A Research Plan to Study Tropical Climate Variability

Report of a Workshop Sponsored

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Executive Summary

In June 2003 20 scientists met at the University of Southern California for a 3 day workshop to discuss the current state of knowledge concerning (1) tropical climate variability during the last glacial episode and Holocene and, (2) the potential role that the tropical ocean/atmosphere system may have played in causing and/or contributing to the large and abrupt climate changes that have occurred during the past 60kyrs. The discussions lead to a consensus opinion on the part of the participants of the workshop that while good progress has been made in the effort to document major episodes of climatic change within the tropics during the past 50 thousand years, there remains a critical need to better quantify the magnitude of sea surface temperature changes throughout the tropics, particularly in the upwelling centers and to quantify how the transport of latent heat out of the tropics changed during episodes of rapid climate change. To accomplish this will require substantial effort from both marine and terrestrial paleoclimate scientists and specific focus on archives that are capable of providing sufficient temporal resolution to resolve leads and lags between the low and high latitude climates. Information of this kind would substantially improve the ability of computer models to simulate global ocean/atmospheric dynamics at times of large climate transitions and begin to assess whether the tropical ocean/atmosphere has multiple modes of natural variability and whether the tropical ocean/atmospheric variability has been responsible for large and sometimes abrupt global climate changes in the past. The workshop participants agreed there is a need for a concentrated community
effort that would test whether large and sometimes abrupt climate change originate in the
tropics or the extratropics. The hypothesis put forward by the group is:

*Large, sometimes abrupt changes in ocean/atmospheric dynamics centered in
the tropics have caused large climate changes in the extratropics.*

**Among the priority questions that will need to be answered by the community in**

**order to validate or reject the hypothesis include:**

- In addition to the interannual variability (ENSO), are there other modes of tropical ocean/atmospheric behavior that can be recognized by studies of paleoarchives? If so, how has the behavior of these modes changed over time in relation to changes in the extratropics?
- Is it possible to determine from proxy records how the tropical ocean/atmosphere system responds to specific changes in forcing including orbital and solar variability?
- What aspects of the tropical ocean/atmospheric system have changed at times of abrupt climate change in the extratropics? (i.e. LIA, MWP, 4kyr event, 8.2kyr event, YD, B/A)?
Introduction

Instrumental records have documented a warming of the lower atmosphere during the late 20\textsuperscript{th} century that has heightened concerns that anthropogenic influences have begun to change the global climate and that additional warming could bring about detrimental effects on human society. Yet, paleoclimate records that extend beyond the pre-industrial age document many episodes of large temperature and environmental change. Even the relatively recent past, the Holocene, which has long been considered a relatively benign climatic interval, is now known to have undergone large, repeated climatic changes (e.g. Bond et al., 1997). Attribution of the 20\textsuperscript{th} century climate change to human influence depends in part on an adequately resolved long-term perspective that can only be obtained from proxy reconstructions.

During the past decade paleoclimatologists made important advances in their effort to document and quantify the history of climate variability and in doing so have begun to build a long perspective that will eventually provide a more complete context against which both natural and human induced change during the 20\textsuperscript{th} century might be evaluated. Furthermore, a more comprehensive knowledge of how the Earth environment has changed can provide insight about how the environment may behave in the future. But there remain critical gaps in the paleo-record and in our ability to adequately assess where the “centers of action” lie within the ocean/climate system and how changes in one region influence or cause change to occur in other regions. The tropics represent a potentially important region that has been inadequately studied. The tropics are a key “center of action” for both seasonal and interannual variability but little is known about
tropical climate variability at longer time scales. Recognizing the need to achieve a more complete understanding of environmental variability in the tropics and ultimately, to assess how tropical ocean/atmospheric changes may have influenced global climate in the past, a workshop was held in June of 2003 where twenty U.S. scientists came together for a three days at the University of Southern California, Los Angeles to discuss the Tropical Influence on Global Climate Change. The goal of this NSF-ATM sponsored workshop was to summarize what is currently known about Tropical Ocean and climate variability during the late Pleistocene and Holocene and secondly to develop a set of priority questions that should be addressed perhaps through a coordinated effort on the part of the paleoclimate and paleoceanographic community. The ultimate goal of such efforts would be to develop quantitative reconstructions of climate history from the tropics.

