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Arctic System on Trajectory to New, Seasonally Ice-Free State

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The Arctic system is moving toward a new state that falls outside the envelope of glacial-interglacial fluctuations that prevailed during recent Earth history. This future Arctic is likely to have dramatically less permanent ice than exists at present. At the present rate of change, a summer ice-free Arctic Ocean within a century is a real possibility, a state not witnessed for at least a million years. The change appears to be driven largely by feedback-enhanced global climate warming, and there seem to be few, if any, processes or feedbacks within the Arctic system that are capable of altering the trajectory toward this "super interglacial" state.

The Changing Arctic

For nearly 30 years, Arctic sea ice extent [e.g., *Stroeve et al.,* 2005] and thickness [*Rothrock et al.,* 2003] have been falling dramatically (Figure 1). Permafrost temperatures are rising and coverage is decreasing [*Osterkamp and Romanovsky,* 1999]. Mountain glaciers and the Greenland ice sheet are shrinking [*Meier et al.,* 2003; *Box et al.,* 2004]. Evidence suggests we are witnessing the early stage of an anthropogenically induced global warming superimposed on natural cycles [*Intergovernmental Panel on Climate Change,* 2001], reinforced by reductions in Arctic ice.

Despite 30 years of warming and ice loss, the Arctic cryosphere is still within the envelope of glacial-interglacial cycles that have characterized the past 800,000 years. However, although the Arctic is still not as warm as it was during the Eemian interglacial 125,000 years ago [e.g., *Andersen et al.,* 2004], the present rate of sea ice loss will likely push the system out of this natural envelope within a century. Climate models corroborate this projection with depictions of sea-ice-free summers within the same time frame [*Arctic Climate Impact Assessment,* 2005]. There is no paleoclimatic evidence for a seasonally ice free Arctic during the last 800 millennia.

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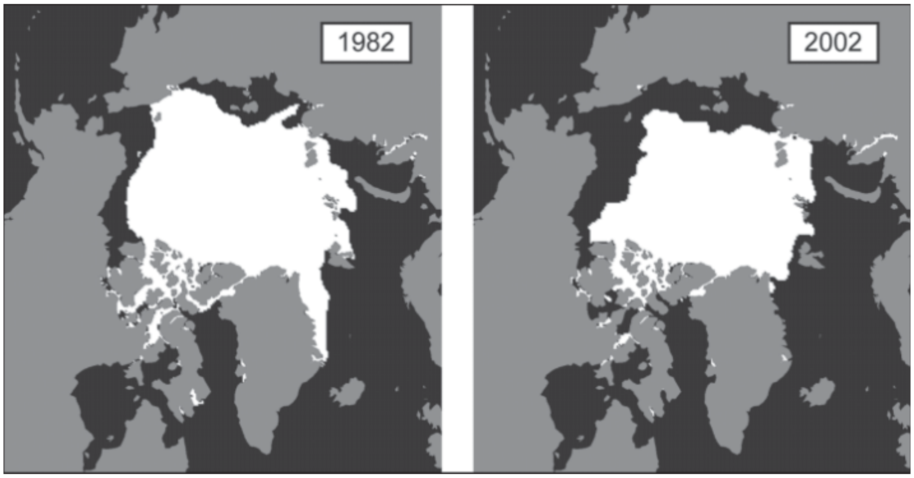

Fig. 1. Sea ice extent (white) at the end of summer in 1982 and 2002 observed with passive microwave satellite sensors. The record minimum extent was observed in 2002, but that record was nearly equaled in 2003 and 2004.

A major deglaciation of Greenland would take many centuries at present rates [*Intergovernmental Panel on Climate Change,* 2001], but destabilizing mechanisms such as basal sliding could accelerate the pace [*Zwally et al.,* 2002]. The third perennial ice type—permafrost—is difficult to observe, and thus little is known about its past state. Recent surveys indicate, however, that it too is warming and thawing in some areas [*Arctic Climate Impact Assessment,* 2005].

