# Annual Records of Tropical Systems (ARTS)

## Recommendations for Research

A PAGES/CLIVAR Initiative

Robert B. Dunbar[1] and Julia E. Cole[2]

[1] Department of Geological and Environmental Sciences
Stanford University, Stanford CA 94305-2115, USA

[2] Department of Geological Sciences and INSTAAR
University of Colorado, Boulder CO 80309-0450, USA

ISBN 3–9521078–8–3

**PAGES WORKSHOP REPORT, SERIES 99-1**

**PAGES** (Past Global Changes) is the International Geosphere-Biosphere Program (IGBP) core project charged with providing a quantitative understanding of the Earth's past environment and defining the envelope of natural variability within which anthropogenic impact on the Earth system can be assessed. Through the organization of coordinated national and international scientific efforts, PAGES seeks to obtain and interpret a variety of paleoclimatic records and to provide the data essential for the evaluation of predictive climatic models.

**CLIVAR** (Climate Variability and Predictability) is an interdisciplinary research effort within the World Climate Research Program (WCRP) focusing on the variability and predictability of seasonally to centennially varying components of the climate system.

**PAGES/CLIVAR**, via a joint effort, seeks to formulate and promote:

1) a program of paleoclimatic reconstruction providing long-term records of quantitative paleoclimatic data with seasonal to interannual resolution in areas which are of direct relevance to IGBP and WCRP (i.e., monsoon and ENSO regions, the North Atlantic and areas of the globe with possible hydrologic predictability).
2) a program for collecting, analyzing and integrating paleoclimatic data in order to reveal evidence of patterns of variability within the climate system over seasonal to century time scales.
3) the use of paleoclimatic data in evaluating predictive physical climate models, as well as the use of inverse models, to understand the variability present in the paleoclimatic and paleoceanographic record, and to cooperate with other modeling activities of relevance to PAGES and CLIVAR.

Cover Illustration: Center map shows monthly average sea surface temperature anomalies for December 1877 derived from the Kaplan SSTA data set [MOHSST5 available at http://ingrid.ldeo.columbia.edu/SOURCES/.KAPLAN/ from A. Kaplan] with overlay symbols showing sites of current annual resolution paleoclimate studies involving corals (gray circles), tree rings (red triangles), ice cores (yellow squares), and sediments (blue diamonds). This figure illustrates how a network of multiple paleoclimate proxies helps define past expressions of extreme climate events such as the 1877/78 El Niño. Other images, clockwise from top: composite time series of coral $\delta^{18}$O from 7 Galapagos coral cores (R. Dunbar and G. Wellington); X-radiograph of a coral core from Malindi, Kenya (R. Dunbar and J. Cole); photograph of late Holocene laminae interpreted as varves in a sediment core from Lake Titicaca (R. Dunbar); an empirically derived Markov model expression for prediction of tropical sea surface temperature anomalies and first EOF of Pacific SST anomalies from January 1965, through June 1993 from COADS data (S. Johnson, D. Battisti, and E. Sarachik); photograph of tree rings (T. Caprio); photograph of annual layers in an ice bluff from the Quelccaya Ice cap (L. Thompson).

# Preface

This PAGES workshop report is derived from the first ARTS science workshop, held in Kauai, Hawaii from September 26–30, 1996. Organized by J. Cole, R. Dunbar, M. Gagan, and J. Recy, the goal of this initial meeting was to review the state of our knowledge of past climate variability in the tropics and to develop a science agenda for ARTS. The workshop included 34 scientists from 9 countries active in various paleoclimatic disciplines (primarily corals, but also tree-rings, ice cores, and laminated sediments) as well as atmospheric and ocean scientists interested in integrating paleoclimate records with numerical models and instrumental data sets. Attendees included climate scientists active in CLIVAR and on the US National Research Council's advisory panels on seasonal-interannual and decadal-century climate variability. This report describes the scientific rationale for the ARTS program as well as specific recommendations derived from workshop discussions. The report has further benefited from additional input solicited from ARTS scientists after the workshop and extending through the PAGES Open Science Meeting held in London during April, 1998. Major contributors to this document include David Battisti, David Stahle, Dan Schrag, Ellen Druffel, Mike Gagan, Tom Guilderson and Glen Shen. We also thank Brad Linsley, Lonnie Thompson, Ping Chang, Peter Swart and Ellen Mosley-Thompson for their assistance. US participation in this workshop was supported by NSF award ATM-9528411. PAGES supported non-US participants.

