## THE PAGES/CLIVAR

# INTERSECTION

Providing the paleoclimatic perspective needed to understand climate variability and predictability

*Coordinated research objectives of the*
*International Geosphere-Biosphere (IGBP)*
*and*
*World Climate Research (WCRP) Programmes*

*Report of a joint IGBP-WCRP Workshop*
*Venice, Italy,*
*November 1994*

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PAGES
PAST GLOBAL CHANGES

Climate Variability & Predictability
CLIVAR
World Climate Research Programme

GLOBAL
IGBP
CHANGE

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# Executive Summary

The instrumental and satellite record of climate variability is too short and spatially incomplete to reveal the full range of seasonal to centennial-scale climate variability, or to provide empirical examples of how the climate system responds to large changes in climate forcing. This recent record is also a complex reflection of both natural and anthropogenic forcing (e.g., trace gas and aerosol). The paleoclimatic record from varied proxy sources, on the other hand, provides the much wider range of realizations needed to describe and understand the full range of natural climate system behavior. The need for an improved paleoclimate perspective is highlighted in the recently produced Science Plan of the World Climate Research Programme (WCRP) Climate Variability and Predictability (CLIVAR) Programme, as are the merits of joining forces with the International Geosphere-Biosphere Programme (IGBP) Past Global Changes (PAGES) Core Project to meet the paleoclimatic needs of CLIVAR.

To determine the extent of intersection between CLIVAR and PAGES, and to begin a productive interdisciplinary collaboration among scientists belonging to these two separate research communities, a joint IGBP-WCRP workshop was held. This workshop brought together members of both the CLIVAR and PAGES communities, and defined specific foci where paleoclimatic research would feed directly into a better understanding of climate variability and predictability. These proposed foci cut across the traditional seasonal-interannual and decadal-centennial time-scales of CLIVAR GOALS (Global Ocean Atmosphere Land System), CLIVAR DEC-CEN (Decade- to Century-scale climate variability) and CLIVAR-ACC (Anthropogenic Climate Change), and center on the (1) dynamics of low-latitude climate change, (2) global ocean thermohaline variability, (3) regional- to global-scale hydrologic variability, (4) dynamics of abrupt climatic change, (5) climate model evaluation and improvement, and (6) climate change detection. Specific research activities were identified for each of these foci and emphasize closer interaction between CLIVAR and PAGES scientists.

A new interdisciplinary PAGES-CLIVAR Working Group is being formed jointly by the IGBP and WCRP to develop specific implementation plans building on the recommendations in this report. The net result will be a program that taps the extensive research network established by IGBP PAGES to provide unprecedented international cooperation in assembling and using the paleoclimatic data needed to improve our understanding of climate variability and predictability.

# 1: Introduction

## 1.1 History of PAGES CLIVAR coordination

Understanding the behavior and predictability of the Earth's physical, chemical, and biological systems is the major focus of the International Geosphere-Biosphere (IGBP) and World Climate Research (WCRP) Programmes. Within this framework, the IGBP Past Global Changes (PAGES) Core Project and the WCRP Climate Variability and Predictability (CLIVAR) Programme share some primary objectives. In particular, CLIVAR needs, and PAGES aims at, a reconstruction of global climate and environmental change over the last centuries to millennia. Both international programs also aim to improve our understanding of the natural processes that drive seasonal- to centennial-scale climate variability.

Empirical studies within CLIVAR will rely first on instrumental data. However, useful as instrumental studies may be, they are limited by the available data record, which generally extends back less than 150 years. This duration is too short to extract the full range of variability likely to be present in the climate system. Diagnostic studies of climate variability will therefore rely in a fundamental way upon paleoclimatic proxy-data such as that derived from the analysis of tree rings, corals, sediments, ice cores, and other sources. To achieve this goal, CLIVAR needs to cooperate with PAGES to assemble the detailed paleoclimatic information needed to study the variations of the Earth's climate over the last 100 to 1,000 years. In addition, paleoclimatologists have identified a variety of striking climatological events on decade to century timescales that are unknown in the short period of instrumental coverage. An understanding of these events requires further interpretative studies based on paleoclimatic evidence and model simulations of past climatic states.

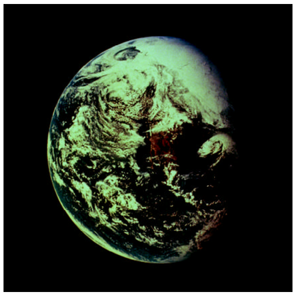
To address common objectives, the CLIVAR Scientific Steering Group (SSG) and the PAGES Scientific Steering Committee (SSC), together with IGBP-Stockholm, sponsored a joint CLIVAR/PAGES workshop that brought together paleoclimatologists, oceanographers, and atmospheric scientists involved in the study of climate dynamics. The aim of this workshop was to (1) inform paleoclimatologists of the data/analyses required to achieve the objectives of CLIVAR; (2) inform climate physicists of the relevant paleo-data that may be obtained by paleoclimatologists; (3) establish a research programme that would strengthen the interactions between paleoclimatologists, climate physicists, and modelers. This workshop was held in Venice, Italy, 16–20 November 1994.

This document summarizes the conclusions of the Venice meeting and presents the first step of a joint PAGES/CLIVAR effort to plan and implement collaboration on a paleo perspective for meeting CLIVAR goals.

## 1.2 Overview of WCRP CLIVAR

CLIVAR 'A Study of Climate Variability and Predictability' focuses on the slowly varying component of the climate system and has as its objectives (CLIVAR Science Plan, 1995):

- To describe and understand the physical processes responsible for climate variability and predictability on seasonal, interannual, decadal, and centennial timescales, through the collection and analysis of observations, and the development and application of models of the coupled climate system.
- To extend the record of climate variability over timescales of interest through the assembly of quality-controlled paleoclimatic and instrumental data sets.
- To extend the range and accuracy of seasonal-to-interannual climate prediction through the development of global coupled predictive models.



The "Paleo" Perspective. One contribution of PAGES is that it has focused scientists and funding around the world on a common set of high-priority paleoenvironmental research objectives. Collaboration with CLIVAR will combine this "paleo" perspective with one based on instrumental observations to reconstruct and understand the full range of climate variability and predictability.

- To understand and predict the response of the climate system to increases of radiatively active gases and aerosols, and to compare these predictions to the observed climate record in order to detect the anthropogenic modification of the natural climate signal.

CLIVAR is organized into three component programs:

- CLIVAR-GOALS, which is built on the results of the TOGA programme, will examine the variability of the Global Ocean Atmosphere Land System on seasonal-to-interannual timescales.
- CLIVAR-DecCen will examine the mechanisms of variability and predictability of climate fluctuations on decadal-to-centennial timescales. It is expected that much of this variability arises from the world oceans.
- CLIVAR-ACC will examine the nature of anthropogenic climate change primarily in a modeling context.

## 1.3 Overview of IGBP PAGES

PAGES 'Past Global Changes' is charged with providing a quantitative reconstruction of the Earth's past environment by obtaining and interpreting a variety of paleoclimatic records. PAGES focuses on specific sets of questions:

- How has global climate changed in the past? What factors are responsible for these changes and how does this knowledge enable us to understand future climate and environmental change?
- What were the initial conditions of the Earth system prior to human intervention? To what extent have the activities of man modified climate and the global environment?
- What are the limits of natural greenhouse gas variations, and what are the natural feedbacks to the global climate system? In what sequence, in the course of environmental variation, do changes in greenhouse gases, surface climate, and ecological systems occur?
- What are the important forcing factors that produce climate change on societal timescales? What are the causes of abrupt climatic changes and the rapid transitions between quasi-stable climatic states that occur on decadal-to-centennial timescales?

Answering these questions requires the retrieval of high quality paleorecords from a variety of proxy-data sources in a global network of field activities. PAGES is structured into three research-observational foci, a climate sensitivity and modeling focus, and a cross-project focus to address the broad analytical, data, and communication needs (Table 1). Within the observational foci, PAGES has designed two temporal streams that have as objectives:

Stream I:

to reconstruct the detailed history of climatic and environmental change for the entire globe for the period since 2000 B.P., with temporal resolution that is at least decadal, and ideally annual or seasonal.

Stream II:

to reconstruct a history of climatic and environmental change through two full glacial cycles, in order to improve our understanding of the natural processes that invoke global climatic changes.

## 1.4 PAGES activities that are relevant to CLIVAR

Because the Earth's environmental and ecological systems operate on a wide range of temporal and spatial scales, PAGES activities are global and encompass timescales varying from 1 to a few x$10^5$ years (Table 1). Part of this temporal focus is too long to be of use to CLIVAR. In addition, many sediment records of past environmental change are very long, but offer a temporal resolution that is too coarse to meet CLIVAR objectives. However, even though some aspects of PAGES are unlikely to be of use to CLIVAR, many PAGES activities are likely to yield significant contributions to meeting the objectives of all three CLIVAR components.

Annually resolved tropical paleoclimatic reconstructions of the last two millennia are of direct relevance to understanding the longer period modulations of the ENSO and monsoon phenomena. In the tropical oceans, the development of multicentury, subseasonally resolved climate records from corals is a central PAGES activity, and should provide new information about the functioning of the tropical ocean-atmosphere system on the Stream I timescale. In addition, corals and sediments from the western Atlantic and Caribbean regions provide an opportunity to obtain long records of variability in the Gulf Stream/Sargasso Sea region and its impact on the thermohaline circulation during the last millennium. Interhemispheric transfer of energy is primarily ensured by the oceanic thermohaline circulation and by atmospheric monsoon circulation. On the annual-to-century timescales, climatic conditions at the continental surface depend strongly on those of the ocean. In order to determine the response of continental climate to ocean changes, PAGES has established three major interhemispheric studies, the PEP (Pole-Equator-Pole) transects, to unravel the paleoclimatic evolution of both hemispheres along three longitudinal bands: one through the Americas (PEP I), a second over Asia and Australia (PEP 2), and the third through Europe and Africa (PEP 3). In addition, the PAGES ARTS, HIPP, and Paleomonsoons (Table 1) efforts will be directly relevant to CLIVAR. Paleoclimatic data with annual resolution should allow the documentation of how systems such as ENSO have influenced continental climate dynamics. PAGES will facilitate the recovery of the needed proxy records from the best sites, and will promote the international collaboration necessary to provide

## Table 1. PAGES Core Project Organization

FOCUS I: Global Paleoclimate and Environmental Variability

- PANASH: Paleoclimates of the Northern and Southern Hemispheres (including the Pole-Equator-Pole [PEP] transects)
  - Activity 1: PEP-1 The Americas Transect
  - Activity 2: PEP-2 Austral-Asian Transect
    - Task 1 - Lake Baikal
    - Task 2 - Himalayan Interdisciplinary Paleoclimate Project (HIPP)
  - Activity 3: PEP-3 Afro-European Transect
    - Task 1 - International Decade of East African Lakes (IDEAL)
    - Task 2 - Paleomonsoons (w/INQUA)
  - Activity 4: The Oceans
    - Task 1 - IMAGES (w/SCOR)
  - Activity 5: PAGES-CLIVAR Interactions
    - Task 1 - Annual Records of Tropical Systems (ARTS)

FOCUS II: Paleoclimate and Environmental Variability in Polar Regions

- Activity 1: Arctic Programme
  - Task 1 - Circum-Arctic Paleo-Environments (CAPE)
  - Task 2 - Nansen Arctic Drilling Project (NAD)
  - Task 3 - Greenland Ice Core Drilling Projects (GISP2 & GRIP)
- Activity 2: Antarctic Programme (w/SCAR)
  - Task 1 - Antarctic Ice Core Research
  - Task 2 - International Trans-Antarctic Scientific Expedition

FOCUS III: Human Interactions in Past Environmental Changes

- Activity 1: Human Impacts on Fluvial Systems
- Activity 2: Human Impacts on Terrestrial Ecosystems

FOCUS IV: Climate System Sensitivity and Modeling

- Activity 1: Climate Forcing and Feedbacks
  - Task 1 - Volcanic Influences (w/INQUA)
  - Task 2 - Solar Influences
  - Task 3 - Greenhouse Gases and Aerosol Influences
  - Task 4 - Abrupt Climate Change and Internal Climate System Dynamics
- Activity 2: Climate Model-Data Intercomparisons
  - Task 1 - Paleoclimate Modelling Intercomparison Project (PMIP)
  - Task 2 - Paleo Multiproxy Analysis and Mapping Project (PMAP) includes: Biome 6000 (with other IGBP Groups)

FOCUS V: Cross-Project Analytical and Interpretive Activities

- Activity 1: Chronological Advances
- Activity 2: Development of New Proxies
  - Task 1 - Isotope Calibration Study
- Activity 3: International Paleo-Data System (with the World Data Center-A for Paleoclimatology)
- Activity 4: REDIE -Regional, Educational and Infrastructure Efforts (with START/IAI)

*Acronyms*: HDP = Human Dimensions Programme; IAI = Inter-American Institute for Global Change Research; ICSU = International Council of Scientific Unions; INQUA = International Quaternary Association; SCAR = Scientific Committee on Antarctic Research (ICSU); SCOR = Scientific Committee on Ocean Research (ICSU); START = System for Analysis, Research and Training (IGBP, HDP, WCRP) the required combination of climatological insight, local expertise, and logistical/analytical capability.

