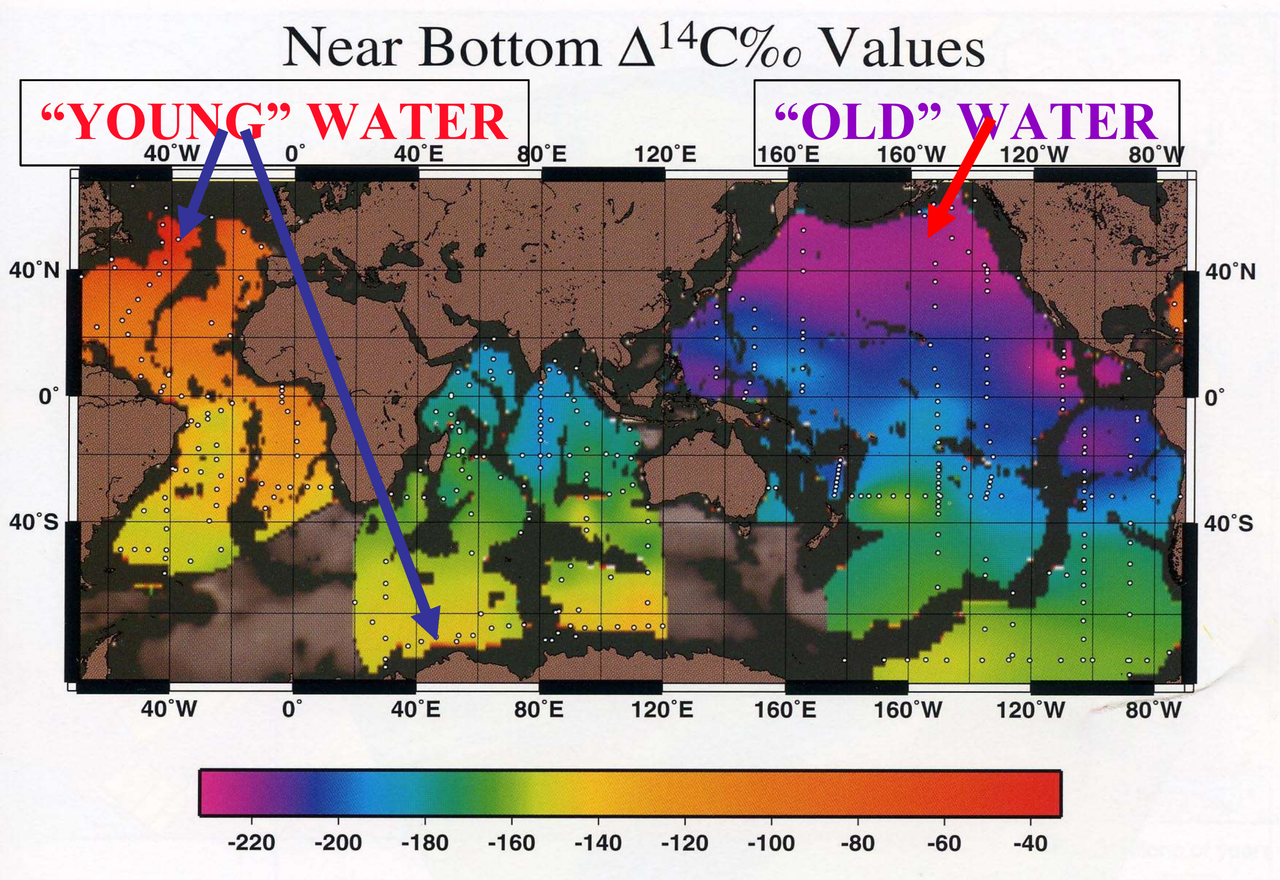
In the South Atlantic, the open ocean water there is relatively fresh since it comes from the ACC, which is a P>E region. Also, there is no warm western boundary current to carry warm saline water poleward since the ACC inhibiths efficient transport of water from middle to polar latitudes.
Some saline water reaches the surface of the southern polar oceans by flowing southward *at intermediate depth* (what makes it enhanced in nutrients that are dissolved from falling detritus and not consumed by photosynthetic organisms) and rising at high latitudes in the South Atlantic.

Deep water in the South Atlantic is thought to be tied to sea-ice formation near coastlines - when sea ice is formed, the sea salt is rejected into the ocean (brine rejection), thus forming cold salty water which then sinks.
The densest deep waters are formed in this region – the **Antarctic bottom water**.

