The Oceans and Rapid Climate Change: Past, Present, and Future

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THE OCEANS AND RAPID CLIMATE CHANGE: PAST, PRESENT, AND FUTURE
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INTRODUCTION
Ocean Currents of Change: Introduction

Scientists have traditionally assumed that climate change occurred on a timescale far in excess of a single human lifespan. In fact, significant global and regional climate changes were thought to occur incrementally over many centuries or millennia. Recently, however, our view of climate change has altered. Paleoclimatic studies now show that the global climate can change quite rapidly. There is substantive evidence that in the past, at least from a regional perspective, mean annual temperatures changed by several degrees Celsius over a few centuries or even decades. Evidence from the instrumented record and from climate models also indicates that humans have the potential to alter the Earth's climate significantly within one century – although the actual sensitivity of the climate system to the growing concentration of anthropogenic carbon dioxide and other greenhouse gases in the atmosphere is highly uncertain. In this regard, paleoclimatology offers perspectives that can enhance our understanding of how the global climate system changes. If we are to develop scenarios of possible climate change with greater reliability from the near to far future, the understanding provided by paleoclimatology will play a significant role.

Needless to say, the attribution of the temperature changes that occurred over the last century to a specific set of factors is the subject of considerable debate. The suggestion that the current warming is predominately related to human emissions of greenhouse gases is countered by a recognition that the climate system is also recovering from the Little Ice Age, the last major climate deterioration. Whichever view, in whole or in part, proves correct, both raise important questions about the role of the ocean in climate change. If we are now in a period of enhanced global warming, for instance, what consequences might we face with the melting of ice in the Arctic or Antarctica? Is it possible that global warming will present unexpected, even counterintuitive consequences, such as altering the deep–water conveyor belt and plunging Europe into a new Little Ice Age? Are the causative factors of the Little Ice Age linked to the internal variability of the Earth system? Answering such questions is difficult. Each requires that we considerably improve our understanding of the climate system, and how it works.

Paleoclimatology provides us with a key perspective here. Combining the geologic record with climate models offers a powerful tool by which to assess climate system dynamics on decadal to millennial timescales. More specifically, we are now able to focus our research on the role of the world ocean, a principal element in governing climate system dynamics on these time scales.

Numerical models provide much of the foundation for projecting future climate change. For more than three decades, increasingly complex computer simulations have assessed the potential impact of anthropogenic greenhouse gases on climate. The attempts to look into the geologic past through a computer terminal have a shorter history. Applications of numerical models used in present–day atmosphere and ocean simulations in paleoclimate studies began slightly more than two decades ago, e.g., *Gates*, [1976]; *Barron* [1983]; *Kutzbach and Guettner* [1984]; *Manabe and Broccoli* [1985]; *Seidov* [1986]; *Bryan and Manabe* [1988]; *Barron and Peterson* [1989]; *Maier-Reimer et al.* [1990], to name just a few examples (the special issue of

Paleoceanography prefaced by *Crowley* [1990] and *Crowley and North* [1991] provide more detail on early paleoceanographic modeling). Early efforts demonstrated that simulations of past climates and ocean circulation patterns have the potential to provide a number of valuable insights into the behavior of the climate system. More advanced and sophisticated paleoclimate and paleoceanographic modeling studies are now yielding significant information about present and possible future climate tendencies.

Earth system history provides a unique contribution to understanding climate change that is principally different from efforts that focus solely on modeling the future. The geologic record contains abundant information that records global changes on a variety of spatial and temporal scales. In particular, the marine record provides a wealth of evidence on past climate changes. Thus, computer models of past climate change on the millennial time scale can be at least partly verified against geologic data – an option that does not exist for predicted future change. Moreover, paleoclimatology provides an important lesson by demonstrating that climate changes, externally and internally driven, can occur extremely quickly, even approaching human time scales. Much of the irregularity and abruptness of these climate changes can be attributed to the ocean. Thus, ocean currents are true “winds of change,” the source of significant climate alterations. For this reason, the last two decades have witnessed an explosion of paleoreconstructions and modeling of the deep ocean and the climatic links associated with the glacial–to–interglacial transition of the Pleistocene. These last two million years of climate history contain a record of substantial climate fluctuation between warmer and colder states with numerous apparent instabilities. The role of the ocean in these fluctuations is still not entirely understood.