# Table of Contents

# Executive Summary

The goals of the Annual Records of Tropical Systems (ARTS) program are to:

1. document and understand the behavior of the tropical ocean-atmosphere and its teleconnections, with seasonal to annual resolution, over the past several centuries; and
2. assess the stability of tropical climate systems and their teleconnections as the background climate and associated forcing phenomena change over seasons to centuries.

The ARTS initiative promotes the synthesis of paleoclimate data with instrumental and modeling perspectives to address uncertainties in our understanding of tropical climate variability and its impacts. Tropical ocean-atmosphere interactions provide the dominant signal in interannual climate variability. Paleoclimate and historical evidence indicate that tropical systems also vary over periods of decades to centuries. The tropics interact with higher latitude climate systems via atmospheric and oceanic teleconnections that, although relatively consistent over the past few decades, appear to have changed substantially over the past century and longer. Paleoclimate reconstructions offer the only source of information on long-term changes in tropical variability and its teleconnections and derive an even broader utility when interfaced with numerical simulations.

ARTS workshop participants identified a need for long, continuous records of interannual to centennial variability in the tropics and of the teleconnections to the extratropics. An important target for paleoclimate reconstruction is the extension of indices of large-scale climate systems into pre-instrumental periods. Well-calibrated, multicentury reconstructions need to be integrated into spatially gridded research products that can be used to drive or test general circulation model simulations. We outlined an ARTS synthesis project to analyze climate of the past several centuries (entitled "Climate of the Nineteenth Century," or CNC) which would coordinate these efforts, including the development of records from critical locations, spatial interpolation techniques to link point reconstructions, model simulations, and model/paleodata comparison. The highest priorities for the CNC project are production of fields of sea surface temperatures (SST's) across the tropical Pacific extending back to at least 1800 AD, and examination of teleconnections within the Indian Ocean, Australasian and American regions. New sampling will be steered by analysis of available data. Workshop participants also recommended the further development and application of tracers of ocean circulation (e.g. $^{14}C$ in corals) as a complement to the CNC project and as a means to examine past variability in oceanic circulation. In addition, analysis of the relationship between background climate and climate variability requires that we develop high-resolution records from targeted Holocene and last-glacial intervals as windows onto climate states forced by boundary conditions substantially different from those prevailing today.

# Introduction

Tropical ocean-atmosphere interactions orchestrate climate variability worldwide over a range of time scales important to society. The El Niño/Southern Oscillation (ENSO) includes a far-reaching system of teleconnected climate anomalies, and billions of people live in areas where agricultural productivity is influenced by the Asian, African, and American monsoons. Intensive observational programs have focused on improving the empirical basis for understanding and modeling the tropical ocean and 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. As instrumental records have lengthened and as high-quality paleoclimate reconstructions have become available, climate dynamicists and modelers have recognized the significance of decadal and longer variability in these tropical systems. In the tropical Pacific, for example, records from long-lived corals indicate the persistence of decadal patterns of ENSO-like variability that are unrecognizable from existing instrumental data and are not simulated by most of the current generation of numerical models. In fact, ENSO appears to vary on decadal time scales, perhaps as a consequence of longer-term background changes. Records from varved sediments, tree-rings, and ice cores substantiate inferred long-term variability in the tropics and indicate that the relationship between tropical and extratropical climate anomalies may not remain stable over decades to centuries.

Paleoclimatic records have a unique and critical role to play in improving our understanding of tropical climate variability and sensitivity and in developing a predictive knowledge of these systems that incorporates multiyear perspectives. Paleoclimatic reconstructions offer the only source of information on long-term changes in tropical variability and its teleconnections, but they require the perspective of instrumental data for calibration, process understanding, and sample site selection, and they derive a broader context when interfaced with numerical simulations. Paleoclimatic reconstructions also provide a testbed for numerical models of the ocean and atmosphere and can suggest new conceptual models for tropical variations. The ARTS (Annual Records of Tropical Systems) initiative was conceived to foster collaboration among paleoclimatologists working with tropical or tropically influenced records and climate dynamicists who use the perspectives of numerical experimentation and instrumental records. Bringing these communities together to plan scientific strategies facilitates a better understanding of each group's priorities, capabilities, and challenges. ARTS promotes the synergistic use of paleoclimate data with instrumental and modeling approaches to define a better understanding of tropical variability and its impacts.

