Using the Geologic Record at Milankovitch (10^4 - 10^5) and Millennial Timescales to Improve Our Understanding of Climate Dynamics

Thematic Working Group White Paper
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About the Thematic Working Group

The U.S. Science Support Program convened the "Forcing of Climate with Milankovitch Periods and Amplitudes since 5 Ma" Thematic Working Group (Milankovitch TWG), to explore the links between climate-ocean dynamics research and paleoceanography results derived from ocean drilling. The Milankovich TWG had two meetings in Boulder, Colorado; the first July 31-August 1, 2006, the second May 7-8, 2007. Co-chairs Peter Molnar (University of Colorado at Boulder) and Christina Ravelo (University of California, Santa Cruz) facilitated the meeting, which was attended by paleoceanographers, paleoclimatologists, physical oceanographers, and climate scientists. The researchers developed a research strategy using sediments recovered by the Integrated Ocean Drilling Program (IODP) to advance fundamental understanding of climate and ocean dynamics by focusing on the influence of orbital (Milankovitch) solar forcing on climate change.

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Thematic Working Group White Paper

Earth's climate appears to be shifting toward a state unlike that observed during the past couple of hundred years of recorded history. Therefore, in our efforts to test theories and models used for predicting future climate, we must rely on scientific evidence from the more distant past, the geologic history of the Earth, which includes examples of climate extremes that might prevail in the 21st Century and beyond. Accordingly, atmospheric scientists and physical oceanographers are increasingly turning their attention to paleoclimatology and paleoceanography not only to solve puzzles posed by past climate states, but also to develop and test theories and models used for predicting future climate. Thus, the time is ripe for enhanced communication between paleoclimatologists and climate-ocean dynamicists, two groups who share a common interest, but who have different training and experience. This white paper describes the advances that we can make toward understanding past and future climates and recommends ways for achieving these goals.

Climate change over the past few million years offers particularly appropriate experiments. An important component of the climate variability at these long periods is related to variations in the Earth's orbit – the changing elliptical shape of the orbit around the sun (with periods of ~100,000 and 400,000 years among the most prominent) and the orientation of the Earth's spin axis (with periods of ~19,000, 23,000, and 41,000 years) – that can be calculated accurately for the past tens of millions of years. Thus, we know with nearly negligible uncertainty how solar radiation at the top of the atmosphere has varied; these variations are referred to as "Milankovitch forcing," after the Yugoslavian scientist who first quantified long term insolation changes in the 1920s. Moreover, a wealth of paleoclimate data demonstrates that climate responds to these changes in solar forcing and challenges us to understand how this variability at the top of the atmosphere writes its geologic signature at the bottom, on the land surface and in the oceans. Meeting this challenge necessitates the investigation of the atmospheric and oceanic processes that comprise the "black box" that connects solar forcing to climate response. This is the same black box that relates modern climate to anthropogenic forcing, for both are commonly cast in terms of energy per unit area incident upon the Earth, in one case at the top of the atmosphere, and in the other at the Earth's surface.

We illustrate the opportunities for improving our knowledge of climate physics and chemistry with the following specific examples.

Paleoceanographic and paleoclimatic data show that between 5 and 3 million years ago, before ice sheets waxed and waned over most of Canada and northernmost Europe, the equatorial Pacific Ocean was in a state resembling that of a permanent El Niño. The eastern Pacific was much warmer than it is now, but general circulation models of the coupled atmosphere-ocean system have failed to replicate such a climatological state. Such a failure calls attention to an inadequacy in these models that modern data cannot expose, let alone test. Paleoclimate data, however, not only can verify climate models, but also improve their ability to predict long-term climate change.

In another example, between roughly 3 and 1 million years ago, paleoclimate data indicate a pattern of advances and retreats of continental ice sheets with a period of 41,000 years, the tempo of changes in Earth's obliquity. It is widely believed that virtually all of this ice accumulated and melted in the Northern Hemisphere and that ice volume in Antarctica has been relatively stable for millions of years. However, Milankovitch theory suggests that summer insolation intensity at high northern latitudes, which varies primary at the 23,000 year rather than the 41,000 year periodicity, dictates snow and ice melt and therefore the growth and decay of ice sheets. Are our assumptions about our ice volume proxies (and where ice is fluctuating) flawed or do we lack a full understanding of how insolation variations control ice volume? Many basic assumptions are now being challenged, including whether ice on Antarctica has varied little over the past few million years, and the extent to which solar insolation in summer at high latitudes is the controlling factor for ice-sheet mass balance.

In another example, a growing community of scientists attributes at least some variability in high latitude climate, and possibly ice volume, to tropical processes that affect high latitudes largely through the atmosphere, but robust theories or models that demonstrate such a low-to-high latitude connection continue to elude us. Therefore, the question of how Milankovitch forcing at the top of the atmosphere affects the growth and decay of ice sheets (Ice Ages) not only remains a challenge for paleoceanographers and paleoclimatologists, but has also emerged at the forefront of modern atmospheric science and physical oceanography because of the need to predict how high-latitude regional climates respond to perturbations.