**Why Focus on the Tropics**

The Earth’s geologic record provides many examples of large and in some cases, abrupt climatic changes. Among the best documented examples are the so-called Dansgaard/Oeschger events and the Heinrich Events that were first recognized in ice core and high latitude marine sediment records from the North Atlantic. The events have been recognized in environments throughout the northern hemisphere, attesting to the widespread influence they had on the Earth’s environment. Each of the D/O events was characterized by an abrupt warming at high latitudes. At lower latitudes the events were characterized by significant hydrologic change. Conceptual models that attempt to explain the origin of these abrupt climatic events have typically called upon ice sheet dynamics as a primary factor in the rapid onset of each event (e.g. Broecker et al., 1990;
Bond 2001; Alley and MacAyeal, 1994; Knutti et al, in press). Yet, evidence is now emerging from studies of high resolution marine and terrestrial records that even in the absence of large ice sheets significant and equally rapid climate oscillations continued to occur at high latitudes through the present interglacial (Bond et al., 1993; 1997; 2001). The recurring nature of large environmental changes under both glacial and interglacial boundary conditions requires persistent internal amplification mechanisms that can translate a relatively small forcing into a large and wide spread response. For example, studies of ocean sediment records indicate the strength of ocean convection in the North Atlantic varied in concert with the large global climate changes in the late Pleistocene and perhaps even during the current interglacial (Bond, 93; Alley 1994; Bond 97; Bond 2001). The ocean conveyor is sensitive to relatively small variations in surface salinity that can disrupt convection. Changes in salinity and in the convective capacity of north Atlantic surface waters is therefore an amplifier, capable of disrupting deep water circulation and climate. But if the ocean conveyor has been a climate amplifier even during the present interglacial it has happened in the absence of large ice sheets. This shifts the emphasis away from the high latitudes to mechanisms capable of affecting the hydrologic balance over the ocean. The tropical ocean/atmospheric system is therefore a candidate for bringing about changes in the hydrologic system that could have caused changes in climate through the redistribution of latent and sensible heating.

Recent analyses of salinity data collected in the Atlantic Ocean during the past several decades have revealed a trend towards increasing surface and deep water salinities at low latitudes but there has been a freshening at high latitudes (Dickson et al., 1996; Dickson et al., 2001; Curry et al., 2003). In the Pacific there has been an apparent
freshening at high latitudes and this has coincided with warming over much of the low latitude oceans (Wong et al., 1999). The pattern of change reflected in these historic records is consistent with change that would be expected from a warming climate and thus could provide support for anthropogenic effects emerging during the 20th century. Yet, given the short length of the observed changes (spanning only the latter part of the 20th century) it is also possible that this type of variability has been operating continuously and is therefore independent of anthropogenic influence. Could this type of variability have occurred previously and account for environmental changes seen in Holocene records? Hoerling et al. (2001) has suggested the recent salinity changes in the North Atlantic are consistent with warming of the tropical Pacific, which affects atmospheric latent heating and can produce downstream effects over the North Atlantic that resemble the positive phase of the NAO. Consequently, there is reason to consider that high latitude changes, even those earlier in the Holocene and the Pleistocene, were influenced by changes taking place at low latitudes.

Bond (2001) argued that during the Holocene cooler sea surface conditions over the north Atlantic were consistent with a change in the strength of North Atlantic overturning. If Bond is correct there must be an internal mechanism to the climate system that acts as a regulator of NADW (e.g. Broecker et al., 1990). The time scale associated with the trend in salinity over the past 50 years or so is too short to be an adequate comparison to earlier periods. On the other hand, if the present trend in atmospheric conditions were to continue, it is appropriate to consider how eventual salinity changes could influence the strength of convective overturning in the North Atlantic. Proxy data from the tropical Atlantic has documented longer-term changes in salinity that (Nyberg et
al., 2002) that may be indicative of persistent and recurring hydrologic variability at low
laticitudes that has influenced salinities in the North Atlantic and thereby affected the
ocean’s convective capacity. Consequently, a comparison of high resolution tropical
salinity and/or hydrologic records to records of NADW change during the Holocene may
be the best opportunity to assess how susceptible NADW is and has been to hydrologic
variations at low latitudes.

At the present time there are too few highly resolved climate records from low
latitudes that can be compared to those from the high latitudes. Until more complete and
highly resolved paleoclimate and paleoceanographic records are available from the
tropics it will be difficult to assess whether the low latitudes have been a primary “center
of action” or whether the primary center of action does in fact lay at higher latitudes. The
recent changes in salinity could portend change in the environment that would have wide
spread implications. This potentiality underscores the need to evaluate the history of
change and in particular, the role the tropics have had affecting global climate changes.

