

# **Paleoclimate Research Workshop Report, 12-2005**

## **Executive Summary**

For the past several years the National Science Foundation has sponsored research under the auspices of the Earth System History (ESH) initiative that has investigated how the Earth's climate has varied during the Holocene. The primary objective of this initiative has been to extend our understanding of the natural variations that take place within the Earth's climate system in the absence of human influence and to compare the temporal and spatial patterns of variability during the Holocene to that of the short instrumental period. This research has required coordinated and cooperative participation of many scientists from different disciplines. The ESH sponsored research has produced findings that indicate the short instrumental record is an inadequate benchmark from which to evaluate whether or not the 20<sup>th</sup> century climate is changing in response to anthropogenic forcing alone. It is now known, for example, that there have been repeated abrupt and regionally extensive climate changes in the past that are not evident within instrumental period. The fact that such climatic variability has not recurred during the instrumental record has likely contributed to some complacency about the prospects of large and unanticipated climate shifts in the future as atmospheric greenhouse gas concentrations continue to rise. Information derived from paleoarchives that can extend the instrumental record is the best opportunity we have to quantify how the climate system varies naturally in response to changing boundary conditions and variable forcing. Paleorecords also provide the only effective way to quantify how rapidly climate will respond to varying forcing and what the impacts of climate change will be on ecosystems. Recent climate events such as Hurricane Katrina and the rapid changes in sea ice taking place at high latitudes today underscore the need to improve our understanding of how the global environment will respond to climate change. Paleoclimate research that ultimately leads to improved estimates of the climate and environmental behavior is therefore timely and of great societal importance.

Quantitative estimates of climate variability can now be obtained with a high degree of accuracy and precision from paleo-proxies such as tree ring chronologies, Mg/Ca and stable isotopic thermometry from fossil carbonates, as well as other geochemical and sedimentologic recorders. Variations in the rate of ocean ventilation and rates of circulation can also be obtained from proxies that are extracted from marine sediment cores. The data base of proxy information contains evidence of repeated large and regionally extensive changes in atmospheric and oceanic temperatures throughout the Holocene. In some instances these changes were associated with hydrologic variability in monsoon regions and with drought in drought-prone regions, including portions of the United States. The magnitude and frequency of the climate variations during the Holocene cannot be attributed to anthropogenic influence and therefore reflect Earth's natural climate variability (a summary of Holocene climate reconstructions is available

for download from the ESH website @ [earth.usc.edu/ESH](http://earth.usc.edu/ESH)). But while it is clear that Earth's climate is much more variable than previously thought, the factors that govern the spatial and temporal patterns of variability are not well understood. Solar variations may have been a critical factor, but at present there exists only circumstantial evidence for solar variability influences on Earth's climate at time scales ranging from decades to centuries. The meridional overturning circulation of the ocean (MOC) may also have varied in the past, but the available evidence indicates that during the Holocene variations in MOC were relatively modest in comparison to those of the earlier glacial period. It is not yet clear whether small changes in the MOC influenced Holocene climate variability. Stratospheric aerosols released from large volcanic eruptions have clearly influenced Earth's mean temperature over the past several centuries. But on longer time scales the record of large eruptions is not well documented, and it has not been possible to quantitatively assess how important explosive volcanism has been in affecting larger changes in Earth climate. It is also possible that there has been substantial stochastic variability in the climate system that has no clear external forcing. Some regions also appear to have been climatically more variable during the Holocene compared to other regions. Paleoarchives have revealed, for example, that during the past ten thousand years the high northern latitudes experienced larger oceanic and atmospheric temperature change than did the low latitudes. Yet, despite smaller changes in temperature, the low latitude regions have experienced substantially greater hydrologic variability. This observation is of particular importance because today millions of people live within monsoon regions where even small changes in the amount of monsoon rainfall can lead to devastating consequences.

There is an urgent need to advance our understanding of how the climate system will respond to the rising concentrations of greenhouse gas in the atmosphere and how specific parts of the climate system, including the hydrologic cycle, will be affected. Modeling efforts are particularly useful in this effort because they provide a globally integrated picture of the climate system. But even the most sophisticated models have large uncertainties when projections extend to decades and longer. The best opportunity we have for advancing our understanding of climate behavior on these time scales is a research program that utilizes both models and paleoclimate data. Paleoclimate proxies represent the only source of climate data for time scale that extend beyond the short instrumental period. With this goal in mind a workshop was convened at the National Science Foundation from November 28 to December 1, 2005 that brought paleoclimate scientists together to discuss ways that a directed research program might lead to advances in our understanding of the factors that have controlled Earth's natural climate variability in the past. As chair of the ESH science steering committee, Lowell Stott was asked to moderate the discussions. Each participating scientist was asked to consider what they believe to be the most pressing and important questions that should be addressed by the paleoclimate community in an effort to advance our knowledge in the next few years. The discussions highlighted six important scientific questions confronting the climate science community that require coordinated, multidisciplinary efforts on the part of many scientists in order to advance our knowledge. In each case a focused research program that seeks to answer these questions would likely have an

immediate benefit to society as it develops strategies for adjusting to future climate change.