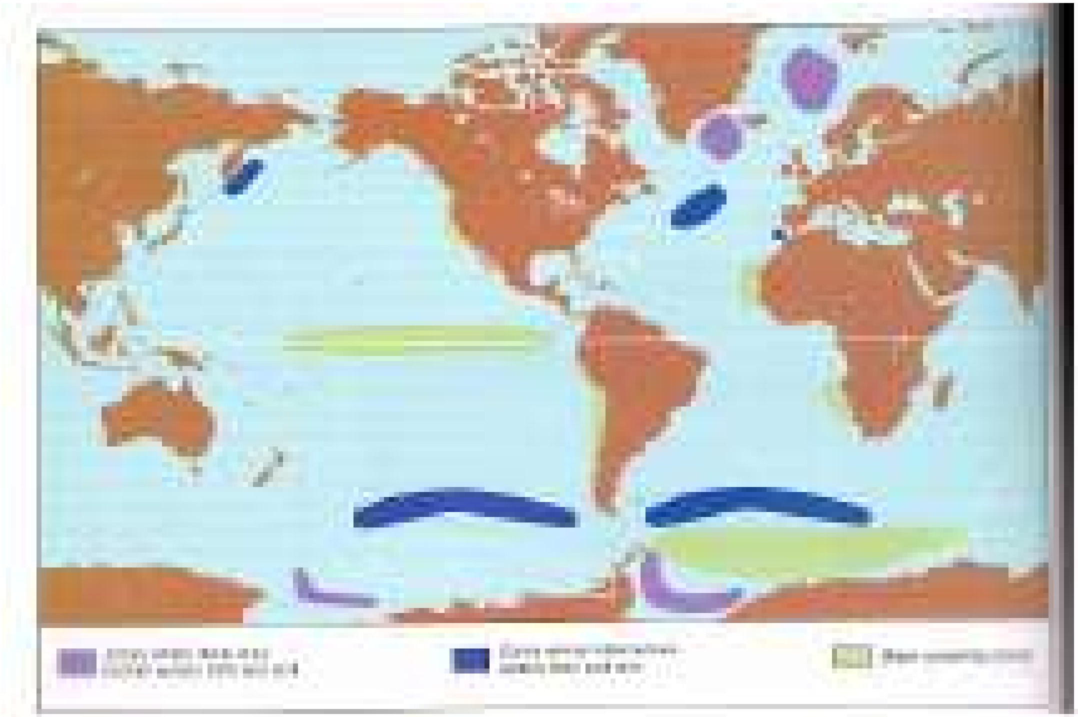
Deep water formation regions occupy a small fraction of the ocean surface: e.g. 75% of the world's ocean has density of 27.4 and higher, but only 4% of the surface water has density that high.

It is estimated that the time required to replace the deep water through deep water formation is on the order of 1000 years (*turnover time*).

Locations of deep water formation: water age through ^{14}C dating



From N and S Atlantic, where deep water is formed, water spreads out at depth to fill the Pacific and the Indian Oceans, where the water gradually rises to the surface. Since the N Pacific is the farthest from either of the twoo deep-water formation locations, the water in the N Pacific is the "oldest" ocean water.



