Abrupt Climate Change and the Oceans

Our ideas about "climate" have been changing, in part due to the recent success in prediction of El Niño in the Equatorial Pacific Ocean. This has alerted people to the continuum of time scales in climate: from long-tern glacial cycles that have been the mindset behind the concept of climate, to interannual changes, where substantial variability in temperatures and precipitation have been identified and in part attributed to one major natural cycle, in which the tropical ocean plays a fundamental role. When one thinks about the issue of global warming, there is some similar re-education needed as well. Evidence has mounted that global warming began in the last century and that man may be in part responsible. Both the Intergovernmental Panel on Climate Change (IPCC) and our National Academy of Sciences have concurred. Computer models are being used to predict climate change under different scenarios of greenhouse forcing and the Kyoto Protocol has advocated active measures to reduce CO_2 emissions which contribute to warming. Thinking is centered around slow changes to our climate and how they will affect humans and the habitability of our planet. Yet this thinking is flawed: it ignores the well-established fact that Earth's climate has changed rapidly in the past and could change rapidly in the future. The issue centers around a paradox: that global warming could instigate substantial cooling in the northern hemisphere.

Evidence for abrupt climate change is readily apparent in ice cores taken from Greenland and Antarctica. One sees clear indications of long-term changes discussed above, with CO_2 and proxy temperature changes associated with the last ice age and its transition into our present interglacial period of warmth. But in addition there is a strong chaotic variation of properties with a quasi-period of around 1500 years. We say chaotic because these millennial shifts look like anything but regular oscillations. Rather they look like rapid, decadal long transitions between a cold and warm climates with long interludes in one of the two states. The best known example of these events is the Younger Dryas cooling of about 12,000 years ago, named for the arctic wildflower remains identified in northern European sediments. This event began and ended within a decade and for its 1000 year duration the North Atlantic region was about 5 degrees Celsius colder. The lack of periodicity and the present failure to isolate a stable forcing mechanism has prompted much scientific debate about the cause of the Younger Dryas and other millennial scale events. Indeed, the Younger Dryas occurred at a time when orbital forcing should have continued to drive climate to the present warm state. A whole volume that reviews the evidence for abrupt climate change and speculates on the mechanisms was published recently by an expert group commissioned by the National Academy of Sciences in the US. This very readable compilation (Abrupt Climate Change, National Academy Press, 2002) contains a breadth and depth of discussion which cannot be matched here. Presently, there is only one viable mechanism identified in the report that may play a major role in determining the stable states of our climate and what causes transitions between them: it involves ocean dynamics.

In order to balance the excess heating near the equator and cooling at the poles of the earth, both the atmosphere and ocean together transport heat from low to high latitudes. Warmer surface water is cooled at high latitudes, releasing heat to the atmosphere, which is then radiated away to space. This heat engine operates to reduce equator to pole temperature differences and is a prime moderating mechanism for climate on Earth. Warmer ocean surface temperatures at low latitudes also release water vapor through an excess of evaporation over precipitation to the atmosphere and this water vapor is transported poleward in the atmosphere along with a portion of the excess heat. At high latitudes where the atmosphere cools, this water vapor falls out as an excess of precipitation over evaporation. This is a second important component of our climate system: the hydrologic cycle. As the ocean waters are cooled in their poleward journey, they become denser. If sufficiently cooled, they can sink to great depths in the ocean forming cold dense flows which spread equatorward at great depths in the ocean, thus returning the warm surface flow entering and warming the high latitude oceans. The cycle is completed by oceanic mixing, which slowly converts the cold deep waters to warm surface waters. Thus, surface forcing and internal mixing are two major players in this overturning circulation, called the great ocean conveyor. The waters moving poleward are relatively salty due to more evaporation at low latitudes, which increases surface salinity. At higher latitudes surface waters become fresher as a consequence of the dominance of precipitation over evaporation at high latitudes. The freshening tendency acts to make the surface water more buoyant and therefore acts to oppose the cooling tendency. If the freshening is sufficiently large, the surface waters may not be dense enough to sink to great depths in the ocean, thus inhibiting the action of the ocean conveyor and upsetting one important part of the earth's heating system.

