

A Research Plan to Study Holocene Climate Variability

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Executive Summary

On August 6-7, 2001, NSF sponsored a workshop to develop a research plan to study the Holocene record of climate variability. The workshop participants, based on the input of the wider scientific community*, identified a series of important research questions that, when answered, will provide important clues to the nature of climate variability that occurred on human time scales beyond the observed instrumental record of climate. The main focus of this research is to reconstruct the recent history of coupled atmosphere-ocean-terrestrial interactions and to understand the impact of these interactions on regional and global climate on time scales of decades to centuries and millennia. It will evaluate the extent to which changes in climate are forced by external means (i.e., variations in solar constant, tides or volcanic eruptions) or internal interactions among components of the climate system (i.e., variations in thermohaline circulation, tropical air-sea interactions, ice-ocean-biosphere feedbacks).

The Holocene was chosen because the climatic boundary conditions are similar to those experienced now and in the near future. There is growing awareness that variations in Holocene climate on land and over the oceans were larger than previously believed. These changes in climate may have affected humans as recently as several hundred years ago during the Little Ice Age (LIA) or a thousand years ago during the Medieval Warm Period (MWP). The goal of this research is to understand the nature, significance and causes of these natural oscillations in climate; how widespread, systematic and abrupt they may have been; and the likelihood of their recurrence in the near future. An important aspect of the research is to document how changes in the behavior of coupled atmosphere-ocean-land systems have affected climate in North America during the Holocene and to forecast the likely future effects of natural climate variability on North American climate.

In addition to the traditional single investigator projects that have been typical of paleoclimate and paleoceanographic research during the last decade, this new effort will encourage multi-investigator, multi-institutional collaborations to bring a broader interdisciplinary perspective and approach to the study of Holocene climate. The research effort will provide resources for members of the marine and terrestrial research communities to work together while helping to develop formal collaborations with researchers in the climate dynamics and numerical modeling communities. In order to stimulate and facilitate these interactions, open meetings of investigators and other interested individuals will be organized at annual meetings of scientific organizations to discuss the current status of the funded research projects and important topics and problems related to Holocene climate variability. This will help educate future paleoclimate researchers and foster the kind of interactions that lead to improved future research strategies in paleoclimatology and paleoceanography.

* Call for Comments, NSF Earth System History Program, EOS volume 82, number 9, February 27, 2001. All verbatim comments are available from the American Geophysical Union at http://www.agu.org/sci_soc/ESHCollation_alpha.pdf.

Introduction

The instrumental record establishes the existence of a relatively small number of fundamental modes of coupled air-sea interaction that collectively are responsible for most known climate variability (or instability) at interannual to century timescales. Chief among these coupled modes are the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation, Arctic Oscillation, North Atlantic Oscillation, Tropical Atlantic Dipole, and the atmosphere-ocean interactions involved in the meridional overturning circulation of the oceans. All of these climate modes of variability involve ocean thermal anomalies and atmospheric feedbacks on a variety of time scales that produce significant climate responses. Although the instrumental record informs us well as to the existence and modern expression of these coupled ocean-atmosphere systems, it is not long enough to resolve past changes in the dynamics and impacts of these climate systems, to extract robust features of climate variability on decadal time scales, or to identify climate variability on centennial to millennial time scales. This initiative promotes research on Holocene climate variability, forcing mechanisms, and continental impacts using time series and time slice strategies as well as model/data synthesis. This effort will help understand the global ocean background climate and climate variation against which we observe and define the recent dramatic warming trends. A primary goal of this effort will be to test the postulated existence of cyclical millennial variability in the Holocene of which the Little Ice Age (LIA) and Medieval Warm Period (MWP) may be the most recent manifestations. The research will also establish the nature of oceanic involvement in significant hydrologic events of the Holocene (i.e., U.S. southwest "mega-droughts", continental interior dryness, subtropical pluvials). The initiative is global in extent and involves both terrestrial and marine paleoclimate archives. However, in order to fill important information gaps there will be an emphasis on: 1) collection of new Holocene paleoclimate records from key locations, 2) examination of marine/terrestrial linkages and North American climate response, and 3) data-model integration efforts that focus on understanding specific forcing mechanisms relevant to Holocene climate variability.