Purple: deep water formation regions

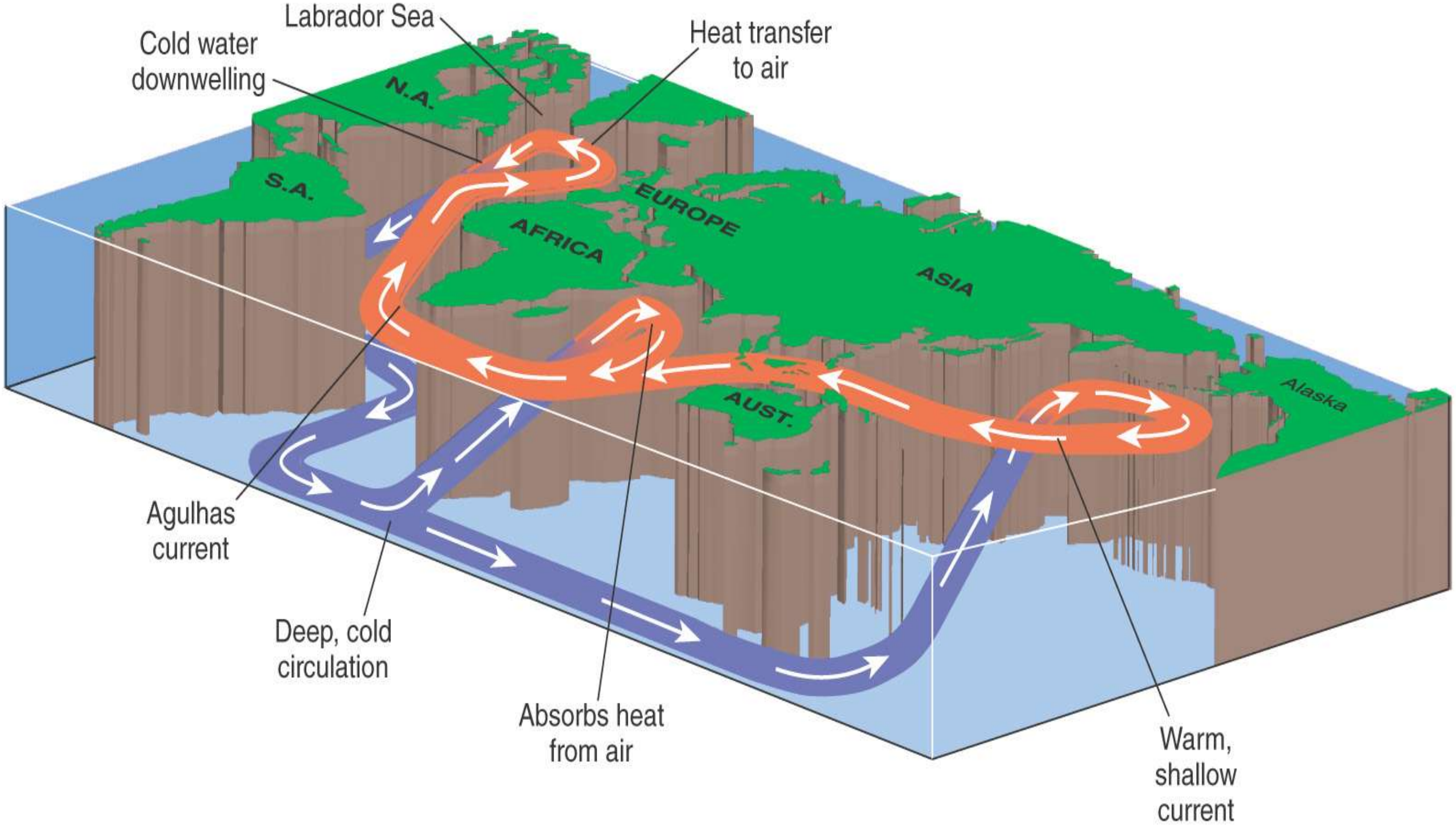
Blue: Intermediate water formation regions

Green: Major upwelling regions

Note there are no deep water formation regions in the North Pacific. The reason is thought to be that the North Pacific surface waters are too fresh - they can’t get dense enough to sink even if they are cooled to near freezing. The same is true for the Arctic ocean.

(from http://earth.usc.edu/~stott/Catalina/Deepwater.html)

Thermohaline ‘conveyor’ and climate

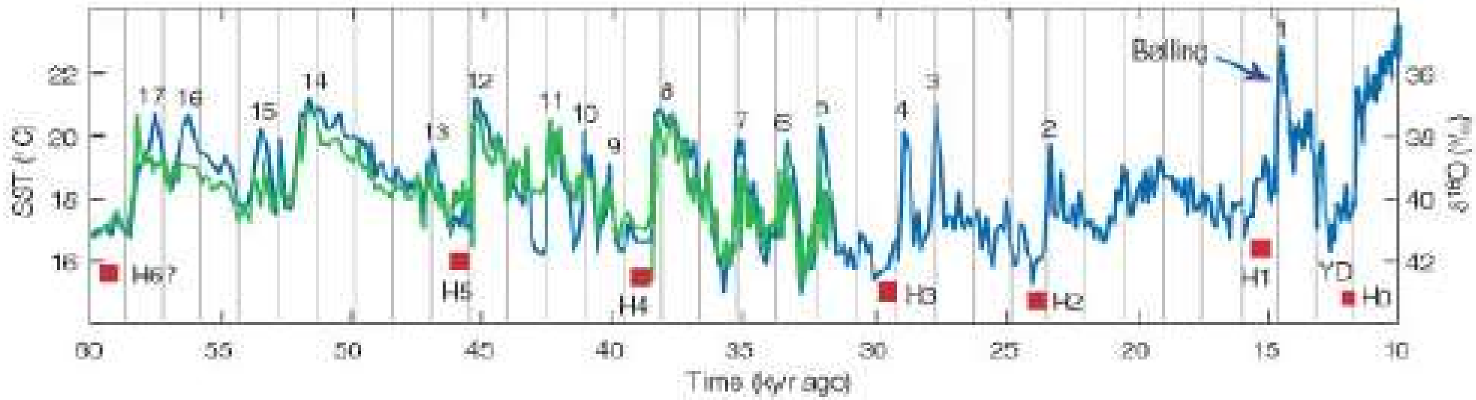


Thermohaline circulation and climate

Where does the motivation for imagining this come from?