The ocean, with its thermal, freshwater and dynamic impacts, controls our environment in a variety of ways. These controls are evident in the nature of ocean–atmosphere interactions, sea–ice dynamics, and in sea level changes. The ocean’s role is thought to be dominant on decadal to millennial timescales because of its enormous heat capacity and its capability to redistribute heat by ocean currents. Although these time intervals are too long for the atmosphere to play a dynamically important role, they are too short to associate with changes in the Earth’s orbital parameters, ice sheet dynamics, or tectonic activity. In addition, we must consider the growing evidence that the thermohaline circulation represents one of the key pacemakers of global climate, given its apparent sensitivity to relatively small changes of freshwater in the high latitudes. Further support of its importance stems from the speculation that anthropogenic global warming may threaten the stability of this oceanic overturning, potentially providing a considerable challenge to human societies.

In his marvelous new book, *The Two–Mile Time Machine*, Richard Alley points out that “most paleoclimatologists spend their time looking at ocean sediments” [*Alley*, 2000]. Most popular oceanographic books, of course, focus on surface ocean currents, using common examples such as the Gulf Stream to capture the significance of the ocean in climate. However, most ocean modelers direct substantial attention to the so–called meridional overturning streamfunction, a mathematical abstraction that describes the volume of water that circulates in the vertical plane. Present–day oceanography recognizes that the meridional overturning is an intrinsic and powerful mechanism by which the ocean imposes vital thermal control over the Earth’s climate. Slow thermohaline circulation, which is driven by density contrasts between low and high latitudes and between the surface and deep layer of the ocean, appears to be the most important link in the climate system on decadal to centennial time scale, and perhaps on even longer time intervals, as this circulation is responsible for the lion part of meridional oceanic poleward heat transport. The key focus of this volume is thus “oceanic overturning” with studies drawn from ice core research, marine sediments, and oceanic modeling.

New evidence from ice cores and deep-sea sediments shows that the climate of the two hemispheres may not be synchronized in their response to climate forcing (e.g., *Blunier et al*. [1998]). These findings add new questions concerning the role of the ocean thermohaline circulation. What is the potential for differential impacts involving both the northern and southern hemisphere? What governs the observed synchronicity? How do changes in freshwater fluxes alter their impacts? In response, we focus on the feedbacks that link ocean circulation with other elements of the climate system. The engine of long–term climate change, the deep–ocean circulation system, can dramatically change in response to freshwater impacts that are usually associated with melting of some elements of the cryosphere, either as sea ice melting or ice sheets surges.

The discovery of cold deepwater in the equatorial regions was followed by early notions that large–scale deep ocean motion was caused by density contrasts (these findings can be traced back to the eighteenth and early nineteen centuries — see details in *Gill* [1982]). Because motion in the abyss is predominantly geostrophic, with weak and slow turbulent mixing in the deep layers, the water density can be modified essentially only at the sea surface in contact with the atmosphere. Hence, the ocean global thermohaline circulation depends on how intensive the buoyancy flux is across the sea surface in the high latitudes. An understanding of how this oceanic overturning works was first provided by the Stommel–Arons theory [*Stommel and Arons*, 1960], which describes a scheme of a dipole high–latitudinal sinking of dense water in the northern North Atlantic in the Northern Hemisphere and in the Weddell and Ross Seas in the Southern Hemisphere (the most recent and enlightening explanation of this keystone theory is given by *Pedlosky* [1996]). Certainly the most important element in this scheme is the formation of deep water: North Atlantic Deep Water (NADW) produced in the deep convection sites in the Nordic Seas and northern North Atlantic, and Antarctic Deep Water (AABW) formed around Antarctica but primarily in the Weddell Sea. Thus, the first understanding of bi–polarity of the thermohaline circulation origin had been put forth.

Another important issue concerns the role of freshwater. Understanding the importance of salinity in ocean dynamics goes back to the Goldsbrough model [*Goldsbrough*, 1933], which suggests that, theoretically, the ocean circulation on a sphere can be maintained by evaporation and precipitation only, or, equivalently, by density contrasts caused by surface freshwater fluxes altering salinity distributions (also see a discussion of the Goldsbrough model in *Stommel* [1957]). However, real advances in our comprehension of the role of salinity in climate are provided in the pioneering work of *Bryan* [1986] followed by key studies of the stability of the ocean thermohaline circulation (e.g., *Manabe and Stouffer* [1988]; [1988]; *Weaver et al.* [1991]). A thermohaline circulation driven by buoyancy fluxes across the sea surface was shown to be sensitive to high–latitudinal density variations and to have more than one stable regime. In essence, salinity has, unlike temperature, no simple restoring feedbacks in the ocean–atmosphere system and therefore can be one of the crucial elements responsible for nonlinearity of climate dynamics, including bifurcation of the circulation regime (e.g., *Rahmstorf* [1995a]).

