

An ESH Research Plan to Study Abrupt Climate Change

**Recommendations of a Research Planning Workshop
Sponsored by the Earth System History Program
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Executive Summary

This research plan is focused on understanding the nature, significance, geographic distribution, and impact of abrupt climate changes in the geological record, with emphasis on the last 120,000 years of earth history. Several broad questions will be addressed:

- 1) What are the characteristics of abrupt climate changes?
- 2) What are the causes of abrupt climate change?
- 3) Is abrupt climate change predictable?
- 4) Are abrupt climate changes affected by the evolving background state of climate?
- 5) What are the regional and global connections involved with abrupt climate changes?
- 6) What are the impacts of abrupt climate changes on earth systems, including marine and terrestrial ecosystems and the hydrological cycle?

To address these questions, the research program will include development of a widespread network of high-quality, well-dated paleoclimate records, and integration of multiple proxy records of climate variables at the best sites. The program will encourage collaboration among the marine, terrestrial, and paleoclimate research communities, and provide for timely outreach to colleagues, students and the public. Products of the program will include an initial synthesis of the current state of knowledge of abrupt climate events; creation of an active database of high-resolution, well-dated climate records for key abrupt events; workshops of PIs and other interested researchers; educational and training programs for graduate students, postdoctoral investigators and junior researchers; presentation of the results of the program in the peer-reviewed literature and publicly-accessible databases; and evaluation of program activities after five years.

Introduction

Despite the seemingly gradual changes in climate that have been experienced during the last century, the geological record suggests that this gradual change is not typical of the earth's climate system. Two decades of research in paleoceanography and paleoclimatology have convincingly demonstrated that in the past the climate system was often quite variable, including abrupt changes that shifted the system quickly from one apparently stable state to another. The best examples of these abrupt climate changes come from ice core records of air temperature over Greenland, but other examples exist in a variety of marine and terrestrial paleoclimate records from around the world. The largest abrupt changes so far documented, rapid warming and cooling of 10° to 16°C, occurred over a time span as short as 10-20 years and have been linked to major reorganizations of the coupled atmosphere-ocean-ice systems of the earth. Although the exact causes and responses are still unclear, such changes in past climate resulted in widespread regional changes in air temperature, disruptions in the hydrological cycle throughout much of the tropical and mid-latitudes, and significant perturbations of terrestrial and marine ecosystems.

Although an examination of the geological record of the last 120,000 years suggests that rapid shifts in the climate state are the norm more than the exception, so far climate models have been unable to simulate the magnitude, rate, or geographic extent of such events. Simulations of future climate changes as a result of increasing greenhouse-gas concentrations typically display gradually rising mean global temperatures. Based on our understanding of past climate variability, however, there is reason to believe that future trends will also be accompanied by abrupt events with strong regional differences and impacts. Indeed, the seemingly gradual changes underway now, such as rising global air temperatures, increasing evaporation at low latitudes, and increasing precipitation and ice melting at high latitudes, may trigger an abrupt reorganization of the climate system.

Recognizing the need for a plan to address the research and policy gaps in our understanding of abrupt climate change, the US Global Change Research Program asked the National Research Council to form the Committee on Abrupt Climate Change to report on the state of knowledge in this field. Three boards of the NRC responded¹. The National Research Council formed the Committee on Abrupt Climate Change, which published its report² "Abrupt Climate Change: Inevitable Surprises" in 2002.

To address the gaps in our knowledge of abrupt climate change and to meet the committee recommendations requires research on past variability in earth's climate, an area that naturally falls within the sponsorship of the Earth System History (ESH) program of the National Science Foundation. A 2001 review of ESH research activities had already recognized the importance of research on rapid climate change but specific guidance for research activities had not been formulated. To address this need the ESH

¹ The Ocean Studies Board, the Polar Research Board, and the Board on Atmospheric Science and Climate

² Abrupt Climate Change: Inevitable Surprises, Committee on Abrupt Climate Change (Chair Richard B. Alley, National Research Council, National Academy Press, Washington, DC. 230 pp., 2002

program convened a group of paleoclimate scholars³ to develop a research plan that outlines research goals and strategies, as well as proposes specific research products and outcomes. The plan will help guide ESH research activities in this important area for the next several years.