The scope and complexity of the questions facing the climate science community cannot be tackled by individual researchers. The questions outlined in this document require a coordinated and collaborative effort on the part of the paleoclimate science community in order to move the science forward and advance our understanding of Earth's natural climate variability and its causes. No single investigator has the breadth of expertise required to tackle the questions alone. However, as the Holocene Earth Science History initiative illustrated, it is highly effective when individuals with different expertise work together in efforts to advance our knowledge. A coordinated and focused scientific initiative such as ESH represents the best way for the paleoclimate community to achieve its stated objectives.

### **Questions:**

**I. Is the instrumental record of climate variability unusual in the context of the past several thousand years?**

**II. What role do cryospheric feedbacks play in climate change?**

**III. What is Earth's climate sensitivity to radiative forcing changes?**

**IV. a. How do ENSO and/or other coupled modes respond to changes in forcing?  
b. How does ENSO respond to changes in mean climate state?**

**V. Is there a link between changes in ocean circulation and climate?**

**VI. What factors within the climate system are responsible for the observed correlation between climate change and solar forcing at shorter than-Milankovitch timescales?**

**I. Is the instrumental record of climate variability unusual in the context of the past several thousand years?**

Since 1976 global mean average temperatures have increased steadily by  $\sim 0.7^{\circ}\text{C}$ . This trend in the instrumental record has coincided with the rise in greenhouse gas (primarily  $\text{CO}_2$  and  $\text{CH}_4$ ) over the same period and leads to increased confidence that warming global temperatures are due in part to an enhanced greenhouse effect. However, the three decades prior to 1976 were relatively cool, and there was no clear relationship between temperature and the rise in greenhouse gas concentrations. On the other hand, general circulation and energy balance models that incorporate explosive volcanism and stratospheric aerosol forcing suggest that the apparent lack of a discernable warming prior to 1976 could be explained by the competing influences of various negative forcings and feedbacks within the climate system.

In the past five years the paleoclimate community has worked to extend the instrumental temperature record back in time with proxy reconstructions that resolve mean annual temperatures (MAT). This has largely been accomplished using dendroclimatology, a method that translates tree ring width data to temperature. These records have now extended the MAT record to more than a thousand years. Within these extended records there are patterns of change on decadal and century time scales, but the late 20<sup>th</sup> century warming trend stands out as the most anomalous warm interval. In fact, it now appears that the years of 1998 and 2005 are two of the warmest years on record over the past 1000 years. Yet, there remains a large uncertainty in the proxy estimates of mean annual temperature, particularly in the so-called “Medieval Warm Period” and the subsequent ‘Little Ice Age’. Furthermore, there is only limited information about temperatures in other regions outside the middle northern hemisphere latitudes. Hence, it is not possible to say with certainty how unique the late 20<sup>th</sup> century warming trend actually is on a global scale or how unique it is in the context of Earth’s longer term history of natural variability. Perhaps even more importantly, the reconstructed temperatures do not resolve how the climate system as a whole has changed. Hydrologic variability, including monsoon variability, drought frequency and flooding, are variables that are likely to be of great concern to human society in the coming decades, and how these aspects of the climate system have varied naturally in the past is simply not known.

There is a pressing need to reduce the uncertainties in the proxy estimates of past climate variability over the past four thousand years. This interval of time offers the best opportunity to assess the uniqueness of the late 20<sup>th</sup> century climate history. The forcings during this period are most like those of the present and there is a high degree of confidence that records from all parts of the globe can be acquired from this time interval in order to develop a comprehensive global coverage. By establishing a comprehensive data base of climate information from the past four millennia it will be possible to use model simulations to assess how the system responds to specific forcing on time scales of decades to centuries. This is a necessary endeavor if we hope to establish with certainty how much of the 20<sup>th</sup> century warming has been caused by rising greenhouse gas concentrations and how the Earth’s climate is likely to vary in the future as atmospheric and oceanic temperatures rise.

### **Scientific Objectives:**

1. To quantify regional temperature and hydrological patterns, particularly in the tropics and monsoon regions where existing data are sparse. Previous and ongoing research has documented changes in the amount of monsoon rainfall in parts of China and India that appear to have been coincident in time with atmospheric and oceanic temperature changes at high northern latitudes during the Holocene. This correlation needs to be validated or rejected and if found to be robust, there is a need to conduct computer modeling experiments that can elucidate the dynamical relationships between these regions. If there exists a strong relationship between climate changes in the high latitudes and in the monsoon regions there is a critical need to develop good estimates of how the dynamical relationship responds to changes in radiative forcing at high and low latitudes.