We know from geologic records that the two main components of the tropical
climate system, the monsoons and the ENSO have varied significantly in strength or
intensity and in frequency through the past glacial/interglacial cycle. Based on proxy
reconstructions it appears that relatively small changes in the amount of solar radiation
received at low latitudes in association with the Earth’s precessional cycle have affected
the strength of the monsoons over India and China (Prell et al., 1986; Clemens et al.,
1991; Overpeck et al., 1996; Burns et al., 2001; Gupta and Anderson, 2003; Wang et al.,
1999). There is also evidence that solar variability may have influenced the strength of
the monsoon systems at millennial to decadal time scales (Neff et al., 1991; Wang et al.,
Coincident with these precessional-scale changes in monsoon, there were comparable changes in the hydrologic cycle over the tropical Atlantic and tropical Pacific as well (Haug et al., 2001; Johnson et al., 2002; Peterson et al., 1991; Baker et al., 2002; Moy et al., 2002; Gagan et al., 1998; de Menocal et al 2000; Stott et al, in press) that have been attributed precessional forcing and to shifts in the mean position of the ITCZ shifts. There also exists evidence to suggest that changes in atmospheric circulation and changes in Earth’s radiative balance come about as a result of intrinsic dynamical reorganizations in atmospheric and ocean circulation that, as yet, are not well understood (Hartman et al., 2002; Chen et al., 2002). All of these observations make it imperative that a more comprehensive data base of tropical climate variability be available if we are to adequately assess how unique the 20th century changes are and begin to assess how susceptible the climate system is to change in response to various forcing factors.

The Tropics and Abrupt Climate Change

In the past decade paleoclimatologists have come to recognize abrupt climate change is a pervasiveness characteristic of Earth’s climate record. In fact, the scale and rate of temperature change documented during the 20th century, pales by comparison with the much larger climatic changes that have occurred in Earth’s past. Large-scale change in Earth’s climate occurring in as little as a few years was first brought to light by the isotopic records of annually sampled ice cores from Greenland (e.g. Johnsen et al., 1992). These records documented a series of millennial-scale climate switches (cold-warm), Dansgaard-Oeschger cycles, that punctuated that last glacial episode 20 to 80 thousand
years ago that (Figure 1H). Subsequently, this sequence of climate oscillations has been observed in climate archives stretching from the high northern latitudes to the tropics (described in more detail later) (Voelker, 2002). The Greenland ice cores also documented a millennial-scale pacing of abrupt climate changes through the last deglaciation including the Bølling-Ållerød warm-Younger Dryas cold oscillation. But, while the ice cores demonstrated the climate system has undergone repeated abrupt oscillations during the cold glacial episodes, the initial results also suggested that the warm interglacial climate of the past 10 thousand years, has been relatively benign and stable. More recently however, efforts to trace the Holocene history of ice rafting in the North Atlantic (a measure of ice sheet and high latitude climate variability) has confirmed that climate oscillations have continued throughout the current interglacial (Bond, 1997) (Figure 2I). Other highly resolved records, including terrestrial and marine records from low latitudes, have also begun to reveal millennial-scale climate changes during the Holocene that appear to have coincided with the ice rafting events in the North Atlantic (Gupta and Anderson, 2003). Hence, it now appears that even under the very different boundary conditions, which characterize the glacial and interglacial periods, the Earth’s climate has continued to experience abrupt and significant change with surprisingly regularity.

**New Understanding of Tropical Climate Variability**

A leading mechanism, which is often called upon to explain the abrupt changes in climate through the glacial and present interglacial are switches in the mode of thermohaline circulation, driven by salinity changes in the North Atlantic (Broecker,
However, general circulation models have been unable to explain the global extent and magnitude of climate change associated with the variable deep water circulation (Rahmstorf, 1994; Mikolajewicz et al., 1997; Manabe and Stouffer, 2000; Velinga-Chiang, 2003). So, while there is evidence that deep water convection in the North Atlantic has undergone repeated variations, it is not clear whether the changes were the cause or were a consequence of the climate change. The tropical ocean-atmosphere system on the other has the capacity to affect climate globally and a sustained change in the behavior of tropical ocean/atmosphere system on longer time scales represents a likely candidate for causing the abrupt climate changes documented in the proxy records (Cane, 1998). The question is; was ocean and atmospheric circulation in the tropics fundamentally different during the glacial and during the Holocene? And, were changes in the tropics directly coupled to changes in the extratropics.

Among the recent findings that have prompted debate about the long term history of tropical climate variability has been the suggestion that during the last glacial the tropical Pacific was characterized by sustained periods of El Nino-like conditions (Koutavas et al., 2002; Stott et al., 2002). Other earlier results seem to be at odds with this notion (e.g. Lea et al., 2000). Recent work has also documented brief, abrupt climate events in the tropics. The most well know of which is the ‘8.2 ka’ cold event documented globally (Alley et al., 1997) and thought to be related to freshwater forcing in the North Atlantic (Barber et al., 1999). Other events stands out in tropical climate reconstructions as well (e.g., Fleitmann et al., 2003; Gupta et al., 2003; Thompson et al., 200X Stott et al., in press) (Figure X). Brief, centennially recurring droughts on the Yucatan Peninsula, Mexico, driven by abrupt changes in the South American hydrological cycle have even
been linked to the collapse of Mayan civilization (Hodell et al., 2001; Haug et al., 2003) Whether or not all of these events had counterparts in the extratropics remains to be determined.

