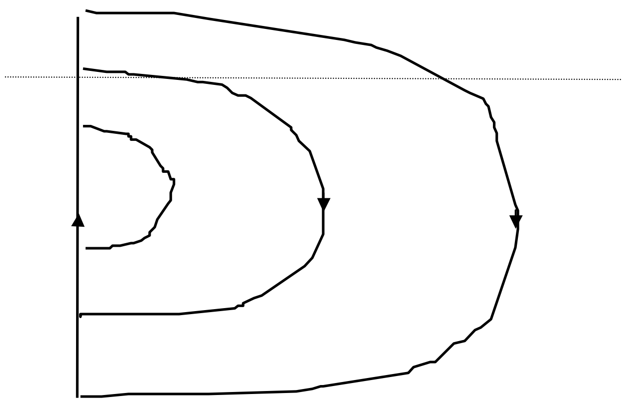
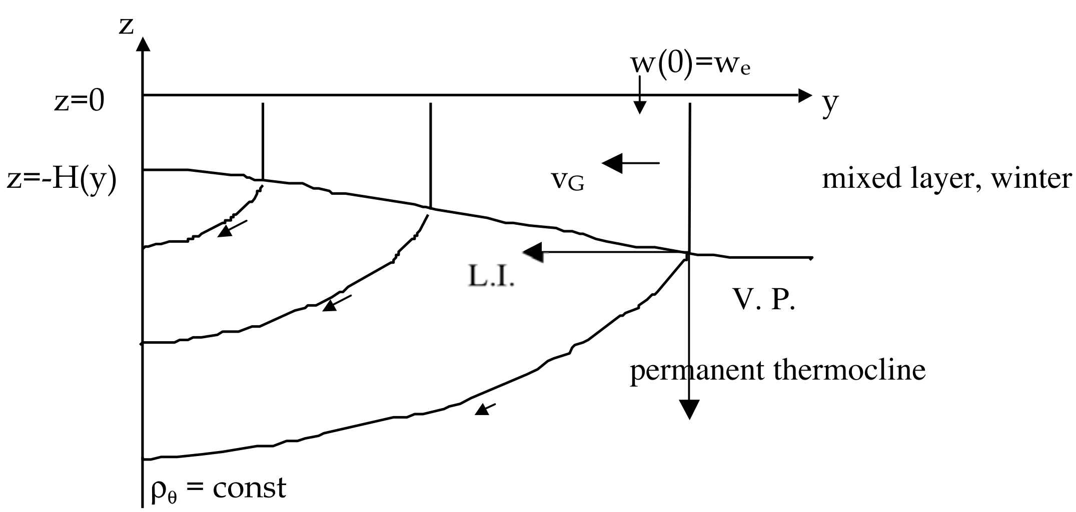
When we are thinking about how the density, temperature and salinity structure is set in the ocean, there are different processes at work depending on where in the water column we are looking. If we are considering the thermocline, then we notice first that north-south distribution of the surface density/temperature/ salinity across the subtropical gyre can be mapped into their structure in the vertical. This suggests that vertical structure originates at the surface. To figure this out, we can look any one particular isopycnal layer, and see that at some point north and south it intersects the sea surface. Poleward of that point, the layer below the mixed layer is a slightly denser layer. Following stratigraphy, we call the point where an isopycnal layer intersects the sea-surface its **outcrop**.





Let's imagine a water parcel starting somewhere at the surface in the northern half of the subtropical gyre. We ignore the Ekman layer, except for the Ekman pumping it produces, which we specify as a boundary condition on vertical velocity at the ocean surface. The geostrophic velocity is southward everywhere (including the mixed layer) in this part of the ocean because of the downward Ekman pumping. Imagine water parcels flowing southward in the mixed layer (and no heating or cooling). A water parcel, when it encounters lighter water to the south will tend to follow its own isopycnal down out of the mixed layer. The point at which it passes below the local annual maximum depth of the mixed layer, it is said to **subduct**. After this point, its temperature, salinity, potential density, potential vorticity and other characteristics are conserved (or modified only slowly, by diffusion). When the parcel reaches the western boundary current and flows north, the isopycnal once again rises towards the surface and the parcel re-enters the mixed layer. This whole cycle takes on order of a decade for the water parcels in the main thermocline.

