Below is my poster, in letter sized pages, titled "Is Ocean Heat Storage Presently Knowable." This will appear at the December meeting of the AGU in San Francisco.

This is my (amateur) attempt to understand the general structure of the oceans as it relates to climate with particular emphasis on ocean heat storage and the potential effect of the overturning circulation on climate.

Ocean heat storage is often claimed to be the reason why the climate is not warming faster - the ocean is supposedly absorbing a large flux of energy that would otherwise warm the climate. However since the ARGO system was deployed ocean warming in the upper 700 meters has not been seen, so if there is a large flux of energy going into the ocean it must be hidden in some fashion.

If the overturning circulation remains in a steady state (on an annual basis) it has neither a cooling or warming effect. Heat can enter the mixed layer very quickly, but to get to the next 100 meters would take a few years and the 100 meters beyond that a decade. Thus it seems that if one looks below about 200 or 300 meters for missing heat, this is heat that went missing decades ago.

If the overturning circulation varies quickly it will exercise either a warming or cooling effect. The reason is the different time constants for the sinking and rising ends of the circulation. The sinking side has a short time constant (about 1 year or less) because cold water that doesn't sink will come back on the gyre, at least in the North Atlantic, and cool the upper ocean. If more water sinks, less cold water comes back on the gyre and the ocean is warmer. However the rising side of the circulation is a slow elevator rising at 4 meters per year. The elevator will quickly respond but the heat flowing downward won't change quickly until the thermocline readjusts it shape to support a lower heat flow. I suspect this will take a long time, multiple years, but it might be hard to compute the time without making some sort of model. Of course this is all greatly oversimplified compared to the reality of the ocean, but may still be a reasonable representation.

It does seem to be to be mistaken to simply take the heat content of the upper N meters of the ocean and plug it into a solution for energy balance. It seems that only the upper 200 meters responds quickly. It also seems that variations of the overturning circulation could mask any change in ocean heat due to radiative imbalances. A 25% change in the overturning circulation could be equal to 1 watt per square meter and we don't have a good way to monitor the overturning circulation. It would seem to be very useful if someone could invent a gauge that could measure the 1 centimeter per day uplift in the ocean.

I welcome any suggestions or corrections.

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Is Ocean Heat Storage Presently Knowable?

Norman Rogers AGU Fall Meeting 2012 **A23A-0182. Atmospheric Sciences General Contributions: Atmospheric Dynamics, Radiation, and Cloud Properties Posters**

When global warming is not progressing as expected, as is now the case, it is usually explained that the ocean is absorbing the forcing flux, sometimes helped by atmospheric aerosols. (Hansen 2005, Hansen 2011) When the ARGO system was deployed and it was discovered that the upper 700 meters of the ocean was not warming as expected, it was suggested that the heat must be hiding in the deeper ocean. However it is difficult to explain how the heat moves to the deeper ocean from the atmosphere without warming the upper ocean on the way.

A point of controversy is the time constant(s) associated with absorption of heat by the ocean. If the time is long, many decades, then the ocean will absorb heat over a long period and when it comes into equilibrium in, say, 50 years, the Earth's temperature will rise as the greenhouse flux stops going into the ocean and goes into the atmosphere. This scary possibility is referred to as "warming in the pipeline."

Heat enters the ocean from the surface and is diffused downward. Heat, or perhaps we should say cold, enters the ocean via the sinking side of the overturning circulation. Since the ocean is very complicated, all the conclusions given here are tentative. The oceans' surface and mixed layer is affected by radiation, evaporation and air temperature. The mixed layer, commonly taken as being 100 meters thick, quickly comes into equilibrium. Below that, except near the poles, heat transfer is much slower, taking around 100 years to penetrate 500 meters below the mixed layer. This slow movement of heat is confirmed by the distribution of tracers such as chlorofluorocarbons that have only been present in the atmosphere for about 60 years. The downward diffusion of such tracers happens by the same process of eddies that moves heat downward.