With a growing data base of tropical climate records spanning the last glacial/interglacial cycle there remains little doubt that the tropical climate does undergo significant variability on decadal and longer time scales, even during the present interglacial. This is an important consideration in the context of concerns about future climate change and how unique the 20th century changes have been. But, it is not yet clear whether there are multiple modes of tropical climate variability. Most proxy records from the tropics do not resolve the interannual scale variability. Marine and terrestrial paleo-records integrate the interannual variability. a modes of variability (e.g. changes in the frequency of ENSO, monsoon failure etc.), and whether the tropical climate changes were directly couple to changes in the extratropics. During the last glacial episode, the changes in the Indian and East African monsoons (Schulz et al; 1998; Altabet et al., 2002; Burns et al., 2003), western tropical Pacific convection (Stott et al., 2002), East Asian monsoon (Wang et al., 2001; Dannenmann et al., 2003), Atlantic tropical hydrological cycle (Peterson et al., 2000) and subtropical SSTs (Sachs and Lehman, 1999) all appear to have varied synchronously with North Atlantic millennial-scale climate variability (Figure X). During the Holocene on the other hand, the Indian monsoon variability (Sirocko et al, 1996; Gupta et al., 2003; Neff et al., 2001; Fleitmann et al., 2003), tropical Atlantic (deMenocal et al., 2000, Haug et al., 2001; Tedesco & Thunell, 2003) and South American (Baker et al., 2001) hydrology and climate, western tropical Pacific convection (Stott et al., in press) exhibited millennial and centennial-scale
variability that may have coincided with climate changes in the North Atlantic (Bond et al., 1997; 2001) (Figure X). But, there remains considerable uncertainty in the relative timing and phasing of change between the tropical and extropical climate variability. Furthermore, it is clear that in some Holocene tropical climate records, such as the central African drought record, that the variability was not linked to changes in the North Atlantic (Russell et al., 2003). The degree of millennial and centennial synchronicity between different tropical regions and the North Atlantic remains a major question.

Paleoclimatologists are just beginning to look into how interannual variability has changed in the past. Abrupt changes in this variability lasting centuries to millennia could have profound global climate impacts (Cane, 1998). Recent work has suggested that the tropical Pacific exhibited a persistent El Niño-like pattern during cool millennial-scale stadials and the Last Glacial Maximum and a La Niña-like pattern during warm interstadials and the mid-Holocene (Stott et al., 2002; Koutavas et al., 2002; Palmer & Pearson, 2003). However, these interpretations have been made from records that do not resolve the annual cycle. Those that do record El Niño and/or La Niña events in some way support these interpretations during some time intervals (Rittenour et al., 2000; Moy et al., 2002) and do not during others (Cobb et al., 2003). Clearly, more annually resolved climate records from different intervals of time are needed to fully address this issue.

The timing of abrupt tropical climate changes relative to those at higher latitudes has implications for the direction of propagation of the abrupt climate change, poles to tropics or tropics to poles, and thus also for the origin of the driving and/or strong amplifying mechanisms. For example, many tropical records exhibit deglacial climate changes before those in the Northern high-latitudes and synchronous with those in
Antarctic suggesting the potential for the tropics to play a large role in either driving or amplifying deglacial climate changes (Lea, 200X; Visser et al., 2003). Similarly, chronological relationships of abrupt climate change at different locations may also shed light on the mechanisms involved in millennial and centennial climate change. For example, Broecker (2003) has suggested that precursor events to the D-O cycles could be useful in determining whether they are driven by thermohaline circulation reorganizations or tropical ocean-atmosphere dynamics. Recent work does suggest that there were changes in the tropics immediately before some D-O events (Sachs and Lehman, 1999; Hendy and Kennett, 2003; Burns et al., 2003).

Reconstructing natural climate variations and understanding the mechanisms responsible for it bears heavily on the current debate concerning the uniqueness of 20th century climate change. Have we entered what has been termed the Anthropocene, the age dominated by humans’ impact on climate? Or, is the recent warming trend just a continuation of the natural centennial and millennial climate variability exhibited throughout the recent geologic past? This question will only be able to be answered by a detailed understanding and projection of the natural climate variability into the future.

The recent paleoclimatic reconstructions from the tropics have yielded many new insights. There is emerging evidence of coherent abrupt global climate change on millennial and centennial time scales. Millennial and centennial changes in the tropical teleconnections to the mid- and high-latitudes may have occurred. There is evidence that abrupt climate changes may have occurred first in the tropics and then propagated to higher-latitudes. These recent discoveries suggest that mechanisms and/or feedbacks originating in the tropics may be a more suitable explanation for abrupt climate change.
**Abrupt Climate Change- Do it originate from the Tropics?**

In looking to the tropics to explain abrupt global climate change, the potential of interannual variability (e.g., ENSO) to play a role in bringing about large and abrupt climate changes stands out (Cane, 1998). Modern interannual variability in the tropics influences climate variability over large regions of the globe.