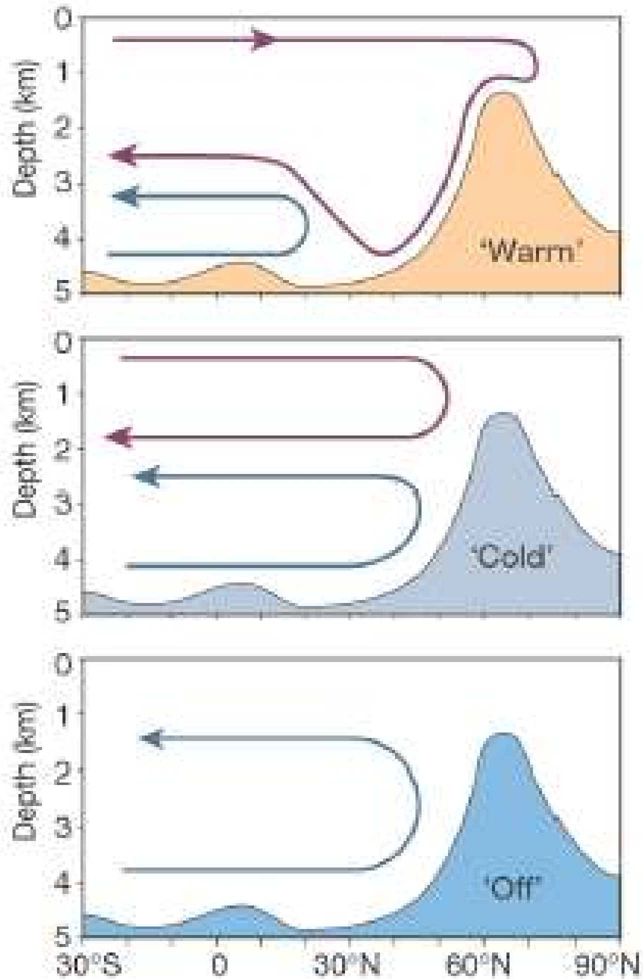
http://www.apple.com/trailers/fox/dayaftertomorrow/

Thermohaline circulation and climate



Temperature reconstructions from ocean sediments and Greenland ice. Proxy data from the subtropical Atlantic86 (green) and from the Greenland ice core GISP2 (ref. 87; blue) show several Dansgaard–Oeschger (D/O) warm events (numbered). The timing of Heinrich events is marked in red. Grey lines at intervals of 1,470 years illustrate the tendency of D/O events to occur with this spacing, or multiples thereof.

(Rahmstorf 2002)



Schematic of the three modes of ocean circulation that prevailed during different times of the last glacial period. Shown is a section along the Atlantic; the rise in bottom topography symbolizes the shallow sill between Greenland and Scotland. North Atlantic overturning is shown by the red line, Antarctic bottom water by the blue line.

(Rahmstorf 2002)

"Day after tomorrow" scenario

Model simulations suggest that a sudden shutdown of the thermohaline circulation will cause global climate changes (from Vellinga and Wood 2002).

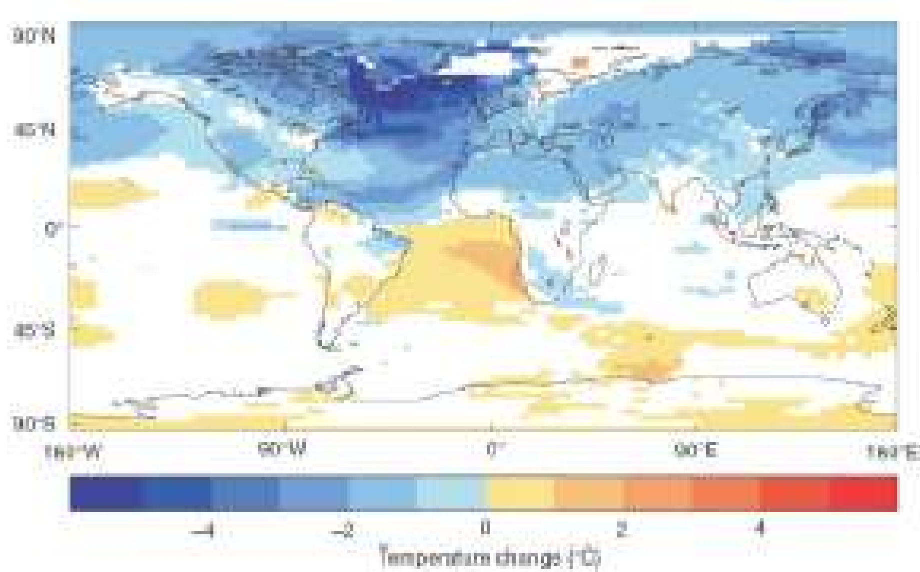


Figure shows surface air temperature changes associated with the collapse of the Atlantic thermohaline circulation). One way that the collapse can be initiated is through introducing large amounts of freshwater from continental ice sheets into the North Atlantic, freshening the surface ocean and inhibiting North Atlantic deep water formation. This is thought to have happened during the "Younger Dryas" when the contents of glacial Lake Agassiz essentially drained into the North Atlantic around 12,700 years ago.

