Global Change Paleoclimatology

Rapidly increasing atmospheric greenhouse gases will alter the climate system in ways that have not been seen on Earth in many millions of years. While much can be learned about the climate system using existing historical observations and current climate models, the record is far too short to study and observe its full response on multi-decadal and longer time scales. For that geological observations are required. The goal of this proposed research is to utilize the key geological and biological records of climate system response that will provide insights into the causes of past climate changes, the sensitivity of the system to large changes in forcing, and the response of key components of the Earth system to the changes.

This research is designed to reduce uncertainties about the future climate with paleoclimate research in five specific, overlapping lines of inquiry related to the Strategic Plan for the US Climate Change Science Program (CCSP - see Appendix 1):

- How sensitive were ice sheets and sea level to past rapid changes in climate especially during past warm climates? (CCSP Strategic Research Questions 4.1 and 4.3)

- What were the regional responses of coupled climate systems like ENSO, the monsoons, NAO, and the MOC during past climate changes? (CSSP Strategic Research Questions 4.2, 4.3 and 4.4)

- What role did changes in the coupled carbon and hydrological cycles play as feedbacks during past changes in climate? (CCSP Strategic Research Question 4.2)

- How sensitive was the Earth's climate system to past changes in radiative forcing? (CCSP Strategic Research Questions 4.1 and 4.2)

- How does the geological record inform us about past abrupt changes in climate under a variety of different boundary conditions, past climate states, or during periods of large and rapid changes in forcing? (CCSP Strategic Research Questions 4.3 and 4.4)

The research will address the timeline, mechanisms, and the integrated Earth system response to past climate oscillations by encouraging interdisciplinary investigations of the atmosphere, ocean, and terrestrial systems. A major goal of the research will be to produce and continue to refine specific paleoclimate data sets ("target paleoclimatologies") that can be used to test current and future models of the coupled climate system. Only by combining observational, theoretical and numerical research strategies that involve researchers from the several NSF divisions and directorates will significant progress be made toward answering these key questions.

Question 1 - How sensitive were ice sheets and sea level to rapid changes in climate especially during past warm climates? (CCSP Strategic Research Questions 4.1 and 4.3)

Future sea-level rise has enormous consequences for society, but just how much of Greenland and Antarctica will melt --- and how quickly --- is poorly understood. There exists some possibility for rapid disintegration of the Greenland and Antarctic ice sheets and a consequent rapid rise in global sea-level. Evaluation of the likelihood and warning signs of such an event will require significant improvements in our understanding of the cryosphere.

Our ability to predict future melting is hampered by an insufficient theoretical understanding of ice sheet behavior, for example involving sub- and englacial hydrology, ice shelf buttressing, and cracking. In addition, the observational record of ice sheet behavior is both sparse and short relative to the timescales at which ice sheets will adjust to climate change. Of course, these two shortcomings are closely intertwined: a strong observational component is necessary to spur insight and test theory. A need to explain observations has historically driven improvement in the understanding of the oceanographic and atmospheric sciences, and a similar trajectory is anticipated for improving our understanding of ice sheets.

Take, for instance, the question of what changes in climate are most likely to induce ice sheet wastage and sea-level rise? Does sea-level rise because of disintegration of ice shelves and loss of buttressing; less accumulation; a warmer ocean or atmosphere, possibly associated with retreating sea-ice; or changes in ice sheet grounding brought about by sea-level rise itself? The paleoclimate record of the climate-cryosphere system offers one of the few avenues to test our understanding of the various mechanisms which contribute to sea level changes. Understanding how responsive ice sheets are to climate change cuts across traditional research programs, requiring expertise in climate, ice sheet physics, and paleoclimate proxies, and is thus best addressed through an interdivisional and focused research program.

We envision that such a paleoclimate program would address the following four relevant questions:

- What mechanisms lead to ice sheet disintegration and consequent sea level rise?
- What was the state of the cryosphere and sea level during the warm periods of the Pliocene, Pleistocene, and Holocene?
- How can the accuracy of climate/ice-sheet models be tested and the skill of these models improved through the utilization of the paleoclimate record?
- What were the climate impacts of melting ice during past climate warmings?