If the overturning circulation is in a steady state, then sinking and upwelling balance and there is no net change in the ocean due to the circulation. However, there is absolutely no reason to suppose that the circulation is ever in a steady state. It maybe perpetually wandering or oscillating. Certainly the multi-decadal oscillations of ocean temperature in the Atlantic and Pacific are suspicious in this regard.

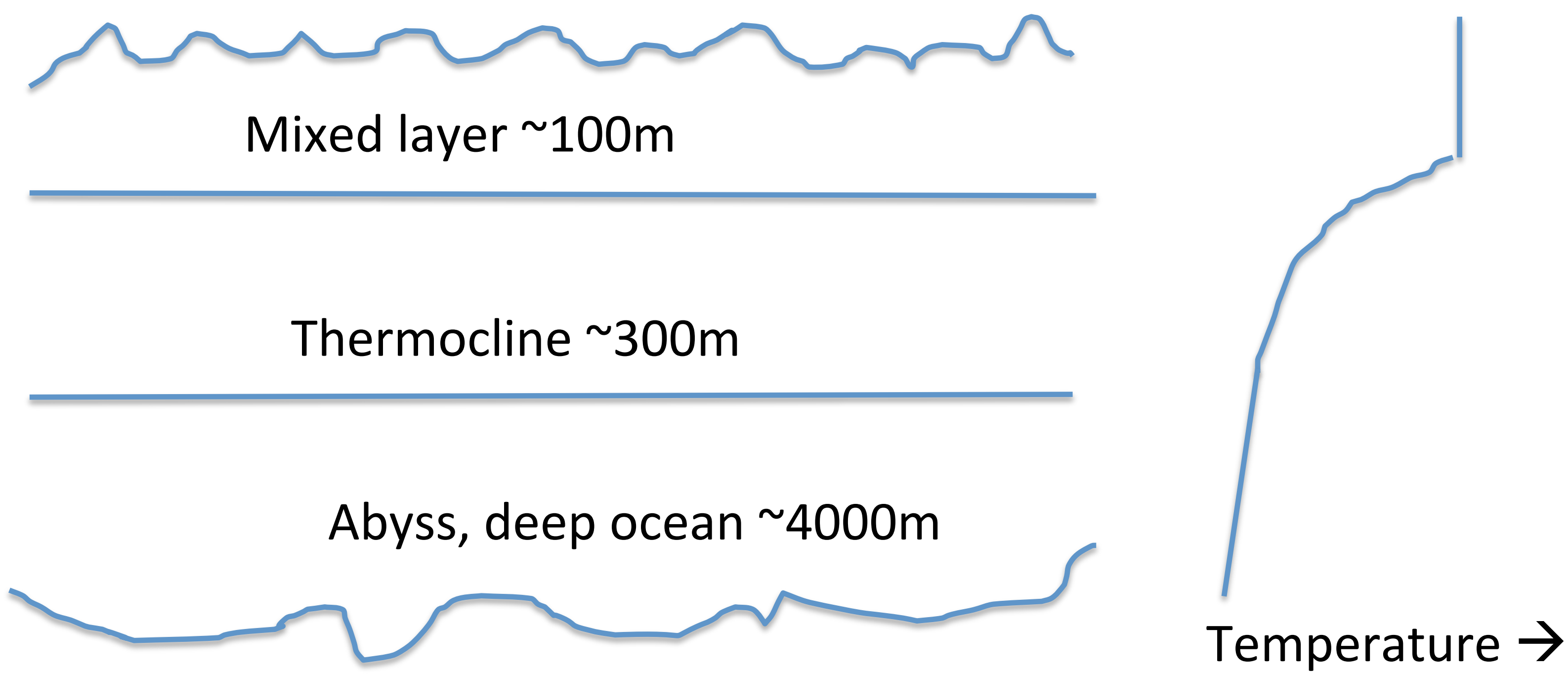
The sinking and upwelling side of the overturning circulation have different time constants, so it is easy to imagine a watt per square meter of forcing from variations in the overturning circulation. This is enough to make estimates of energy flux from the greenhouse effect a joke.