The thermohaline circulation variability is one major process that can be linked to long-term climatic changes (from decades to millennia). Paleoclimate data were recently the first to point to the ability of the Earth's climate system to switch abruptly between significantly different climatic modes. For example, major deep water circulation changes have been reconstructed during the last glaciation. Some of these changes develop on decade-to-century timescales in response to the injection of freshwater at the sea surface of the northern North Atlantic Ocean. Massive iceberg discharges from the Laurentide or Eurasian ice sheets are assumed to be responsible for abrupt sea-surface salinity decreases. However, during the present Holocene interglacial, the paleoceanographic record of the North Atlantic Ocean reveals phenomena that may be related to changes in surface salinity much larger than the Great Salinity Anomaly in the 1970s. These changes must be attributed to variations of the hydrological cycle, since the continental ice sheet had already disappeared. We still do not know whether these surface water salinity and density changes were responsible for significant changes in the thermohaline circulation and the heat budget of the Northern Hemisphere. However, these variations coincide with significant changes of climate and lake levels in various areas of the world. PAGES goals include the elucidation of this complex array of past climate variability. In this respect, PAGES polar efforts, IMAGES, and the PEPs (Table 1) will be of particular relevance to CLIVAR.

In addition to these observational programs, PAGES promotes three tasks devoted to the integration of data and paleoclimate modeling:

1) PMIP (Paleoclimate Modelling Intercomparison Project—also endorsed separately by the WCRP)—helps the evaluation of climate models by comparing simulations performed using identical imposed paleoclimate boundary conditions (insolation, ice sheet distribution, sea-surface temperatures, and $CO_2$ concentration) for two periods (6 kyr and 21 kyr B.P.).
2) PMAP (Paleoenvironmental Multiproxy Analysis and Mapping Project) aims at mapping reconstructed paleoclimates for well-defined time slices, including those of interest to PMIP. The maps that will be derived from both Stream I and Stream II activities should allow us to document spatial and temporal changes in terrestrial environments in the past and provide terms of validation of model simulations of past change.
3) The PAGES international data system, part of the ICSU World Data Center system, gathers compiled sets of validated paleodata stored digitally in formats that are easily available to meet the needs of the different research activities.

PAGES was developed to provide the paleoclimatic perspective for the IGBP, but can also be of use to other international programs in need of a long temporal framework. Just as CLIVAR must tap an understanding of past climate dynamics to meet many of its goals, the PAGES research community must be ready to provide CLIVAR with much of this understanding.

# 2: The Major PAGES/CLIVAR Research Foci

The workshop was organized around defining state-of-the-art questions, and how to answer these questions using an integrated paleoclimate data and modeling approach. A selected number of plenary talks by CLIVAR and PAGES scientists introduced issues in each focus, and group discussions then developed the scientific questions and research needed to answer them. The specifics of each identified PAGES/CLIVAR focus are presented in this section, whereas general implementation issues are presented in Section 3 of this document. It is recognized that the six PAGES/CLIVAR foci described below are interrelated and mutually supportive:

- Dynamics of low-latitude climate change
- Global ocean thermohaline variability
- Regional-to-global scale hydrologic variability
- Dynamics of abrupt climatic change
- Model evaluation and improvement
- Climate change detection

## 2.1 Dynamics of low-latitude climate change

Tropical ocean-atmosphere systems orchestrate climate variability worldwide over interannual-decadal timescales, and the tropical ocean is the primary source of energy and water vapor to the global atmosphere. Intensive observational programs, such as the family of TOGA/GOALS-related programs, have focused on improving our empirical basis for understanding and modeling the tropical ocean-atmosphere. Still, most instrumental observations of tropical climate span only the past few decades, and only a handful of instrumental records from the tropics predate the turn of the century. Thus, state-of-the-art predictive models are based only on the information available from the past several decades at most. Paleoclimatic records from corals, tree rings, ice cores, sediments, and other sources can be used to extend the observational baseline of tropical variability and document the sensitivity of these systems to past changes in forcings (Fig. 1). Such reconstructions offer new opportunities to gain insight into the intrinsic variability of tropical systems and to validate numerical model simulations of regional and global climate variability.

Ocean-atmosphere systems include distinct climatic signatures within and beyond the tropics that are readily recorded in paleoclimatic archives. In the shallow tropical oceans, corals offer the potential for multicentury, subseasonal reconstructions of the surface ocean and related atmospheric processes such as rainfall (Fig. 2; Dunbar and Cole, 1993; Quinn et al., 1993; Gagan et al., 1994; Tudhope et al, 1995, 1996; Wellington et al., 1996). In the few tropical areas with distinct seasonality (and throughout the mid- and high-latitudes), tree-ring analysis can provide annual records of seasonally specific climate variables over the past several centuries to millennium (D'Arrigo and Jacoby, 1992). High-altitude ice cores in Peru and Tibet (and potentially Africa) preserve chemical and physical records of accumulation, temperature, and atmospheric transport and chemistry over one to tens of millennia (Thompson et al., 1992, 1995). Historical climate records from certain cultures can provide detailed documentation of climate-related variables over centuries to occasionally millennia (e.g., Nicholson, 1989; Quinn et al., 1987).

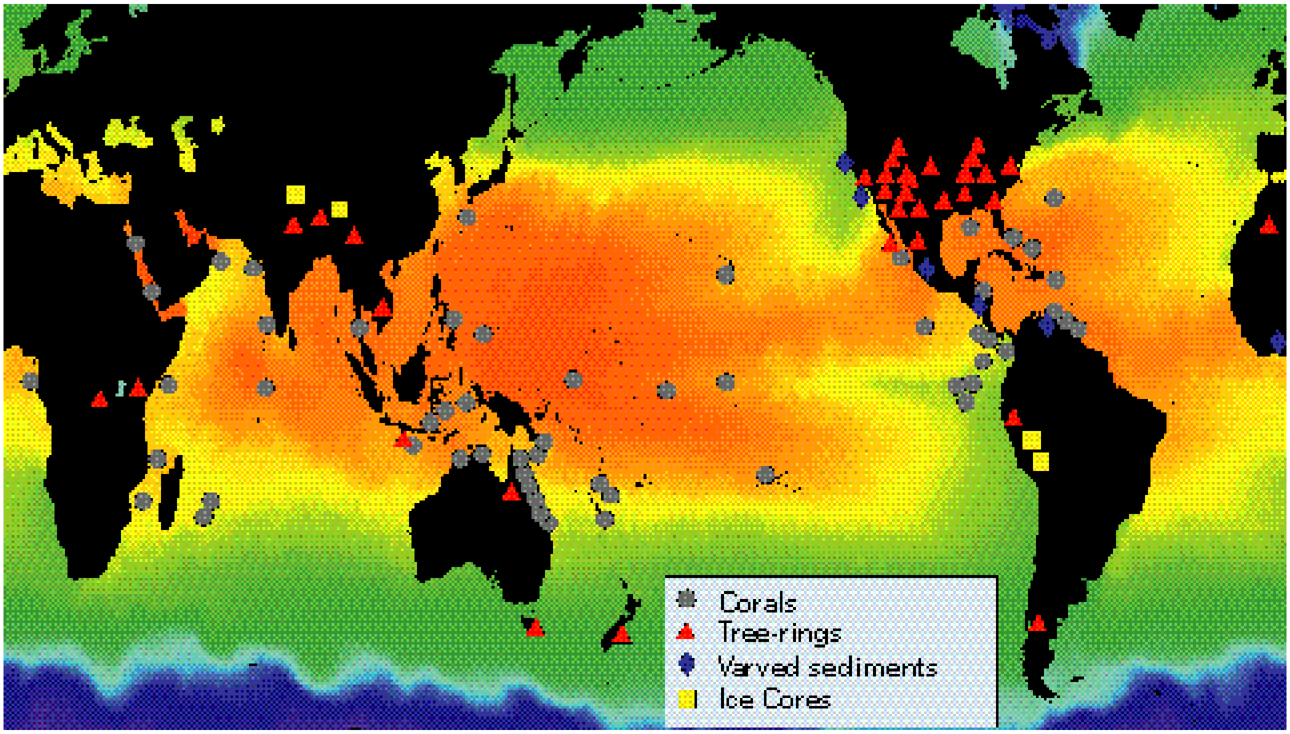
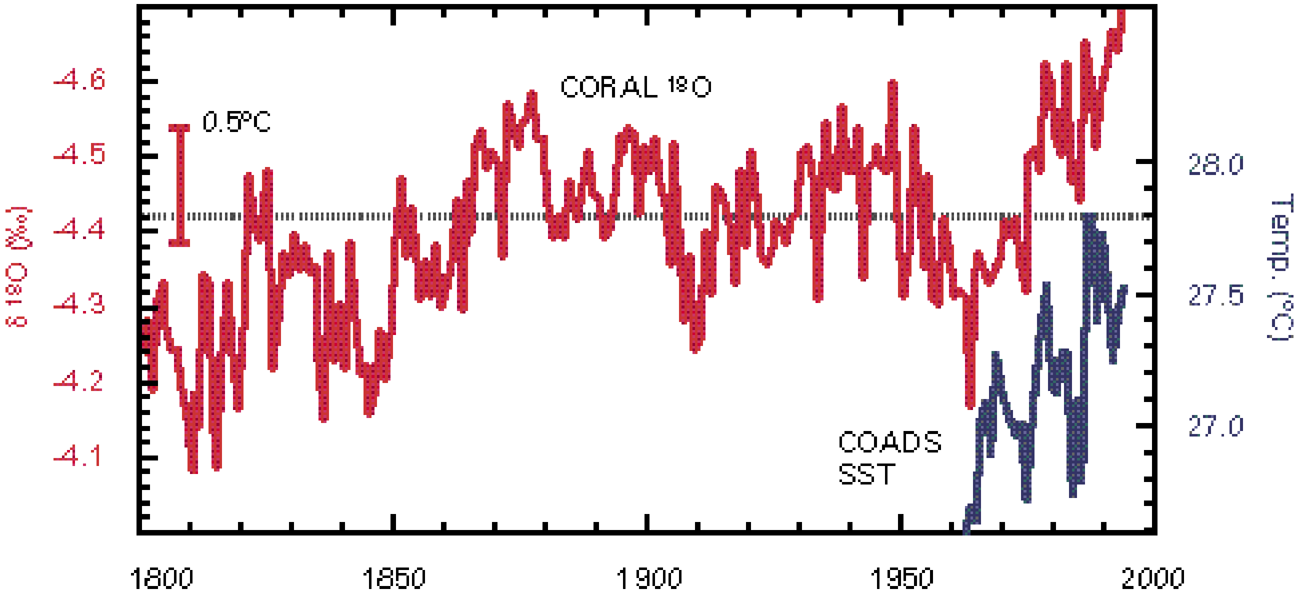



*Figure 1. Map of the global mid- to low-latitude SST indicating sites where centuries-long coral, ice-core, tree-ring, and varied sediment sources of past climate variability have been or are being studied. Many additional sites exist for future study. Large numbers of additional records exist at higher latitudes.*

The PAGES/CLIVAR working group on low-latitude dynamics identified several research foci in which a paleoclimatic perspective would contribute significantly to the goals of CLIVAR. These include:

- *Intrinsic variability of the spatial and temporal signatures that characterize modern tropical climate variability*

Modern tropical climate variability is dominated by ocean-atmosphere systems that have characteristic signatures in time and space. The primary examples of these are the El Niño/Southern Oscillation (ENSO), the Asian monsoon, and the African monsoon (with related Atlantic variability). The tropical conditions that enable these modes of variability and the extratropical patterns associated with these modes can be reconstructed readily from paleoclimatic records with annual or better resolution. An important first-order question to be addressed is whether these modes have persisted through time with the temporal and spatial signatures that characterize their modern variability (e.g., Cane et al., 1994).