There is the need to develop strong interdisciplinary collaborations for success in this research and the natural partners for this program include the three Geosciences divisions, the Office of Polar Programs and the various groups developing sophisticated community ice sheet models.

Question 2 - What were the regional responses of coupled climate systems like ENSO, the monsoons, NAO, and the MOC during past climate changes? (CCSP Strategic Research Questions 4.2, 4.3 and 4.4)

The regional expression of climate change, and in particular hydrological variability, extreme events, and possible abrupt transitions, are likely to be among the most serious concerns to society in the future, making research into this area one of the Strategic Research Questions of the US Global Change Research Program and the Climate Change Science Program. Dynamical modes of climate variability, such as ENSO, the Northern Annular Mode (NAM), and the meridional overturning circulation (MOC), have large-scale influences and strong regional impacts around the globe. Changes in the response of these modes of varibility are likely to be among the primary mechanisms by which global-scale radiative forcing impacts regional-scale climate.

Of particular interest and focus for this research will be understanding large-scale hydrological variability of tropical and extra-tropical regions. Previous paleoenvironmental reconstructions have highlighted that regional climate varied significantly in the past, with large regional differences in the hydrological cycle being particularly noteworthy. Changes in the frequency and intensity of the ENSO system during the Holocene and earlier warm intervals of the Pleistocene and Pliocene are documented by large precipitation changes in South America. Reductions in Atlantic overturning circulation affected the position of the Intertropical Convergence Zone and precipitation throughout the regions of south Asia and South America affected by monsoons. We can use these and similar records to determine how temperature, hydrology, climate modes (*e.g.*, ENSO, NAM, monsoons) and extreme climate events (*e.g.*, drought, flood, tropical storms), varied – and interacted - on seasonal to longer time-scales in the past, what drove this observed variability, and how realistically this full-range of regional climate variability can be simulated with climate models.

Some specific areas to be addressed include:

- How have regional climates, including temperature, precipitation-evaporation, climate modes (*e.g.*, ENSO, NAM, monsoons) and extreme climate events (*e.g.*, droughts, floods, tropical storms), varied – and interacted - on seasonal to longer time-scales?

- What drove this observed variability in the geological record, and how realistically can this full-range of regional climate variability be simulated with current climate models?

- What are the regional implications for the future?

To achieve success will require: 1) expanded spatial networks of paleoclimate proxy time series that constrain both the mean state and seasonal- to longer-scale variability of the key internal climate modes and regional responses of the climate system; 2) networks of paleoclimate proxy time series of sufficient resolution and temporal duration to capture both the mean state and seasonal- and longer-scale variability of the frequency, duration, and severity of droughts, floods and severe tropical storms; and 3) close data-model integration to understand the processes that drive time and space variability in regional climate;

The proposed research is large in scope and research requirements and would involve researchers from the three divisions of the Geosciences directorate. The initial, highest-priority focus should be on research that contributes to spatial-temporal networks needed to understand variability in ENSO, monsoons, ITCZ position and regional hydrologic variability (*e.g.*, droughts and floods) in North America and the tropics with a strong emphasis on understanding the possibility for abrupt changes as the Earth continues to warm.

Question 3 - What role did changes in the coupled carbon and hydrological cycles play as feedbacks during past changes in climate? (CCSP Strategic Research Question 4.2)

Marine and terrestrial carbon cycling have been integral components of Earth's evolving greenhouse effect and climate history. In turn, the water cycle has acted as an integrator within the global climate system through its interaction with the carbon cycle and associated internal feedbacks. Earth's climate history reveals repeated perturbations to carbon and water cycling in the past, typically under conditions significantly different from today**.** These unique archives reveal key carbon-water cycle feedback mechanisms that strongly impacted the rates, amplitudes and duration of the response of the climate system to past greenhouse forcing. A better understanding of the feedback processes that control the interactions between the global carbon and hydrological cycles and their impact on other aspects of the climate system – over a full spectrum of atmospheric CO_2 levels and climatic conditions - is critical for model projections of future atmospheric greenhouse gas contents and climatic conditions. Paleoclimate studies are required to understand what mechanisms control, and at what time scales, regional-to-global-scale changes in rainfall patterns, water resources, and the release of carbon from soil, permafrost, and gas hydrate carbon reservoirs. Moreover, a geologic perspective of the long-term interactions of the carbon and water cycles and their potential for large feedbacks to the climate system is key to the successful development and management of engineered carbon sequestration strategies and to a refined understanding of the natural patterns of biologically-mediated carbon storage.