The first ARTS planning meeting was convened in Kauai, Hawaii, in September 1996. Participants included representatives from research groups working with high-resolution tropical paleoclimate archives as well as tropical climate dynamicists and oceanographers. Workshop speakers provided state-of-the-art information about the climate phenomena and time scales of greatest interest to the climate dynamics community and also described the capabilities and limitations of the paleoclimate record for studying time-dependent behavior of these systems. Working groups and individuals defined potential foci for the implementation of ARTS, including new field campaigns in undersampled regions of the tropics and a variety of conceptual frameworks for organizing regional field efforts around process-oriented themes. This report presents the scientific goals of ARTS and its initial implementation strategies and summarizes the current status of ARTS science, as presented at the Kauai meeting and in subsequent ARTS-related gatherings and communications.

Participants defined two broad goals for the new ARTS initiative:

- To document and understand the behavior of the tropical ocean-atmosphere and its teleconnections, with seasonal to annual resolution, over the past several centuries;
- To assess the stability of tropical climate systems and their teleconnections as background climate and associated forcing phenomena change over longer periods.

The ARTS program will require coordinated efforts directed towards new data collection, data-model integration, paleoclimate record enhancements (e.g. improved chronologies, calibration, and replication strategies), and the regular interaction of scientists using the different perspectives of proxy based paleoclimate reconstruction, modeling, and instrumental studies. Our specific objectives center on the climatic phenomena of interest described in the following section. Implementation plans that coordinate all of these inputs are partially developed, but further definition will require smaller, focused groups of scientists to lay out strategies by which these objectives can be realized. Such interaction is occurring even now, and we anticipate that future ARTS workshops will (in conjunction with other PAGES and CLIVAR efforts) focus on planning the implementation of specific objectives that contribute to ARTS goals.

# 1. Background: Tropical Climate Systems and their Impacts

## 1.1 Pacific Ocean/Americas/Australia: ENSO and Decadal ENSO-like Variability

The ENSO system dominates interannual variability of the ocean and atmosphere in the tropical and subtropical Pacific (Figure 1, upper series, and Figure 2, left panel). This signal propagates through the global atmosphere to leave its imprint on planetary systems as diverse as polar sea ice, maize growth in Africa, and rainfall in Florida. ENSO results from instabilities in the coupled ocean-atmosphere system that drive interannual shifts in oceanographic and atmospheric variables throughout the Pacific. Features that are dramatically influenced by ENSO (and participate actively in the evolution of ENSO anomalies) include the intensity and location of atmospheric convection over the western Pacific, the east-west equatorial Pacific SST gradient, the strength of the zonal atmospheric Walker circulation, and the three-dimensional distribution of ocean currents. Although ENSO variability is defined on an interannual scale, decadal variations in ENSO-related parameters are clear in paleoclimatic records and have recently emerged from the lengthening instrumental record. Seasonal, interannual, and decadal modes of variability appear to change in concert through time in the tropical Pacific. How these changes modulate ENSO's extratropical influences remains unknown. The sensitivity of ENSO and its teleconnections to rising greenhouse gas concentrations also requires further investigation.