Intrinsic variability around these well-known modes is a major impediment to predictability. This variability is well documented from observations and supported by models. Only paleoclimatic records, however, offer the opportunity to document the natural variability of tropical systems on time scales longer than the past few decades of observational records. To evaluate the utility of climate predictions, we need to document whether this natural (unforced) variability exceeds the level of anomalies that result from specific forcings.

- *Long-term variability in ENSO and its teleconnections*

A particular focus on ENSO allows this effort to take advantage of ongoing programs both in paleoclimate record development and numerical modeling. Coral-based ENSO reconstructions enable the extension of existing ENSO indices, which can be used both to compare with observed extratropical variability and to validate the statistics of the multicentury synthetic time series generated by models (Cane et al., 1995).

Initial records from Pacific corals spanning the past one to four centuries have revealed synchronous shifts in the frequency domain among annual, interannual, and multidecadal modes of Pacific

*Figure 2. Annual $\delta^{18}O$ values for a western Indian Ocean (off Kenya) coral compared to annual average instrumental (COADS) SST values. Coral records from around the globe allow the extension of tropical climate records back centuries, and thus reveal more complete realizations of the variability associated with climate systems such as ENSO and the African/Asian monsoons (courtesy J. Cole and R. Dunbar).*

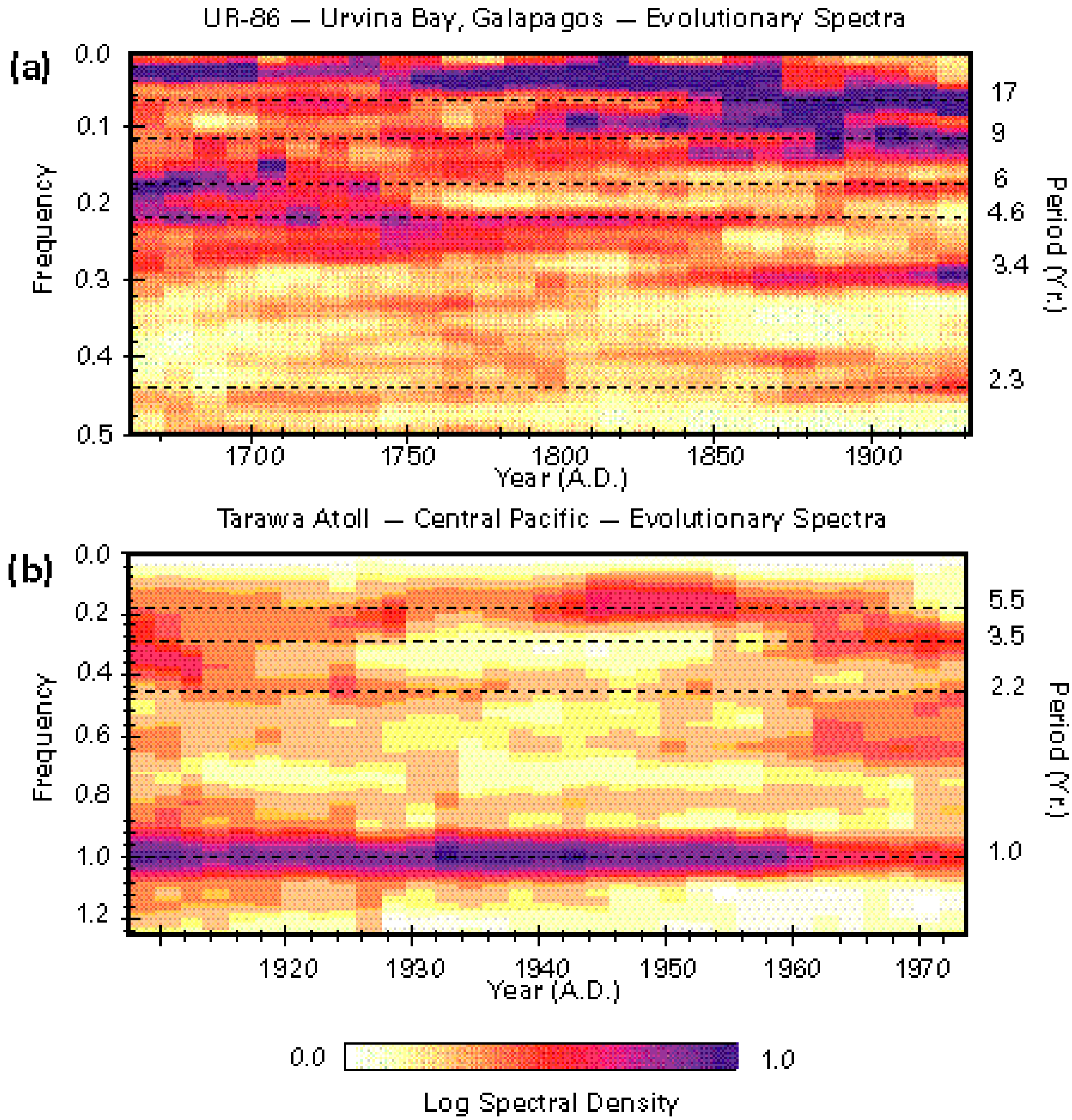



*Figure 3. Evolutionary variance spectra from (a) a 97-year coral-based precipitation record from the Tarawa Atoll (central Pacific), and (b) a 375-year coral-based SST record from the Galapagos (eastern Pacific), illustrating how the variance of tropical Pacific climate has changed over the past four centuries. Note how the variability mode of the last few decades is unique with respect to the longer record (courtesy R. Dunbar and J. Cole).*

variability, implying coupling across timescales (Fig. 3; Cole et al., 1993; Dunbar et al., 1994). Testing whether frequency-domain shifts in parts of the Pacific reflect multidecadal changes in ENSO will require long records from other sites in the core of the ENSO region. Key extratropical records will also help us to evaluate whether these shifts affect the pattern and magnitude of teleconnections.

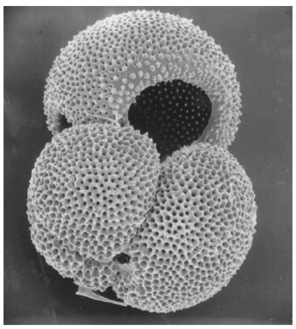
- *Causes of interannual-decadal monsoon variability*

Interannual-decadal changes in the African and Asian monsoons hold severe human consequences for hundreds of millions of people, yet their causes remain obscure. By providing a longer baseline of observations for both monsoon-related climate variables and certain potential monsoon forcings, paleoclimatic records can help to distinguish between certain causes of monsoon variability. One of the hypothesized causes of monsoon variability is Eurasian snow cover (Dickson, 1984), which, if extensive or deep, delays warming of the Asian continent in springtime due to the energy required for increased evaporation and results in a weakened monsoon (Barnett et al., 1988). An alternative hypothesized forcing for a weak monsoon is above-average sea-surface temperature (SST) in the equatorial Indian Ocean, which results in the preferential convergence of moisture in this region, leaving less to be transported over the Asian continent.

Over longer timescales (e.g., the last 10,000-15,000 years), paleoclimatic observations of hydrologic extremes and abrupt hydrologic changes in regions influenced by the modern monsoon provide a challenge to our understanding of how the monsoon operates. Known forcings during this period are gradual (e.g., changes in the seasonal distribution of insolation), yet observed changes in monsoon strength are abrupt and synchronous over large regions (Fig. 4; Street-Perrott and Roberts, 1983; Street-Perrott and Perrott, 1990; Gasse and Van Campo, 1994; Overpeck et al., 1996). The implication is that the monsoon may be highly sensitive to small “threshold” changes, or that there are some as yet unknown causes/mechanisms for large abrupt changes in monsoon strength.

- *Tropical system sensitivity*

The response of mean background conditions to large changes in climate boundary conditions has been extensively explored using both data and numerical simulations, but changes in variability related to these background shifts have received little attention. Changes in ENSO, for example, during the past 20,000 years would have important implications for climate variability worldwide. Yet the resolution of existing data permits only tentative evaluation of whether ENSO operated at all during the last glacial maximum (Markgraf et al., 1992). Recovery of fossil corals that date to the Holocene or last Glacial should allow evaluation of near-monthly variability in the tropical surface ocean during periods with much different boundary conditions than today. Such information offers valuable insights into the sensitivity of tropical systems to changes in climate boundary conditions that are relevant to the future as well as the past.



Ocean Dynamics. Paleoceanographic variability can now be reconstructed using a wide range of biological, sedimentological, and geochemical proxies. The result has been an increasingly detailed understanding of ocean dynamics on time scales spanning seasons to millennia.

- *The role of tropical variability in extratropical climate*

The relative contribution of the tropical Pacific to extratropical climate variability on decadal timescales has been debated in a series of recent articles, some of which emphasize a primary role of the tropical Pacific in generating extratropical anomalies (Kumar et al., 1994; Graham et al., 1994; Lau and Nath, 1994; Graham, 1995), while others stress the importance of mid- to high-latitude ocean-atmosphere interactions (Jacobs et al., 1994; Latif and Barnett, 1994, 1996; White and Peterson, 1996). Trenberth and Hurrell (1994) point to mid-latitude mechanisms that may amplify and impose a longer timescale on an initial signal of tropical origin. Better records from the tropical Pacific, coupled with the appropriate mid-latitude reconstructions from tree rings and other sources, will allow us to address this issue over time periods beyond the instrumental record.

## 2.2 Global ocean thermohaline variability

The thermohaline circulation is that part of the total ocean circulation that is driven by fluxes of heat and fresh water through the sea surface. Paleoclimatic data have shown that the strength and pattern of the thermohaline circulation have changed significantly not only between glacial and interglacial periods, but also within the last glaciation and perhaps within interglacials as well. The North Atlantic Drift carries northward warm water, which is cooled almost to the freezing point before sinking to the abyss. Under modern conditions, the heat flux released to the atmosphere by this process enhances by about 33% the heat received from the sun by the troposphere over the northern Atlantic and contributes to the maintenance of mild conditions over western Europe (Broecker, 1987). The heat transport was significantly smaller during the last glacial maximum (Fig. 5), and may have varied significantly during the Holocene as well (Fig. 4). The variability of the thermohaline circulation is therefore one major process that can be linked to long-term climatic changes (from decades to millennia).