Energy transport in the ocean

It is difficult to directly measure heat transport in the ocean, since there are few direct concurrent measurements of the currents and temperature at the same locations, over the entire ocean basins. Distinguishing features of the ocean as compared to the atmosphere is that the *ocean spatial scales of motion are smaller than the ocean, and the temporal scales are longer*. The former implies we need denser spatial coverage of measurements, the latter means we need to measure for longer periods of time to get a representation of the *climate*.

The alternative is to use atmospheric and TOA measurements to infer ocean heat transports, under the energy balance assumption.

There are two flavors of this.

This first comes from simply noting that

Ocn ht transport =

(ht transport by atm + ocn) ***minus*** **(ht transport by atm)**

Recall the equation for the poleward energy transport for a region of the Earth (see Global Energy Balance II):

$$\frac{\partial E_{ao}}{\partial t} = R_{TOA} - \Delta F_{ao}$$

In the annual mean, $\partial \mathbf{E}_{ao} / \partial \mathbf{t} = \mathbf{0}$, so $\mathbf{R}_{TOA} = \Delta \mathbf{F}_{ao}$. If we assume $\Delta \mathbf{F}_{ao} = \Delta \mathbf{F}_a + \Delta \mathbf{F}_o$ we get $\mathbf{R}_{TOA} = \Delta \mathbf{F}_a + \Delta \mathbf{F}_o$.

But as we have seen, $\mathbf{R}_{TOA}$ can be integrated from the south pole to the latitude ϕ, to get ***total meridional energy flux*** $\mathbf{F}_{ao}$; therefore we can write

$$\mathbf{F}_o = \mathbf{F}_{ao} - \mathbf{F}_a$$

and deduce $\mathbf{F}_o$ from $\mathbf{F}_{ao}$ and from $\mathbf{F}_a$, obtained by (say) the available atmospheric measurements.

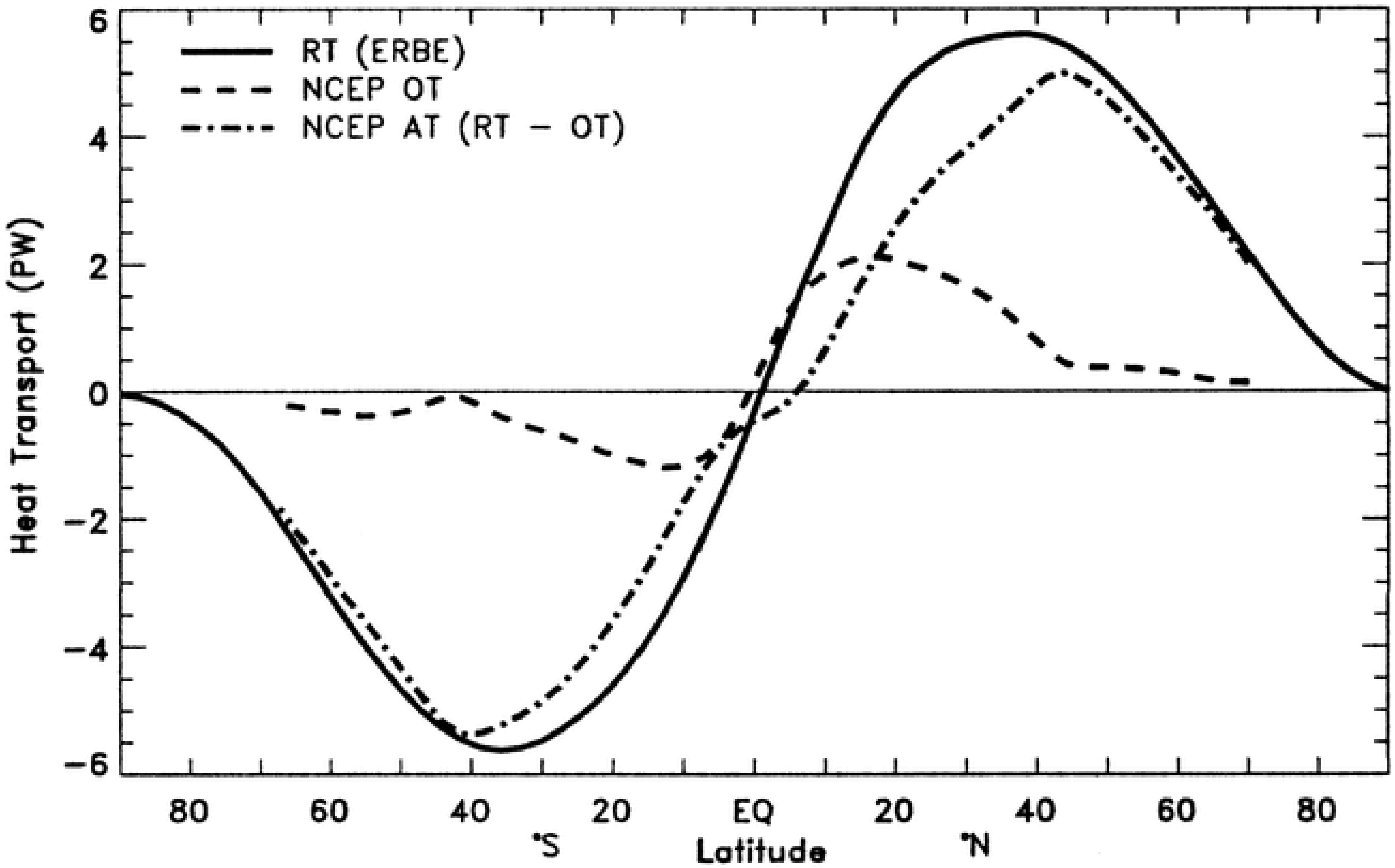
The alternative is to measure surface fluxes out of the ocean to infer the ocean heat transport. (This is the same technique we applied to measuring heat transport by the atmosphere and the ocean, except that now we use the ocean surface instead of the TOA, and that on the ocean surface it is not just radiative fluxes, but also latent and sensible heat fluxes):