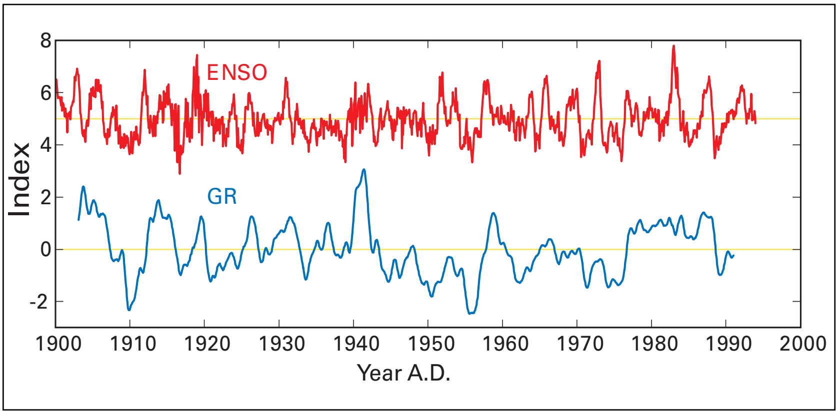


*Figure 1*
Time series of ENSO (upper line in red) and the decadal ENSO-like (GR - lower line in blue) climate variability. The index of ENSO is the cold tongue index (CT), which is the SST averaged monthly and from 4°N to 4°S, 90°W to 180°W. The index of the decadal ENSO-like variability is the time series of the dominant pattern of global SST anomalies after the ENSO-related (CT) SST anomalies have been removed from the global SST data (from D. Battisti using data in Zhang *et al.* 1997).

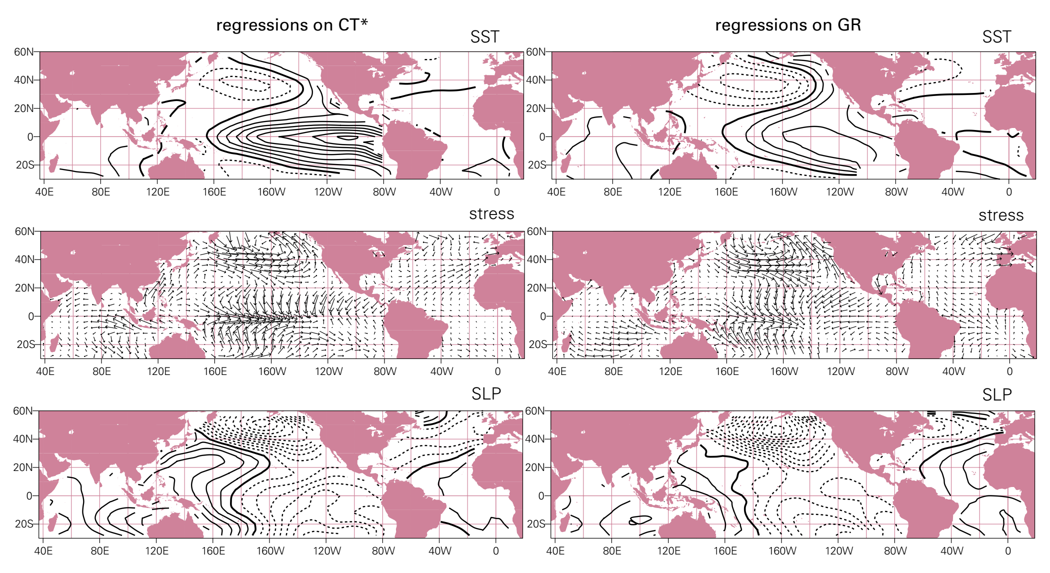


*Figure 2*
Global fields regressed upon the monthly ENSO (CT) time series (at left) and the monthly ENSO-like decadal variability (GR) time series, as displayed in Figure 1.
Top panel: Sea Surface Temperature, Middle: wind stress, and Bottom: Sea Level Pressure. The contour interval is (per unit standard deviation): (top) 0.1°C, (middle) 8.3 $m^2/s$ for the longest vector, and (bottom) 0.1 mb. Negative contours are dashed and the zero contour is thickened. Reproduced from Figures 11 and 12 of Zhang et al. (1997).

A detailed analysis of the historical record spanning the past century has produced a new view of the spatial patterns of ENSO variability through time (Allan *et al.* 1997). This compilation suggests that rainfall, SST, and wind field anomalies associated with ENSO events (both "warm" and "cool") differ strongly from event to event, and that the centers of action also shift. For example the eastern pole of the Southern Oscillation of sea level pressure, conventionally defined as Tahiti for the construction of a standard Southern Oscillation Index (SOI), appears to have wandered during the present century. In addition, comparison of both instrumental and paleoclimatic records of US drought with ENSO records shows that patterns of ENSO-related drought in the US have not remained stable over this interval (Cole and Cook 1998). *Clearly, the interannual ENSO phenomenon experiences significant variations from its canonical state, and the predictability of this system and its impacts depends on understanding these variations.*

