The Oceans and Climate Change

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The ocean serves as the memory of the climate system, storing heat, fresh water, and chemicals over time spans from decades to millennia. This memory results from the chemical and physical properties of seawater. First, water is heavier than air. A 10 meter column of water is heavier than a column of air that extends to the top of the earth's atmosphere. Second, water has four-fold higher specific heat than air and five-fold higher specific heat than soil. Because it takes vastly more energy to heat up the ocean, ocean temperature is much more resistant to change than air or land temperature. Although, the temperature of surface waters of the ocean varies according to latitude, the temperature of deep water in all oceans is almost always close to freezing. Finally, gases such as carbon dioxide dissolve in water making the ocean a major storage depot. In fact, fifty-fold more carbon dioxide is stored in the ocean than in the atmosphere. Without absorption of carbon dioxide by the ocean, atmospheric concentrations of this greenhouse gas would be even higher. Thus the oceans provide a damper that keeps the Earth's climate relatively constant and benign.

Over the past 50 years, large research programs have greatly informed how this ocean damper works. In 1957-1958, under the auspices of the International Geophysical Year, detailed profiles of temperature and salinity were done in the Atlantic Ocean. These surveys allowed oceanographers to see clearly that the sources of the deep (below 1500 m depth) and intermediate water (between 500 and 1500 m depth) of the world's oceans come from geographically isolated regions, with deep water forming in the Northern North Atlantic and near Antarctica, and intermediate water originating at high latitudes and in marginal seas.

In the 1970s, data collected during the Geosecs (Geochemical Ocean Sections Study) Program greatly added to our knowledge of the role of the ocean in global cycles of nutrients and gasses such as carbon dioxide and oxygen. By this time, a fairly complete picture of the full three-dimensional structure of the ocean water properties was developed and there was general acceptance that the modern ocean system was relatively stable. In the 1980's a simple cartoon of the global ocean circulation called the great ocean conveyor belt (Figure 9.14) was popularized. This cartoon suggests that cold water created in the high northern latitudes of the North Atlantic sinks to the abyss and moves slowly towards the North Pacific and Indian Oceans where it rises to the surface, warms, and then makes its way back to the Nordic Seas via surface currents and ultimately the Gulf Stream.

In the mid-1980s through the 1990s, extensive and detailed ocean surveys were conducted as part of the World Ocean Circulation Experiment (WOCE). These studies generated the most comprehensive observational analyses of the ocean general circulation and indicated that the conveyer belt circulation model is an over simplification. Analyses of WOCE data clearly emphasize the significance of deep water formed near Antarctica, suggest that much of the upwelling of deep water may occur in the Southern Ocean, and

that there are multiple routes by which water is exchanged among the various ocean basins.

The role the ocean plays in climate variability and change is becoming clearer. Geochemical tracers show that deep water cycles in the ocean take several centuries, while water cycles through waters above the thermocline much more quickly, on the order of decades. Analyses of satellite measurements suggest that the oceans carry the bulk of the excess heat away from the equator in the tropics. However, the amount of heat transferred by the oceans amount falls off at higher latitudes, and poleward of 40° the atmosphere carries the lion's share. These results have called into the question how important the conveyor belt circulation is to maintaining the climate of Europe, and whether we would expect large and abrupt climate changes in the future if there were a large influx if fresh water into the high latitude North Atlantic Ocean from the rapid melting of Greenland ice, for example.

At the same time that more comprehensive observations of the oceans were being made, the first general circulation models of the ocean and the climate system were constructed. In the early 1970s numerical modeling of ocean circulation was born with the construction of the first general circulation model of the ocean that qualitatively reproduced the major ocean currents. Shortly thereafter, this model was coupled to an atmosphere and exchange of heat and water across the air-sea interface was modeled. These models are the predecessors of the models used today. Written in Fortran, a scientific programming language, they divided the ocean up into boxes, with the sides of each box about 200 to 300 km, and the depth about 100-500m. The original models were written on paper computer cards. Each model run took weeks or more of computer time even though necessarily restricted to poor resolution of features and physical processes in the ocean and the atmosphere.

The development of comprehensive climate models has allowed testing of hypotheses of how the climate system would respond to changes in both the greenhouse effect and to other climatic perturbations. For example, these models can be used to ask if Europe would rapidly cool if a significant fraction of Greenland were to melt. In experiments where a large influx of fresh water caps off the North Atlantic, there is significant cooling over Scandinavia, but not to the south, suggesting that the effect of the heat transport by the ocean on climate for areas surrounding the North Atlantic Ocean may be much smaller than previously thought. In fact, the most likely scenario is that Scandanavians may be saved from some effects of global warming by the changes wrought by a melting Greenland, but that they will not experience rapid or extreme cooling. Unlike the scenario suggested in the movie "The Day After Tomorrow" the picture emerging is that ocean currents with relatively small spatial scales play an important role in controlling the redistribution of both fresh water and heat around the globe, and that the simple schematic ideas about the large-scale ocean circulation are not sufficient for understanding the role the oceans will play in a changing climate. Also, while the lessons learned about the climate system from data originating during glacial times are useful, they are probably not the best indicators for what may happen in the future.