2. To better quantify rainfall estimates and the duration of droughts in regions outside of North America and Europe.

3. To generate complementary records of terrestrial and ocean surface temperatures. Sea surface temperatures can now be estimated using Mg/Ca and alkenone paleothermometry for marine cores, and Sr/Ca for surface corals. These methodologies have undergone significant improvement over the last ten years. At the present time there are specific calibrations that allow sea surface temperatures to be estimated for specific sites to within 1°C for marine sediments and to within 0.5°C for surface corals. However, in order to reconstruct changes in spatial SST patterns through time (a key feature of many oceanic dynamical modes, e.g., ENSO, AMO) the accuracy of sea surface temperature estimates will need to be improved. There is some confidence that this can be done, but it will require a large community effort. Similarly, there is a need to improve atmospheric (lower troposphere) temperature estimates in low latitude regions, particularly the tropics. Tree ring climatology in tropical trees has been improving but calibrations need additional work. Also, improving methods are making it possible to extract better rainfall estimates using the oxygen isotope composition of tree cellulose. This technique has the distinct advantage of being able to resolve seasonal and annual temperatures (tree ring width) and rainfall (oxygen isotope composition) at the same location.

## **II. What role do cryospheric feedbacks play in climate change?**

A rapid retreat of sea ice around the Arctic Ocean since the mid-1970's has prompted concern that the Arctic could become ice free during this century. In addition, the melting of land-based glaciers and ice sheets in polar regions could lead to a profound rise in global sea level and perturb thermohaline circulation. At low latitudes seasonal snow cover as well as high elevation glaciers have shown recent signs of retreat. Paleoclimatic research can address key questions about the response of sea and land ice to warming in the past, and regional environmental impacts.

Recently detected, rapid changes in today's ice sheets contributing to sea-level rise may indicate greater ice-sheet sensitivity to warming than previously considered. Ice sheets represent the largest readily exchangeable reservoir of fresh water on Earth. Past ice sheets had a large impact on Earth's climate by rearranging continental drainage paths and by changing the Earth's topography and albedo, with attendant affects on atmospheric and oceanic circulation and mean climate state. Associated changes in atmospheric energetics and continental runoff caused changes in the global hydrological cycle, and changes in albedo contributed as much as 50% of the total LGM radiative forcing. Ice-volume changes caused a measurable change in the salinity and  $\delta^{18}\text{O}$  composition of the global ocean. Finally, the redistribution of mass involved in the growth of ice sheets and attendant eustatic lowering significantly impacted solid Earth geodynamics.

Sea ice variations may constitute an important climate amplifier that influence how the high latitude climates respond to rising atmospheric temperatures. Sea ice also constitutes an important influence on ocean ventilation and therefore on the exchange of CO<sub>2</sub> between the ocean and atmospheric reservoirs. At the last glacial termination sea ice retreat in the southern ocean appears to have coincided with the rapid rise in atmospheric CO<sub>2</sub>, leading to the idea that the southern ocean sea ice extent may act as a capacitor to atmospheric CO<sub>2</sub> exchange. If so, it is an important regulator of Earth's climate. However, several studies have questioned the efficiency of this capacitor for regulating atmospheric CO<sub>2</sub>. Paleoclimate research is needed that would establish how (or if) sea ice has influenced the history of atmospheric CO<sub>2</sub> in the past. There is currently no clear explanation for the rapid rise in atmospheric CO<sub>2</sub> at the end of the last ice age. Research that focuses on the past several glacial/interglacial cycles, for which there exists detailed ice core CO<sub>2</sub> records, would offer the best opportunity for the paleoclimate community to establish how/if changing sea ice influenced atmospheric CO<sub>2</sub> and climate.

Warm intervals and interglacials such as the Eemian (MIS 5e), MIS11, or intervals during the mid-Pliocene offer additional opportunities to evaluate climate system response to changing sea ice cover and ice-sheet volume and whether there is a specific scale or polar amplification factor. Of particular interest is the sensitivity of the system to rapid changes in sea ice extent and vegetation with respect to changes in precipitation and albedo feedbacks, like that expected to occur over the next half century. Current model experiments disagree in modeling polar amplification during different time periods and in evaluating changes in polar-equator gradients.

Several key questions that should be addressed include:

- 1.) How do precipitation, vegetation and temperatures at high latitudes change with Arctic basin ice extent?
- 2.) On what time scales does the high latitude climate respond to changing sea ice extent? Is there a threshold in sea ice extent that would, if exceeded, lead to rapid and large changes in temperature (and further sea ice retreat) at high latitudes?
- 3.) In the northern and southern high latitude oceans, sea ice coverage and the freshwater balance have important influences on the stratification of the ocean and the capacity of the ocean to convect. Has the MOC varied in the past in response to changing sea ice extent and freshwater flux changes?
- 4.) What is sensitivity of ice sheets to varying levels of climate change? How rapidly do ice sheets lose or gain mass, and thus change sea level? Do ice sheets play an integral role in affecting the salinity of adjacent areas of deepwater formation?