Instrumental and paleoclimatic data indicate significant decadal variability in the tropical Pacific climate system (Figure 1, lower series). This variability is similar in structure to ENSO (Zhang *et al.* 1997; Figure 2). Although primarily a low frequency climate anomaly, the changes in amplitude can be rapid and include the well documented Pacific basin "regime shift" of 1976 (Trenberth and Hurrell 1994; Graham 1994). The physical mechanisms responsible for decadal ENSO-like variability are not known, but the resulting climate anomalies are significant. Furthermore, the interannual ENSO and decadal ENSO-like phenomena are associated with qualitatively different climate anomalies at mid and high latitudes (Ebbesmeyer *et al.* 1991; Zhang *et al.* 1997; Mantua *et al.* 1997; Figure 3). Climate anomalies associated with interannual ENSO variability feature a more zonal perturbation in the western hemisphere circulation at mid-latitudes and explain a lower fraction of the variance in the mid-latitude cli-

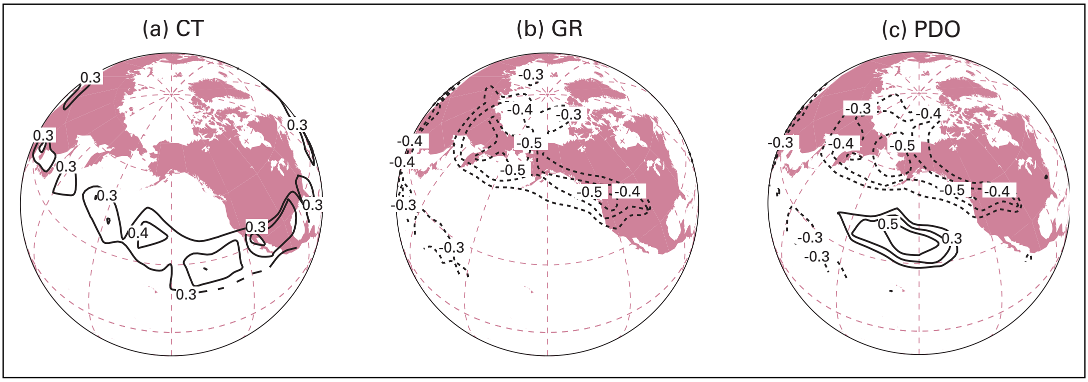


*Figure 3*
Correlation maps of the winter mean storminess (NDJFMA band-passed 500 mb height anomalies) with winter mean climate indices for the period 1947-1994. Maps show correlations between storminess and indices of a) ENSO (the Cold Tongue index - CT), b) the decadal ENSO-like variability index GR (as defined in Bitz and Battisti, 1999), and c) the Pacific Decadal Oscillation (PDO) as defined by Mantua *et al.* (1997). Contours show correlations exceeding the 95% confidence level where each year is considered to be independent of the last. Positive correlations indicate more storminess associated with warmer water in the tropical Pacific and colder water in the North Pacific. Reproduced from Figure 11 of Bitz and Battisti (J. Climate, in press).

mate anomalies. The ENSO-like decadal variability features a classic Pacific North America (PNA) pattern (Kawamura 1994) and explains a significant portion of winter climate anomalies in the mid-latitude northern hemisphere (Graham 1994; Zhang *et al.* 1997; Bitz and Battisti 1999).

Numerical and statistical models indicate skill in predicting the state of ENSO about a year in advance (Barnett *et al.* 1988; Zebiak and Cane 1987; Latif *et al.* 1998). However, there are substantial differences in forecast skill from decade to decade (Chen *et al.* 1995, Balmaseda *et al.* 1995). The cause of these changes is not clear; leading candidates include a change in the basic state of the tropical climate system and a change in the phase of the decadal ENSO-like climate anomaly (i.e., the 1976 regime shift). Both of these possibilities suggest a need for improved understanding of the decadal to centennial variations in the tropical Pacific.