$$\nabla \bullet \vec{F}_o = R_s - \mathrm{LE} - \mathrm{SH} - \frac{\partial E_s}{\partial t}$$

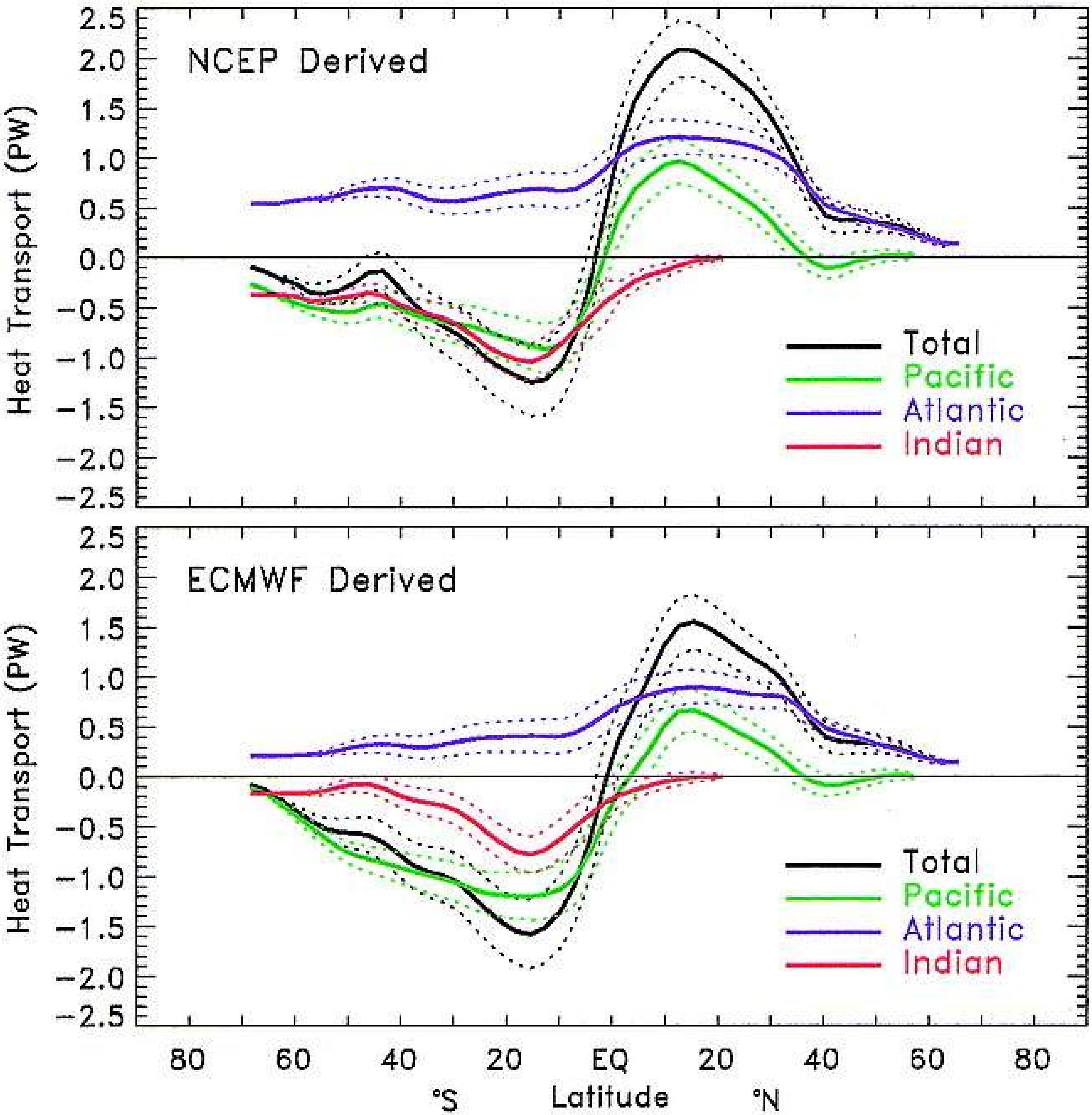
Divergence of ocn ht transport = surface net radiative flux - latent ht flx - sensible ht flux - time rate of change of energy storage in ocean