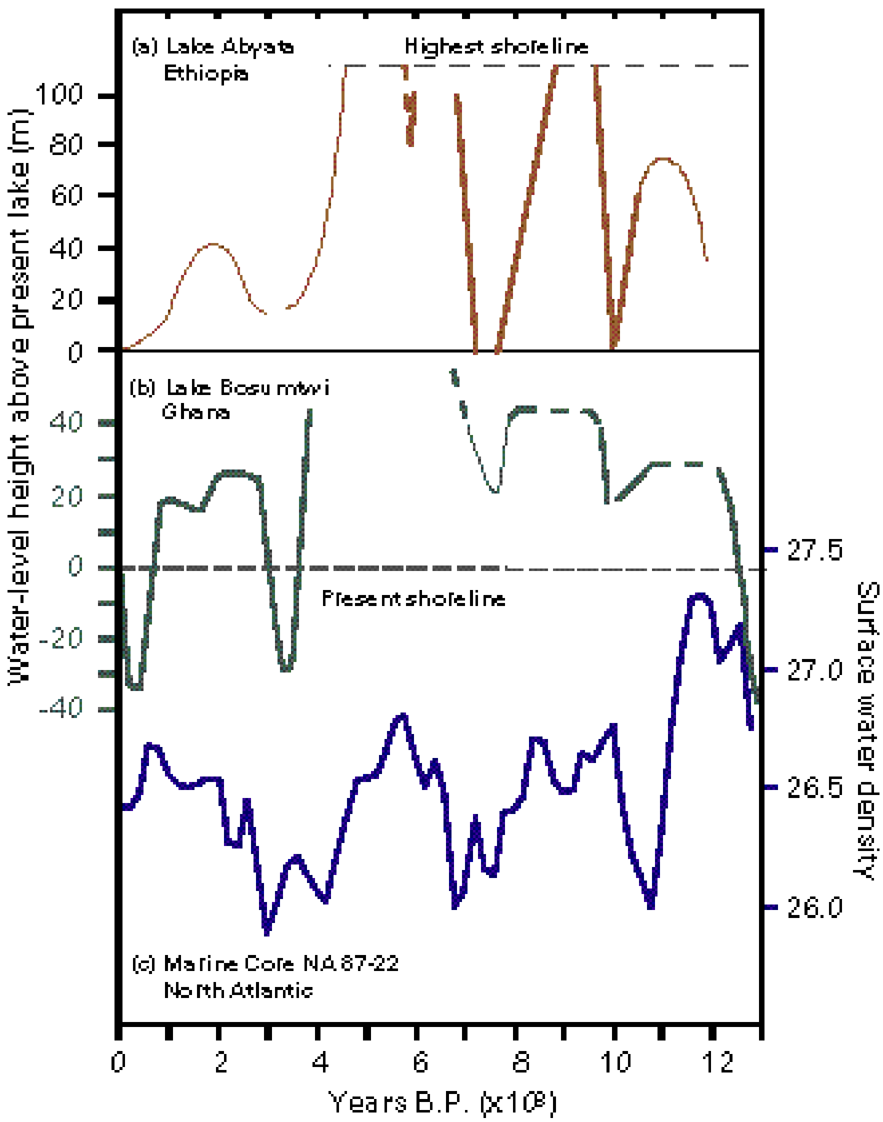
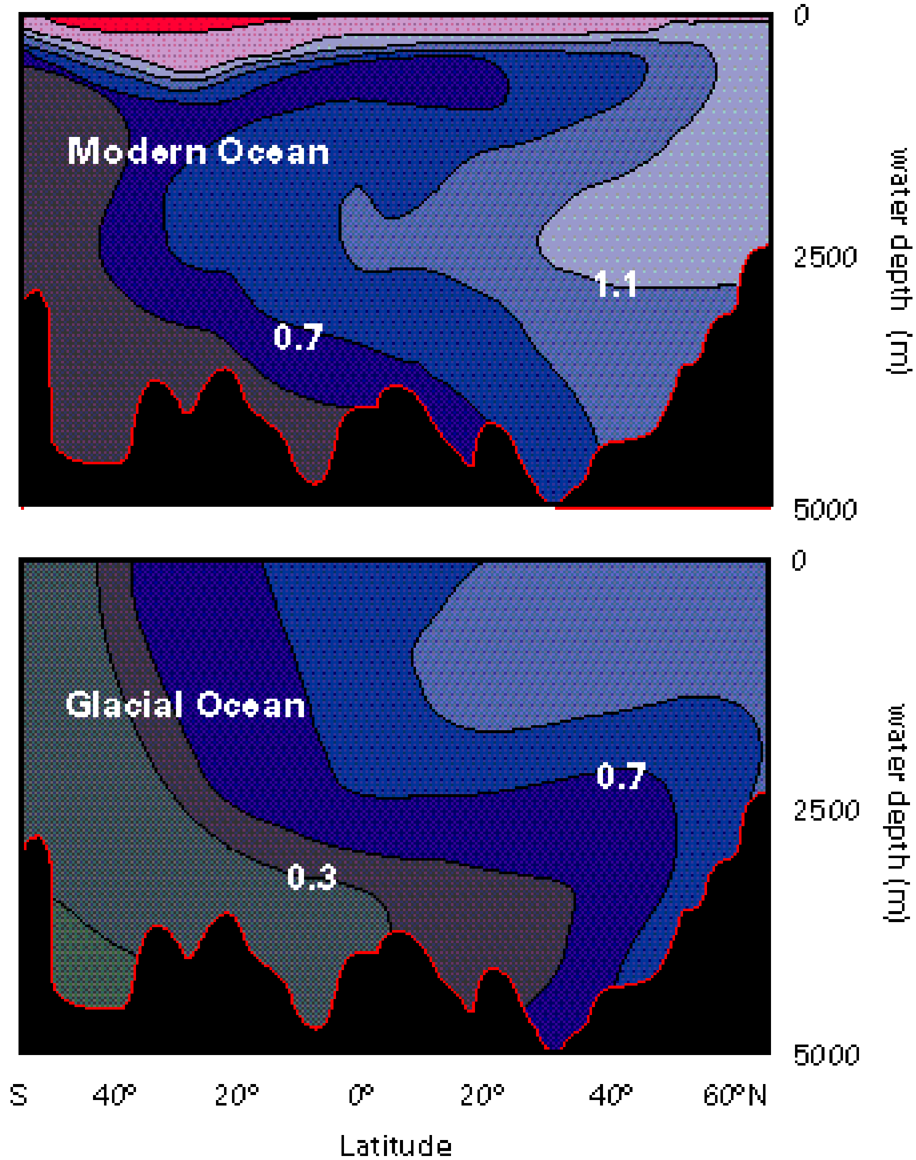



*Figure 4. (a, b) Hydrologic balance reconstructed for two sites in tropical Africa using late Quaternary sediments (from Gasse and Van Campo, 1994), and (c) North Atlantic sea-surface density changes reconstructed using marine faunal and isotopic changes (from Duplessy et al., 1992, unit for density defined as sigma = [density -1] x 1,000). The observed paleohydrological changes suggest that dramatic abrupt shifts in hydrologic balance can occur on a spectrum of societal-relevant timescales. Although the deglacial (i.e., 13 to 7ka) shifts have been linked with meltwater discharge events into the North Atlantic, the cause(s) of the Holocene aridity and sea surface density events remain poorly understood.*

*Figure 5. Latitudinal distribution of δ¹³C versus depth for the modern (top) and glacial (bottom) Atlantic Ocean. The modern measurements were made on water samples, whereas the paleoceanographic reconstruction is based on the isotopic composition of benthic foraminifera that lived at the sediment-water interface deep in the ocean. Rates of North Atlantic Deep Water formation varied dramatically during the last glacial-interglacial cycle, and were significantly reduced during much of the last glacial period (after Labeyrie et al., 1992).*



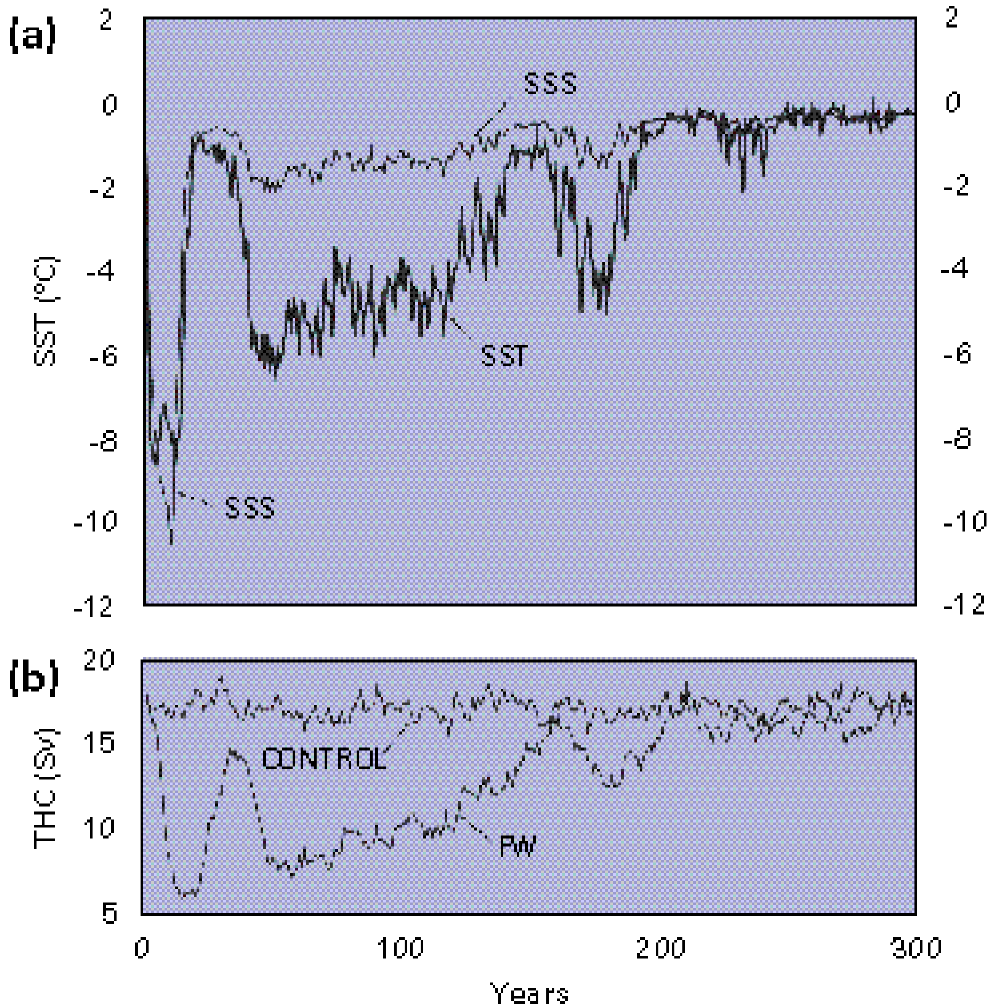



*Figure 6 (a) Time series of the deviations (from a control simulation) of SST and sea surface salinity (SSS; p.s.u.: practical salinity units) from their initial values at a coupled ocean-atmosphere model grid point in the Denmark Straight, showing the simulated response to a massive (1 Sv) surface flux of freshwater into the high-latitude North Atlantic during the first 10 years of the simulation. (b) Temporal variations of the rate of thermohaline circulation (THC) in the North Atlantic obtained from the control and fresh-water (FW) perturbation experiments. These simulated model responses mimic the type of abrupt ocean change observed in late-glacial paleoenvironmental data (figure after Manabe and Stouffer, 1995).*

One of the most fruitful interactions between the modern climate dynamics and the paleo-sciences communities has been the study of multiple states of the thermohaline circulation under various forcing factors (Fig. 6; Bryan, 1986; Manabe and Stouffer, 1988, 1995; Maier-Reimer and Mikolajewicz, 1989). This characteristic feature of coupled ocean-atmosphere models would have been left aside without the abundant evidence provided by paleoceanographers and paleoclimatologists. Numerical climate models (i.e., GCM's) are now used to quantify the rapidity of swings between modes (Stocker et al., 1992; Rahmstorf, 1994).

The paleoclimate community should thus continue to have a central role in documenting the variability of the thermohaline circulation on decadal-to-centennial timescales. The construction of high-resolution time series will undoubtedly lead to progress in our understanding of the thermohaline circulation. The understanding of the causes of rapid change will of course prove to be useful for forecasting the future behavior of the thermohaline circulation. In the context of CLIVAR, it seems logical to concentrate efforts on the main thermohaline convection zones of the North Atlantic and in particular the Labrador Sea component that appears to be crucial for understanding the recent convection variability.

The PAGES/CLIVAR working group on thermohaline variability identified several research foci in which a paleoclimatic perspective would contribute significantly to the goals of CLIVAR. These include:

- *Direct information on oceanic parameters*

From corals it is possible to obtain seasonal reconstructions of SST, salinity, ventilation, and nutrient content from high-resolution geochemical profiles of large coral heads ($\delta^{18}O$, $\delta^{14}C$, trace-elements). For example, in Florida, the Bahamas, and Bermuda it is possible to obtain long series in coral enabling the study of the variability in the Gulf Stream/Sargasso Sea region during the last millennium with a temporal resolution of a few months. At high latitudes, it may be possible to use molluscs and deep sea corals that have been collected and dredged at various depths and latitudes in the North Atlantic. From those corals and molluscs it could be possible to obtain short records of a few decades or centuries for deep sea parameters such as salinity, temperature, ventilation time, and nutrient content.

The use of oceanic sediments is important since it is a convenient way to obtain very long records of surface and deep sea parameters, such as sea surface temperature, sea surface salinity, deep water $\delta^{18}O$, $\delta^{13}C$, Cd (a proxy for phosphate), and benthic fauna. The temporal resolution is a direct function of sedimentation and bioturbation rates. Consequently, in the context of CLIVAR, it will be important to concentrate our efforts on specific areas characterized by extremely high accumulation rates on the order of several centimeters per century. In such cases, it has been shown that centennial and even decadal events can be dated and studied accurately using a variety of methods (Boyle and Keigwin, 1987; Duplessy et al., 1988, 1991, 1992, Lehman et al., 1991; Hughen et al., 1996).

- *Information on atmospheric parameters influenced directly by the North Atlantic variability*

Greenland and Arctic Canada ice cores make it possible to measure geochemical tracers in order to reconstruct long annual climate records from numerous chemical and physical measurements (Alley et al., 1993; Dansgaard et al., 1993; Grootes et al., 1993; Fisher and Koerner, 1994; Mayewski et al., 1994; O'Brien et al., 1995). These records will enable the reconstruction of time series of atmospheric and oceanic temperatures, atmospheric water sources, and air mass trajectories. Useful information can also be gathered from trees by studying ring width, densitometric and isotopic data (Briffa et al., 1992a; Jacoby and D'Arrigo, 1989). These annual records can provide constraints on atmospheric temperature and humidity, whereas annually laminated sediment records can be tapped for air temperature and wind strength (Lamoureux and Bradley, 1996; Hughen et al., 1996).