The relationship of ENSO to anthropogenic warming remains an important and controversial topic. Several studies support potential links between ENSO and increasing greenhouse gas concentrations. The shift towards generally more ENSO-like conditions in 1976 is consistent with atmospheric GCM predictions of an intensified hydrologic cycle under doubled $CO_2$ scenarios (Graham 1995). Both the recent tendency for more ENSO warm anomalies and the prolonged warm anomaly that persisted through the early 1990's are unprecedented in the instrumental climate record. A simple statistical model indicates that given the characteristics of the historical record, these anomalous periods would have a very low probability of occurrence in a stationary system (Trenberth and Hoar 1996). This result raises the question of whether recent ENSO anomalies occurred as a result of increasing greenhouse gases (Trenberth and Hoar 1996; Rajagopalan *et al.* 1997). Yet studies utilizing paleoclimatic records suggest that similar anomalies of the duration of the 1991–4 event have occurred over the past three centuries, implying no relation to recent greenhouse gas increases (Allan and D'Arrigo 1999). A recent modeling study suggests that greenhouse gas increases may ultimately result in cooler SST's in the easternmost tropical Pacific (Cane *et al.* 1997) via a process involving warming of the western Pacific, a stronger east-west equatorial SST gradient, and resulting stronger trade winds that enhance upwelling of cool water in the east. Attributing any observed recent changes to anthropogenic greenhouse gas forcing ultimately requires a more extensive

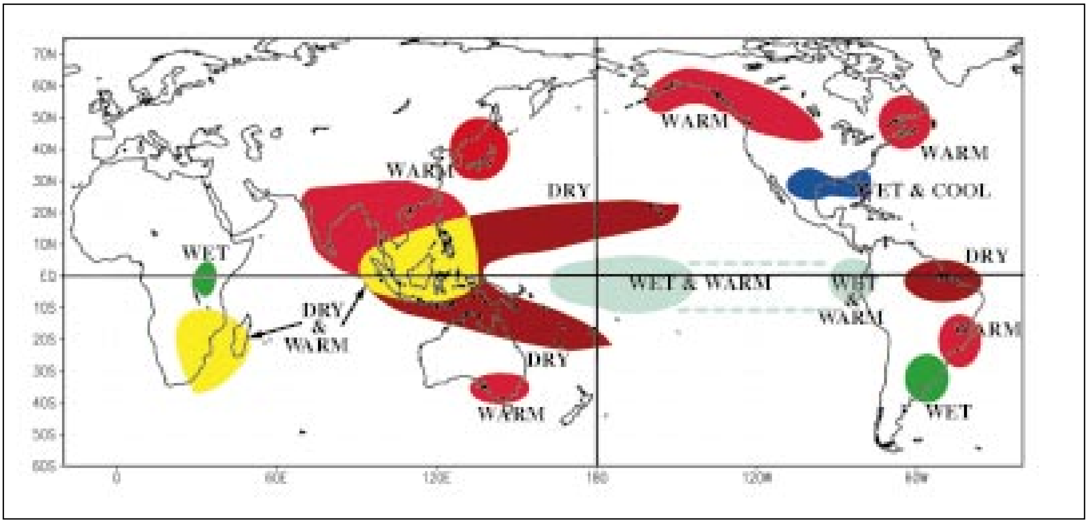


*Figure 4*
Commonly observed ENSO warm mode impacts during December–January (NOAA Network Information Center, at http://www. nnic.noaa.gov/products/analysis_monitoring/ensostuff/).

baseline of ENSO observation than currently exists – temporally, spatially, and with respect to multiple processes. The question of whether ENSO is influenced by changes in global climate forcing may also be partly addressed by examining its sensitivity to past periods of altered boundary conditions (see section 1.4).

ENSO sensitivity and predictability would be of less interest if ENSO affected only the tropical Pacific, but this system produces a far-reaching set of global climate teleconnections that allows the predictability of ENSO to be translated to predictability of anomalies in many other regions, tropical and extratropical (Figure 4). ARTS goals include characterizing the temporal and spatial stability of these teleconnections. A GCM-based study indicates that ENSO teleconnections may vary as background climate changes (Meehl and Branstator 1992), and a recent characterization of the Pacific decadal pattern (Zhang *et al.* 1997) indicates that the mid-latitude anomalies associated with decadal variations in the Pacific differ from those associated with interannual ENSO variations (Figure 3). Over the past century, patterns of ENSO-related drought in the US have varied significantly (Figure 5; Cole and Cook 1998). Variations in ENSO teleconnections may result from changes in the “flavor” of ENSO as seen in the historical record (i.e. the locations of centers of action, seasonal timing, intensity of anomalies) or from the interaction of ENSO with mid-latitude anomalies or other decadally varying aspects of climate (Simmons *et al.* 1983, Barsugli *et al.* 1996; Kumar and Hoerling 1997, Cole and Cook 1998, Gershunov and Barnett 1998, Trenberth *et al.*). Understanding the nature and causes of teleconnection instability is crucial for ongoing climate prediction efforts related to ENSO and is a major objective of ARTS research.