Holocene Climate Variability - Evidence from Marine and Terrestrial Records

Holocene climate was thought to be remarkably stable with no evidence for the abrupt changes that characterize glacial periods. New paleoceanographic data, however, document that the Holocene was punctuated by a series of cool events which persisted for centuries and recurred roughly every 1000-2000 years, confirming earlier observations based on the history of alpine glaciation. The most recent cool millennial scale climate event was the LIA (1300-1850 A.D). During the LIA, northern Europe and many other regions of the world were much cooler than the historical range of instrumental climate variability spanning the last few decades. The LIA was characterized by subtropical Atlantic sea surface temperatures (SST) 1-2° C cooler than modern values. These SST were preceded by 1° C warmer-than-modern ocean temperatures during the MWP. The LIA appears to be the latest in a series of climatic events occurring every 1000 to 2000 years that are characterized by synchronous Holocene cooling events in both the western and eastern basins of the subpolar North Atlantic. Each of these Holocene cooling events is characterized by an increase in the concentration of ice-rafted grains, diagnostic

changes in the petrology of those grains, and a shift to cooler SST. Most importantly, the Holocene events appear to be lower-amplitude expressions of the well-known Dansgaard-Oeschger millennial-scale oscillations that punctuated glacial Stage 3. This persistence suggests that this particular millennial scale mode of climate variability occurs regardless of glacial state. The cause of this variability is unknown, although variations in deep water production have been suggested. So far, geochemical tracer studies have failed to indicate significant changes in deep water circulation during the Holocene other than perhaps for events early in the Holocene. Evidence for Holocene changes in deep water circulation, however, may lie in variations in sediment grain size and oceanographic tracer inventory data.

Terrestrial archives of Holocene climate of North America have documented the response of atmospheric circulation around North America (and the attendant responses of surface climates), the disintegrating Laurentide Ice Sheet and the changing seasonal cycle of solar insolation. They have also provided critical information about the magnitude and severity of drought on the American Great Plains. These data sets vary in resolution, record length and specificity, but there are several robust features of the reconstructed climate variations that are common. These robust features include: 1) basic patterns of temporal variability, including progressive and abrupt changes (from cold to warm, wet to dry) over time; 2) appearances of “regime shifts” that may be superimposed on longer-term changes, but in general, show no strong indication of cyclicity or strictly periodic variations of climate; and (3) frequent expression of spatial heterogeneous variations of climate ultimately related to the control of surface climates by atmospheric circulation. These studies have led to an evolving understanding of the manner in which the individual environmental subsystems represented by paleoclimatic indicators respond to large-scale forcing.

To date the records from land and sea have not been integrated, yet understanding the mechanisms that control Holocene climate variations on North America will require the coordinated analysis of both terrestrial and marine records. For example, climate anomalies on land during the span of the instrumental records (roughly 100 years) can generally be related to atmospheric circulation anomalies that themselves have explanations that involve ocean-atmosphere interactions. On longer timescales throughout the Holocene, similar coupled ocean-atmosphere-land interactions are likely to have occurred. Moreover, the larger and more gradual changes in ice volume and insolation controls throughout the Holocene are sufficient in magnitude to produce responses in the surface conditions and circulation of the ocean. This raises the possibility that the modes of atmosphere-ocean interaction recognized in the instrumental record may themselves undergo changes in frequency or kind as the larger-scale controls of climate vary.

Statement of Research Objectives

The research plan is focused on answering questions about the nature, significance and impact of Holocene climate variability, with a particular emphasis on understanding how climate changes have affected the climate of North America by addressing a series of research questions:

1) What is the nature of Holocene climate variability on decadal through millennial timescales?