Summary of NRC Recommendations with relevance to paleoclimate studies

The NRC Committee on Abrupt Climate Change defined abrupt climate change as an interval:

“...when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause.”

The committee’s recommendations to further the study of abrupt climate change fell into two general categories: (1) research to expand instrumental and paleoclimatic observations and (2) modeling efforts to explore the causes of abrupt climate change and its effects on ecosystems, the economy and society. Although only one of the five recommendations specifically mentioned the acquisition of new paleoclimate data, four recommendations clearly require information on the geological record of abrupt climate change to successfully meet their goals. Relevant portions of the four recommendations are quoted and summarized below.

NRC Recommendation 1. “Research programs should be initiated to collect data to improve understanding of thresholds and nonlinearities in geophysical, ecological, and economic systems. Geophysical efforts should focus especially on modes of coupled atmosphere-ocean behavior, oceanic deep water processes, hydrology and ice.”

This recommendation to increase research on climate variability and the possibility of nonlinearities and thresholds in the climate system involves modern process studies and modeling, as well as paleoclimatological information. To fully understand modern modes of behavior will require a longer time perspective than offered in the instrumental record. The geological record provides an opportunity to examine thresholds and nonlinearities of different magnitude, intensity, and spatial extent in the past and thus is an important context for the present.

Recommendation 2. “New modeling efforts that integrate geophysical, ecological, and social-science analysis should be developed...In addition, new mechanisms that can cause abrupt climate change should be investigated, especially those operating during warm climate intervals...”

This recommendation will likewise require paleoclimate studies to develop integrated geophysical and ecological models, to test their ability to simulate abrupt climate changes, and assess the impacts of such changes on the biosphere and hydrosphere. Past

³ See Appendix 1

intervals of warm conditions, when the role of humans on the climate system was minimal, provide an important comparison for understanding the changes occurring at present and projected in the future.

Recommendation 3. “The quantity of paleoclimatic data on abrupt change and ecological response should be enhanced with special emphasis on:

- Selected, coordinated projects to produce especially robust, multi-parameter, high-resolution histories of climate change and ecological response
- Additional proxies, including those that focus on water (e.g. droughts, floods, etc.)
- Multidisciplinary studies of selected abrupt climate changes”

This recommendation specifically identifies the need for better, high-resolution, multi-proxy research on abrupt climate changes and ecological responses. The need for better proxies that reconstruct aspects of the hydrological cycle is also identified as important.

Recommendation 4. The conceptual basis and the application of climatic statistics should be re-examined with an eye to providing realistic estimates of the likelihood of extreme events.

To be successful, research to meet this recommendation will require well-dated, high-resolution time series of extreme events, such as like floods, droughts, hurricanes, fire weather, and storm surges.. Without this information, the statistics of extreme events are likely to be biased.

Statement of ESH Abrupt Climate Change Research Objectives

This research plan is focused on understanding the nature, significance, geographic distribution, and impact of abrupt climate changes in the geological record, with emphasis on the last 120,000 years of earth history. Several broad questions will be addressed:

1) What are the characteristics of abrupt climate changes?

- Are rapid changes in climate a significant component of the climate record of the last 120,000 years? If so, what is their temporal and spatial dimension? Based on information in the geologic record, are the current rates of change in the climate system unprecedented? Are more rapid and unexpected changes possible or likely in the future?

2) What are the causes of abrupt climate change?

- What is the role of the atmosphere, oceans, including the meridional overturning circulation and tropical oceans, hydrosphere, and biosphere in causing abrupt

climate change? How do these components of the climate system interact during abrupt climate changes?

3) Is abrupt climate change predictable?

- Is it possible to determine thresholds at which the earth's climate rapidly shifts to another regime?

4) Are abrupt climate changes affected by the changing background state of climate?

- How do the slowly varying components of climate system, such as the variations in ice-sheet size, seasonal cycle of solar radiation, and levels of greenhouse gases, influence the occurrence of short-term climate events? How is the background state likely to affect the occurrence of future abrupt events?

5) What are the regional and global connections involved with abrupt climate changes?

- Specifically, how are climate events transmitted from one region to another and why are some areas sensitive and others insensitive to abrupt climate changes?
- How are coupled atmosphere-ocean systems, such as El Niño-Southern Oscillation, the Arctic/North Atlantic Oscillation, the Pacific Decadal Oscillation and Meridional Overturning Circulation, involved in the transmission of abrupt events through the climate system.