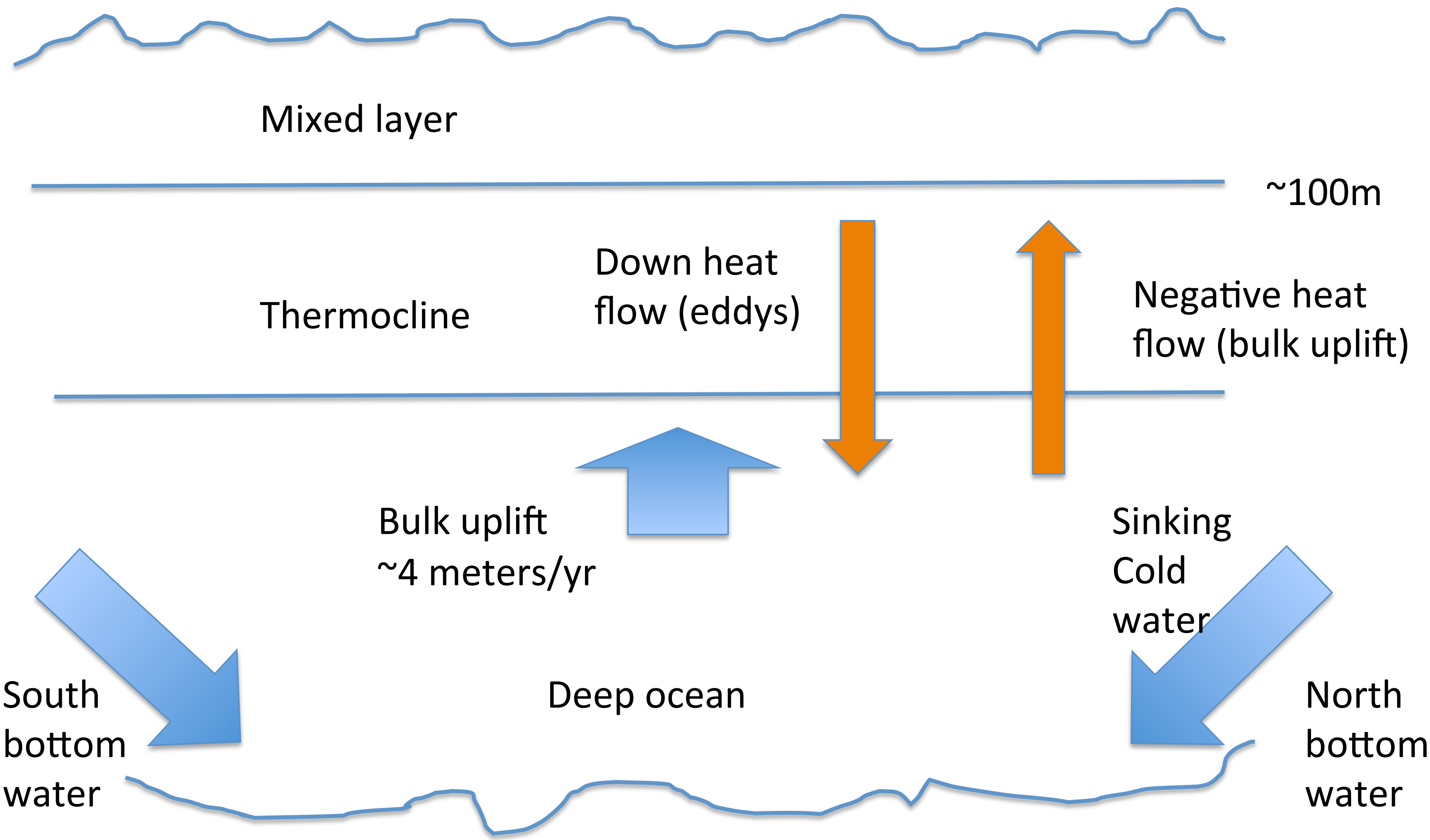
Excepting the overturning circulation, heat enters the ocean from the top and takes a very long time to go below 4 or 5 hundred meters. The great majority of the heat will be in the mixed layer with a smaller contribution by the next 100 meters. This indicates a short time constant of a few years and there are many investigators who have advocated this. (Schwartz 2007) (Douglass 2005)