- How do known modes of climate variability and coupled atmosphere-ocean-terrestrial interactions vary as a function of changing state of climate?
- How do the coupled modes differ on the different timescales? Are decadal-centennial variations fundamentally different from millennial variations or are they related in a dynamical sense?
- What terrestrial-ocean-atmosphere-ice interactions are causing the variability? How much Holocene climate variability is externally forced versus internally forced?

2) Is coherent millennial-scale variability an important, widespread feature of Holocene climate variability? Were the MWP and the LIA the most recent manifestations of a regular millennial oscillation? Where and how warm was the MWP? Was it as warm or warmer than the present?

3) What is the nature and extent of abrupt climate change in the Holocene? Are these stochastic events or the result of periodic forcing?

4) How have changes in the large-scale ocean-atmospheric-terrestrial systems affected the climate of North America? What are the large-scale atmosphere-ocean interactions that affect the hydrological cycle of North America, how have they varied in the past, and how might they vary in the near future?

Research Strategy

This research effort will document the record of and help understand the forcing for natural climate variability at decadal to millennial timescales during a period when the large-scale controls on climate were in a configuration broadly similar to the present one. To achieve this goal, a network of records is needed that includes key climate indicators at appropriate resolution to address the different modes of climate variability.

Hierarchy of Sampling. In order to achieve the goals of this research effort, records of climate variability will be produced using a hierarchical sampling network. The first order sites of the network will include a suite of marine- and terrestrial- based records of Holocene climate covering the last 10,000 years that will provide near global coverage at century-scale resolution. These records will be distributed in key geographic locations to document the global extent of the millennial-scale variability of climate change, and the phasing of the variability between high and low latitudes, between the northern and southern hemispheres, and between the land and the sea (Figure 1).

A subset of key records from the first order sites will then be selected that will focus on the finest possible temporal resolution to provide detailed (at least decadal) scale resolution for the entire Holocene.

Finally, another subset of samples will be analyzed from key sites that have the potential to produce annually resolved records for critical intervals of the Holocene climate history. These records will focus on interannual to decadal variability during the end member states of the Holocene records. This third order of sampling will help us understand higher frequency climate variability against the background of changing climate (i.e., LIA versus MWP).

Geographic Coverage and Climate Systems. The sampling design will be optimized to evaluate the major climate forcing and coupled atmosphere-ocean-terrestrial interactions with an emphasis on understanding the impact of these changes on North America. Global coverage is needed to evaluate the impact of variations in solar forcing, tidal mixing, volcanic eruptions and other forcings with global impact. Detailed regional studies are needed to understand the impact of coupled atmosphere-ocean-land interactions with more limited geographic impact. For each sampling order and sample resolution, an appropriate geographic coverage of the response of North American climate will be produced. Development of integrated terrestrial and marine records of climate from the margins of North America are required to provide the necessary degree of correlation of climate changes between the oceans and land.

Many well-dated terrestrial paleoclimate records exist and will be incorporated into this effort. However new terrestrial records and improved sample resolution within existing records will be needed from key areas. In contrast, the number of existing, high-resolution marine records of Holocene climate is far fewer than the existing number of terrestrial records (tree rings, lakes, glaciers) by a factor of 100 or more. Yet recent evidence suggests that these marine records are obtainable, contain significant variability, and faithfully record short-term events like the LIA and the MWP. Since it is likely that changes in ocean circulation and in coupled atmosphere-ocean climate systems have had (and will have future) important effects on climate, the development of additional high-quality marine records is of great importance to our understanding of Holocene climate.

Temporal Resolution of Time Series and Chronology. An important component of the research is to provide the highest temporal resolution possible using the most appropriate records available. The sample spacing for the full Holocene time series (i.e., those terrestrial and marine records produced to evaluate the extent of millennial-scale climate variability), will be approximately 100 years with radiometric dates spaced at about 250-500 years depending on the character of the record. Higher resolution sampling studies will require greater chronological control, as appropriate. For those studies attempting to determine changes in interannual to decadal-scale climate variability, annually-resolved records such as tree rings, varves, growth bands, and other laminated or layered systems will be measured and independent radiometric dating will be used to place the sequence of events into a well-dated time series.