One aspect of how the oceans will respond as the climate warms is certain – sea level will rise. The heat-trapping capacity of the planet is increased with the addition of greenhouse gases, such as carbon dioxide, to the atmosphere by human activities. Some 80 to 90% of this heat has been transferred to the oceans, resulting in thermal expansion of the seawater. Over the last decade, global warming has caused an increase in sea level, about half of which is due to thermal expansion of the ocean (warmer water expands), and half due to melting of land ice outside of the polar regions. The recent (2007) dramatic reduction in summer sea-ice extent in the Arctic is not associated with sea-level rise because sea-ice floats on the top of the ocean. Because the ocean and atmosphere equilibrate slowly, even if we were to maintain the amount of human induced greenhouse gases in the atmosphere at 2007 levels, the climate system would warm by an additional 0.5°C by the end of the 21st century and sea level would rise through thermal expansion by about 10 cm.

Modeling studies suggest that as the upper ocean warms, ocean stratification will increase, decreasing the exchange of surface waters with those at depth. This will decrease the supply of nutrients to the surface ocean, thus decreasing primary productivity and likely the activity of the biological pump. Most climate models do not take these effects into account when predicting the future climate.

As the climate changes, ocean chemistry will also change. As of 2007, humans are releasing carbon into the atmosphere at a rate of around 7 gigatons (15,000,000,000,000 pounds) per year. Historically, about one third to one-half of human (or anthropogenic) carbon releases has been absorbed by the ocean. Much of this absorption occurs at high latitudes where the ocean is cold and can hold more carbon dioxide than at lower latitudes (think of how flat a warm can of soda is compared to a cold one). The surface ocean carbon dioxide concentrations can comes into equilibrium with the atmosphere in less than a century, which tells us that if we stop emitting carbon dioxide into the atmosphere now, it will take about century for the amount in the atmosphere to approach the levels last seen in the 19th century. It will take several millennia before the carbon dioxide stored in the water column is buried in sediments at the bottom of the ocean.

The addition of carbon dioxide to the water column is not benign. Carbon dioxide dissolved in sea water forms carbonic acid, lowering the slightly alkaline pH level of the ocean. The shift towards increasing acidity and associated changes in ocean chemistry due to increasing carbon dioxide levels in the overlying atmosphere will likely impact marine organisms that build shells out of calcium carbonate. In particular, corals are in danger as "ocean acidification" combines with other environmental stresses. The level of acidification will vary geographically, with high latitudes (colder water) being more affected. In the Southern Ocean, the shells of pterapods, an important component of the food web, will be in danger of acid corrosion by the end of the 21st century.

There are several tools to bring to bear on the challenges of understanding the role of the oceans in climate and climate change. Numerical models of the climate system are improving constantly, both because of incorporation of improved understanding of fundamental climate processes, but also because computers keep getting more powerful.

For instance, the increase in computing power alone allows improved modeling of the strong ocean currents that play such an important role in moving heat, salt and chemicals around in the ocean. Scientists are also advancing the inclusion of ocean biogeochemistry in these models.

Continued ocean observations are also vital to increasing our understanding of the climate system. The Global Ocean Observing System, which is currently being implemented, is already providing insights into the changing ocean. Satellites that measure sea surface height variations provide scientists with data to monitor sea-level and surface ocean currents. Satellite sea surface temperature, sea surface salinity and surface winds provide global ground truths for models of the climate system. In addition, the subsurface ocean is observed by over 3000 autonomous floats that drift freely at 1000-m depth, and every 10 days sink to 2000 m before rising to the surface, measuring temperature and salinity (and recently dissolved oxygen and other chemical parameters), which is then reported back via satellite before the float sinks back to 1000 m again. Repeat measurements of water properties and currents in the deepest parts of the oceans are also being made, although at the current time, these measurements are only feasible from ships, so they are less frequent. These measurements are revealing significant warming in many parts of the deep ocean.

Humans are changing the climate system in ways that we are only now beginning to understand. Scientists are just now beginning to be able to accurately and globally measure ocean variations through new technologies including satellites and autonomous platforms, and to model the oceans, a very important aspect of the climate system. Changes are evident in the most remote areas of the ocean, with melting ice in the high latitudes and warming all the way to the ocean floor. These observations are evidence of the magnitude of the changes that we are making in the Earth's climate.