The growing interest in paleoclimate modeling, and in an improved understanding of the role of freshwater in climate change, coincided with the development of new concepts about global ocean circulation. Based on extensive observational, theoretical and modeling efforts, a new vision of the global interhemispheric and interoceanic water transport in the deep-ocean flow system began to emerge about a decade ago (e.g., *Gordon* [1986]; *Broecker and Denton* [1989]; *Cox* [1989]). This new image of deep-ocean currents as a major player has been transformed into the concept of a "global ocean conveyor" connecting the most remote ocean regions and being most sensitive to high-latitudinal freshwater fluxes, and thus to high-latitudinal salinity fluctuations (a "salinity conveyor belt" according to *Broecker* [1991]). Further progress in understanding of freshwater impacts in the high latitudes has been achieved through a number of studies (e.g., in modeling effort of *Weaver et al.* [1991; *Maier-Reimer et al.* [1993]; *Manabe and Stouffer* [1995]; *Rahmstorf* [1995b] to name just a few).

The current paradigm of the global ocean thermohaline conveyor is that it is driven by the formation of the NADW, with surface poleward currents compensating the NADW outflow (e.g., a review in [1992] and a discussion in *Boyle and Weaver* [1994]). As the NADW crosses the equator, there must be a compensating flow at the surface that maintains continuity of the ocean circulation. The compensating northward warm surface flow crosses the equator and thus provides cross–equatorial heat transport to the high latitudes in the Northern Hemisphere in the Atlantic sector. This cross-equatorial warm flow allows northern Europe to enjoy a far warmer climate than the countries in the Southern Hemisphere at the same distance from the equator. Thus, the high latitudes are potent regulators of the impact of the ocean on global climate (e.g., *Stocker et al.* [1992]; *Stocker* [1994]; *Sakai and Peltier* [1995]; *Broecker et al.* [1999]; *Schmittner and Stocker* [1999];

[2000]; *Ganopolski and Rahmstorf* [2001]).

One of the most noticeable attributes of present-day climate is its hemispheric asymmetry, with a warm ocean surface in the northern North Atlantic, a moderately cool northern North Pacific and a much colder Southern Ocean (e.g., *Weyl* [1968]; see also the most recent discussion of this issue in *Weaver et al.* [1999]). The salinity contrasts between different ocean regions, and most notably between a saltier Atlantic and fresher Pacific, is a signature of a global abyssal connection that may be responsible for the climate state in which we are living. Therefore, a change in this connection may be at least partly responsible for past and possibly future long–term climate fluctuations that are not externally driven (for example, due to tectonics or change of the Earth's orbit). The bi-polar character of the deep-ocean circulation – a prominent feature of the thermohaline engine – may be helpful in understanding these issues.

The idea of the so-called bi-polar ocean seesaw [*Broecker*, 1998; *Stocker*, 1998; *Broecker*, 2000] (see also a discussion in this volume [*Seidov et al.*, 2001; *Stocker et al.*, 2001]) is the most recent and one of the most exciting additions to the Stommel-Arons scheme and to the whole global conveyor paradigm. The bi-polar seesaw is a fluctuating meridional overturning regime driven by two deepwater sources — the NADW in the north, and the AABW in the south — responding primarily to high-latitudinal freshwater fluctuations and therefore presumably linked to the major glacial cycles of the Pleistocene. However, it has been shown that changes in the intensity of the AABW do not impose a direct impact on the deep–ocean thermal regime. AABW variability controls deep–ocean warming or cooling via NADW, which has been shown to vary, at least in some cases, in counter–phase with the AABW fluctuations (*Seidov et al.* [2001], this volume). The bi–polar seesaw idea appears to be a conceivable mechanism of some of the glacial-to-interglacial fluctuations linked to the global ocean conveyor variability. It may also imply that the observed north-south asymmetry of the millennial-scale climate variability, including the Little Ice Age, was caused by a flip-flopping of the deep-ocean circulation regime [*Broecker*, 2000].

This introduction is not intended to be a comprehensive listing of the many very important and enlightening publications on the role of the oceans in climate change. A Herculean amount of work would be needed to outline the state of science for either observations or modeling efforts addressing this topic. Rather, our intent is to give a sense of the excitement and advances associated with the main issue of the volume — the role of the ocean in fast climate change in the past and future. This volume is a rather balanced presentation of both observational and modeling directions within this theme. Hundreds of references in individual papers within the volume give a broad array of relevant publications supporting the interesting conclusions reached by the authors within the volume. The papers themselves provide an equally broad perspective on the core ideas of the ocean's impact on climate, and specifically on the role of deep-ocean in climate change. Thus, this introductory text reflects only the views outlined above that demonstrate why so much research attention is needed on the role of the ocean in understanding past and possible future climate changes. In essence, we argue that it is time to think along the lines of "ocean currents of change".

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