Two different physical processes involved in subduction:

(1) **Vertical pumping**. Ekman pumping modified for the change in vertical velocity between the base of the Ekman layer and the base of the mixed layer.
(2) **Lateral induction**. Horizontal advection across the base of the mixed layer by lateral geostrophic flow.

One consequence of this process by which water parcels flow through the main thermocline is found on a TS diagram.

In a schematic TS diagram for the Atlantic Ocean in the upper ocean, passing through the thermocline, there is a nearly linear relationship for temperature and salinity from warm saline values at the lightest densities to colder fresher values at higher densities. Similar structure is found in all the oceans, and it has historically been referred to sometimes as Central Water. What causes this structure? Originally thought due to vertical mixing between surface water and intermediate water which is the name given to water at minumum salinity that is found just below the thermocline. But mixing it turns out is far too inefficient. It is, instead, primarily due to this flow along isopycnals, subduction.

In the North Atlantic, if you were to inventory the volume of water at a particular point along the central water TS line, you would find that there is more water at 18°C than any other value. This water mass is called Subtropical Mode Water. It is formed in the western North Atlantic south of the Gulf Stream where heat loss to the atmosphere during the winter creates very deep thick mixed layers. These thick layers are then subducted into the ocean interior to form largely homogeneous water masses. Because of their large volume, it is thought that mode waters may be important in climate through preserving the thermal memory of conditions in a given winter that may re-emerge into the mixed layer to interact with the atmosphere one to several years later. You can see the spreading of the isotherms and isopycnals in the density sections in the figures.

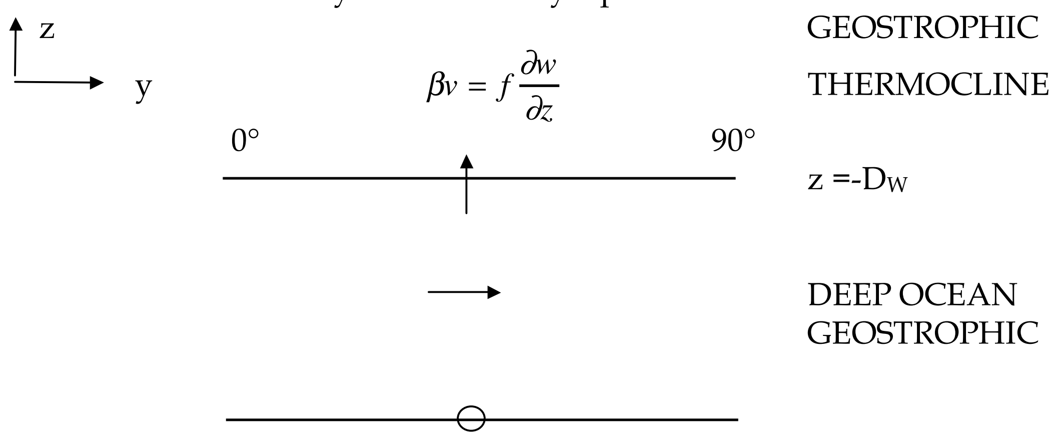
The next thing in the water column are intermediate waters, including Labrador Sea Water, Antarctic Intermediate Water, North Pacific Intermediate Water, Mediterranean Water and Red Sea Water.

Below that are the deep waters, North Atlantic Deep Water (formed by open ocean convection) and Antarctic Bottom water (formed by brine rejection under ice shelves). Both of these can be seen in the T/S diagram.
Basic driving force of thermohaline circulation is the pressure gradients that result from horizontal density contrasts.

What drives the circulation in the abyss? It is primarily associated with deep water formation at high latitudes. However, circulation driven by lateral density contrasts can be found at all depths, although they may be overwhelmed by wind-driven circulation near the sea-surface

.
Again will be constrained by linear vorticity equation.

$$\beta v = f\frac{\partial w}{\partial z}$$



What is w? Not as simple and robust as theory for Ekman layer.