The research will focus on the carbon and hydrological cycle feedbacks and their influence on other aspects of the climate system during past intervals characterized by a spectrum of atmospheric CO_2 levels - including those significantly higher than pre-industrial CO_2 levels. The research will address scientific questions such as:

- How have large carbon reservoirs that are susceptible to rapid release contributed to global warming in the past?

- How have the oceans responded chemically and biologically to higher or lower pH (*e.g.*, ocean acidification due to elevated CO2 levels)?

- Have shifts in moisture balance had positive or negative feedbacks on carbon dioxide and methane release and sequestration in the past?

For example, an improved understanding of the carbon-water cycle feedback mechanisms during Plio-Pleistocene glacial-interglacial variations should help us understand the changes in carbon reservoirs that led to significantly lower atmospheric pCO_2 levels during past glacial periods. Data reconstruction and successful model simulation of reconstructed glacial-interglacial changes will provide us the confidence that we can model future carbon-water cycle variability. Earlier geological periods document major climate changes associated with significant perturbations in carbon cycling and large changes in the hydrologic cycle. The specific periods which warrant further study include the stepwise transition into our current glacial state in the Eocene-Oligocene transition, the rapid warming of the Paleocene-Eocene Thermal Maximum and the oceanic anoxic events of the mid-Cretaceous. Critical to the success of these research endeavors is better integration of highly resolved marine-terrestrial proxy records that will illuminate the nature of relationships between marine and terrestrial carbon and water cycle dynamics, ecosystem variability, and climate across a wide array of spatial and temporal scales of change. These data in turn will facilitate the development of GCMs that fully integrate terrestrial and marine carbon and water cycling.

To make rapid progress in this line of inquiry, there is a significant need for further refinement of proxies of past atmospheric greenhouse gases (for periods before the ice core record), and of past surface temperatures and hydrologic cycle for records in the Earth's distant past. Such work may also provide greater insights into underlying changes in soil/terrestrial environments and plant ecology that may result from abrupt future warming.

Understanding the character and time-scales over which carbon-water cycle dynamics have responded to past greenhouse-gas forcing requires a concerted multidisciplinary research effort that draws on the research expertise of marine, terrestrial, and atmospheric scientists, geologists, ecosystem biologists and paleoecologists, hydrologists and climate modelers. Such an interdisciplinary paleoclimate research program would complement other U.S. initiatives focused on better constraining recent and future carbon cycle dynamics such as those of the Climate Change Research Program.

Question 4 - How sensitive was the Earth's climate system to past changes in radiative forcing? (CCSP Strategic Research Questions 4.1 and 4.2)

The primary goal of this research theme is to describe the response of the Earth system to changes in forcing over different time and spatial scales beyond the range of the instrumental record over the past century. The responsiveness of the Earth system incorporates not only the classic definition of climate sensitivity (*i.e.*, the global temperature response of doubled CO_2), but also how different parts of the climate system behave and interact including oceans, clouds, ice sheets, ecosystems, and the hydrologic cycle. Study of past climate response is one of the only ways to directly calibrate the response of the Earth system to known forcing levels.

The questions to be addressed include:

- How do feedbacks in the Earth system (*i.e.*, water vapor, land and sea ice, land surfaces, vegetation, dust) act to amplify a primary radiative forcing?
- How is the behavior of these feedbacks different in warm versus cold climates?
- How is the amplification of climate change affected by the presence/absence or extent of land ice?
- How warm can the tropics become? Is there a tropical thermostat?
- How can changes over different time scales in the past inform us about changes we may see over the next few centuries?
- Do non-linearities in the climate system limit our ability to use past climates as analogs for future climate changes?