■ *Causes of thermohaline circulation variability*

Paleoclimatic studies should continue to investigate the importance of the high-latitude salinity field in controlling the location of deep water formation and in driving interhemispheric circulation. Deep water formation occurs in only a few localized regions where events of drastic heat loss can lead to destabilization of the water column down to a great depth. Under modern conditions, deep winter convection develops primarily in the high-latitude North Atlantic and around the Antarctic continent. By contrast, the surface salinity is too low in the North Pacific to allow deep convection with the more saline deep waters, even if the sea surface is cooled to the freezing point.

The reconstructed glacial-interglacial changes of deep water circulation have been related to changes in North Atlantic surface salinity, due to changes in the fresh water budget (Broecker et al., 1990; Duplessy et al., 1992). Several mechanisms have been proposed to explain them:

1) Changes in the precipitation plus runoff minus evaporation budget: Anomalies of precipitation minus evaporation of ±35 cm result in salinity anomalies of ±0.25 psu in a 50 m mixed layer. These values are typical of year-to-year variations in near-surface salinity.

2) Changes in the advection of low-latitude saline water and mixing with high-latitude water.

3) Changes in the flux of fresh North Pacific water through the Bering Strait into the northern North Atlantic (Shaffer and Bendtsen, 1994).

4) Massive iceberg discharge released from large continental ice sheets and melting into subpolar waters (Bond and Lotti, 1995).

All of these mechanisms were probably active at one time or another to trigger the deep water circulation changes of the last 150,000 years. Whereas the last mechanism could act only during glacial climates, when a significant amount of excess ice developed over Canada and northern Europe, the first three mechanisms may also have been active during interglacial conditions, and may result in determinant salinity fluctuations of

Abrupt Climate Change. Analysis of polar ice and deep-sea sediment cores has revolutionized how we view climate dynamics. Without this “paleo” perspective, we would have little inkling that the Earth’s climate system can shift from one mode of variability to a dramatically different one in the period of a decade or less.

interannual-to-decadal and centennial timescales (Duplessy et al., 1992; Rind and Overpeck, 1993; Rahmstorf, 1995; Stocker, 1995).

- *Sensitivity of thermohaline circulation variability to altered salinity forcing*

Paleoclimatic data have documented changes in the location of the sites of deep water formation and the depth of North Atlantic Deep Water. The available sediment records do not allow us to estimate directly the rate of change of meridional heat transport or mean meridional flow in response to high-latitude surface salinity variation. The sensitivity of the Atlantic thermohaline circulation to changes in salinity in the North Atlantic north of 40°N, or in the Southern Ocean south of 45°S, has been documented only through sensitivity experiments performed with 2-D general circulation models of the ocean (Fichefet et al., 1994). In these experiments, a glacial experiment was first performed using glacial boundary conditions (reconstructed SST and sea-surface salinity [SSS]) and a wind stress derived from the Ice-Age response of an atmospheric GCM. A series of experiments were then carried out with positive or negative anomalies of salinity either north of 40°N or south of 45°S. Results show that the strength of the Atlantic overturning is governed by the density contrast between the regions where deep convection takes place. Decreasing the salinity by 0.4 psu in the north, or increasing it by the same amount in the south, leads to a significant weakening of the thermohaline overturning and to a more pronounced intrusion of Antarctic Bottom Water (AABW). Increasing the salinity in the North by 0.4 psu, or decreasing it by the same amount in the South, results in an intensification of the overturning. The continued interplay of paleoclimate data analysis and modeling is needed to narrow uncertainties regarding the sensitivity of the thermohaline system to altered salinity forcing (Manabe and Stouffer, 1995).

## 2.3 Regional- to global-scale hydrologic variability

An objective of CLIVAR-GOALS is to document the range of climate and hydrological variability over the continents, and to exploit any predictability associated with this variability. As discussed in Section 2.1, the paleoclimate community is already developing the long-term perspective necessary to understand tropical ocean (e.g., ENSO) and monsoon variability in a manner that is directly applicable to understanding the effect these systems have on climate variability within and outside the tropics. In parallel to this work, others in the paleoclimate community are also focused on reconstructing and understanding regional- to continental-scale climate and hydrologic variability. Given the significant dependence of societies around the world on this latter variability, a high priority has been placed on using the paleoclimate perspective to improve skill in predicting this hydrologic variability, particularly in the way it is influenced by the oceans.

Regional- to subcontinental-scale, seasonally-to-annually-resolved reconstructions have already been generated using data from trees and historical documents. These include 250–300-year reconstructions of spring/summer temperature for western North America and western Europe (Briffa et al., 1988, 1992a), winter half-year precipitation and annual temperature in western North America (Fritts, 1991), drought in the coterminous United States (Fig. 7; Meko et al., 1993; Cook et al., 1996), El Niño strength in Peru (Quinn, 1992), and a wide range of variables for Europe, China, and Japan (Frenzel et al., 1994; Zhang, 1988; Mikami, 1992). A number of smaller regional or local reconstructions exist for similar or longer periods, for example, in Morocco (Till and Guiot, 1990; Chbouki, 1992), the southeastern U.S. (Stahle and

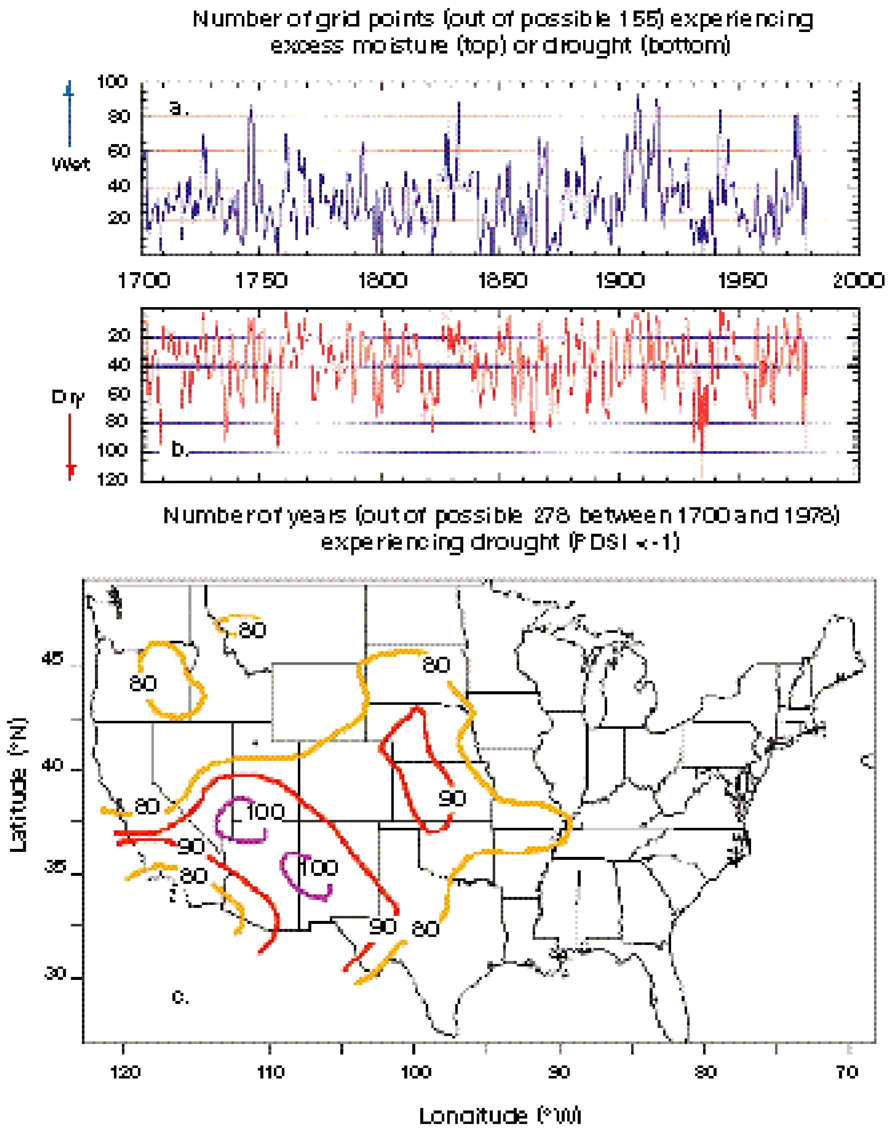



*Figure 7. Gridded U.S. drought reconstructions based on a new 388-site network of tree-ring records from across the coterminous U.S. Time series showing the number of 155 2°x3° grid points characterized by (a) exessive moisture (Palmer Drought Severity Index <+1) or (b) drought (PDSI >–1) for each of the 278 years reconstructed. (c) Mapped areas characterized by drought for at least 80 years of the total AD 1700 to 1978 record. Together, these reconstructions suggest that the most widespread drought of the last three centuries occurred during the "dust-bowl" years of the 20th century, and that the southwestern U.S. and High Plains are most susceptible to drought. Other data (see text) suggest that droughts both more extreme and persistent occurred earlier in the Holocene (figure after Cook et al., in press).*

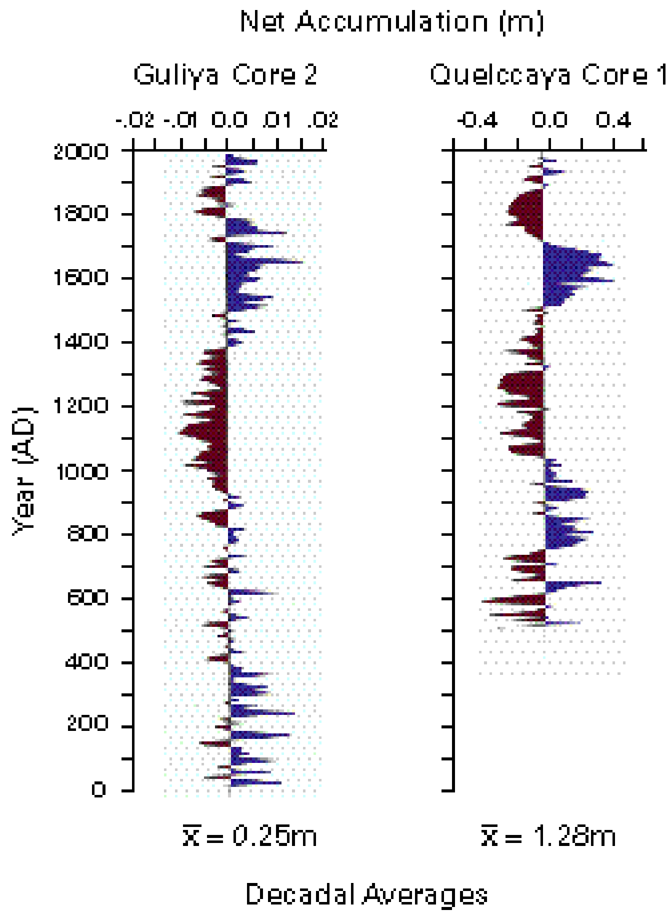



*Figure 8. Net ice (precipitation) accumulation for two ice cores located 20,000 km apart: Guliya, located on the Tibetan Plateau, and Quelccaya, located in the central Andes. Numerous paleoclimatic proxies can be used to extend the record of past moisture balance back centuries and millennia, thus revealing the full range of climatic variability (figure from Thompson, 1996).*

Cleaveland, 1992), high-latitude North America (Jacoby and D'Arrigo, 1989), California (Graumlich, 1993; Hughes and Brown, 1992), Scandinavia (Briffa et al., 1992b), the Mediterranean region (Serre-Bachet, 1994), Siberia (Graybill and Shiyatov, 1992), southern South America (Lara and Villalba, 1993; Boninsegna, 1992; Villalba, 1990), the Himalaya (Hughes, 1992), China (Hughes et al., 1994), Tasmania (Cook, 1992), and New Zealand (Norton and Palmer, 1992). Ice-core and laminated sediment records have provided key reconstructions as well (Fig. 8; Dansgaard et al., 1993; Mosley-Thompson et al., 1993; Thompson et al., 1992; Baumgartner et al., 1989; Lange and Schimmelman, 1994; Fisher and Koerner, 1994; Meese et al., 1994; O'Brien et al., 1995; Thompson, 1996)

Although networks of annually dated paleohydrologic records spanning the last several centuries will be critical to understanding climate and hydrological variability over the continents, it is also recognized that an understanding of the full range of hydrologic variability requires an even-longer perspective. Holocene-length (10,000 years) records indicate that major decade- to century-scale shifts in moisture balance, dwarfing those of the last couple of centuries, can occur (Figs. 4 and 9; Street-Perrott and Perrott, 1990; Forman et al., 1992, 1995; Knox, 1993; Ely et al., 1993; Gasse and Van Campo, 1994; Hodell et al., 1995; Muhs and Holliday, 1995; Lamb et al., 1995; Laird et al., 1996; Overpeck, 1996). PAGES/CLIVAR needs to take the lead in mapping out the time-space patterns of these unprecedented changes, and in understanding their causes.