Stommel and Arons noticed that deep water is formed in only a few points around the world, mostly in high latitude marginal seas where water sinks to the bottom. In order to conserve volume, there must be upwelling somewhere in the world of comparable magnitude. In the absence of knowing where the upwelling occured, they proposed the simplest model - that the upwelling from the deep to the shallow layer is uniform everywhere in the world.

The net amount of water sinking is about 30 Sv. If you want to know the average upwelling rate assuming that it is the same everywhere in the world

$$w(-D_W) = \frac{\text{total DW formation rate}}{\text{area}} = \frac{30\times 10^{6}\, m^{3}/s}{3\times 10^{14}\, m^{2}} = 10^{-7}\ \text{m/s} > 0$$

Simplest assumption they could make in the absence of any measurements.
SINCE W > 0, ALL FLOW IS POLEWARD! in opposite sense to what we expect.

Overhead: Stommel-Arons transport for world ocean. GC6

What is wrong with this model?

(1) Single homogeneous deep layer:

(2) Assumption that upwelling is uniformly distributed horizontally.

As you learned last quarter, the vertical heat balance has often been modeled by:

$$w\frac{\partial T}{\partial z} = K_V \frac{\partial^2 T}{\partial z^2}$$

So, the rate of upwelling, under this model, is related to the strength of vertical mixing processes…it is the slow downward diffusion of heat from the surface that gradually warms the deep water and allows it to move upward.

If you fit a model like this one to observed profiles in the open ocean, you get numbers like

$K_v = 10^{-4}$ m^2/s
w = 10^{-7} m/s

which was very encouraging.

However, in the past decade, scientists have been measuring the rate of mixing in the deep ocean explicitly. They measure microstructure – the velocity and temperature fluctuations on the scale of mm to cm, which reflects the intensity of turbulence on small scales, and thus this mixing coefficient.

They find that a value more like $K_v = 10^{-5}$ m2/s is supported by the data.

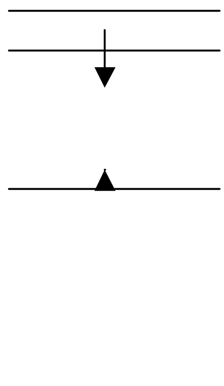
Overhead: Polzin et al., Brazil Basin

However, there are certain places: over rough topography, like the flank of the mid-Atlantic ridge, or where the abyssal flow is being forced through a narrow canyon, like the one here that the South Pacific DWBC must pass through to reach the North Pacific: where Kv can be orders of magnitude higher. It looks like all the return flow happens in these particular places, and that the rest of the "background" deep ocean flow is along isopycnals.

We don't know know the global pattern of mixing, and thus the structure of upwelling that forces the deep ocean.

Strong mixing also has implications for upper level circulation. Assumption that vertical velocity goes to zero below the wind driven circulation may be violated.

Ekman



$W > 10^{-6}$ m/s

WD geo

SA w ~ 10^{-7} m/s, real w?

Abyssal geo

Meridional Overturning Circulation

We can define a stream function that represents the vertical circulation such that

$$V = -\frac{\partial \psi}{\partial z}$$
$$W = \frac{\partial \psi}{\partial y}$$

Here the units of ψ are m^3/s, and V and W have units of m^2/s and represent the zonally integrated vertical and meridional transport. This overturning circulation acts on the background temperature gradients to result in a net heat transport. The net heat transport will be given by

$$Heat\_transport = \rho c_p \int_{west}^{east} dx \int_{bottom}^{top} vTdz$$

So we have to know the distribution of both velocity and temperature as a function x,y and z to determine the net heat transport. We also want to have

$$Net\_Volume\_transport = \int_{west}^{east} dx \int_{bottom}^{top} vdz = 0$$

The heat transport can come about because of the net meridional overturning ciruculation which in the Pacific is dominated by shallow overturning near the equator and symmetric about the equator, and in the Atlantic by deep overturning that crosses the equator. It can also come about because of horizontal circulation.