6) What are the impacts of abrupt climate changes on:

- Terrestrial and marine ecosystems
- The hydrological cycle, including droughts and floods

Research Strategy

In order to address these questions, the research program must include the development of a widespread network of high-quality, well-dated paleoclimate records; integrate multiple proxy records of climate variables at the best sites; and encourage the collaboration of marine, terrestrial, and paleoclimate research community. Research programs must also provide for timely dissemination of information to colleagues, students, and the public.

Development of quality proxy records of abrupt climate change.

The development of quantitative and reproducible records of past climatological data, with realistic, quantitative estimates of uncertainty, is a primary goal of the program. The best records will provide information on key climatological indices, for example, air temperature, rainfall, and drought; ocean temperature and salinity; wind speed and direction; and land cover. These quantitative climatological data will help to

initialize GCM boundary conditions and provide direct comparison with model output. The research strategy may include time-series development or studies of regional variability.

Multiple proxy analysis on the same records is essential where possible. In marine records, multiple proxies of SST, such as Mg/Ca, fossil abundance reconstructions, and/or organic molecular approaches should be analyzed on the same samples. For salinity calculations, both $\delta^{18}\text{O}$ and Mg/Ca should be produced on the same fossil samples in order to calculate changes in temperature and salinity of surface and deep-water properties. For deep-water reconstructions, combined tracer methods ($\delta^{13}\text{C}$, Cd/Ca, Zn/Ca), radiometric approaches ($\Delta^{14}\text{C}$, $^{231}\text{Pa}/^{230}\text{Th}$) and geostrophic reconstructions will be needed to define changes in deep-water geometry and transport. For terrestrial records, parallel reconstructions of air temperature and P/E conditions using fossil, dendrochronological and geochemical approaches should be made from the same records or parallel studies from the same region. The research program will encourage collaborative, multiple investigator work on the highest-quality samples, cores and sections (a type-section strategy similar to the approach used in ice-core research) in order to develop the best records of climate variability. Indeed, replication of time series and other proxy records from multiple sites within a region will be encouraged to identify and constrain the true climatological signal from the noise created by differences in sampling resolution, sedimentation, bioturbation, or other problems associated with geological archives of past climate.

Time Scales and Chronology.

In order to focus the program toward the most relevant studies, the time scales of the research projects will be limited to the last ~120,000 years of earth history, the timescale of the highest resolution ice core records of climate such as GISP, GRIP and North GRIP. Of primary importance will be the ability to determine the timing and rate of change of climate events among different regions or within different components of the climate system. Thus, the climate records will need very well-resolved and accurate chronologies, developed with independent methodologies where possible, and adequate sampling resolution to assess climate changes at the appropriate temporal scale. The resolution of climate time series may range from annual to millennial, depending on the type and magnitude of the event under studied. Likewise, the geographic coverage of records will need to be adequate to elucidate the spatial extent of the climate signal, including areas where it is not registered.

Model/Data Collaboration.

This program will encourage an active integration of empirical and observational paleoclimatological data with a variety of model simulations of regional and global climate change. Initiatives and programs that bring together paleoclimate observations and models will be facilitated in a variety of ways. First, multi-investigator collaborations of empiricists, climate dynamicists/theorists, and atmosphere and ocean numerical modelers will be encouraged by the program. Second, the program will host

regular workshops of PIs to synthesize results and provide contact between individuals producing the observations and individuals who are integrating the observations into the models, evaluating the results, and improving model performance. The program will also promote model development and research directly related to specific paleoclimate proxies, including the incorporation of such key indicators as $\delta^{18}\text{O}$ and δD in the water cycle. It is expected that modeling efforts will be undertaken at a variety of geographic and temporal scales, and involved a variety of model types and complexities, from simple box models to fully coupled general circulation models. Close collaboration with major centers for model development, such as NCAR and GFDL, will be encouraged.