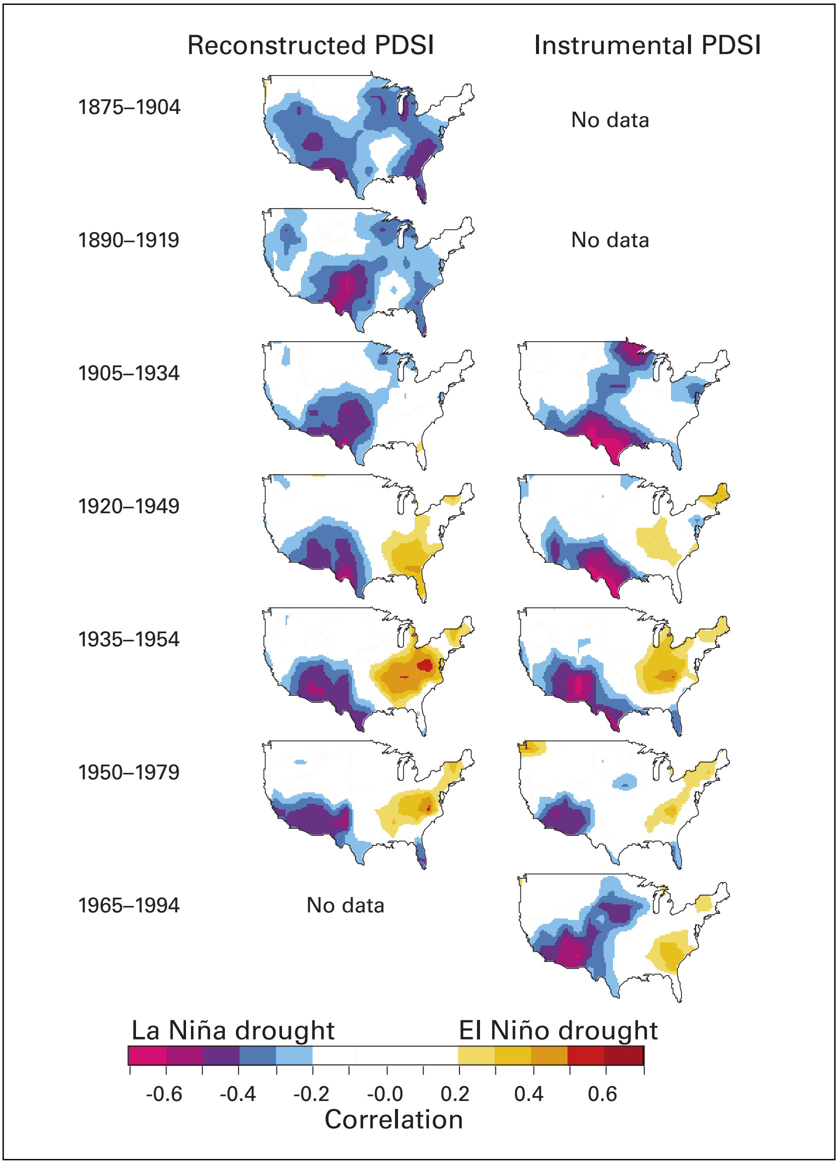


*Figure 5*
Maps of correlation coefficients between Palmer Drought Severity Index (PDSI, both instrumental and reconstructed versions) and instrumental December, January, February Southern Oscillation Index for 30 year intervals during the late 19th through 20th centuries. The reconstructed PDSI is based on a continental U.S. tree ring database and ends in 1978. These maps capture the essential details of the changing relationship between ENSO and drought in the United States. The strongest drought signature is in the southwest and is associated with la Niña. The mid-Atlantic states experience an anomaly of the opposite sign, strongest in the mid-20th century, whose emergence may be related to North Pacific influences. The general pattern of ENSO-related drought is broader in the cooler 19th century than more recently. The locus of maximum ENSO-related drought shifts from Texas northwestward towards Arizona and California over the course of the past century. From Cole and Cook (1998).