The PAGES/CLIVAR working group on hydrologic variability identified several research foci in which a paleoclimatic perspective would contribute significantly to the goals of CLIVAR. These include:

- *Time-space reconstructions of past climate and hydrologic variability*

The compilation and integration of seasonally-to-annually resolved paleoclimatic time series into broad-scale networks suitable for synoptic analysis has been identified as a priority for PAGES, and would provide the time series needed to extend CLIVAR's record back beyond the limited period of instrumental data coverage. A well-organized, documented, easy-to-access, public domain database should include raw paleoclimatic data, climatic reconstructions based on these data, and time series of hypothesized climatic forcing (e.g., trace-gas, solar, and volcanic). Both time-series and spatial reconstructions should be made available for joint investigations within the PAGES/CLIVAR framework.

- *Investigating hypothesized climate system interactions and forcing*

Many of the available data discussed above have already been used to examine aspects of climate variability of relevance to CLIVAR. For example, spatial networks of tree-ring chronologies have been used to investigate the past interaction of the tropical Pacific variability and climate change in the Americas, Africa, and China (Cleaveland et al., 1992; Diaz and Pulwarty, 1994). The urgency for investigating the paleoclimatic record of climate and hydrologic variability is highlighted by the greater range of variability observed in some paleoclimatic time series than is observed in instrumental records. For example, paleoclimatic reconstructions point increasingly to the pre-instrumental period occurrence of extreme multidecadal drought in California (Graumlich, 1993; Stine, 1994; Hughes and Graumlich, 1995). PAGES/CLIVAR collaboration should focus on understanding the full range of past climatic and hydrologic variability, including any possible linkages to oceanic, trace-gas, solar, or volcanic forcing.

Hydrologic Variability. Extensive networks of trees and other proxy sources provide the unique opportunity for annually-dated spatial reconstructions of past hydrologic variability extending back centuries. PAGES-CLIVAR collaboration will tap this opportunity to help determine the extent to which the full range of hydrologic variability (e.g., droughts and floods) is predictable.

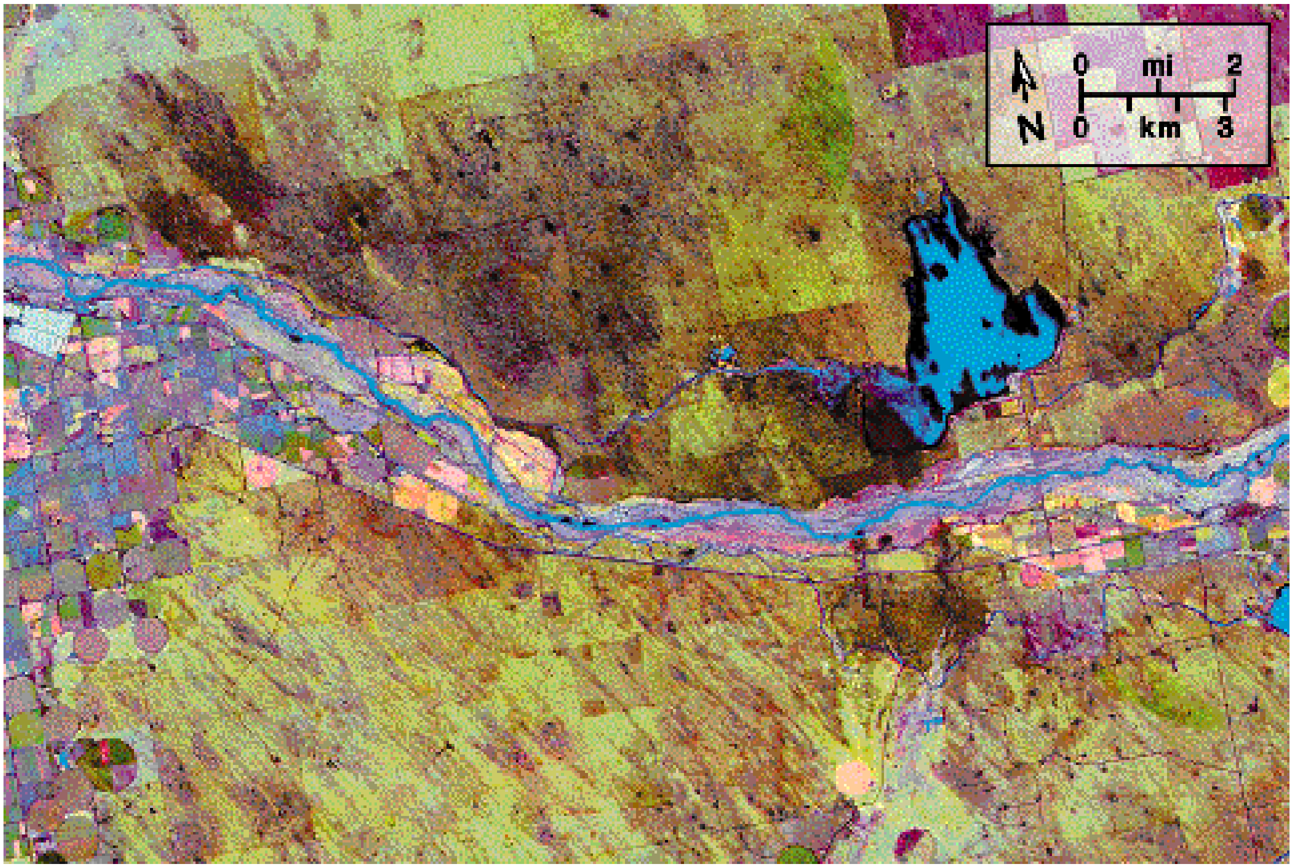



*Figure 9. Enhanced Landsat Thematic Mapper (TM) principal components image developed by georegistering and processing data acquired on 12 August and 15 October 1985. Dark parabolic landforms adjacent to the South Platte River in northeastern Colorado are currently stabilized dunes found to have been mobile at least four times during the Holocene. The origin(s) of these unprecedented drought events are poorly understood (image from Overpeck, 1996, and courtesy of R. Yuhas and A. Goetz, Center for the Study of Earth from Space, University of Colorado at Boulder).*

- *Evaluating predictive climate and hydrologic models*

The need for an expanded paleoclimatic model evaluation framework is highlighted in Section 2.5, but this need clearly extends to understanding how well predictive models can simulate the full range of observed climatic and hydrologic variability. Priority efforts should include networks of well-dated time series from periods characterized by modes of variability unlike today's. These include periods within the current Holocene interglacial, but also during the last glacial maximum.

## 2.4 Dynamics of abrupt climatic change

The paleoclimate record of past environmental change clearly shows that the instrumental record contains only a subset of possible climate system behavior. This is highlighted, for example, by paleoclimatic evidence that the climate system repeatedly switched, in a matter of years to decades, between significantly different climatic modes during the last glacial period (Fig. 10; Oeschger et al., 1985; Broecker and Denton, 1989; Bond et al., 1993; Dansgaard et al., 1993). Many of these changes were apparently episodic pulses of century-millennial duration, but also included abrupt (i.e., of annual- to decadal-scale duration) step-function changes in climate state during the switch from cold/glacial to warm/interglacial climate between 14,000 and 9,000 years ago (Grootes et al., 1993; Alley et al., 1993). More recently, there has been the growing realization that abrupt climatic events also characterized the present Holocene interglacial, particularly at low- to mid-latitudes (Fig 4; Street-Perrott and Roberts, 1983; Street-Perrott and Perrot, 1990; Kadomura, 1992; Knox, 1993; Ely et al., 1993; Gasse and Van Campo, 1994; Hodell et al., 1995; Lamb et al., 1995).

The significance of past abrupt climatic changes is heightened by the fact that they cannot be studied using instrumental data, and because their origins are poorly understood. Careful work is needed to map out the spatial-temporal patterns of change associated with past abrupt events, to determine their causes, and to determine if they are predictable. It is quite plausible that abrupt changes of the Holocene could be of the type that might occur in the future. Equally important is the manner in which the climatic system responds to abrupt change. It is possible that trace-gas-induced warming could manifest itself as a geologically abrupt event, and studies of past abrupt events are necessary for developing and evaluating predictive models that can simulate abrupt change.

This section explicitly addresses the kinds of large abrupt change that are not observed in the instrumental record of the past 100 years. Important abrupt shifts in seasonal-to-interannual variability of the coupled ocean-atmosphere, such as the Pacific shifts of the 1970s and 1990s (Trenberth, 1990; Trenberth and Hoar, 1996), or similar events observed in the coral record of Pacific variability over the past 400 years (Cole et al., 1993; Dunbar et al., 1994), are highlighted foci of Section 2.1.

The PAGES/CLIVAR working group on abrupt climatic change identified several research foci in which a paleoclimatic perspective would contribute significantly to the goals of CLIVAR. These include:

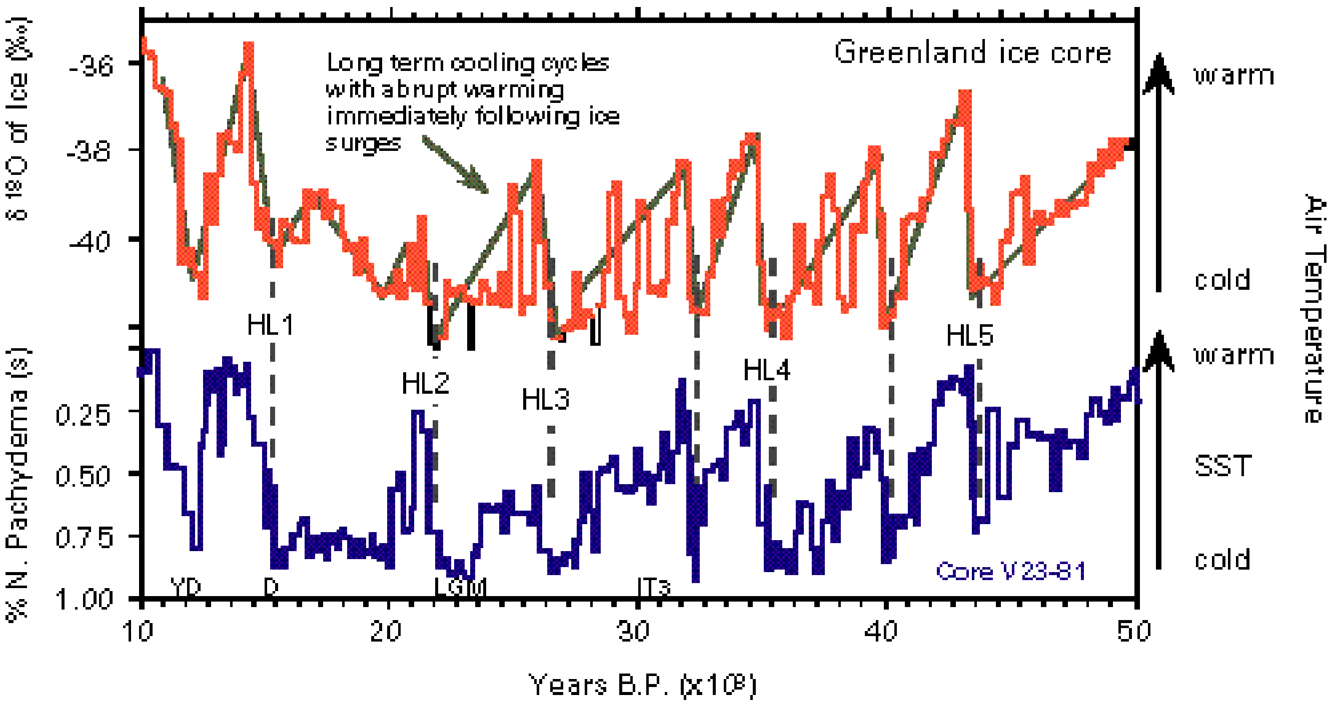



*Figure 10. Comparison of a Greenland ice core oxygen isotope record (GRIP) with the relative abundance of a polar foraminifera* (N. pachyderma) *in the North Atlantic sediment core V23-81 for the period 10 to 50 kyr B.P., illustrating the close coupling of abrupt climatic change in the glacial atmosphere and ocean (YD: Younger Dryas; D: Deglaciation; LGM: Last Glacial Maximum; IT3: Interstadial 3; HL: Heinrich Layer) (after Bond et al., 1993).*

- *Past abrupt climatic events with hypothesized oceanic causes*

Several past abrupt climatic events have been linked to hypothesized changes in ocean circulation. Attention should not necessarily exclude the exploration of any paleoclimatic event that may provide new insights into how the climate system may behave, but PAGES/CLIVAR needs to focus attention first on events that are relatively well studied. The termination of the Younger Dryas event in the North Atlantic region (ca. 10 ka) may have global implications, but it has also been linked to changes in the coupled ocean-cryosphere-atmosphere system of the high northern latitudes (Fig. 10). The existing wealth of data in this high-latitude region needs to be augmented with a reliable, well-dated global perspective, and then integrated with coupled atmosphere-ocean models to determine the causes, processes, and predictability of this type of major abrupt climatic shift.