Munk in his paper *Abyssal Recipes* (Munk 1966) painted a picture of how heat moves in the ocean and what controls the shape of the thermocline. Normal molecular diffusion (the coefficients of heat conductivity for water in tables) is much too weak to account for the heat flow actually observed in the ocean. It is thought that ocean heat flow is maintained by turbulent stirring effected by wind and waves but also where currents interact with disturbances such as coasts or undersea mountains. Heat can be transferred horizontally much more rapidly than vertically – where it doesn't fight against the density gradient - so the temperature homogenizes horizontally, making it seem that heat moves downward more uniformly than it really does. So as an approximation it is commonly assumed that heat moves down uniformly. Heat must move down to the bottom of the ocean or the overturning circulation could not be maintained – the ocean would simply fill up with bottom water and the circulation would stop.

A mixed layer at the surface of the ocean, around 100 meters thick, but highly variable, is well stirred by the wind, and energy is deposited by sunlight penetrating into the layer. The mixed layer has a near uniform temperature and quickly responds to changes in atmospheric temperature such as seasonal change.

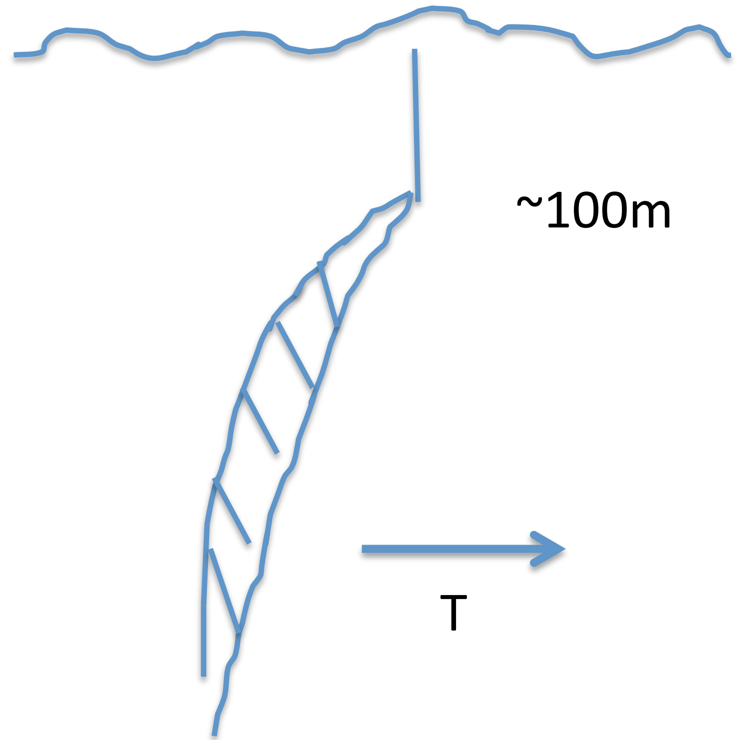
Between bottom of the mixed layer and the cold abyss, is the thermocline, a transitional region where temperature drops rapidly with depth. The shape of the thermocline is defined by two countervailing effects that are in balance throughout a stable thermocline. The first effect is downward flow of heat from the bottom of the mixed layer and the second effect is an upward flow of cold water, driven by the overturning circulation, at about 1 centimeter per day or 4 meters per year. This results in a stable thermocline where the temperature at any depth does not change with time (as long as the countervailing effects remain the same). The shape of the curve is theoretically exponential with an initial slope proportional to the downward flow of heat.