Generally (and perhaps wrongly) the change in energy storage term is assumed to be zero.

Northward heat transport across each latitude
(1PW=10^{15}W)



Trenberth and Caron (J Clim v14 p3433 2001)
Solid line - atm+ocn transport; Dashed - ocn only; dash-dot - atm only



Heat transport by the individual oceans (two different estimates; positive implies northward transport)

Mechanisms of ocean heat transport

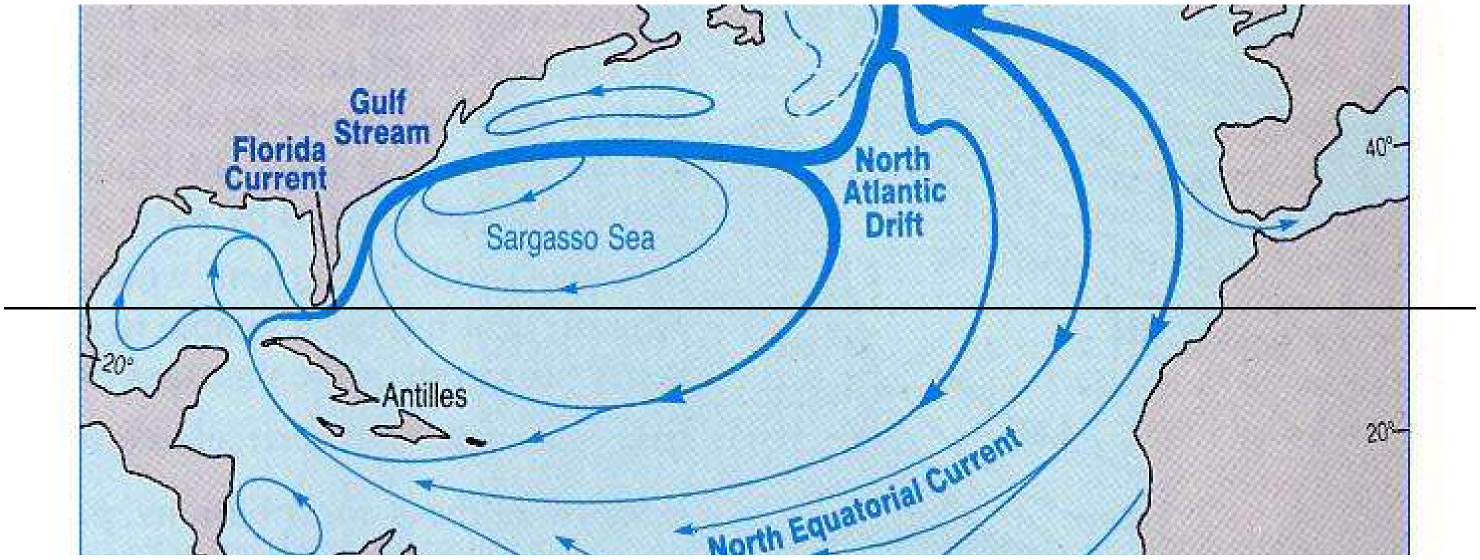
Basic question: ***how much of the transport is due to the 'steady' wind-driven circulation, how much due to the thermohaline circulation, and how much is due to mid-ocean eddies?***

We don't really have a good handle on this. The reason why we need to worry about this is that climate change may result in changes to one or more of them, and so to understand how (say) the climate changes if thermohaline circulation change, we need to know how much heat the thermohaline circulation carries in the first place.

Wind-driven circulation: let's estimate the contribution by Gulf Stream and its return flow at the latitude of Florida.