Milankovitch forcing also bears directly on a subject that much of the public now recognizes: the sensitivity of future climate to variations in CO_2 within the atmosphere. Over the past several hundred thousand years, variations in virtually all measures of climate have followed a similar pattern of changing slowly as CO_2 gradually falls and then rapidly when CO_2 rises. This pattern has reoccurred five times over the last 500,000 years with a typical repeat time of roughly 100,000 years. These measures of climate include not only greenhouse gases CO_2 and methane preserved in gas bubbles in the ice cores, but also the volume of ice stored on land and past sea surface temperatures and ice-core records (from Antarctica and Greenland) of the heavy isotopes of oxygen (^{18}O) and hydrogen (deuterium) found in the ice. Moreover, when examined in detail, and in particular when variability at periods of 19,000, 23,000, and 41,000 years are considered, most show strong signatures at these periods and therefore responses to varying solar insolation. The most prominent exception is the concentration of CO_2 in ice cores, and hence in the atmosphere; variability in CO_2 concentrations at these periods is decidedly smaller than, for instance, those of deuterium, which serves as a measure of air temperature, and the other greenhouse gas, methane. Because both variations in solar insolation and concentrations of CO_2 profoundly affect global and regional temperature on geologic time scales, the differing records of CO_2 from other measures of climate at Milankovitch periods offer both clues to how the climate system responds to varying concentrations of this gas and how CO_2 is exchanged between the atmosphere, biosphere, and deep ocean on millennial time scales.

The oceans provide both the Earth's largest reservoir of readily available CO_2 and its geologically most readily accessed storage bin. The Southern Ocean, surrounding Antarctica, provides the widest door into that storage bin. Atmospheric CO_2 variations observed in the Antarctic ice core record result mainly from the degree to which the deep ocean retains CO_2 that is respired from sinking particles. The CO_2 in the particles comes from the atmosphere via photosynthesis by marine flora. During warm periods, the respired CO_2 is freely vented from the deep ocean back up to the atmosphere via the Southern Ocean such that more CO_2 resides in the atmosphere than during the cold periods. During glaciations, this venting is blocked, and CO_2 accumulates in the deep ocean, with correspondingly less residing in the atmosphere. The blocking is related to the stratification of the ocean around Antarctica: venting is active when the ocean is warm and the surface and deep waters around Antarctica are well mixed; it is blocked when fresh surface waters and extensive sea ice literally put a cap over the Southern Ocean. Despite its distance from most of us and its persistent inclement weather, the Southern Ocean looms as the obvious target for paleoceanographic investigation of processes that ultimately will lead to a more sophisticated understanding of carbon-climate feedbacks and improved predictions of climate change.

Although global and regional temperatures respond to forcing at Milankovitch periods, significant regional climate variations also occur at much shorter periods of 1000 – 2000 year, with abrupt changes from one state to another occurring in periods as short as decades. In some respects these abrupt changes are harder to understand than those associated with Milankovitch forcing, because no clear cause for them exists; rather they appear to represent a natural mode of internal, stochastic variability. Accordingly, both the causes of these abrupt changes and the global responses to them pose challenges for climate dynamicists. First, millennial scale variations in CO_2 seem to be negligible, and thus scientists can use them to contrast how CO_2 affects climate with how it does not. Second, they offer examples of direct climatic links between distant regions. For instance, abrupt changes in surface temperature over Greenland during the last glacial period (between ~90,000 and 20,000 years ago) seem to correlate with changes in precipitation over eastern China. The global atmosphere can respond quickly to changes in one region, but in this case, the changes in Greenland almost surely reflect variable winter conditions, while those in China indicate the opposite – changes in summer precipitation. Such observations, which surprised many scientists, present opportunities to study dynamical seasonal processes that link distant regions.

The specific questions noted above, among many others, call attention to the common interests of scientists who study modern climate and those who use geological data to place constraints on the geologic history of climate. Although oceanographic institutions have traditionally offered intensive training to graduate students in physical *or* geological oceanography, few graduates appreciate *both* the physical processes that dictate ocean and atmospheric circulation and the data that constrain the geologic history of the Earth's climate. The two groups speak different languages, with one exploiting differential equations embodying classical laws of physics that relate quantities with speeds and temperatures, and the other relying on chemical or biological proxies that can be related to temperature, for instance, via empirical formulae, which in turn require continual improvement. These differences in approach have hindered the communication needed for fruitful collaboration between climate dynamicists on one side and paleoceanographers and paleoclimatologists on the other, but both groups now see the need to dissolve the boundaries between these disciplines. Educational institutions and science agencies could encourage and support collaboration between appropriate programs to assure the training of a new generation of scientists well versed in both disciplines.