For a steady state net heat flow at any level is zero – downward flow of heat from warm to cold is balanced by bulk uplift of cold water.

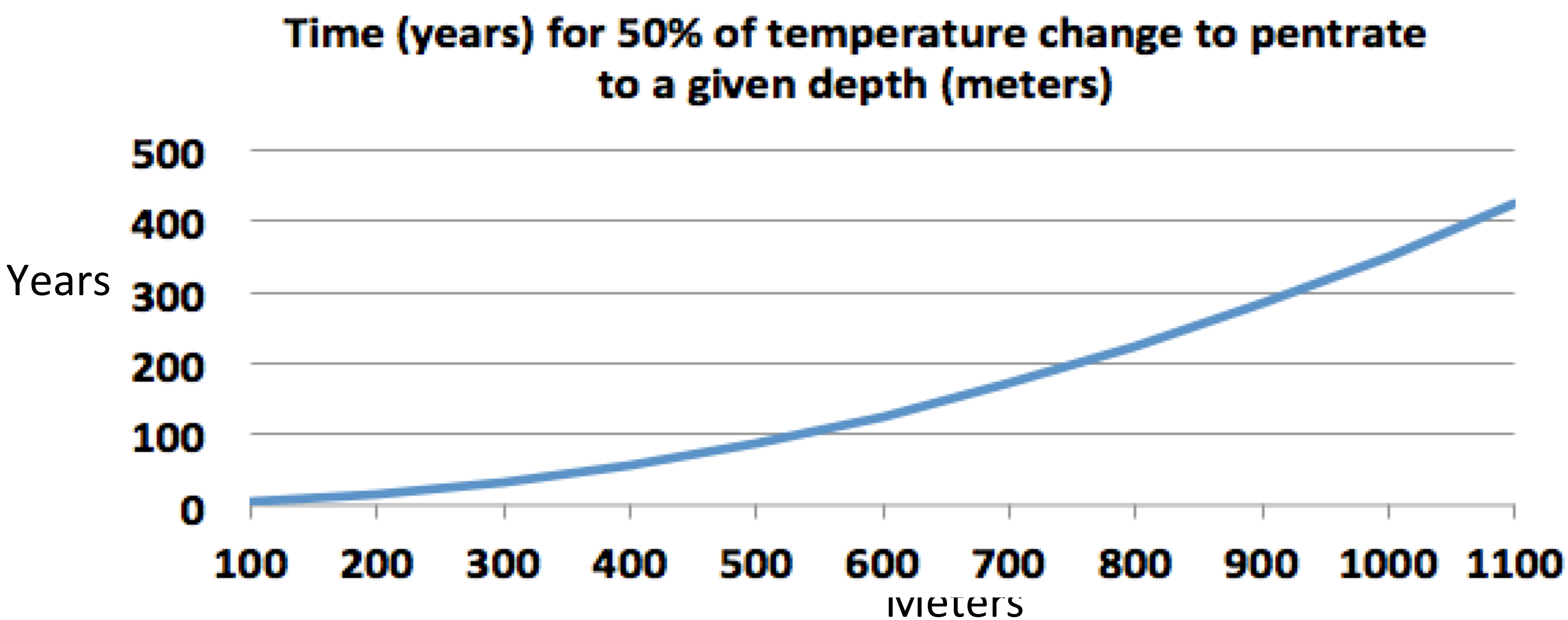
If the overturning circulation changes the temperature of the mixed layer changes and the rate of upwelling changes. This results in a new equilibrium shape for the thermocline. The time required to reach near the new equilibrium state depends on how long it takes to warm or cool the area between the two exponential shaped curves.



How long does it take for heat to penetrate down in the ocean? The analytical Solution for step function input to the 1-dimensional heat equation gives a rough answer.