Variations in solar insulation have the potential to modulate the interannual variability. For example, using a model capable that simulates tropical ocean dynamics Clement et al. (1999) showed that the redistribution of incoming seasonal solar energy in the tropics due to precessional forcing can alter ENSO behavior. The modeling results compare well with proxy-records of El Nino history from Ecuador (Moy et al., 2002), providing additional support for the relationship between solar forcing and tropical climate variability. The agreement between the model and data is remarkable, showing that both the increase in number of warm events over the Holocene as well as the peak around 1,000 BP can be explained as the response to the orbital forcing over the last 12,000. Furthermore, during certain orbital configurations, ENSO variability can lock to the seasonal cycle for centuries producing persistent La Niña-like conditions (Clement et al., 2001).

These changes in interannual variability on orbital, millennial, and centennial time scales could translate into abrupt global climate change. During an El Niño, the southward displacement of the ITCZ increases the flux of water vapor from the Atlantic to the Pacific (Schmittner et al., 2000). The Atlantic-Pacific interbasin salinity gradient is an important control on thermohaline circulation (Seidov and Haupt, 2002). Past changes
in the tropical Atlantic and Pacific hydrological cycles on orbital and millennial time scales did occur (Peterson et al., 2000; Stott et al., submitted). Furthermore, variations in the freshwater flux from the Atlantic to the Pacific could in turn affect interannual variability (A. Fedorov, pers. comm.).

Recent evidence suggests that sub-orbital variations in solar radiation may have occurred and that they may be associated with millennial and centennial climate change. North Atlantic IRD variations seem to be correlated with $^{14}$C and $^{10}$Be production oscillations which are used as a proxy for solar variability (Bond et al., 2001). Millennial and centennial variations in the Indian monsoon appear to follow these solar variability proxies (Neff et al., 2001; Fleitmann et al., 2003).

**Recommendations of Workshop**

Participants of the workshop agreed that is now an important need to have a focused research initiative that would investigate whether the tropical ocean/atmosphere system has played causal role in large, abrupt climate changes that have been documented in paleorecords from the past 60 thousand years. Participants in the workshop agreed that in order to assess whether the tropical ocean/atmospheric system has affected large abrupt global climate changes it will be necessary to develop a coordinated modeling/data acquisition program in which modeling and data acquisition efforts provide feedback to one another and, in this way, help guide the evolution of the program. The goal of such an effort is to obtain records from the tropics that will be used to test model experiments and provide better documentation of how tropical ocean/climate behavior on centennial to millennial time scales over the past 60 thousand years. The outcome of these efforts
will provide a test of the overarching hypothesis: “Large, sometimes abrupt, changes in ocean/atmospheric dynamics centered in the tropics have been responsible for the large climate changes experienced in the extratropics.” To confirm or reject this hypothesis will require a larger number of new, highly resolved marine and terrestrial records that are accurately dated. These data will be the basis of tests to determine the phase relationships between high and low latitude climate changes.

Secondly, the initiative will obtain information that will help assess what factors have been responsible for tropical climate variability at centennial to millennial time scales and whether there is a pattern of cyclic climate variability at time scales ranging from decadal to millennial. Climate models will help guide where data should be collected and the types of data that will be most useful for testing the model experiments. Similarly, the acquisition of new high resolution data is likely to lead to new ideas and hypotheses that will require additional model experiments. It is also highly probable that as new data and model results become available through this initiative these results will identify additional field programs to locations where data is needed. The amount of new data required by such an initiative will require multiple labs and multiple PI’s and students. The large amount of new analytical data that will be generated this initiative combined with new modeling results will necessitate an organizational and data management system that can help scientists share and exchange information and resources effectively and provide frequent opportunities for scientists to meet and discuss their results and ideas.

The participants of the workshop concluded that in order to undertake an adequate test of the primary hypotheses it will also be necessary to limit the timescale of
investigation. It was agreed that the most appropriate time frame for testing the hypothesis would be the last 60 thousand years, with particular emphasis on the past 30 thousand years for which the prospects are excellent for obtaining high quality data records from both marine and terrestrial archives that can be adequately dated with radiometric techniques. The ability to accurately date records using radiometric techniques over this time interval is particularly important in order to determine leads and lags between different regions. Furthermore, the boundary conditions can be adequately constrained for model simulations.