Other events, such as one at approximately 8ka in the Northern Hemisphere, and another at 2ka in the Southern Hemisphere, are now becoming more widely recognized, and may also relate to fundamental changes in ocean circulation. Whereas these events do not appear to be as large in magnitude as the Younger Dryas event, they do point to the existence of additional climate system processes that may give rise to abrupt climatic change during warm/interglacial climates.

- *Past abrupt climatic events without known forcing*

Pre-20th century cold episodes, and associated hydrologic and other anomalies, are widely recognized from seasonally-to-annually dated corals, ice cores, tree rings, sediments, and historical documents from around the globe (Bradley and Jones, 1992; Jones et al., 1995). High priority must be given to developing proxy records of past volcanic, solar, aerosol, and trace-gas forcing, and then using these records in a combined data-model context to determine the extent to which these hypothesized forcing mechanisms can explain the climatic events of the past 1,000 years (Rind and Overpeck, 1993; Lean et al., 1995; Crowley and Kim, 1996). At the same time, PAGES/CLIVAR efforts need to focus on how the coupled climate system can give rise to abrupt events in the absence of abrupt external forcing (Table 2; Stocker, 1995).

- *The possible abrupt events of the last interglacial*

The Greenland ice-core records uncovered possible evidence for abrupt cold episodes during the last interglacial that, if correct, have major implications for possible climate change in the future (Dansgaard et al., 1993; Taylor et al., 1993; Grootes et al., 1993; Alley et al., 1995). The possible existence of these and other events in the past emphasizes the obligation of the PAGES community to keep the CLIVAR community informed of the full range of possible climate system behavior. The occurrence of rapid climatic changes over Europe during the Eemian period is also supported by pollen and rock magnetism studies performed on lake deposits in the French Massif Central (Thouveny et al., 1994). A major cooling preceding the continental ice-sheet growth phase and appearing like a precursor of the glaciation has been detected in the Greenland-Norwegian Sea (Cortijo et al., 1994). However, at lower latitudes, the sea surface temperature and water chemistry records covering the same time period from the North Atlantic Ocean that have so far been examined exhibit much more muted changes and do not correlate with the Greenland air temperature record (Keigwin et al., 1994; McManus et al., 1994; Cortijo et al., 1994). These results suggest the possibility that the Eemian section of the GRIP ice record is disturbed or, alternatively, that the temperature variations are local to Greenland and the Nordic Seas and had no impact over the North Atlantic area. In either case, it is important to understand whether interglacial periods are associated with climatic stability or whether our climate could return to a phase of climatic instability either by chance or through human influences. Networks of well-dated paleoclimatic time series are needed to distinguish true climatic events from those that may be nonclimatic artifacts of the proxy record.

## 2.5 Climate model evaluation and improvement

A major intersection of PAGES and CLIVAR objectives falls in the area of climate modeling. Whereas PAGES focuses heavily on the development and use of paleoenvironmental reconstructions, and CLIVAR emphasizes the development and implementation of a hierarchy of climate models, both programs share the ultimate goals of climate dynamics: to arrive at a theoretical synthesis of climate change over all scales of variability, and to use this theory to achieve

Table 2. Internal Variability Found in Various Numerical Models (after Stocker, 1995).

| Model | Period (Year) | Mechanism | Author |
|---|---|---|---|
| 3d box OGCM | 9 | Advection of SSS anomaly, interaction gyre-thermohaline | Weaver and Sarachik (1991) |
| 3d global A/OGCM | 10-20 | Advection of T anomalies in the Pacific | Von Storch (1994) |
| 3d global A/OGCM | 15-20 | Southern Ocean sea ice dynamics | Manabe and Stouffer (1996) |
| 3d N. Atlantic OGCM | 20 | Labrador Sea, zonal and meridional overturning | Weaver *et al.* (1993) |
| 3d global AGCM | 5-40 | Chaotic nature, subtropical and mid-latitude atmospheric jets | James and James (1992) |
| 3d global OGCM | 10-40 | Labrador Sea, stochastic integrator | Weisse *et al.* (1994) |
| 3d global A/OGCM | 40-60 | West Atlantic gyre anomaly | Delworth *et al.* (1993); Manabe and Stouffer (1996) |
| 2d zonally-averaged OCM | 200-300 | Large-scale SSS advection | Mysak *et al.* (1993) |
| 3d global OGCM | 320 | Large-scale SSS advection in the Atlantic | Mikolajewicz and Maier-Reimer (1990) |
| 3d box OGCM | 400 | Interaction between convection and diffusion | Winton (1993) |
| 3d global A/OGCM | 400 | Southern Ocean sea ice dynamics | Manabe and Stouffer (1996) |

maximum predictive skill. At present, only parts of these ambitious goals have been reached. On the interannual timescale, a synthesis between process models and observations for ENSO has been found, and a considerable skill of prediction has been achieved (Cane et al., 1986, 1994, 1995; Barnett et al., 1993). However, serious gaps exist: three-dimensional models are not yet capable of simulating all of the observed dynamics of ENSO. At the other end of the timescale spectrum, a theory of glacial cycles has been formulated that successfully predicts the periodic components observed in the paleoclimatic record (Berger, 1992; Imbrie et al., 1992, 1993). However, quantitative modeling has not been satisfactory in representing this glacial theory, because uncertainties exist regarding the sensitivity of the climate system (e.g., 100 kyr cycle), and high-resolution archives exhibit much richer dynamics than predicted by the theory.

For the timescales that are of interest to both PAGES and CLIVAR, namely interannual to centennial, an effort is needed to first standardize the interface between climate models and paleoclimate data. Advanced statistical methods in the spatial, temporal, and frequency domains must be employed to extract patterns of change and variability from the observed data. Likewise, model data have to be analyzed using the same tools. Second, even more urgent is the establishment of a comprehensive theory for interannual-, decadal-, and century-scale climate variability. This will require a better understanding of atmosphere-upper ocean interaction, the role of sea ice, and the dynamics of thermohaline circulation.

The PAGES/CLIVAR working group on model evaluation and improvement expanded on model-oriented foci of the other working groups, and identified several research foci in which a paleoclimatic perspective would contribute significantly to the goals of CLIVAR. These include:

- *Simulation of "extreme" climate conditions*

Climate models that are developed for use in CLIVAR should be able to reproduce climatic conditions significantly unlike those of the past 150 years, and in doing so delineate the limits of the range of variability present in the climate system. For atmospheric general circulation models (AGCMs), the international Paleoclimate Modelling Intercomparison Project (PMIP) is already involving over 18 3-D modeling groups in simulating the quasi steady-state climate of two late Quaternary periods (Table 3):

6 ka:

A period by which the Northern Hemisphere ice sheets were gone, but in which insolation was different from today. This is a test of the sensitivity of AGCMs to orbital changes in radiation. Reconstructions of temperature, hydrology, vegetation, and other parameters indicate that they were significantly different from today (Fig. 11).

21 ka:

(Last Glacial Maximum - LGM): A period characterized by radiation similar to today, but with decreased atmospheric trace-gas concentrations and a large modification of the atmospheric flow due to Northern Hemisphere ice sheets. Simulation of this period tests the sensitivity of the dynamics of these models. LGM conditions around the globe were substantially different from those of today.

## Table 3. PMIP Modeling Groups and Investigators

| Group/ Institution | Investigators |
|---|---|
| Bureau of Meteorology Research Centre | B. McAvaney |
| Canadian Climate Center, GCM 6&7 | N. McFarlane, D. Verseghy |
| CCSR/NIES (Japan) | A. Abe-Ouchi |
| CSIRO Division of Atmospheric Research | J. Syktus |
| GFDL Climate Model | A. Broccoli, S. Manabe |
| Laboratiore de Modelisation du Climate de l'Environnement (SECHIBA) | S. Joussaume, N. Ducoudre, G. Ramsteinet |
| LLN 2D | M-F. Loutre |
| Max Plank Institute for Meteorology, ECHAM3/LSG/T42 | K. Herterich, M. Lautenschlager, L. Bengtsson |
| Meteorological Research Institute, Tsukuba | A. Kitoh |
| Moscow University | A. Kislov |
| NASA/GISS Model 2' | D. Rind, R. Webb, J. Overpeck |
| NCAR CCM 1&2 Model | J. Kutzbach, R. Oglesby |
| NCAR GENESIS Model | S. Thompson, D. Pollard; K. Taylor, L. Sloan |
| UGAMP Version 2 | P. Valdes, N. Hall |
| UKMO Hadley Centre | C. Hewitt , J. Mitchell |
| University of Illinois Model | M. Schlesinger |
| University of Melbourne Climate Model | B. Budd |
| Yonsei University (Korea) | J. Oh |

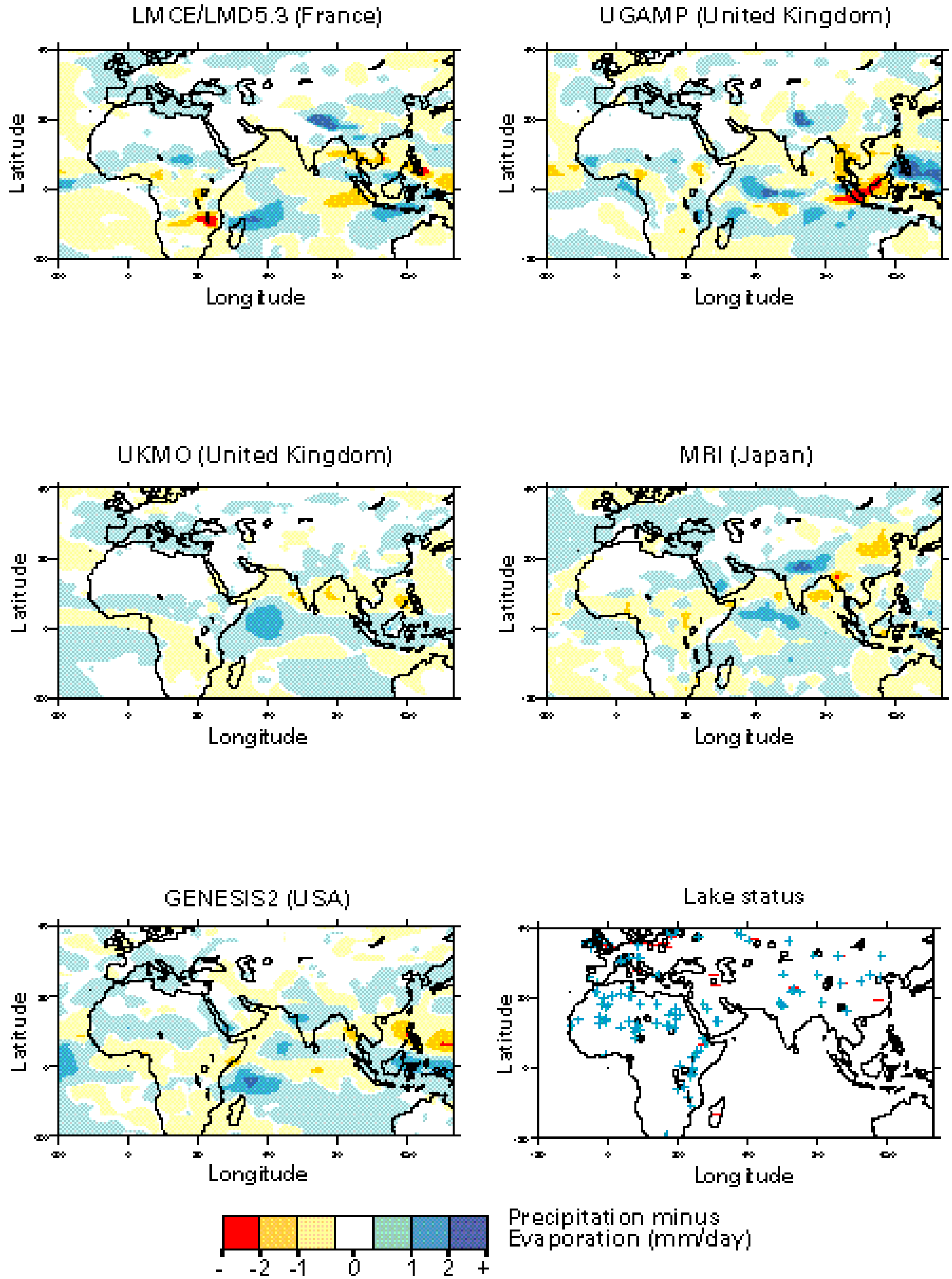
Extension of the PMIP model evaluation framework to ocean, and coupled ocean-atmosphere models will be central to the success of CLIVAR. Unfortunately, our understanding of paleocean dynamics is lagging behind, because past boundary conditions are much less well defined than for the atmosphere. In order to reconstruct quasi-steady state oceanic conditions at certain times in the past, the surface buoyancy field has to be known in a detailed way. Recent modeling studies (two- and three-dimensional) have shown that steady states are very sensitive to the north-south buoyancy contrast in the world ocean (Stocker et al., 1992; Fichefet et al., 1994; Manabe and Stouffer, 1995). Additional constraints, such as tracer distributions ($^{14}C$ and $^{13}C$), must be incorporated. Within PAGES, those efforts that aim at a reconstruction of past sea surface conditions (e.g., maps of SST, SSS) have to be enhanced, while information from the ocean interior, such as the mix of water masses, is indispensable for checking the steady states of various ocean models.