Fraction of ultimate temp= $\mathrm{erfc}\left(\frac{x}{2\sqrt{\alpha t}}\right)$

Where erfc is the complementary error function, x is the depth in meters, t is the time in seconds, and α is 1e-4 as suggested by (Munk 1966). (Hancock 2006)

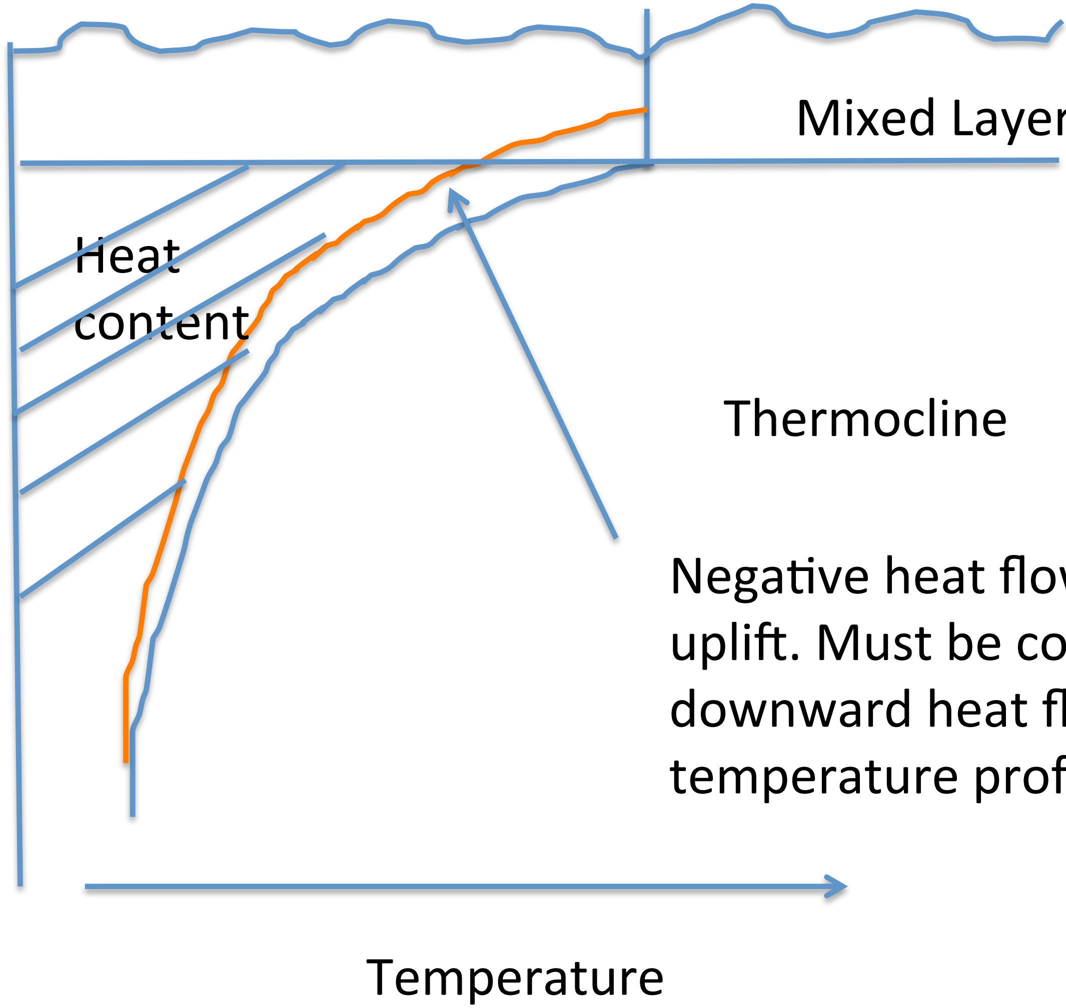


depth	years
100	3.5
200	14
300	31.5
400	56
500	87.5
600	126
700	171.5
800	224
900	283.5
1000	350
1100	423.5