**Anticipated Achievements of a Tropics Initiative**

It is expected that through the collaborative efforts of a tropics initiative it will be possible to determine whether large abrupt climate changes in Earth’s past originated as tropical ocean/atmospheric changes. Answering this question will contribute significantly to an understanding of Earth’s natural climate variability and will provide an important perspective on potential future climate change. In addition, the initiative is expected to provide a broad spectrum of new information about tropical ocean/atmospheric variability. This includes:

1) What is the nature of tropical climate variability on decadal through millennial timescales?
- How do known modes of tropical climate variability and coupled atmosphere-ocean-terrestrial interactions, such as ENSO and the monsoons 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? What is the likelihood that the large, ocean/atmospheric variability due to external forcing (e.g. solar variability).

2) Is coherent centennial and millennial-scale variability an important characteristic of tropical climate variability?

**Research Strategy**

Among the specific products to be produced are:
- Correlated time series of tropical sea surface temperatures, sea surface salinities (using combined $\delta^{18}$O and Mg/Ca paleothermometry), deepwater characteristics,
- 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.

Climate/Ocean Reconstructions – In order to successfully accomplish the goals outlined above it will be necessary to develop a network of paleoclimate and paleoceanographic records that include 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 tropical climate covering the last 30,000 years that will provide coverage of tropical latitudes 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. These are likely to include tropical ice cores, speleothems, and varved lake records. This third order of sampling will help us understand higher frequency climate variability against the background of changing climate.

2. Modeling - An important step in understanding the processes and geographical patterns of the glacial-interglacial transition in the tropics is to study the response to changing boundary conditions in climate models. Some of this kind of work is already ongoing using coupled general circulation models (e.g. Liu et al. 2002, Otto-Bliesner et al. 2003). Further diagnostic work using experiments that have already been performed will elucidate the mechanisms that operate in the models in response to the forcings. Moreover, given that the response of ENSO to both past and future climate forcings appears to be model dependent, it is important to have similar experiments with multiple coupled GCMs. The emphasis of such modeling studies would be on identifying robust spatial patterns that can be compared with observations (e.g. SST, thermocline depth, precipitation, net freshwater flux and interannual variability in these quantities), along with physical insight into the origin of such patterns.

While studies using coupled GCMs will tend to focus on the equilibrium response to changing boundary conditions, because of computational constraints they are not likely to capture transient behavior that may be responsible for abrupt climate changes. Such behavior can be studied using simplified models of the climate. In addition, long
simulations with coupled GCMs are also possible (c.f. Hall and Stouffer 2001), and can provide some estimates of the internal variability of the system. The emphasis of such studies would be on the mechanisms in the tropics that are capable of generating abrupt change, and where possible, the spatial patterns associated with such mechanisms to be tested with observations.

Climate models can also be used to explore the linkages between the tropics and extra-tropics. Studies would focus on the mechanisms in both the ocean and atmosphere that link the tropics and extra-tropics, and how these may play a role in abrupt change. Such studies would shed light on the timescales of leads and lags between the low and high latitudes that could be tested against observations.

3. 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.
4. Regular PI workshops

5. Student involvement

6. Summer short courses

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Figure Captions:

Figure 1. Locations of recently developed tropical climate records covering some portion of the last 60 ka with millennial or better resolution.

Figure 2. Comparison of abrupt climate changes in the tropics during MIS 3 to North Atlantic climate represented by the Greenland ice core record. From top to bottom: (A) planktonic $\delta^{18}O$ record from Sulu Sea representing East Asian Monsoon variations (Dannenmann et al., 2003); (B) inferred surface-water $\delta^{18}O$ record from the western tropical Pacific representing shifts in atmospheric convection away from the region (Stott et al., 2002); (C) $\delta^{18}O$ records from Hulu Cave stalagmites representing East Asian Monsoon variations (Wang et al., 2001); (D) $\delta^{18}O$ record from Moomi Cave stalagmite representing East African-Indian Monsoon variations (Burns et al., 2003); (E) organic matter $\delta^{15}N$ record from Arabian Sea representing denitrification variations related to the intensity of summer monsoonal upwelling (Altabet et al., 2002); (F) percentage of total organic carbon in Arabian Sea sediments representing monsoon-induced biological productivity variations (Schulz et al; 1998); (G) bulk Ti content in Cariaco Basin sediments representing precipitation variations (Peterson et al., 2000); (H) $\delta^{18}O$ record from GISP2 ice core representing Greenland air temperature variations (Stuiver and Grootes, 2000).