To address these broader questions requires advances in our understanding of both the magnitude of past forcing as well as the magnitude of the climate response. On the timescales of ice core atmospheric greenhouse gas records (*i.e.*, the last ~800,000 years), the radiative forcing changes are well known and the main challenge is to reconstruct the past climate responses to such forcings. Research on these timescales should focus on well characterized intervals such as the Last Glacial Maximum and the warm and cold intervals of the past several millennia, for which well-dated and well-constrained reconstructions by multi-proxy methods may enable a confident estimation of the climate system response to specific changes in forcing. A particular goal should be to determine of how climate responds at the regional level to a specific forcing. Proxy reconstructions at this level will be most useful if they can be linked to GCM reconstructions of climate. In this way it should be possible to test how the various climate feedbacks interacted to produce the observed response.

A second important objective is to target warm interglacial time periods that had similar greenhouse gas levels as the late Holocene but climatic conditions that were different. What feedbacks caused the climate of these intervals to be different under similar mean forcing? Targeted warm intervals might include MIS 5e (125 kyr BP), which is thought to have been warmer than the Holocene pre-industrial period, had higher sea level (~4-6 m), and a partially deglaciated Greenland. Another interglacial, MIS 11, may have been characterized by higher sea level (more than 20 m higher than present) and warmer conditions in the polar regions and perhaps also in the tropics. Both of these time intervals comprise better analogues to a globally warmed Earth than do earlier cold periods like the LGM, although these warm periods carry significantly greater challenges in terms of dating and chronology. MIS 11 is also a compelling time interval for study because orbital parameters were similar to the present. However because an extensive data set of proxy reconstructions does not exist for these earlier warm intervals and because dating is not as precise as for the LGM, a research program would require a well-coordinated effort on the part of the paleoclimate community to achieve a quantitative estimate of climate sensitivity.

Further back in time, key time intervals should include the Pliocene warm period, Eocene/Oligocene transition and two early Eocene hyperthermals, including the Paleocene-Eocene Thermal Maximum (PETM). For each of these time periods, a key challenge is to reconstruct levels of radiative forcing from indirect proxies of atmospheric composition. Such reconstructions of past forcing are difficult and uncertain, but they must be a major goal if we are to successfully use past warm climates to gauge climate sensitivity. Despite the uncertainty in forcing, the earlier warm periods have an advantage: the changes in forcing during these warm periods are potentially much larger than what characterized glacial – interglacial change. For example, the PETM exhibits hallmarks of a fast, transient rise in greenhouse gas levels similar to the anticipated rise over the next 200 years. The larger climate response during past warm periods can be used to advantage even if the proxies are more uncertain.

Warm climates may also differ in other fundamental ways. For example, recent data from the Pliocene suggests that the tropical Pacific might have been in a continuous El Niño-like state. Is this the equilibrium response to slightly higher atmospheric carbon dioxide levels? There are other fundamental questions associated with the Pliocene that must be addressed – what was the mean increase in global temperatures, how was it distributed, and how did ice sheets and sea level respond? Even though the Pliocene and PETM are commonly characterized as global warming analogs, they have been less well studied, with fewer solid constraints on the forcings prevailing at these times and the climate system response.

New evidence from several climate intervals in the early Eocene and Cretaceous now suggest that the tropics were substantially warmer than present which raises an important question: with rising greenhouse gas levels, will the tropics continue to warm, or is there a dynamical thermostat that limits temperatures? This is a particularly important question as higher tropical temperatures may have dire effects on tropical ecosystems. To address this question, it is critical that changes in tropical temperatures be established for periods of abrupt warming such as the PETM.

The transitions into and out of climate states such as a glacial or interglacial also provide valuable insight into the temporal patterns of climate behavior that occur in response to a particular change in forcing. The temporal and spatial behavior of the climate system during a transient change from one climate state to another, such as last deglaciation or the PETM, is a prime opportunity to test how the climate system responds when forcing changes rapidly and will provide valuable insights into how the Earth system will respond to the predicted rise in greenhouse gas concentrations over the next century.

