The interesting pattern of surface currents of the ocean that we've seen in that video are largely driven by surface winds of the atmosphere, as we'll demonstrate later on in this section. Somewhat more mysterious is the circulation of the deep ocean. Not as much is known about that because of the difficulty of measuring things at depth in the ocean. But let's begin by looking at this cross-section, from north to south, in the Atlantic Ocean showing the distribution of temperature. So this chart extends from a latitude of about 55 degrees south in the southern ocean northward to the high Arctic. And goes from the surface to a depth of about 6 kilometers, here. And the quantity contoured is the temperature of the water, in degrees Celsius.

Now temperature in the ocean is roughly conserved except near the surface. That this, once water is submerged, it tends to retain its temperature over time. What we see when we look at this chart is a strong vertical temperature gradient in the ocean except, perhaps, in the southern ocean and the high Arctic. Most of that temperature gradient is concentrated very close to the surface. So for example, here near the equator, we see that the temperature goes from nearly four degrees C at a depth of about a kilometer all the way up into the upper 20s at the surface. Whereas deeper in the ocean, the temperature gradients tend to be weaker.

Now this pattern of temperature also reflects what we believe to be a pattern of deep circulation of the ocean, with very cold water sinking in the southern ocean and flowing equatorward along the ocean bottom. We have another pool of cold water forming near the surfaces of the high latitude North Atlantic, sinking down. This Is called North Atlantic Deep Water, again traveling equatorward, perhaps even into the southern hemisphere. And we may have another pattern of circulation of water sinking in high mid-latitudes in the northern hemisphere, traveling southward, upwelling in the high extratropics of the southern hemisphere and then returning near the surface.

To understand this deep circulation of the ocean, which is also important in transporting heat poleward, we have to recognize that there are various different mechanisms by which these water masses can be set into motion. The deep overturning is sometimes idealized by this conveyor belt, where we have water sinking in the high latitude North Atlantic, traveling near the bottom into the south Atlantic, and then eastward to the southern ocean, upwelling in the Indian and Pacific Oceans and returning along the surface to the North Atlantic. This is almost certainly an oversimplification of this deep conveyor belt circulation, or the so-called meridional overturning circulation. But it is important in transporting heat poleward in the oceans.

As we saw before, the oceans are important for energy transport in the climate system. So once again, this is a chart running from the South Pole at the bottom to the North Pole at the top, showing the heat transport northward in units of 10 to the 15th watts, or petawatts. The black curve shows the total northward transport, the red curve the northward transport by the atmosphere, and the blue curve the northward transport by the oceans. So particularly near the equator, but not at the equator, the oceans are very important in heat transport but remarkably even in middle latitudes, carry about the same order of magnitude of heat as the atmosphere. To understand the climate system, it's important to understand the mechanism by which the ocean transports heat. That will allow us to say something about how that heat transport might respond to climate change.

So what drives the circulation of the ocean? This is a gross simplification, but we get some idea with these diagrams. The turn at the top shows a north-south cross section. You might think of this as the north and south Atlantic Oceans, spanning from the South Pole at the left to the North Pole at the right. And the thin black contours, like this one here, are meant to represent isotherms. So one way that we can get the ocean to move is to drive it with the wind. We'll talk about that later in this section. The particular distribution of winds around the world favor upwelling of water in the southern hemisphere and downwelling in the northern hemisphere, with the return flow concentrated in the very upper part of the ocean, here.

This kind of circulation below the surface is adiabatic. This adiabatic motion is more or less along isotherms, whereas in the upper part of the ocean, as water moves equatorward, it's warmed by contact with the surface and by radiation and so forth. And as it moves from low latitudes to high latitudes, it's cooled. So water can flow across isotherms this way. This kind of circulation, because you have relatively warm water traveling northward, relatively cold water traveling southward, does transport heat toward the north, in this case.

We can talk about another sort of circulation in which vertical mixing is key. In which water may sink adiabatically, but to get back to the surface it has to cross these isotherms. That is, there has to be a heat source for the upwelling water, and the only way really to get heat down into the ocean is through vertical mixing. To this day, it's not particularly well understood how much of the net heat transport by the ocean is related directly to wind, as in the top diagram versus vertical mixing, as in the lower diagram .

We can think about the mixing-driven circulation by this simple thought experiment involving not the real ocean, but a swimming pool. It's not rotating, it's very simple. And this swimming pool has thermally-insulating boundaries, that is the bottom boundary and the side boundaries here are assumed to be thermally-insulating, no heat travels through them. Whereas at the top of the fluid, we're going to put a plate right along the top. We're going to keep one half of the plate at high temperature, on the left. So this is the warm side. And the other half of the plate at cold temperature. This is the cold side. And we're going to ask, what does the water in the swimming pool do?

Well, it turns out that if you wait long enough, you get a somewhat steady overturning circulation. And that almost all of this thermally-insulated swimming pool has the temperature of the cold part of the plate. It's mostly filled with cold water, bad news for swimmers. But on the warm side, heat diffuses down into the water and warms the water, but as soon as that water becomes warm it's buoyant, it wants to rise back up. So this part of the fluid is rising, and it reaches a steady state when the upward advection of cold water here is balanced by the downward diffusion of heat. So this kind of circulation is powerfully limited by the diffusivity on this side. If you take away the diffusivity, you don't have any kind of circulation. Now the actual molecular diffusivity of ocean water is very, very small. And such a circulation, if it were really driven by molecular diffusion, would be too weak to be detected.

But now let's add another ingredient of this system. We're going to keep the system exactly the same, but we're going to put an egg beater into the warm side of the swimming pool that constantly, turbulently, mixes water up and down in this region, OK? That's going to make this circulation much more efficient. It's going to drive heat down into the deep ocean much more rapidly. That water, of course, is buoyant. It wants to rise. And so you're going to have a circulation here which acts as a heat engine. That is, relatively buoyant fluid rising, fluid with negative buoyancy, low temperature sinking.

But if you turn off these beaters, the circulation collapses. And one can show that the strength of this kind of circulation is proportional both to the imposed temperature gradient at the surface and the power that one puts into these beaters. So you can drive a deep circulation by turbulent mixing in the ocean. The next question is what actually causes that turbulent mixing, and that's a subject that is still debated today. It's not really known how much of the ocean circulation is driven in this manner, versus directly by the winds.

The real ocean, of course, is much more complicated than the swimming pool. For one thing, it exists on a rotating planet and that complicates the response to vertical mixing. But if we go back to this diagram of a north-south cross section through the Atlantic Ocean showing the temperature, we have some of the same issues to deal with. That is, if we place a source of turbulent mixing somewhere where there's a strong vertical temperature gradient such as here, or here, or anywhere else where there exists such gradient, that will drive an overturning circulation that transports heat.

And an interesting issue in physical oceanography is if such circulations exist in any appreciable magnitude, what actually causes the mixing? Mixing might be caused by breaking internal waves that might be caused by tidal flows over the topography of the bottom of the ocean. Might be caused by stirring by winds in the atmosphere, so storms, for example, can stir up the upper ocean. It's even been proposed that some of the mixing that might be important is driven by fish. So we have some interesting issues in the physics of ocean circulations driven by mixing.