### **Scientific Objectives:**

1. To develop improved proxies for sea ice cover (open ocean and coastal).

2. To collect suites of cores along transects that provide spatial coverage across key parts of the sea ice regime where sea ice waxes and wanes. Single site or single transects are inadequate because sea ice may undergo complex shifts that would not be captured in a single core or transect. Collecting cores not a good scientific objective. Should state what will be tested with new cores.
3. To integrate proxy data and modeling in sensitivity experiments using coupled GCMs that incorporate sea ice routines.
4. To further establish changes in global ice volume and its relationship to climate change by developing high-resolution, well-dated records of eustatic sea level from direct measures (e.g., corals) or from the oxygen-isotope record in benthic marine carbonates corrected for temperature change by proxies such as Mg/Ca.
5. To develop well-dated records of individual glacier and ice-sheet fluctuations to infer how these responded to climate change in the past in order to guide and test models needed to understand future sea-level change.
6. To evaluate, through models and data, the role of ice sheets in the hydrological cycle and their influence on the ocean meridional overturning circulation.

### **III. What is Earth's climate sensitivity to radiative forcing changes?**

Climate sensitivity, the response of the climate system to a specific level of radiative forcing, is the key uncertainty in projections of future climate change (IPCC, 2001). But clearly the response of the climate system to the progressive increase in radiative forcing due to greenhouse gases will be the dominant factor determining the climate state of the next several centuries. Paleoclimate records provide the opportunity to directly calibrate the response of the climate system to specific levels of forcing. Paleoclimate data provides the opportunity to map the response of different climate variables, including temperature, precipitation, ice volume, and associated feedback including the carbon cycle and ecosystem changes. Paleoclimate records also provide a measure of how key climate variables respond in the time domain to a specific forcing. Finally, paleoclimate data allows for the verification of model physics under boundary conditions that are very different than the present but analogous to the high CO<sub>2</sub> world that will evolve over the next few centuries. Paleoclimate data also can lead to the causes of the non-linear climate behavior associated with the D-O temperature fluctuations over Greenland during Marine Isotope Stage 3 or the factors responsible for the onset of glaciation in Antarctica at OI-1 (34 MA BP).

Advances in the estimation of climate sensitivity from paleoclimate data would ideally help narrow the canonical range of sensitivity, 1.5-4.5°C for a doubling of CO<sub>2</sub> that has been accepted since the Charney report (1979). For this reason, climate intervals for which quantitative estimates of greenhouse gas forcing can be made and the associated climate response can be determined must be the primary targets. For some

more distant time intervals (i.e., the Paleocene/Eocene Thermal Maximum, PETM), it should be possible to infer greenhouse gas levels from associated changes in oceanic carbonate parameters.

Examples of time intervals in which we expect that the most quantitative and improved estimates of climate sensitivity can be made include the Last Glacial Maximum (LGM) (19-23 kyr BP), for which there is broad data coverage and records, high signal to noise ratio, the capability to establish accurate age estimates via radiocarbon and U-Th disequilibrium dating, and a known and well studied forcing change associated with greenhouse gases, ice albedo, land surface changes and aerosols. Some initial attempts to determine climate sensitivity from LGM data show promise because they yield values within the Charney Report's canonical range, but these studies either rely on data from one site or on very broad global averages. It should now be possible to achieve comprehensive data coverage for the LGM that would allow a much more specific assessment and estimate of climate sensitivity that would include how temperature and other climatic parameters respond in specific regions to a specific forcing and associated feedbacks. Such an assessment promises to improve our understanding of the Earth's climate behavior resulting from a specific forcing through validations of general circulation model results.

A second objective is to target interglacial time periods that had similar greenhouse gas levels as the late Holocene but climatic conditions that were different. Targeted warm intervals might include MIS 5e (125 kyr BP), which was estimated to have been 1-2°C warmer than the Holocene, had higher sea level, 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. MIS 11 is also a compelling time interval for study because orbital parameters were similar to the present. But because there does not currently exist an extensive data set of proxy reconstructions 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 might include the Pliocene warm period, Eocene/Oligocene transition and two early Eocene hyperthermals, the PETM and ELMO. Recent data from the Pliocene suggests that the tropical Pacific might have been in a continuous El Niño state. How would such a large shift be manifested in terms of the sensitivity of the tropics to external forcing? The PETM might have experienced a change in CO<sub>2</sub> and greenhouse forcing that was similar in magnitude to the anthropogenic changes. There is also some indication in data from this time interval that changes in atmospheric CO<sub>2</sub> approached the rapidity of changes within our own time. The PETM might also provide an appropriate analogue to the emerging problem of ocean acidification associated with carbon dioxide invasion into the ocean.

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. A focused research program that investigates how the behavior varies in response to variable rates of change in forcing would provide valuable insight about how Earth's climate could respond in the future to a continual rise in greenhouse gas concentrations. The temporal and spatial behavior of the climate system during a transient change from one climate state to another, such as the deglaciations or the PETM, is a prime opportunity to test how the climate system responds when the forcing changes rapidly. Such research would provide the closest analogue to the evolution of the modern climate system in response to the increase in greenhouse gases.