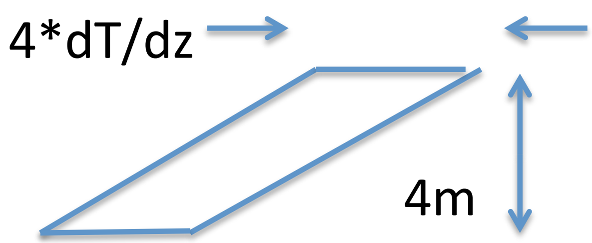
The above graph exaggerates the rate of heat penetration into the ocean because the general ocean uplift slows down the downward diffusion of heat. The depictions of the ocean shown above are idealized. At times and places the mixed layer may almost disappear or conversely become several hundred meters deep. In polar regions the stratification of the ocean often disappears entirely with uniform temperature reaching to the bottom.

Tracers are ocean contaminants that can be detected in very low concentrations. For example chlorofluorocarbons or CFC's began to be produced in the 20th century for use as refrigerants. They entered the atmosphere and then the ocean. As the CFC's dissolved in the surface of the ocean they were diffused downward, in the same fashion as heat. The equations governing the diffusion of CFC's are identical to those governing the diffusion of heat. However, rather than making the stratification of the ocean clear, tracer measurements show that the situation is quite complicated and varied.

Heat flow effect of the uplift of cold abyssal waters.