Question 5 - How does the geological record inform us about past abrupt changes in climate under a variety of different boundary conditions, past climate states, or during periods of large and rapid changes in forcing? (CCSP Strategic Research Questions 4.3 and 4.4)

Both data and models support the notion that the Earth's climate system does not always respond linearly to external forcing and, even in the apparent absence of forcing, is capable of abrupt transitions between states. The U.S. Climate Change Science Program strategic plan has identified assessing the likelihood of future abrupt climate change as a key question (CCSP Strategic Plan Question 4.3), and identifies a need for improved paleoclimate data sets and rigorous paleoclimate modeling studies in order to identify the causes and mechanisms of past abrupt climate change. In particular, this document underscores the need to understand the relationship between abrupt climate change and (1) ocean circulation, particularly related to deep water formation, (2) sea-ice transport and processes, particularly where they interact with deep water formation (3) land-ice behavior, (4) modes of atmospheric variability and how they are altered by changes in mean climate conditions, and (5) the hydrological cycle, including storage, runoff and permafrost changes.

The specific research questions described below define abrupt climate change following CCSP SAP 3-4: A large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems:

- What caused abrupt changes in water availability in the past?

- Were there abrupt shifts in the character of modes of atmospheric variability and the frequency of extreme weather events?

- What drove abrupt changes in ocean circulation and the climate response to these changes?

- How abruptly did sea ice distribution and land ice amount change in the past and what were the dominant controls on the rates of change?

The onset of drought conditions in the paleoclimate record is often abrupt, even when the forcing is gradual. It is hypothesized that vegetation feedbacks provide at least some of this nonlinear response. Areas of the world where rainfall is controlled by the monsoons seem to be particularly prone to this threshold behavior in the past. As the climate system responds to the additional radiative forcing provided by greenhouse gases it is of great importance to society to be able to predict when and under what conditions these abrupt shifts to drought will occur, and to identify whether an ongoing shift to drought is likely to be permanent or temporary.

We need to know the extent to which abrupt climate changes are associated with changes in the modes of atmospheric variability (*e.g.* enhanced or reduced ENSO activity, more persistent positive or negative NAO). Indeed, are the changes in the behavior of these modes the fundamental mechanism behind the abrupt climate changes? Or does the behavior of these modes change in response to the abrupt climate changes that have their origin elsewhere? Can they provide a mechanism to globalize the abrupt changes?

In order to better constrain the likelihood of future abrupt changes in ocean circulation and to test the coupled ocean-atmosphere models used to predict these changes we need to better understand the relationship between the magnitude, location and duration of fluxes of freshwater and heat at the sea surface and changes in ocean circulation. Model improvements such as better resolution and representation of deepwater formation processes are also necessary. A more complete set of paleoclimate observations is also needed to identify the global response of the climate system to changes in ocean circulation.

Better records of past sea ice extent and the relationship between sea ice and climate change are needed to explore whether the mechanisms that lead to non-linear behavior in models have operated in the climate system. Future predictions of the rate of sea level rise are also highly uncertain due to our incomplete knowledge of the response of ice sheets to climate change. A more complete set of paleoclimate observations will be needed to document the past rates of change in ice sheets and the climate forcing that caused the changes. These data sets will lead to the development of more complete ice sheet models and better constrain future predictions of ice sheet melting.

A research plan to address abrupt climate change will require a deeper understanding of the ocean, atmosphere, biosphere and cryosphere as well as the geologic archives within which the paleoclimate information is recorded. This can only be accomplished via an interdisciplinary and interdivisional research program and a close collaboration between observationalists and climate modelers. Integrated data/model studies will be particularly useful in understanding both how the coupled climate/biotic system can respond abruptly to gradual forcing, as well as how abrupt changes in other parts of the climate system (ENSO, annular modes, and MOC) can lead to changes in the hydrological cycle around the globe.

Closer Model-Data Integration

While close integration of data generation and modeling is a general goal of this program, a major new goal will be to provide comprehensive paleoclimate data sets to the IPCC community that can serve as test data sets much as they use their present major model validation target: the 20^{th} century instrumental observations. This is a new challenge to the paleoclimate community because it requires the development of climate targets with sufficiently large signal, low noise, well-constrained boundary conditions of the land-sea-ice-biosphere distribution, accurately-determined radiative forcing, and paleoclimate reconstructions with chronologies able to identify short-term changes in climate with well-resolved spatial distributions. The instrumental records currently used by IPCC have, in spite of their low noise, a low signal of climate change for long term climate trends. A goal of this research will be to encourage syntheses of paleoclimate data and modeling to understand the response to the longer-term and higher magnitude variability in the climate system observed in the geological record.