A System View of the Arctic

In a recent synthesis by the authors, it was found that the fundamental Arctic system could be understood by links among nine key components, or hubs. Three are related to the permanent ice types, and two others involve net precipitation (precipitation minus evaporation, or P-E) and the thermohaline circulation (THC). Putative changes in the interactions among these five hubs reveal how radically the future Arctic might be altered. The remaining four hubs capture the living parts of the system: terrestrial biomass, marine primary productivity, economic productivity, and human population.

Interactions among all hubs are shown schematically in Figure 2a. P-E is the fundamental driver of Arctic hydrology, but also affects the surface energy budget. Snow depth largely governs river runoff and also influences surface reflectivity, sea ice melt, and atmosphere/ocean coupling. The THC, long recognized as a primary driver of Arctic and North Atlantic temperatures, has strong ties with atmospheric circulation, P-E, and the cryosphere as a whole. The THC is also driven by changes in P-E either directly (weakened by freshening the North Atlantic) or indirectly (through the export of freshwater to the North Atlantic as sea ice and low-salinity water [*Curry and Mauritzen,* 2005]).

Interactions between hubs can be unidirectional or bidirectional (single or double arrowheads), strong or weak (arrow thickness), and positive or negative. In a positive interaction, a change in one component produces a change in another of the same sign. On the basis of whether a hub primarily affects or is affected by other hubs, the components can be classified as either drivers (blue) or recipients (yellow). This classification is important because feedbacks start at driver hubs and must loop back to amplify or dampen the initial change. Feedbacks also operate within each hub; but from an Arctic system perspec-

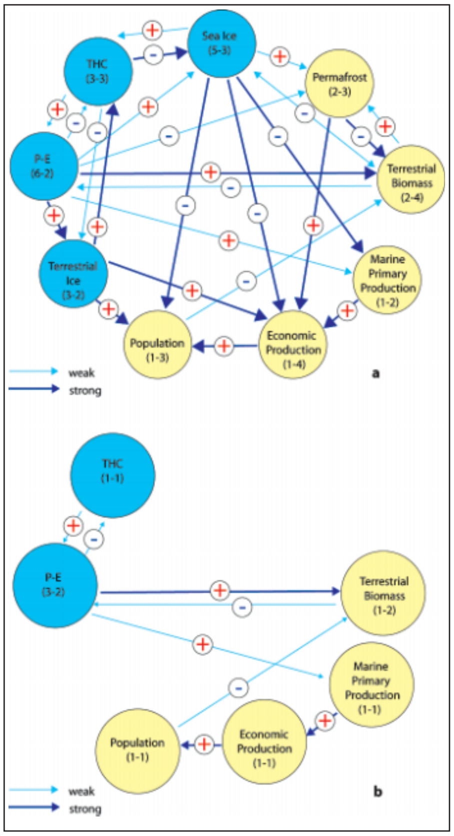

Fig. 2. (a) Schematic of the essential components (or hubs) of the present Arctic system. The main interactions between hubs are denoted by arrows: Single or double arrowheads indicate one- or two-way interactions. Interaction strength is designated by arrow thickness, and the sign (plus or minus) indicates whether a change in one component produces a change in another of the same (plus) or opposite (minus) sign. Numbers in parentheses within each hub indicate the number of interactions going out of, and coming into, that hub. Driver hubs are blue; recipient hubs are yellow. (b) The Arctic system in the future after loss of substantial permanent ice.

tive, the key is how the interactions between hubs change as the permanent ice disappears.

The Present Arctic System: Physical climate hubs have a more direct impact on the Arctic system (more outward arrows) than do biological and human hubs. The strongest drivers are P-E (defined by the number of other hubs affected), followed by sea ice. Anthropogenic greenhouse emissions occur primarily outside the region and affect the entire globe, and thus they do not appear as a strong Arctic driver. Surprisingly, Figure 2a shows only three feedbacks between system components: two amplifying (sea ice/THC/P-E and terrestrial ice/THC/P-E) and one damping (P-E/THC/sea ice). This leads to a notable conclusion: The processes and interactions among primary components of the Arctic system, as presently understood, cannot reverse the observed trends toward significant reductions in ice.