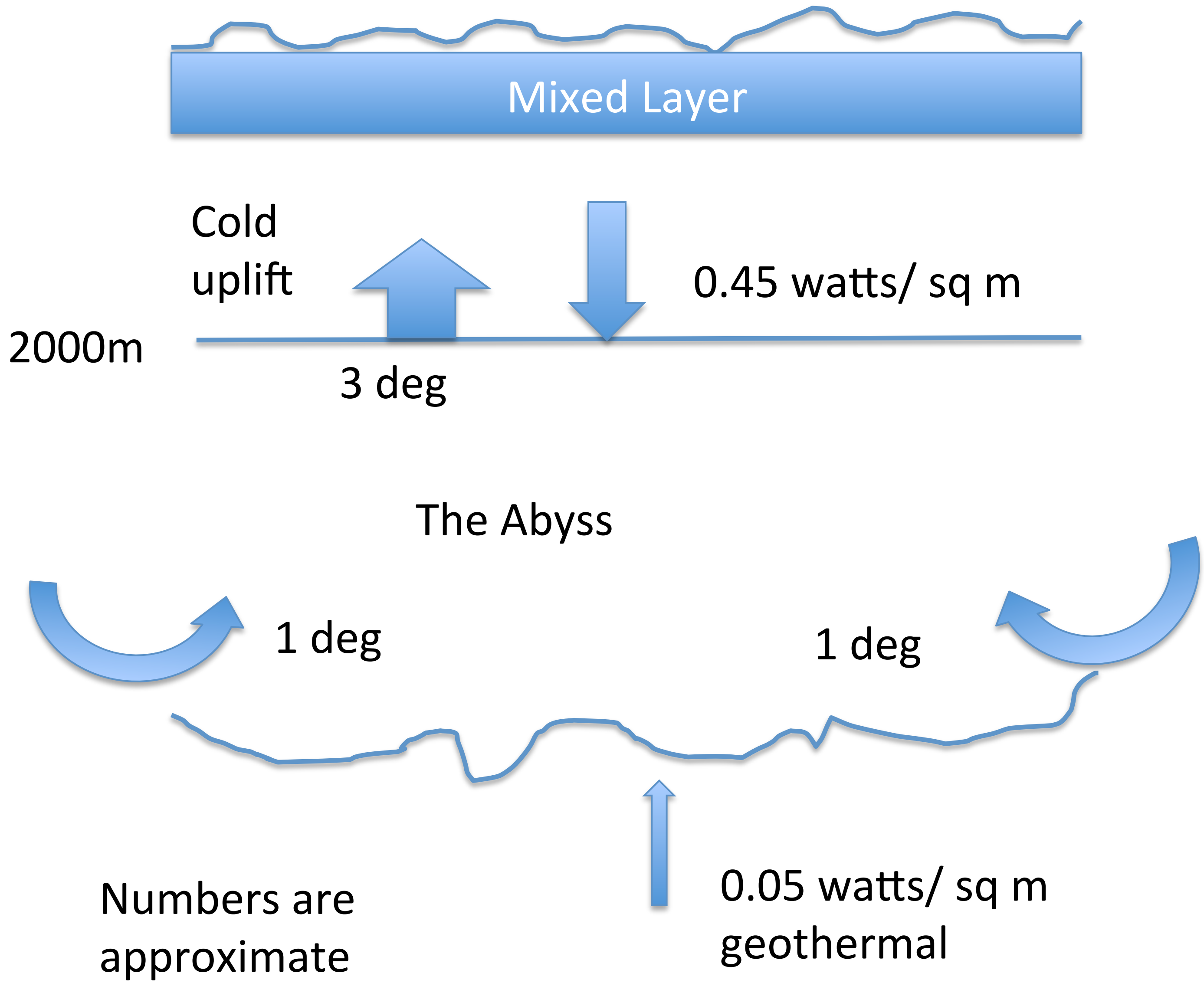


Negative heat flow due to bulk uplift. Must be countered by downward heat flow for stable temperature profile.



Heat added per year per cubic meter
if uplift was working alone 4.18e6*dT/dz
joules. dT/dz ~ 0.1 tropical thermocline.
Differential flux in watts for a cubic meter:
~ .013 watts/sq m stays in cubic meter volume

Heat entering abyss can be computed as 30 sv (10^6 m^3/sec) with 2 degree temp change. This is consistent with Munk's estimate of 1e-4 as the coefficient of thermal diffusivity and 0.45 watts flow of heat over 2 degrees and 2000m.



Numbers are approximate

The above illustration shows the energy balance in the abyss, here taken as the ocean below 2000m. Approximately 30 sv of cold water enters the abyss as bottom water and slowly rises at about 4 meters per year. By the time the water reaches 2000m it is warmed by about 2 degrees. The warming is from heat diffused downward at approximately .45 watts per square meter of the ocean surface at 2000m. This result of 0.45 watts per square meter can be computed by two independent means. The first method is simply the energy content change from 30 sv or water in at ~1. degrees vs 30 sv out at ~3 degrees. The alternative method is to use Munk's estimate of the coefficient of thermal diffusivity of 1e-4 and the temperature difference of 2 degrees and the average depth of the abyss of 2000 meters. The two methods agree approximately.

The energy flows in and out of the abyss are the sinking and rising side of the overturning circulation, which are always equal except for the 0.45 watts of downward heat flow (and the small geothermal contribution). If the overturning circulation were suddenly to stop, the abyss would warm very slowly by about 0.2 degrees per century.

What happens if overturning circulation stops?

The sinking side of the overturning circulation dumps water into the abyss at an average rate of 30 sv. This warms the Earth, because water is removed from the surface system that is 15 degrees colder than the average temperature of the Earth. The warming effect is approximately 4 watts per square meter over the surface of the Earth. In concrete terms, in the Atlantic, cold water that would return on the gyre is instead being sent to the abyss, where it is as out of communication as if it were sent to outer space.

The warming effect is countered by a cooling effect from rising cold water. However the cooling effect would not quickly change just because the sinking side stopped. If cold water uplift stopped from the abyss the thermocline would start to deepen. However this would happen slowly due to the slow downward transfer of heat below the mixed layer.

The time required for the thermocline to respond is obviously longer since the mixed layer cooling is a required precursor.

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