### **Scientific Objectives:**

1. to obtain highly resolved Mg/Ca and alkenone unsaturation paleothermometry estimates of sea surface temperature in key oceanic regions. Long cores will be required from key oceanic regions such as the tropical warm pools that extend through warm time periods. This will require additional coring operations.
2. Where possible, to obtain paleoestimates of atmospheric temperature from continental proxies such as pollen. Other proxies of atmospheric temperature need to be investigated.

Note: this work should be coordinated with other European efforts such as MARGO to ensure maximum data coverage and avoid duplication.

#### **IV. a. How do ENSO and/or other coupled modes respond to changes in forcing? b. How does ENSO respond to changes in mean climate state?**

The El Niño-Southern Oscillation (ENSO) represents the largest source of global-scale interannual climate variability, exerting a dominant influence on societal relevant climate phenomena ranging from monsoonal rains to Western U.S. drought. Two additional interannual coupled climate modes, the North Atlantic Oscillation (NAO) and the Indian Ocean Dipole (IOD) play key roles in determining climate patterns in and around the Atlantic and Indian Ocean basins, respectively. On decadal to multi-decadal timescales, the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) extend the climate impact of coupled ocean-atmosphere interactions to lower frequencies, and have been linked to U.S. fisheries catches (PDO) and Atlantic hurricane activity (AMO). A focused effort on understanding of the dynamics of these modes of variability in past centuries and millennia can shed considerable light on our understanding of the roles of these modes of variability in future climate change.

Global climate models yield a wide range of responses of the tropical Pacific ocean-atmosphere system to continued greenhouse forcing. Specifically, large

uncertainties in the tropical Pacific zonal SST gradient and/or ENSO variability prevent meaningful long-term predictions of regional temperature and precipitation patterns. Given the role of ENSO on interannual drought variations in the Southwestern U.S., it is relevant to ask whether long-term variations in ENSO may be associated with century-scale variations in drought in the region. Preliminary evidence suggests a relationship between long-term changes in natural radiative forcing, the character (mean state and variability) of ENSO, and past variations in drought in the western U.S. If these relationships are robust, they may have important implications for the response of ENSO and North American drought to anthropogenic radiative forcing.

Paleoclimate research can help to address such societal relevant questions by providing definitive answers to the following research questions:

1. Is there any evidence that ENSO responds to a) external forcing, and/or b) changes in mean climate state?

ENSO exhibits significant natural variability with in frequency and amplitude, but as yet there is no statistically significant evidence that ENSO responds to either external forcing or changes in mean climate state.

Time period for focused research: LGM (warm vs. cold mean climate), mid-Holocene (orbital forcing), last millennium (volcanic/solar forcing)

2. Do low-frequency (decadal to millennial) changes in the tropical Pacific's zonal SST gradient play a primary role in shaping global climate patterns? Are these changes independent of ENSO variability?

Subtle yet prolonged changes in the tropical Pacific's zonal SST gradient (i.e. PDO) likely have a profound effect on global climate patterns, yet the nature of such variations, and their global impacts, remain largely unknown. A related question concerns the extent to which such low-frequency changes shape the amplitude and frequency of ENSO.

Time period of focused research: Holocene

North Atlantic climate variability (NAO and AMO) affects climate patterns in Europe and along the East Coast of North America, and may affect larger-scale climate across the northern extratropics, including the Pacific and the continental U.S. The coupled ocean-atmosphere dynamics that give rise to the NAO are fairly well understood. What is less well understood are the factors determining NAO-related climate on longer timescales, such as the AMO. Modeling experiments suggest that the AMO is a coupled model of ocean-atmosphere variability involving interrelationships between the North Atlantic meridional overturning circulation, sea surface temperatures and salinity over the tropical and extratropical North Atlantic, with larger-scale atmospheric teleconnections to the rest of the Northern Hemisphere. Past studies using climate proxy data suggest that the AMO has been a persistent mode of variability for at least the past several centuries. A number of outstanding questions nonetheless remain: (1) how persistent is the AMO

further back in time, through the so-called “Medieval Climate Anomaly” and beyond?; (2) What is the role of both the ocean and atmosphere in determining the behavior of the AMO? In particular, to what extent is the AMO related to changes in the North Atlantic thermohaline circulation of the ocean, and the North Atlantic Oscillation (“NAO”) pattern of variability in the atmosphere?; (3) What, if any, are the connections between the AMO, and past variations in societal relevant phenomena such as Atlantic Hurricane activity, and North American continental drought patterns?; (4) What are the relative roles of internal variability vs. external forcing, in the past behavior of the AMO?

