The ocean also moves. And if one looks at elementary science textbooks, one often sees depictions like this, which show the ocean as consisting of a few relatively simple gyres, this large clockwise gyre in the North Atlantic and a counterclockwise gyre in the South Atlantic. Similar gyres exist in the North and South Pacific and Indian Oceans.

These circulations are primarily driven by the wind. But depictions like this are in some ways misleading, because the actual circulation of the ocean looks a bit more like this. These white contours show streamlines of the surface circulation of the ocean in a very detailed numerical simulation. Later in the course we'll put this into animation and see how these vary in time.

But like the atmosphere, the circulation of the ocean is dominated by eddies. These eddies tend to be smaller in scale than their atmospheric counterparts, measuring a few hundred kilometers, typically. There are also strong features, like this gulf stream with its eddies, which moves water from the Gulf of Mexico out into the North Atlantic.

These circulations are very important, as are the atmospheric circulations in transporting heat poleward. Later in the course we'll talk in more detail about how such circulations arise.

How do atmospheric and oceanic circulations actually affect climate? Let's begin by talking about the effects of atmospheric circulation. The circulation in the atmosphere is important in transporting energy, both poleward and vertically. So in the real world, not only do we have transfer of energy by radiation and small-scale atmospheric motions in the form of convection, but we also have transport by larger scale motions.

These circulations also transport water vapor and thereby control the distribution of one of the most important greenhouse gases in the atmosphere, as well as of clouds. Not only that, but the circulations mix important trace gases, including greenhouse gases, laterally and vertically. And they transport aerosols, like dust and sea salt. The vertical component of the circulation also leads to large-scale condensation and evaporation of water in the atmosphere.

How does this affect global energy balance? Well, let's look at this quantitatively. If we look at the long-term average of the atmospheric energy balance, we can express that by the equation that you see at the top of this page. The divergence of a vector flux of energy is equal to 0. This simply says that every chunk of the atmosphere over the long run is in energy balance.

Now, what are the components of this vector? Well two we've talked about extensively so far in this course, the radiative flux and the convective flux, both of which act in the vertical. So k hat here is the unit vector in the vertical. But now we're going to consider another kind of flux that's caused by the motions of the atmosphere here. And it can be expressed as the density of the air , rho, times the vector velocity times the specific energy content E of the air.

So E is defined here. It's the heat capacity at constant pressure of air times temperature, plus gravity times altitude-- this is the potential energy component here-- plus the latent heat of vaporization times the concentration of water vapor, plus the kinetic energy per unit mass of the air, 1/2 times the absolute value of V squared. Now, it turns out that for our atmosphere, if we look at fluctuations of these individual components of what we call the specific energy, fluctuations of the kinetic energy are really small compared to the others. So in practice, we can usually neglect this last term in this equation.

Now, what happens if we take this equation and integrate it from the surface of the Earth to the top of the atmosphere? Well, then we get the equation that you see at the bottom of this page. We have now the two- dimensional or horizontal divergence of the vertically averaged flux of energy by motions in the atmosphere. The overbar in this case indicates a vertical average.

Now, when we take the divergence of the radiative and convective fluxes and integrate them vertically, what we get is the difference between the total radiative flux at the top of the atmosphere-- of course, there's no convective flux at the top the atmosphere-- and the radiative and convective fluxes at the surface. So what this equation tells us is the net convergence of flux by radiation and convection in the atmosphere must be balanced by a divergence of the energy flux by the movement of the atmosphere.

Now, if the surface itself is an energy balance-- that is, there's no net flow of energy into the Earth's surface, which is approximately true over land-- then the last two terms in this equation cancel. There's no net flux at the surface. And the resulting equation tells us that the net radiative flux at the top of the atmosphere must be in the long run balanced by divergence of energy flux by motions in the atmosphere.

Let's have a look at what those fluxes really look like in the real world. So what we see on this diagram is the heat transport by the ocean, by the atmosphere, and by their sum as a function of latitude and averaged over time. So we're going from the South Pole at the bottom of this diagram to the North Pole. Heat transport is defined here as being positive toward the north. And the units here are in petawatts, or 10 to the 15th watts. That's a lot of energy.

The black curve is the total. And in this case, it's been derived from careful observations of the net radiative flux as a function of latitude. If we look at that net radiative flux and we integrate it in latitude, starting from either pole and going toward the other pole, that tells us what the net divergence of the total energy flux by the atmosphere and the ocean has to be. The red curves and the blue curves on this diagram show the individual components, the atmosphere and the ocean.

Let's have a look at what this picture is really telling us. So naturally, by symmetry, the flux has to be zero at the poles. In both hemispheres there's a strong energy flux away from the equator and toward the poles, most of which, but not all of which, is carried by the atmosphere, given by the red curve. When we go down into the tropics, to the deep tropics, the ocean fluxes in particular are just as important as the atmosphere fluxes.

As we go into mid-latitudes, the ocean fluxes become less important than the atmosphere fluxes. But considering that these two media are very, very different-- they have densities that differ by a factor of 1,000. They move in completely different ways-- it's quite remarkable that fluxes by these two media are of the same order of magnitude.

This has a profound effect on climate. In fact, these poleward fluxes by the atmosphere and by the oceans drive the time mean temperature gradient to be roughly half of what it would be if we really were, at each latitude, in radiative-convective equilibrium.