The Future Arctic System: Extrapolating the present rate of ice loss into the future yields Figure 2b. The defining feature of the present Arctic system—permanent ice—is almost gone. Sea ice is absent in summer, and the Greenland ice sheet is smaller. Permafrost has thawed to form a thick active layer that functions similarly to soils outside the Arctic. This new Arctic system has only six hubs, two of which are drivers, and only eight linkages. Feedback loops of great importance today, such as the ice-albedo feedback, have diminished.

The ramifications of a transition to this new system state would be profound. The deglaciation of Greenland alone would cause a substantial (up to 6 m) rise in sea level, resulting in flooding along coastal areas where much of the world's population resides. Shrubs and boreal forest will likely expand northward, further decreasing the albedo. Less certain is the fate of vast stores of carbon previously frozen in the permafrost. Would they be exhaled as carbon dioxide and methane, further accelerating warming?

The Arctic system balances on the freezing point of water. Each summer, the system swings toward the liquid phase; each winter, it returns to the solid phase. Will present warming shift the fulcrum far enough to make this new state a reality? If so, the incremental changes over the past 30 years may be replaced by more abrupt changes as thresholds are crossed and change in a system component accelerates rapidly relative to the global climate change forcing (e.g., when a perennially unfrozen zone forms at the base of the permafrost active layer, and results in abrupt draining of surface soil moisture). The ability to predict the response of such a radically altered system is poor, and the answers society needs depend not only on the future state, but also on how the transition occurs.

Possible Brakes on the System

Approximately 98% of the energy supplied annually to the Arctic system is advected from lower latitudes by the atmosphere [*Nakamura and Oort*, 1988]. Models predict (and observations seem to confirm) that warming is enhanced in the Arctic [*Arctic Climate Impact Assessment*, 2005]. Consequently, the meridional poleward temperature gradient may decrease and reduce the northward transport of sensible heat into the Arctic (heat that is associated with the physical temperature of air parcels). This negative feedback could slow the transition to the new state, but a compensating increase in the poleward transport of latent heat may occur (heat stored as water vapor, which is released upon condensation). Thus, changes in energy transport from lower latitudes provide no definite brake on the system.

Arctic cloud cover might also slow the warming: Cloud cover is decreasing in winter and increasing in other seasons [*Wang and Key*, 2003]. Over ice-covered areas, however, the shading effect will be small owing to low surface-cloud contrast in reflectivity, and thus additional clouds should enhance longwave emission and warm the surface [*Shupe and Intrieri,* 2004]. Therefore, cloud-radiation feedbacks are not expected to derail the Arctic's trajectory.

Increased P-E will reduce surface-layer salinity in the ocean, which may weaken the THC and lead to increased sea ice, thereby slowing Arctic warming (Figure 2a). Model projections suggest, however, that a weaker THC would primarily affect Nordic rather than Arctic seas, with heat transport to the Arctic basin remaining constant or even increasing [*Holland and Bitz,* 2003].

Arresting Future Surprises

The Arctic is rapidly losing its permanent ice. At the present rate, a summer ice-free Arctic Ocean within a century is a real possibility, a state not witnessed for at least a million years, perhaps much longer. The changes appear to be driven by both natural variability and anthropogenic forcing. Present-day concentrations of greenhouse gases [*Intergovernmental Panel on Climate Change*, 2001] are well outside the interglacial bounds, and are continuing to rise. Physics dictate that the Arctic, and the globe as a whole, must ultimately respond to these increases in trace gases. This could mean an even greater reduction in Arctic ice, and further acceleration toward an unprecedented state. Arctic residents produce only a minor amount of the trace gases, yet they are experiencing a disproportionate impact of the consequences: Any real chance of a trajectory change must come from outside the Arctic.