The Indian Ocean Dipole (IOD) was uncovered in 1998, shortly after Indian monsoon predictions during the large El Niño event of 1997 proved wholly inaccurate. Indeed, interactions between the Indian and Pacific Oceans on interannual to millennial timescales likely play a role in the evolution of individual El Niño events, decadal to centennial monsoon variability, and perhaps even mechanisms of abrupt climate change. The IOD remains severely understudied with respect to the ENSO and NAO phenomena. Knowledge of its role in global climate variability could be improved by answering the following questions: 1) Do changes in the Indian Ocean SST gradient occur on low-frequency timescales? 2) Are these changes independent of low-frequency changes in the tropical Pacific zonal SST gradient? 3) How do low-frequency changes in the ocean-atmosphere system in the Indian Ocean affect regional temperature and precipitation patterns? 4) Does the IOD (or its low-frequency equivalent, if it exists) respond to external forcing?

The potential payoff of focused activities in this area is quite clear. ENSO and other coupled climate modes may play a significant role in future, anthropogenic climate change. Furthermore, such phenomena are known to play key roles in societal relevant climate impacts associated with monsoon variability, continental North American drought, and destructive Atlantic Hurricane activity. To the extent that we can better document and understand the sources of past variation in ENSO and other coupled modes, we will be in a better position to assess how climate change may influence these societal relevant climate impacts.

### **Scientific Objectives:**

1. Priority 1, Focused research on the last two millennia.

Significant advances towards answering the above questions can be made by focusing paleoclimate reconstruction and modeling efforts on the last 2ky, when there exists the highest potential for high-resolution (annual to monthly-resolved) reconstructions of ENSO and other coupled climate modes. The histories of external forcing are also relatively well-constrained through this time interval, enabling the direct comparison of external forcing reconstructions and the climate variables of interest. Moreover, a timeframe of the past two millennia will help us place 20<sup>th</sup> century changes in the context of long-term natural variability. Finally, a targeted program in this area should encourage the close collaboration of researchers involved in the development of these proxy data and the associated climate reconstructions, with climate modelers. Such

activities are most likely to provide insight into the causal factors underlying past observed changes.

Investigations of the magnitude and global impact of low-frequency variations in the tropical Pacific (ENSO), North Atlantic (NAO), and tropical Indian (IOD) Oceans will require both high- and low-resolution records of temperature and/or hydrological variability from centers of action as well as strongly teleconnected regions. For example, by directly comparing indices of ENSO variability (from fossil corals and/or speleothems), low-frequency records of tropical Pacific climate, and low-frequency records from ENSO-teleconnected regions over the last 2ky, it will be possible to distinguish ENSO variability and its signature in the paleo-record from low-frequency tropical Pacific variability and its signature in the paleo-record. Paleoclimate modeling studies are required both to maximize the information derived from a sparse, heterogeneous set of paleoclimate data, and to isolate the dynamics that are most important in moderating the relationship between external forcing, coupled ocean-atmosphere variability, and climate responses in teleconnected regions.

2. Priority 2. Focused research on the last 60ky (the early- and mid-Holocene; LGM; stage 3)

After the 2ky exercise is completed, similar types of records from other periods of interest (early- to mid-Holocene, LGM, and stage 3) can be generated, their interpretation significantly aided by the 2ky focus. These longer, lower-resolution records are required to address if and how ENSO and tropical Pacific mean state responded to a variety of forcings and background climate conditions.

#### **Potential tools and approaches for 2ky project**

- Data mining exercise to determine what data are available for last 2ky.
- Support interdisciplinary teams of paleo-data and paleo-modeling researchers that will develop data assimilation strategies towards resolving large-scale climate patterns in paleo-networks.
- Focus on generating data from tropical Pacific centers of action and regions with strong ENSO teleconnections at seasonal to multi-decadal resolution.

#### **Immediate needs:**

1. fossil coral data from the tropical Pacific ( $\delta^{18}\text{O}$  and Sr/Ca), monthly-resolution
2. speleothem records from strongly ENSO-teleconnected regions (with emphasis on pursuing subannual-resolved data and much-needed on-site calibration work)
3. high-resolution (decadally-resolved) marine cores from the tropical Pacific

### **V. Is there a link between changes in ocean circulation and climate?**

It is well documented that there is a tight coupling between changes in deep ocean circulation and climate on millennial time scales during the last glacial epoch. The most recent example of this occurred during the Younger Dryas (YD) cooling of about 12,000

years ago. At that time, many proxy data such as  $\delta^{13}\text{C}$ , Cd/Ca,  $\Delta^{14}\text{C}$ , and Pa/Th show that an older and more nutrient-rich water mass of probable southern origin replaced North Atlantic Deep Water (NADW), and less dense northern source water occupied intermediate water depths. Although some of the best data come from the YD, abundant evidence indicates that a similar "switch" in water masses occurred during the LGM and during earlier millennial-scale events (such as D-O events). Climate models show that reduced production of NADW is associated with reduced heat flux in the North Atlantic region through interruption of the so-called "conveyor," and indeed large international programs are geared to studying the future threat of breakdown of the Atlantic's meridional overturning circulation (MOC).