Figure 3. Comparison of abrupt climate changes in the tropics during the Holocene to North Atlantic climate represented by the Greenland ice core and North Atlantic records.
From top to bottom: (A) number of moderate-to-strong El Niño events per 100 yr reconstructed from clastic sediment layers in Laguna Pallcacocha, Southern Ecuador (Moy et al., 2002) (B) foraminiferal transfer function derived warm season SST anomaly from eastern tropical Atlantic (deMenocal et al., 2000) (C) factor analysis of 14 rare earth elements (REE) from Arabian Sea sediments representing monsoon variations (Sirocko et al., 1996) (D) *G. bulloides* percentage in Arabian Sea sediments reflecting southwest monsoon variations (Gupta et al., 2003) (E) δ¹⁸O record from Qunf Cave stalagmite representing East African-Indian Monsoon variations (Fleitmann et al., 2003) (F) inferred surface-water δ¹⁸O record from the western tropical Pacific representing shifts in atmospheric convection away from the region (Stott et al., submitted) (G) bulk Ti content in Cariaco Basin sediments representing precipitation variations (Haug et al., 2001) (H) δ¹⁸O record from NorthGRIP ice core representing Greenland air temperature variations (Johnsen et al., 2001) (I) stacked record of petrologic tracers representing North Atlantic drift ice variations (Bond et al., 2001).

Figure 4. Detailed comparison of Holocene millennial and centennial variations in inferred surface-water δ¹⁸O record from the western tropical Pacific representing shifts in atmospheric convection away from the region (Stott et al., submitted) to the δ¹⁸O record from NorthGRIP ice core representing Greenland air temperature variations (Johnsen et al., 2001). Note the high degree of correlation of millennial and centennial variations between the records.
Figure 2
Figure 4
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Monsoon Portion

4. Modeling initiatives

During the deliberation, it became clear that the priority problems of monsoon AGCM modeling are:

- Most AGCMS still have significant systematic errors in simulating the climatological regional features of the seasonal mean monsoon.
- Although AGCMs show considerable potential predictability, the skill of seasonal-to-interannual monsoon prediction, based on model hindcast is poor. The cause of the poor prediction skill is likely due to the inability of models to simulate the internal dynamics of the region, i.e., the intraseasonal oscillations. Short-term modeling initiatives are focused toward making a serious attempt to improve the simulation of the regional features of the seasonal mean monsoon and toward improving skill in simulating the interannual variability of the monsoon.

OGCMs:

It has been known for many years that ocean models perform well in capturing SST anomalies (SSTAs) in the central equatorial Pacific Ocean, but elsewhere the known inaccuracy of all surface fluxes severely limit the ability of OGCM's to accurately simulate SSTAs. This fact has inhibited many ocean models from critically examining their model's SSTA performance, over all regions where those SSTAs have strong
statistical correlation with land climate parameters (e.g. monsoon rainfall). However, in the last 3 years at least 4 groups worldwide have started such work for the Pacific and Indian Ocean basins - the probable region of SST influence on the monsoon. As outlined in the Panel's Implementation Plan, OGCMs that accurately reproduce observed SSTAs when forced with observed fluxes (if the latter were perfect) are crucial to successful simulation of the monsoon in coupled models.

Initial results from OGCMs forced with observed fluxes show encouraging skill in simulating SSTAs in the Indian Ocean and off-equatorial Pacific Ocean, though it is considered that this skill is as yet probably well below the level required for successful coupled modelling of the monsoons.

**Modeling recommendations:**

Bearing in mind the modelling "state-of-the art", and the characteristics of SSTAs in the Indian Ocean, the usual strength of the intraseasonal variability during the 1997-98 ENSO, the Panel proposes the following recommendations to the CLIVAR SSG:

**AGCMs**

- Simulation by a set of AGCMs that have demonstrated skills in simulating the monsoon for 20 years (1979-1998). Comparison by different AGCMs will
establish the state of the art in simulating the mean monsoon and to indicate
directions for improved simulation.

- Ensemble runs to be carried out with monthly SST and weekly SST, to decipher
  the role of short-term SST forcing on intraseasonal oscillations.
- It is proposed that a detailed GCM intercomparison of ensemble forecasts should
  be carried out for the following period.

  a) DJF (96-97)
  b) MAM (97)
  c) JJA (97)
  d) SON (97)
  d) DJF (97-98)

A subcommittee within the monsoon panel was set up to coordinate the modeling (Drs.
Kang, Shukla and Goswami)

**OGCMs:**

The Panel recommends that an ocean equivalent of the "AMIP" experiments should be
undertaken, to assess the present-day skill of OGCMs in simulating SSTAs, in global,
Pacific-Indian and Indian Ocean OGCMs. Since this is a new initiative, it is worth
spelling out the steps required. They are being negotiated with likely modeling groups at
the time of writing, but a possible procedure is as follows:
a. A standard global climatology of surface wind stresses and heat and freshwater fluxes should be prepared for use in the intercomparison study. A climatology of observed seasonal values of the Indonesian Throughflow should also be prepared, based on XBT data.

b. Ocean modelling groups should be invited to participate in an intercomparison of model SST performance over the Indian Ocean. Groups with global or Pacific-Indian models should use the full surface flux climatology; those with Indian Ocean models should use the XBT-based Indonesian Throughflow as a boundary condition. Participants would be asked to find the seasonal heat and freshwater flux corrections needed in their models to restore their model to observed mean seasonal SST and SSS, respectively.

c. A gridded data set of wind stresses and speeds, based on SSM/I winds, should be prepared to cover the period 1996 through 1998. OGCM performance in simulating observed Indian Ocean SSTAs during this unusual period, using this data set and assuming climatological shortwave radiation, would be intercompared.

