Let's now recap some of the major issues and challenges facing physical oceanography's application to climate science. Some of the outstanding issues are, first of all, what are the relative roles of ocean circulation induced by vertical mixing versus by large-scale wind stress, in transporting heat, salt, and tracers such as carbon dioxide? How do these various circulations interact? What is the energy source for vertical mixing in the ocean? How important are the transient eddies that we saw so beautifully in the NASA film, in ocean dynamics and in transport by the ocean? And finally, how does climate change affect ocean heat transport and other properties of the ocean?

Well, we have some interesting measurements in that regard. Here's a chart showing, from 1960 to about 2013, of the heat content of the roughly upper half of the ocean. That is, from the surface to two kilometers depth. And it shows, in blue, a pentadal average through the years 2008 to 2012. In black, a yearly average to 2012. And then looking at higher frequency motions based mostly on Argo data, and the red, three month averages from April through June of 2013.

All this data has been based on bathythermographs which are generally deployed from ships, and after 2004 from the Argo robotic measurements. What one sees is that beginning in 1970, there has been a fairly steady increase in the heat content of the oceans, continuing right through the present. Now, it's important to recognize that this is the bulk of the change of the heat content of planet Earth. And that's illustrated by this next slide, which shows here in light blue, the ocean heat content from the surface to 700 meters depth. In darker blue, the ocean heat content from 700 to 2000 meters. And red is basically the heat content of every other aspect of the planet, whose heat content may change appreciably. That's basically the land surface, ice, and the atmosphere. So it's easy to see, looking at this chart, that much of what we call global warming is actually warming of the oceans.

The oceans are not only an important sink for heat on the planet, but they're also an important sink for trace gases such as carbon dioxide. This chart, extending from about the year 1775 to just about the present, shows the various sinks and sources of carbon in the system. The black line, with confidence intervals given by the black dashed lines, show the source to the system from fossil fuel combustion and cement production. Also from changes in land use. The sinks are the atmosphere, ocean, and land components, indicated respectively by red, blue, and green.

So going forward from 1775, one can see that both the atmosphere and the ocean have been taking up carbon dioxide in very roughly equal measure. About half of the carbon is going into the oceans, the other half into the atmosphere. But there is some uncertainty, particularly in the amount going into the land system, given by the green curve. That is again, roughly speaking, comparable to the other components. So the terrestrial biosphere, which is really what we mean by the land, the oceans, and the atmosphere, are in round numbers equal sinks for anthropogenically produced carbon.

Because the oceans are absorbing so much carbon dioxide in dissolved form, that lowers the pH of ocean water, that is it increases its acidity. This map shows the estimated change in the annual mean surface pH of the ocean between the pre-industrial period of the 1700s and roughly the present day. One can see that the carbon uptake is not globally uniform, but is concentrated principally in the Atlantic and southern oceans.

The increase of ocean acidity is thought to be part of the reasons for the observed degradation of certain marine biota, including corals. So the photograph on the left shows a healthy coral reef system, the one on the right a less healthy system, degraded coral, dead coral, poor water visibility. Some of this degradation might be because of the increase in ocean acidity as a direct result of the lower pH due to increased dissolved carbon dioxide content.

The ocean is a major player in the global carbon cycle, as this diagram shows. Changes in atmospheric carbon dioxide content result in changes in dissolved carbon dioxide content of the ocean. Some of the carbon is used up organically in the shells of marine organisms. Some of that settles to the bottom of the ocean when those organisms die. And some of that is, in turn, buried in ocean sediments. Over geological time scales, plate tectonics results in the burying of that carbon, and finally it's re-emisson in volcanoes. But there's also an inorganic part of the cycle. One can dissolve more carbon dioxide in colder water than in warm water, so as water warms it is less able to take up carbon dioxide, for one thing.

The ocean biogeochemical cycle is largely responsible for the long time scales of the return to normalcy of carbon dioxide once we cease emissions. And that's shown rather dramatically by this chart, projecting atmospheric carbon dioxide content as a function of time, but going back to the year 1800. So on this particular chart, if we start in 1800, carbon dioxide goes up as observed, and is projected to keep going up. Now hypothetically, if we stop emissions, completely stop emissions of carbon dioxide into the atmosphere when it reaches various levels given by these numbers, 450, 550, and so forth, the carbon dioxide content of the atmosphere will decay back toward pre-industrial levels at a rate that's dictated by the global biogeochemical cycle. One can see that those time scales are quite long. It takes thousands of years for the carbon dioxide to return to its pre-industrial value. The length of that time scale is largely owing to storage of carbon in the deep oceans. And the long time scale is associated with ocean circulation.