Modeling is a critical element of paleo-circulation studies. At present, coupled ocean-atmosphere models disagree about the timing and severity of changes in the MOC in response to elevated  $\text{CO}_2$  levels. These same models, when prescribed glacial boundary conditions, produce strengthened or weakened, shallower or deeper Atlantic MOC. We are in a unique position to contribute to this debate by providing data for past changes which have likely been larger than those observed over the instrumental period.

Because there is evidence that millennial-scale climate changes continue from the Pleistocene right through to the Holocene, it is logical to ask if there have been important changes in ocean circulation in the present interglacial epoch. This question can be answered through multiproxy measurements in samples from deep ocean sediment drifts, where sedimentation rates are sufficiently high. However, if something like the glacial mode of ocean operation continued in the Holocene, then there should be a ventilation or circulation signal of opposite sign at intermediate depths. In the Pacific Ocean, where laminated sediments are often found at intermediate depth associated with the oxygen minimum zone, it should be possible to document ventilation changes on the continental margin.

What might cause such changes in circulation? Climate models often introduce massive quantities of fresh water to the surface ocean to initiate changes in the MOC. Although these "hosing experiments" are unrealistic except perhaps for Heinrich events, it is well known from these studies and from paleo data that changes in fresh water distribution have probably affected climate in the past. This is especially true as the last great ice sheets melted, but hydrological changes associated with the ITCZ, and with the East Asian Monsoon, for example can significantly affect salinity of the surface ocean, and these salinity changes can feed back on the large-scale ocean circulation and the MOC. Atmosphere-ocean couplings like this provide a mechanism for affecting climate on decadal, centennial and longer time scales and a better understanding of this coupling may help to better forecast the climate changes expected in the next century. Thus, research on this topic draws together various disciplines as it seeks to integrate atmospheric changes in moisture flux, runoff from land, melting of glaciers, the salinity distribution of the surface ocean, and resulting changes in deep ocean circulation.

## Scientific Objectives:

1. To generate robust time series of past changes in Atlantic MOC
  - We will need to use multiple tracers of water mass characteristics and those which contain information about rate.
  - The best time interval for initial studies is the last 40kyr (when radiocarbon can be used for dating and as a water mass tracer) at highest possible resolution
  - Identify location and properties of deep water mass end members
2. To reconstruct the global climate impacts of the Atlantic MOC changes
  - Develop proxy records of climate such as SST and atmospheric temperature changes at the same timescale over large regional scales.
  - Determine heat transport associated with MOC changes
  - Southern hemisphere records are particularly needed
  - Records of hydrologic variability will be particularly relevant for human impact
3. Improve ocean and climate models (ability to produce accurate predictions/reconstructions of MOC and climate impact of MOC changes)
  - Direct comparison of data and models
  - Higher spatial resolution will facilitate the comparison and increase the realism of the ocean processes
    - Better resolve regions of freshwater input
    - Better representation of small scale processes, such as mixing and convection
4. To better quantify which forcing mechanisms have had the greatest influence on MOC changes such as fluxes, discharge location, and pathways of meltwater inputs.
  - Reconstruction of surface hydrography near potential source regions

## **VI. Does solar forcing of Earth's climate take place on suborbital timescales, and if so, how does the climate system respond to this forcing?**

There are a growing number of quality paleoclimate records that appear correlated to proxies for solar variability (e.g., sunspots,  $\Delta^{14}\text{C}$ , and  $^{10}\text{Be}$ ) on suborbital timescales. This suggests a causal relationship between changes in the sun and abrupt climate change. Cosmogenic isotope records are taken as proxies for solar variability because their production rate is modulated by the flux of incoming galactic cosmic rays, which is influenced by the solar wind (and geomagnetic intensity). This relationship is supported by the correlation between annual tree-ring  $\Delta^{14}\text{C}$  and ice core  $^{10}\text{Be}$  with the sunspot record, which exhibit the classic 11 yr (Schwabe) solar cycle and the Maunder Minimum. Longer multidecadal (88 yr) and centennial (~206 yr) periods are also observed in the cosmogenic isotope records. Most paleoclimate records that appear correlated to the solar variability proxies exhibit these longer multidecadal and centennial frequencies. However, this may be a consequence of the records' temporal resolution.

The short and limited instrumental record of solar variability makes it difficult to scale the magnitude of the multidecadal and centennial variations indicated by the proxies. However, such scaling attempts generally agree that climate forcing by the visible spectrum is very weak, a few tenths of a percent of incoming insolation ( $\sim 1\text{W}/\text{m}^2$ ) and climate models predict a small impact on climate. The ultraviolet spectrum may be a better candidate likely having a larger climate forcing through atmospheric chemistry changes in the stratosphere.

Another problem is the fidelity of the solar variability proxies. The extent to which other factors affect the cosmogenic nuclide records is unknown. For example, temporal changes in the residence times of marine and terrestrial carbon reservoirs are likely imprinted on the  $\Delta^{14}\text{C}$  record. Attempts to correct for this create significant offsets (centuries) in the timing of inferred solar changes. Furthermore, there are likely significant regional and local climate change imprints on the  $^{10}\text{Be}$  records. An interesting suite of potentially important observations is the recent recognition of “solar periods” in geomagnetic data sets. If these preliminary observations are borne out with additional studies, climate may not be responding to solar variability, but to the geomagnetic influence on incident cosmic rays. Incident cosmic rays and their particle physics may impact the formation and distribution of cloud condensation nuclei and concomitant insolation scattering effects.