Mass transport at Florida strait ~ 30Sv x density of seawater ~ $3x10^{10}$kg/s

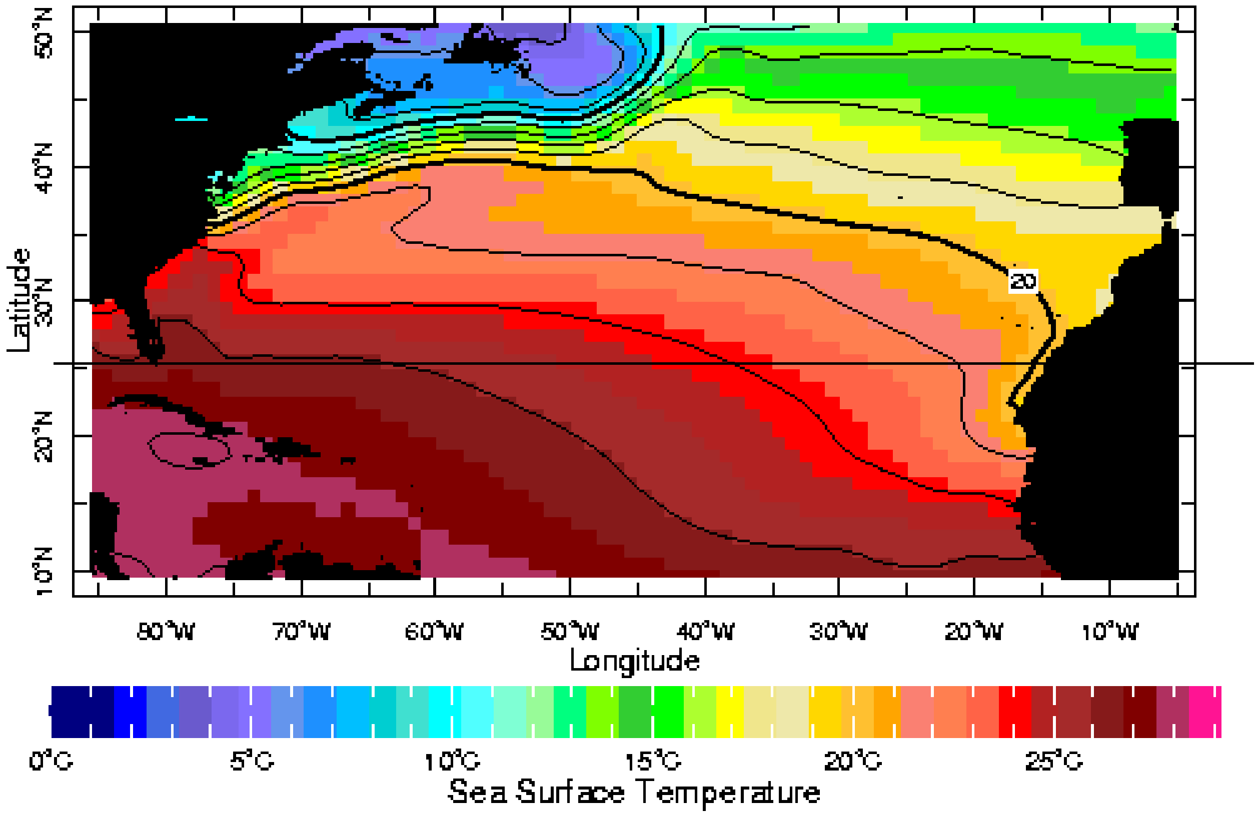
Heat capacity of seawater = 4281 J/(K.kg)



Energy transport by gulf stream and return flow (Watts) =
Ht capacity x mass transport x ***temperature difference between Gulf Stream water and the return flow water*** (ΔSST).

The temperature difference of the ***surface*** water between the Gulf Stream and the interior at 25N is 3-4 degrees.

However, the return flow of Gulf Stream water is not all at the surface, so the temperature difference is in fact higher (perhaps substantially). If we take ΔSST ~ 5K then the energy transport is ~ 0.6×10^{15}W or 0.6 PW.



By comparison, the total ocean heat transport in the Atlantic at 25N is around 1.2 PW (according to the Trenberth and Caron estimates)

So, if we take 0.6 PW as the portion driven by the Gulf stream (a wind-driven flow), then the other 0.6 PW comes from the thermohaline and the mid-ocean eddy contributions.

In principle, we can compute the **thermohaline contribution** to ocean heat transport the same as for the Gulf Stream. We won't do it all the way here, but here's how it goes…

Recent estimates for deep water formation are 15 Sv for the North Atlantic, or 1.5×10^{10} kg/s. Note that this for 25N, this rate is the upper bound as there is significant recirculation of the thermohaline circulation polewards of 25N. As for the thermohaline circulation, what is the equivalent 'difference in temperature' needed to compute the heat transport?

The ocean above the thermocline (where the poleward flow) is around 12C (rough estimate), whereas in the interior it is around 2C. So the temperature difference is ~ 10C $\rightarrow$ the thermohaline contribution to ocean heat transport is 0.6 PW.

Therefore **mid-ocean eddies should not contribute much**.

It is reasonable that long-lived eddies such as those generated by the Gulf Stream only give a small contribution because their scale is small compared to that of the oceans and because they are best developed well polewards the latitude of the maximum oceanic transport (15-20^{0}N).