The proposed targets include several intervals that have been the subject of previous syntheses (the LGM, 6K, the mid-Pliocene), several time-transient targets (the last several millennia, the Younger Dryas, the mid-Holocene transition) and several new targets from past warm intervals in Earth history (including the Paleocene-Eocene Thermal Maximum). The activities will involve synthesis of the existing data and regular updating of the syntheses with new observational data. The syntheses will be developed through regular meetings of the involved PIs (modelers and data providers) and the principals active in the continuing evaluation process of climate system models as part of IPCC.

Appendix 1. Strategic research questions identified as priorities by the US Climate Change Science Program in the program element "Climate Variability and Change" (http://www.usgcrp.gov/usgcrp/ProgramElements/understanding.htm).

- Question 4.1: To what extent can uncertainties in model projections due to climate system feedbacks be reduced?

- Question 4.2: How can predictions of climate variability and projections of climate change be improved, and what are the limits of their predictability?

- Question 4.3: What is the likelihood of abrupt changes in the climate system such as the collapse of the ocean thermohaline circulation, inception of a decades-long mega-drought, or rapid melting of the major ice sheets?

- Question 4.4: How are extreme events, such as droughts, floods, wildfires, heat waves, and hurricanes, related to climate variability and change?

- Question 4.5: How can information on climate variability and change be most efficiently developed, integrated with non-climatic knowledge, and communicated in order to best serve societal needs?

Appendix 2. Post-ESH Workshop Steering Committee.

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Appendix 3. Workshop participants.

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Appendix 4. Workshop agenda

Post-ESH Planning Workshop

AGU Headquarters
2000 Florida Ave, NW
Washington, DC 20009
March 29-30, 2007

Thursday, March 29

0830	Meeting room opens – coffee and breakfast fare available		
0900	Welcome and introductory remarks		Lonnie Thompson
0915	History of ESH		David Verardo
0930	Briefing:	Post ESH workshop November 2005 ESH Program Review November 2006	Lowell Stott
1000	Key results and needs identified by IPCC		Jonathan Overpeck
1030	Briefing:	CCSP Abrupt Climate Change meeting March 26-28, 2007	Jean Lynch-Stieglitz
1100	Coffee break		
1115	"Climate Sensitivity from Paleoclimate Data and Models"		David Lea
1200	Lunch – served at the meeting room		
1300	Discussion of Post-ESH Research Themes: Are these the right questions?		Michael Mann

Questions from the Post-ESH Workshop:

- Is the instrumental record of climate variability unusual in the context of the past several thousand years?
- What role do cryospheric feedbacks play in climate change?
- What is Earth's climate sensitivity to changes in radiative forcing?

- How do ENSO and/or other coupled modes respond to changes in forcing? How does ENSO respond to changes in mean climate state?

- Is there a link between changes in ocean circulation and climate?

- What factors within the climate system are responsible for the observed correlation between climate change and solar forcing at shorter than Milankovitch time scales?

"Major" Challenges Identified by the ESH Program Review:

- Is the warming of the past several decades unique? To what extent can these changes be attributed to either anthropogenic or natural forcing?

- How does the climate system respond abruptly to internal and external forcing?

- How will regional and temporal climate variability change in response to global change?

- What is the nature of climate sensitivity to internal and external forcing? Can we increase our confidence in the sensitivity of climate models used to predict the future?

- How sensitive are the climate features of most significance to human populations (*e.g.* extreme weather events) to changes in forcing?

1500 Coffee break

1515 Continued discussion — Bette Otto-Bliesner

1700 End of first day

Friday, March 30, 2007

0830 Meeting room opens – coffee and breakfast fare available

0900 Plenary meeting – is there a consensus of the group? — William Curry

0930 Task assignment – break into small groups for further discussion and writing assignments

1200 Lunch - provided at the meeting room

1600 Plenary meeting and adjournment — William Curry