Significant progress in addressing the impact of solar variability on climate will likely come from climate model-paleoclimate data inter-comparisons. Specific spatial patterns of climate change may be associated with the impacts of solar variability. For example, the pattern of climate change associated with the Maunder Minimum implicates decreased solar output as the cause. Currently, it appears that the paleoclimate data that have frequencies similar to or visual correlations to the solar variability proxies tend to be related to regional hydrologic budgets (e.g., monsoon systems), low latitude regions influenced by the strength and position of the ITCZ, and high latitudes (e.g., Arctic).

### **Scientific Objectives:**

1. To establish the fidelity of the solar variability proxies by answering:
  - To what extent have variations in the marine and terrestrial carbon reservoirs impacted the  $\Delta^{14}\text{C}$  record of solar variability during the Holocene?
  - To what extent have variations in local and regional climate affected the  $^{10}\text{Be}$  records of solar variability?
  - To what extent has geomagnetic variability influenced the proxies used to estimate solar variability?
  - To what extent are different proxies of solar variability coherent? Will this require concurrent measurements of each proxy?
  - Is there a true periodic solar variability that has an influence on climate?

2. To map the temporal and spatial components within the climate system that corresponds to estimates of solar forcing change.
  - To generate well-dated high-resolution paleoclimate records of different components of the climate system over broad areas of the Earth.
  - Emphasis should be placed on those climate archives that have the resolution to address multidecadal and centennial-length periods of the solar variability.
  - To determine what aspects of the Earth's climate are most sensitive to changes in solar forcing.
  - To determine whether solar variability excite different modes of variability in ENSO, NAO, AMO and if so what is the mechanism?
3. To utilize climate model-paleoclimate data inter-comparisons to test the mechanisms by which solar variability may impact climate by:
  - Using GCMs with sufficient spatial resolution to determine whether the spatial patterns of past climate change are consistent with climate model predictions forced by changes in solar forcing.

**Recommendations:**

The participants of this workshop wish to propose to the National Science Foundation that support be provided for several follow-up meetings in order to develop science plans for each of the six topics outlined above. Each follow-up workshop would host a small number of representative scientists who would be charged with contacting members of their community for advice and suggestions that would be integrated into a science plan for submission to the National Science Foundation for consideration.

It is also proposed that in conjunction with the implementation of a directed research program on any of these topics, there be regular meetings for PIs. These meetings would provide PIs an opportunity to discuss strategies for coordinating ongoing efforts, discussing collaborative endeavors and promoting better communication within the community. We believe these meetings would help insure that there is good cooperation among scientists and that appropriate progress is being made throughout the program.

The ESH office could act as host for these follow-up workshops and could help coordinate all the logistical aspects of preparing the science plans and communicating with the scientific community. The University of Southern California has appropriate facilities and support staff to insure that the meetings would be productive and successful.

## List of Attendees

Name	E-mail
David Anderson	david.m.anderson@noaa.gov
Julie Brigham-Grette	juliebg@geo.umass.edu
Brendan Buckley	bmb@ldeo.columbia.edu
Kevin Cannariato	cannaria@usc.edu
Peter Clark	clarkp@onid.orst.edu
Kim Cobb	kcobb@eas.gatech.edu
Ed Cook	drdendro@ldeo.columbia.edu
Bill Curry	wcurry@whoi.edu
Bob DeConto	deconto@geo.umass.edu
Peter DeMenocal	peter@ldeo.columbia.edu)
Tom Guilderson	tguilderson@lnl.gov
Lloyd Keigwin	lkeigwin@whoi.edu
David Lea	lea@geol.ucsb.edu)
Jean Lynch-Stieglitz	jean@eas.gatech.edu
Tom Marchitto	tom.marchitto@colorado.edu
Mike Mann	mann@meteo.psu.edu
Olivier Marchal	omarchal@whoi.edu
Jerry McManus	jmcmanus@whoi.edu
Alan Mix	amix@oce.orst.edu
Catherine O'Riordan	coriordan@agu.org
Joe Ortiz	jortiz@kent.edu
Larry Peterson	lpeterson@rsmas.miami.edu
Dick Poore	rpoore@usgs.gov
Terry Quinn	quinn@marine.usf.edu
Yair Rosenthal	yroenthal@sonne.rf-gmbh.de
Julian Sachs	jsachs@mit.edu
Dan Schrag	schrag@eps.harvard.edu
Howie Spero	spero@geology.ucdavis.edu
Lowell Stott	stott@usc.edu
Lonnie Thompson	thompson.3@osu.edu
Jim Zachos	jzachos@emerald.ucsc.edu