This system of regulation does not operate the same in all oceans. The Asian continent limits the northern extent of the Indian Ocean to the tropics, and deep water does not presently form in the North Pacific: surface waters are just too fresh. Our present climate is such that cold deep waters are formed around Antarctica and in the northern North Atlantic Ocean. The conveyor circulation increases by about 50% the northward transport warmer waters in the Gulf Stream at mid-latitudes over what is expected by the wind-driven transport. Our limited knowledge of ocean climate on long time scales, extracted from the analysis of sediment cores taken around the world ocean, has generally implicated the North Atlantic as the most unstable member of the conveyor: during millennial periods of cold climate, North Atlantic Deep Water (NADW) formation either stopped or was seriously reduced. And this has generally followed periods of large freshwater discharge into the northern N. Atlantic caused by rapid melting of glacial or multi-year ice in the Arctic Basin. It is thought that these fresh waters, which have been transported into the regions of deep water formation, have interrupted the conveyor by overcoming the high latitude cooling effect with excessive freshening. The ocean conveyor need not stop entirely when the NADW formation is curtailed: it can continue at shallower depths in the N. Atlantic and persist in the Southern Ocean where Antarctic Bottom Water formation continues or is even accelerated. Yet a disruption of the northern limb of the overturning circulation will affect the heat balance of the northern hemisphere and could affect both the oceanic and atmospheric climate. Model calculations have indicated the potential for cooling of 3 to 5 degree Celsius in the ocean and atmosphere should a total disruption occur. This is a third to a half the temperature change experienced during major ice ages. These changes are twice as large as we have experienced in our worst winters of the past century in the eastern US, and are likely to persist for decades to centuries after a climate transition occurs. They are of a magnitude comparable to the Little Ice Age, which had profound effects on human settlements in Europe and North America during the 16th through 18th centuries. The issue of their geographic extent is in doubt; it might be limited to regions bounding the N. Atlantic Ocean. High latitude temperature changes in the ocean are much less capable of affecting the global atmosphere than low latitude ones such as produced by El Niño. Whether the pathway for propagation of climate change is atmospheric or oceanic, or if changes in oceanic and terrestrial sequestration of carbon may globalize effects of climate change, as suspected for glacial/inter-glacial climate changes, is an open question. Yet we begin to approach how the paradox mentioned above can happen: global warming can induce a colder climate for many of us.

Consider next some observations of oceanic change over the modern instrumental record going back 40 years. During this time interval, we have observed a rise in mean global temperatures. Because of its large heat capacity, the ocean has registered small but significant changes in temperature. The largest temperature increases are in the near surface waters, but warming has been measurable to depths as great as 3000m in the N. Atlantic. Superimposed on this long-term increase are interannual and decadal changes that often obscure these trends, causing regional variability and cooling in some regions, and warming in others. Now added to this is recent evidence that the high latitude oceans have freshened while the subtropics and tropics have become saltier. These possible changes in the hydrological cycle have not been limited to the North Atlantic, but have been seen in all major oceans. Yet it is the N. Atlantic where these changes can act to disrupt the overturning circulation and cause a rapid climate transition. A high latitude buildup of freshwater over this time period equivalent to about 3-4 meters has lowered water column salinities throughout the subpolar N. Atlantic to more than 2000m. At the same time, subtropical and northern tropical salinities have increased. The degree to which the two effects balance out in terms of freshwater is important for climate change. If the net effect is a lowering of salinity, then freshwater must have been added from other sources: river runoff, melting of multi-year arctic ice, or glaciers. A continued flooding of the northern Atlantic with freshwater from these various sources has the potential to reduce or even disrupt the overturning circulation. Whether or not the latter will happen is the nexus of the problem, and one which is hardest to predict with confidence. At present we do not even have a system in place for monitoring the overturning circulation.

Models of the overturning circulation have been shown to be very sensitive to how internal mixing is parameterized. Recall that internal mixing of heat and salt is an integral part of the overturning circulation problem. One recent study has shown that for a model with constant vertical mixing, commonly used in coupled ocean-atmosphere climate runs, there is only one stable climate state: our present one with substantial sinking and dense water formation in the northern N. Atlantic. With a slightly different formulation, more consistent with some recent measurements of oceanic mixing rates that are small near the surface and become larger over rough bottom topography, it has been found that a second stable state emerges with little or no deepwater production in the northern N. Atlantic. The existence of a second stable state is crucial to understanding when and if abrupt climate change occurs. When it occurs in model runs and in geological data, it is invariably linked to rapid addition of freshwater at high northern latitudes. And now perhaps you begin to see the scope of the problem. In addition to incorporating a terrestrial biosphere and polar ice, which both play a large role in the reflectivity of solar radiation, one has to accurately parameterize mixing which occurs on centimeter to tens of centimeter scales in the ocean. And one has to produce long coupled global climate runs of many centuries! This is a daunting task but is necessary before we can confidently rely on models to predict future climate change.

Besides needing believable models that can accurately predict climate change, we also need data that can properly initialize them. Errors in initial data can lead to poor atmospheric weather predictions in several days. So one sure pathway to better weather prediction is better initial data. For the ocean, our data coverage is wholly inadequate. We can't say now what the overturning circulation looks like with any confidence and are faced with the task of predicting what it may be like in 10 years! Efforts are now underway to remedy this. Global coverage of upper ocean temperature and salinity measurements with autonomous floats is well within our capability within the next decade as are surface measures of wind stress and ocean circulation from satellites. The measurement of deep flows is harder, but knowledge about the locations of critical avenues of dense water flows exists, and efforts are underway to measure them in some key locations with moored arrays. Our knowledge about past climate change is limited as well. There are only a handful of high-resolution ice core climate records of the past 100,000 yrs, and even fewer ocean records of comparable resolution. Better definition of past climate states is needed not only in and of itself, but to be used by modelers to test their best climate models in reproducing what we know happened in the past before believing model projections about the future. We are not there yet, and progress needs to be made on both better data and improved models before we can begin to answer some critical questions about future climate change.

But researchers always tell you that more research funding is needed and I am not any different. My message is not just that, however. It is that global climate is moving in a direction that makes abrupt climate change more probable, that these dynamics lie beyond the capability of many of the models used in IPCC reports, and the consequences of ignoring this may be large. For those of us living around the edge of the N. Atlantic Ocean, and that includes Chicago where we are meeting today, we may be planning for climate scenarios of global warming that are opposite to what might actually occur.

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