Paleoclimate Proxies. Since nearly all numerical climate simulations, from uncoupled atmospheric models to fully coupled ocean-atmosphere general circulation models (OAGCM) use sea surface temperatures (SST) as either model input or output, the new marine records produced under this initiative will deliver, as its most important product, well-dated estimates of SST throughout the Holocene. In addition, other proxies relevant to the coupled atmosphere-ocean system will be produced to develop histories of upwelling, deep-water production, variations in wind intensity and direction, and other relevant climate-related processes. Well-dated multi-proxy records from a variety of regions will include more than one estimate of SST or air temperature for each record and concurrent measurements of other important climate variables such as deep water chemistry and vegetation response. This approach will require that teams of investigators work together on the best cores and produce complementary climate records on common time scales.

Deliverables/products

Among the specific products to be produced are:

- Correlated time series of ocean SST, deepwater characteristics, and North American response for the last 10,000 years in the key regions of the major climate systems.
- Maps of surface temperature at 500-year resolution for the Holocene.
- High-resolution records of interannual to century scale climate variability for the extremes of millennial scale climate variability.
- A synthesis of the Holocene climate record.

During the course of the study, open annual meetings will be held for researchers and other interested investigators to share results and to develop new and productive research plans for the analysis of Holocene climate variability.

Implementation Plan and Time Line

Successful completion of this research effort requires a phased approach to conducting a variety of activities ranging from generating new records, synthesizing existing information, modeling, and interactive data model comparisons (Figure 2). The effort may also require independent technical evaluation to determine how the research is progressing.

Phase I. Determining whether or not coherent millennial scale variability is pervasive in the Holocene is an important aspect of this effort. In addition, linking marine and terrestrial records of climate variability is also critical. Thus the initial phase of the study will consist primarily of the following types of specific research projects.

1. Development of records of climate variability for the entire Holocene in key areas (Figure 1). These records will span the entire Holocene with a sample resolution of approximately 100 years. The studies should be designed to provide estimates of SST and air temperature from at least two proxies. One or more proxies for deep water characteristics are also desired. Documenting the extent and persistence of millennial-scale variability requires global coverage. Thus records from high, middle, and low latitudes in both hemispheres will be produced. An important goal of the project, however, will be to understand the impact of the key coupled ocean-atmosphere-land systems on climate variability on decadal to millennial time scales.
2. Synthesis of existing Holocene climate records from North America with an emphasis on identifying records suitable for incorporating into synthesis maps and time series and identifying the existence of gaps requiring new information.
3. Synthesis of existing Holocene climate records along the margins of the North American continent and identification of areas suitable for conducting decadal to century scale studies incorporating marine and terrestrial proxies.
4. Modeling studies that are designed to identify the data and information needed to study the forcing mechanisms for decadal to millennial scale climate variability in the Holocene.

Phase II. As the global pattern of Holocene millennial climate variability emerges, the research effort will begin to focus on developing decadal-scale records for selected intervals representing end-member states of Holocene variability. It is likely that the LIA and the MWP will be targets for the annual to decadal scale studies, but the final selection of the "key intervals" will await development and evaluation of the millennial scale studies. Phase II will include research begun under Phase I as well as the following:

1. Annual to decadal-scale studies for key intervals of the Holocene (specific intervals to be determined)
2. Generation of new terrestrial and marine records in areas identified in Phase I.
3. Development of marine and terrestrial Holocene records from margins of the North American continent. These integrated studies should include proxies for both marine and terrestrial climate conditions.
4. Development of annual-scale marine climate records. These records will be developed in the key regions and time-intervals identified for the millennial and decadal scale studies.
5. Assessment and analysis of the observational results on Holocene climate variability using integrated model-data comparisons.

Phase III. Assessment and Synthesis

At this stage, the research results will be evaluated in the context of knowledge gained regarding the climate of the Holocene and research plans for possible further research will be developed.

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Planning Workshop
Decadal to Millennial Climate Variability in the Holocene**

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