- *Simulation of natural variability*

As noted earlier, we currently lack an established and accepted theory of natural decade- to century-scale climate variability. Models do not replace theory—they are based on it. From recent limited model results (Table 2), we have learned that several modes of natural variability can be generated in a few geographical areas of the climate system, but the processes involved are not well understood. More clues are needed from the paleoclimatic record, as well as from efforts to simulate aspects of observed past change. Simplified models have to be developed and employed where individual processes can be analyzed. At the same time, efforts need to be made to identify a few well-defined patterns (spatial and frequency domain) that all models should strive to simulate. The definition of such patterns can only come from the analysis of paleoclimatic data.

PAGES/CLIVAR interaction centered on seasonal-to-interannual ocean variability is limited somewhat to low latitudes where a good collection of coral records is becoming available. At higher latitudes, annually dated paleoceanographic data are more limited, but extensive networks of

Reducing Uncertainty. Numerical models are the backbone of modern climate prediction, yet results from the large number of models now in use suggest a wide range of possible future climatic changes. PAGES-CLIVAR interaction will focus efforts to use the extensive record of past climatic changes to evaluate and improve the performance of predictive models.


LMCE/LMD5.3 (France)
UGAMP (United Kingdom)
UKMO (United Kingdom)
MRI (Japan)
GENESIS2 (USA)
Lake status
Latitude
Longitude
Precipitation minus
Evaporation (mm/day)
- -2 -1 0 1 2 +

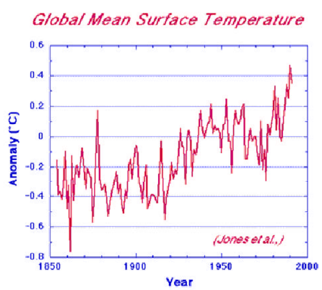
time series are available for land areas. Mid- to high-latitude paleoceanographic prospects are more encouraging for studies of decade- to century-scale variability given the increasing availability of high accumulation-rate sediment cores. Emphasis must be put on the Labrador Sea, since recent observations showed a great variability in the period 1970–1980, notably in relation to the Great Salinity Anomaly that propagated around the margins of this sea (Lazier, 1980, 1988; Wallace and Lazier, 1988). Best use can be made of a network of high-resolution data with SST and SSS as the target variables. On the other hand, PAGES may suggest additional areas where models should exhibit defined patterns of interannual- to century-scale variability, and so serve as an independent check for these models.

The problem of sparse data may also be attacked by defining a series of paleoclimate indices. This approach has proven to be a fruitful and efficient step in characterizing and describing ENSO (Philander, 1990). It should be employed also for paleoclimatic studies as a useful guide for more quantitative studies. Such indices must be defined in a way characteristic of decadal to century variability (e.g., SST, SSS differences across ocean basins, phase-lagged SST, and SSS). PAGES can provide the records and interpretation from which these indices could be constructed.

- *Simulation of abrupt change*

Given the significance of abrupt paleoclimatic events for understanding the true range of climate variability and predictability, the PAGES community must strive to ensure that data describing past abrupt events is reliable. Data are essential to indicate whether an abrupt change may have been caused or triggered by a perturbation of the climate system (e.g., the collapse of an ice sheet), or whether the abrupt event was the manifestation of natural but rapid changes. High-resolution records should then be used in combination to indicate leads and lags of different climatic variables. For a verification of climate models, paleoclimatic data analysis must not focus on a single region, such as the North Atlantic, but should document amplitudes, timescales, and phase relations of abrupt change on the entire globe. From such an analysis, spatial patterns can be extracted that will be essential in assessing climate model performance.

*Figure 11. (opposite page) Precipitation-minus-evaporation anomalies for 6000 years B.P. (compared to the present-day) simulated by five atmospheric climate models compared to a map of observed 6ka lake status anomalies reconstructed from paleoclimate data (heavy blue pluses denote much wetter than today, lighter blue pluses wetter, heavy red minuses much drier, light red minuses drier, black circles no change from today). Paleoclimate data such as these are being used to evaluate the performance of climate models in the Paleoclimate Modelling Intercomparison Project (PMIP - Table 3) (courtesy of PMIP and S. Harrison).*




Detecting Change.
A key issue in climate research is the extent to which various hypothesized natural and anthropogenic forcing mechanisms have affected the last 150 years of climate variability. This question cannot be answered definitively, however, until the full range of natural decade- to century-scale variability is understood. This goal will be a point of PAGES-CLIVAR intersection.

The sensitivity of climate models, and hence the transient behavior to perturbations, depends very strongly on the initial state; thus transient coupled atmosphere-ocean general circulation model experiments aimed at simulating the Younger Dryas event will be difficult. In contrast, efforts to simulate the time-dependent patterns of change associated with abrupt events of the Holocene (see Section 2.4) may be more likely to succeed. Careful work will still be needed to define initial model states, as well as to define the exact time-space nature of the abrupt events. Here the information collected for simulating past extreme conditions (see PMIP above) will prove useful. In particular, the hydrological cycle and its large-scale changes should be better known. Again, a hierarchy of models should be employed to study individual feedback mechanisms and their importance in determining sensitivity, variability, and abrupt change in these models.

## 2.6 Climate Change Detection

The PAGES/CLIVAR workshop did not focus specifically on the climate-detection objectives of CLIVAR-ACC, but many of the PAGES/CLIVAR activities described earlier in this section will result in both the long observational time series and the validated models that are needed to separate unambiguously natural from anthropogenically induced climatic change. Well-validated models and statistical analyses will be used to identify “fingerprints” of anthropogenic climate change (Madden and Ramanathan, 1980; Wigley and Raper, 1990; Schneider, 1994; Taylor and Penner, 1994; Santer et al., 1995b). Similarly, centuries-long reconstructions of hypothesized natural climate forcing (e.g., solar, volcanic, trace-gas, and ENSO) can be combined with the same models to recognize the climatic “fingerprints” of natural climate variability (Santer et al., 1995a). A global network of centuries-long paleoclimatic time series can then be integrated with available instrumental data and appropriate statistical methods to isolate the roles of natural and anthropogenic climate change.

# 3: Recommendations for Implementation

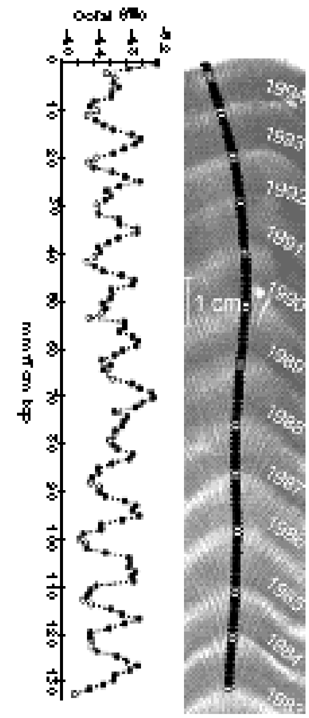
## 3.1 The PAGES/CLIVAR program and working group

Both PAGES and CLIVAR have steering bodies as well as management structures for each of their various activities. Coordination between the two programs should be enhanced with a formal PAGES/CLIVAR liaison, most likely a PAGES/CLIVAR Working Group (P/C WG) made up of PAGES and CLIVAR representatives. This WG would serve to inform the PAGES SSC and CLIVAR SSG of joint PAGES/CLIVAR activities and interests. The P/C WG would make sure that appropriate PAGES or CLIVAR activities and workshops had representatives from the other community. Most important, the P/C WG would have the responsibility for encouraging the sharing of ideas, data, and joint research. It is envisioned that a formal PAGES/CLIVAR program would last 10 years, in parallel with the lifespan of CLIVAR, and that PAGES and CLIVAR would have explicit linkages to each other through this formal PAGES/CLIVAR program.

## 3.2 Joint workshops, short-courses, and research

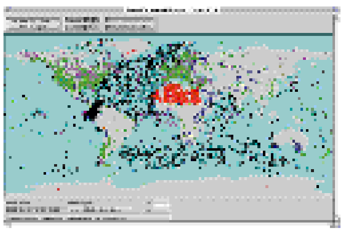
Many participants of the Venice workshop found the interdisciplinary discussions educational and stimulating. PAGES/CLIVAR should move from a planning mode into one where scientists from both communities routinely interact to carry out the research described in this report. Many activities are already underway that would both help meet PAGES/CLIVAR goals and benefit from greater PAGES/CLIVAR interaction. Other joint research programs need more active encouragement.

In addition to fostering cross-disciplinary joint research proposals, the P/C WG should encourage workshops, such as annual investigators meetings, that are specifically focused on PAGES/CLIVAR goals. In the early years of the PAGES/CLIVAR program, the P/C WG could also sponsor short courses designed to familiarize the PAGES and CLIVAR communities with the methods, data, models, and strategies used by the other community. For example, there is an expressed desire on the part of paleoclimate scientists to become more familiar with state-of-the-art ENSO modeling, whereas PAGES scientists could provide their CLIVAR colleagues with a better understanding of the signal contained in proxy climate records. Greater interdisciplinary awareness will lead to better collaboration.




### Cross-disciplinary Understanding

In addition to joint research, PAGES/CLIVAR interaction will also be focused on activities that foster understanding across disciplinary boundaries. For example, the PAGES community will work to make sure that CLIVAR scientists understand how paleo-environmental proxy data are developed and used, whereas the CLIVAR scientists will provide PAGES scientists with a better understanding of climate dynamics and state-of-the-art models.



Global Databases.
Another unique achievement of PAGES has been the development of a successful global paleoenvironmental data management system. The coordination of scientific and database efforts around the world will continue to grow, and will provide a key resource for PAGES-CLIVAR interaction.

## 3.3 Data management and access

Instrumental and paleoenvironmental observations are a foundation for both the PAGES and the CLIVAR programs. In most cases, formal data management activities are already in place, as are protocols for data sharing (PAGES, 1995). PAGES has built a strong international data system through the establishment of the World Data Center-A (WDC-A) for Paleoclimatology in Boulder. All data generated by or used in PAGES activities will eventually be shared freely via the WDC-A. These include data used in or generated from paleoclimate model simulations. The WDC-A has established Internet access to all data and works closely with numerous regional, national, and topical data management efforts around the world to ensure that all data are clearly documented and readily available to enhance research opportunities and thus guarantee a PAGES data legacy.

Non-paleoenvironmental data used and generated by the CLIVAR program will also all be safely archived and shared via electronic means in a distributed fashion. A key to the success of joint PAGES/CLIVAR interaction is the existence of well-tested data-sharing mechanisms.

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