Deliverables/Products

Initial Synthesis. A synthesis of existing abrupt climate change records will be produced as one of the first products of this research plan. To produce the synthesis, a meeting will be held to gather, discuss and integrate the most relevant data sets and to synthesize and publish the results in a volume of individual papers and group syntheses. The model for this initial synthesis will be the 1998 AGU Chapman Conference on “Mechanisms of Millennial Scale Global Climate Change”, which proved to be a timely and valuable meeting and resulted in a widely-cited synthesis of the state of knowledge.⁴

Research Products. The products of this research will include detailed high-resolution records of key climatological data for the last 120,000 years, published in important peer-reviewed journals, and catalogued and archived at publicly-accessible data archives such as the NOAA World Data Center for Paleoclimatology and the European data archive PANGAEA - Network for Geological and Environmental Data. A component of the project will be to develop a relational data-base of climate proxy information and ecological responses for a variety of important abrupt climate events. Maps and time-slice reconstructions for critical climate variables will be produced for important abrupt climate events of the last 120,000 years, including the most recent deglacial and Holocene events, such as the Younger Dryas, the 8.2 ka meltwater pulse, the Neoglaciation, and the Little Ice Age. The synthesized data sets and spatial reconstructions will be used for data-model comparison and synthesis to understand the underlying, fundamental mechanisms and linkages involved with abrupt climate change.

Outreach and Communication. The program will host regular PI meetings/workshops that will be open to members of the research community. The purpose of these meetings will be to inform PIs and colleagues of progress and results to date and to develop strategies for future research activities and collaborations. In a program that includes researchers with diverse interests, backgrounds and approaches, these meetings will be an important opportunity to facilitate collaborations and define the interdisciplinary research goals of the program.

⁴ Mechanisms of Global Climate Change at Millennial Time Scales, Peter U. Clark, Robert S. Webb, and Lloyd D. Keigwin, editors, Geophysical Monograph 112, American Geophysical Union, Washington, DC 1999.

Broader educational activities will be included in the program by developing a series of workshops/summer institutes for graduate students, postdoctoral fellows and junior faculty on topics and methods in abrupt climate change research. The educational programs will bring together a small number of experts, across a variety of climate subdisciplines, to present short courses on important, controversial or fundamental areas related to abrupt climate change. We see these workshops as a way to improve communication across the diverse subdisciplines, as well as an effective way of educating the next generation of researchers in the field.

Five-year synthesis. After the first five years of the program, a series of peer-reviewed papers and a synthesis of accomplishments will be produced, archived and widely distributed.

Implementation Plan/Time line

The implementation of the plan will take place in overlapping phases that will include an initial synthesis phase of existing data, a phase of data generation, including the acquisition of new, high-quality, high-resolution records of past abrupt climate changes, and model development; and a final phase involving data/model comparisons and synthesis.

Phase 1: Initial synthesis

The goal of this phase is to bring together published and unpublished data into a state-of-the-art synthesis of observations and theories about abrupt climate change. Previous syntheses, including the NRC report, have proven extremely beneficial. Because this is a rapidly changing area of research with discoveries and theories being presented across a wide range of disciplines, it is timely for updated synthesis of data and theories relevant to abrupt climate change.. The products of this initial synthesis will include a published volume of research results as well as the establishment of a new database of paleoclimate data, the initial step in the development of the data base for this program.

Phase 2: Acquisition and development of new paleoclimate records and initial modeling

The second phase of the program will include the development of new, high-quality paleoclimate records from locations around the globe. The goal of this phase will be to enhance the spatial coverage within key coupled climate systems with an emphasis on filling in the gaps identified in the initial synthesis. The focus will be to acquire and produce climate records capability of resolving abrupt climate events occurring on annual to millennial time scales, and provide adequate spatial coverage to assess atmosphere, marine, and terrestrial linkages. Concurrently, modeling studies will be undertaken to help identify the forcing mechanisms and thresholds that may force the climate system from one state to another.

Phase 3: Integration of data and models

The new and previously published data will be organized into a global data set that illustrates the magnitude, spatial distribution and effects of past abrupt climate changes. The data will be compared with a variety of regional and global model simulations of abrupt climate events in order to test model sensitivity, to identify the thresholds in the system that cause rapid changes in climate, and to examine the linkages and connections in the climate system that transmit climate perturbations well beyond their local causes. Maps of climate conditions during key abrupt events of the last 120,000 years will be produced during this phase of the program. All results of the program will be available at publicly-accessible data archives such as the NOAA World Data Center for Paleoclimatology at Boulder, CO, and the European data archive PANGAEA - Network for Geological and Environmental Data.

Appendix 1. Workshop participant list

Participant List (Alphabetical)

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