This project needs to be coordinated with the CLIVAR Upper Ocean Panel.

(Coordinators: Godfrey, Murtugudde, McCreary).

Regional models
For accurate simulation of regional climate, it may be necessary to embed nested high resolution regional climate model in AGCMs.

- Carry out and assess the performance of regional models in simulating the 1997-98 monsoon over (a) the Indian monsoon region and (b) the East Asian region.
- Explore the sensitivity of regional climate models to changes in vegetation and soil moisture.

Monsoon definition

There is a need to better define the monsoon and its interannual variability in terms its regional and global contexts. Research in this direction is encouraged.

5. Long-term monitoring (LTM)

LTM of monsoon-related parameters e.g. SST, salinity, ocean surface wind, precipitation, land surface temperature, soil moisture, snow cover, vegetation and tropospheric wind, temperature and humidity fields should be maintained both by ground based and satellite observations.

Recommendations
• Selected surface flux measurement platforms implemented during GAME/SCSMEX for long-term monitoring.

• GAME-AAN, including Tibetan Plateau, Central Asia should be maintained up to the 2005 time frame.

• The buoy arrays and AWS in SCSMEX also need to be continued.

• Japanese ship observations (JEXAM) need to be continued.

In order to fill gaps in the monitoring arrays:

• ATLAS/TRITON buoys need to be expanded to the equatorial East Indian Ocean to coordinate with JASMINE

• Relatively sparse observation network of GCOS over the Indian Ocean basin need to be enhanced. In particular the upper air sounding/wind profiling over Gan Island need to be deployed.

Long-term data collection and re-construction

• Long-term daily precipitation archive over the whole AA monsoon region should be processed in cooperation with GEWEX/GPCP, with support from WCRP/CLIVAR for necessary capacity building capabilities, e.g. PC, software and training.

• Daily station precipitation data over land regions and islands.
• Precipitation over oceans in the AA monsoon region from field experiments, SCSMEX, JASMINE.

• Snow cover and soil moisture data over Asian monsoon land mass

Satellite monitorings

• Maximize usage of satellite data in conjunction with in situ observations for monsoon studies

• The following variables are most important in meeting the AA-monsoon program objectives:

  - Rainfall, water vapor - TRMM, SSM/I
  - Ocean altimetry - TOPEX, JASON
  - Surface wind and fluxes over ocean - NSCAT, QICKSCAT
  - Sea surface temperature - AVHRR, MODIS
  - Soil moisture, surface vegetation - AVHRR, MODIS, ASTER
  - Clouds and radiation - CERES

The proposed GPS sounding of temperature and water vapor profiles is particularly relevant to the AA-monsoon program and it will alleviate some of the problems in conventional data in the AA-monsoon regions.
A good example of ocean’s ability to amplify climate change is the recurrent Heinrich events of the last glacial. Instabilities in the large northern hemisphere ice sheets during the last ice age are thought to have caused rapid discharges of ice into the North Atlantic that freshened surface waters and diminished the convective capacity of the high latitude surface waters. With the conveyor system turned off (or turned down) by lower salinities, less heat would have been advected into the northern Atlantic and this becomes an amplifier that leads to the climatic cooling throughout the northern hemisphere. These conceptual models are supported by coupled ocean/atmospheric model experiments that examine downstream effects of an ocean conveyor turned on and off (refs). But in the case of the Holocene, ice sheet dynamics cannot be called upon to explain the pattern of climate variability (Bond et al., 2001). Proxy data imply relatively small changes in solar irradiance may be responsible for Holocene variability observed in high latitude marine records. Solar variability influences stratospheric ozone levels and stratospheric circulation and, through a dynamical coupling with the troposphere can alter low level winds. Bond (2001) argued that enhanced northerly winds resulting from these solar fluctuations would have increased the amount of drift ice brought into the North Atlantic and this would lead to lower surface salinity and reduced oceanic overturning. The paleotemperature reconstructions from the North Atlantic seem therefore, to implicate variable thermohaline overturning as the amplifier in the case of the cold events documented by Bond (2001).

If correct, Bond’s findings would have important implications for assessing the cause of climate change on many different time scales. It implies there is considerable sensitivity to small changes in solar forcing and that under both glacial and non-glacial boundary
conditions small changes in radiative forcing can lead to hemispheric and perhaps global scale climate change through an amplification mechanisms such as the ocean’s heat transport. This is particularly relevant to present concerns about global warming in response to rising levels of greenhouse gases in the atmosphere.