Surprisingly, it is difficult to identify a single feedback mechanism within the Arctic that has the potency or speed to alter the system's present course. Thresholds may produce unexpected system responses. The challenge is to understand and predict the magnitude and timing of the changes, which requires a fundamental shift from the business-as-usual analysis of individual system components to an approach that emphasizes a system-wide understanding of the Arctic.

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A U.S. Interagency Distributed Climate Modeling Project

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When the Intergovernmental Panel on Climate Change (IPCC) publishes its Fourth Assessment Report of the Scientific Basis of Climate Change (AR4) in 2007, a significant portion of the report will analyze coupled general circulation model (GCM) simulations of the climate of the past century as well as scenarios of future climates under prescribed emission scenarios.

Modeling groups worldwide have contributed to the report. Three U.S. contributors are: the Community Climate System Model (CCSM) project, the NASA Goddard Institute for Space Sciences, and the U.S. National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL). This collection of model results is providing a wealth of new information that will be used to examine the state of climate science, the potential impacts from climate changes, and the policy consequences that they imply.

This article focuses on the CCSM project and the interagency cooperation that has made it a success. Although the project is centered at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, the CCSM version 3 (CCSM3) was designed, developed, and applied in a uniquely distributed fashion with participation by many institutions. This model has produced some of the most scientifically complete and highest-resolution simulations of climate change to date, thanks to the teamwork of many scientists and software engineers.

Interagency cooperation and multi-institutional coordination, at a level unprecedented for these groups, provided the direction and resources necessary to make the CCSM project successful. Contrary to the widely held opinion that the U.S. climate research effort in general, and the climate modeling effort in particular, are fragmented and disorganized [*National Research Council,* 1998, 2001], the CCSM project demonstrates that a uniquely U.S. approach to model development can produce a world-class model.

The Need for a U.S. Modeling Strategy

Prior to 1988, GCM-based climate modeling was primarily a research activity. In the United States, several independent projects existed at federal research laboratories and universities that had access to the supercomputing resources necessary to perform the most comprehensive simulations; however, there was no imperative for a national modeling strategy.

In 1988, the IPCC was chartered to assess the potential for anthropogenic climate change. Less than a year later, the interagency U.S. Global Change Research Program (GCRP) was established. One of its three overarching objectives was to "develop integrated conceptual and predictive Earth system models" [*Committee on Earth and Environmental Sciences,* 1989].

Four agencies—NASA, NOAA, the U.S. National Science Foundation (NSF), and the U.S. Department of Energy (DOE)—emerged as the primary supporters of model development and application within the GCRP. U.S. participation in the 1990 IPCC Scientific Assessment demonstrated global leadership in climate modeling, as the only transient CO_2 concentration experiments were carried out at NCAR with NSF and DOE support, and at GFDL with NOAA support. Although climate modeling was central to the mission of NCAR and GFDL, neither was focused exclusively, or even predominantly, on anthropogenic climate change.

With the publication of the IPCC Second Assessment Report, in 1995, however, many believed that U.S. leadership had been eclipsed by the Hadley Centre for Climate Prediction and Research in the United Kingdom and the Max Planck Institute for Meteorology (MPI) in Germany. Both centers had a well-defined mission to understand and predict century-scale climate change, and had dedicated computing resources on which to build, test, and evaluate their models.

A 1995 letter from senior climate researchers in the U.S. to the four modeling agencies discussed the "crisis in U.S. climate modeling" [*National Research Council,* 1998]. This community attitude precipitated a series of high-level studies between 1996 and 2001 [e.g., *National Research Council,* 1998, 2001] on how to restore U.S. leadership. The studies concluded that while the United States remained a global leader in climate research, it lacked the structure and mechanisms to integrate that knowledge within a comprehensive modeling effort. The visionary and comprehensive solutions that the studies proposed required a wholesale restructuring and a reallocation