## 1.2 Indian Ocean/Asia/Africa/Australia: The Monsoon

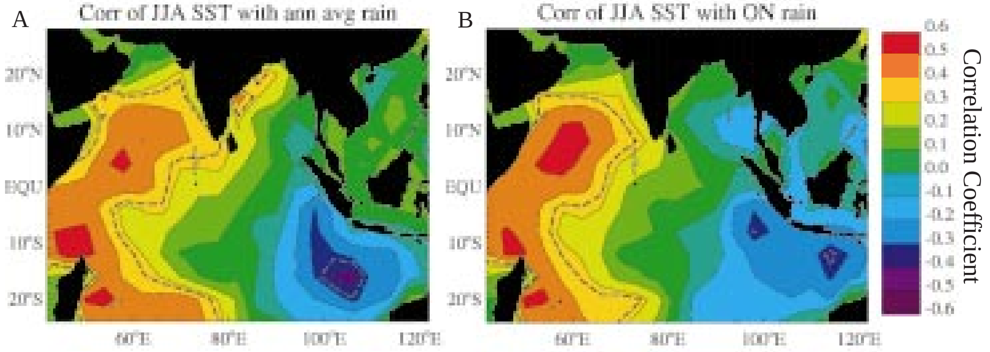
The irregularities of the monsoon govern food production for billions of people, often in countries where poorly developed infrastructure and lack of financial and agricultural reserves exacerbate vulnerability to climate variability. A weak monsoon can bring drought; an abundant one can result in flooding and infrastructure damage. Early attempts at monsoon prediction led to the discovery of the Southern Oscillation (Walker 1923, 1924) but monsoon predictability remains an elusive goal (Webster *et al.* 1998). Knowledge of the fundamental cause of monsoon circulation, the imbalance in the rate and magnitude of seasonal heating and cooling over the land and ocean, has not yet led to a thorough understanding of the factors that govern interannual and decadal variations in this system.

ENSO variations are linked to monsoon strength in many regions. In Australia the monsoon is weakened during ENSO warm phases as the convective system that usually resides over the maritime continent migrates northeastward. In Asia, although the monsoon and ENSO are linked, a weak monsoon tends to precede the season of strong ENSO warm conditions, reducing the utility of ENSO as a predictor (Webster and Yang 1992). In East Africa, rainfall during the lesser of the two annual rainy seasons (October-November) is strongly correlated with ENSO but the strength of the more substantial rainy period (March-May) is unrelated (Hastenrath *et al.* 1993). ARTS research can define these linkages through time and can also help characterize other influences on monsoon rainfall when ENSO is weak (e.g. 1920-1950) or, for whatever reason, does not correlate well with monsoon rainfall.

The cause of interannual to centennial variability in the Asian monsoon remains a subject of debate; better observations of this long-term variation will help to distinguish among candidate hypotheses. In general, two classes of explanations have been put forth: those attributing monsoon variations to oceanic conditions and those invoking land-surface processes. For example, studies exploring the impact of Indian Ocean SST on Asian monsoon strength have reached disparate conclusions, perhaps as a consequence of limited SST data (Terray 1995). South of the equator, warm SST's in the boreal summer can induce rising air that acts as an alternative site for moisture convergence in the region, reducing available moisture for convergence over land and leading to a weak monsoon (Cadet 1979; Cadet and Reverdin 1981; Shukla 1987). Alternatively, land-surface feedbacks related to Eurasian snow cover, vegetation, and soil conditions may impart interannual and longer variability to the monsoon due to changes in the radiation balance over land (Vernekar *et al.* 1995).

With respect to the East African monsoon, large-scale SST fields likely play a role in the seasonal transit of the Inter-Tropical Convergence Zone (ITCZ) southwards from the Asian continent (following boreal summer), as it crosses the East African coast in the boreal fall and spring, and moves back towards Asia the following summer. However, this relationship has

*Figure 6*
Map of correlation coefficients between June-August Indian Ocean SST anomalies and East African coastal rainfall for A) full year and B) October-November. The correlation pattern indicates that during rainy periods on the East African coast, offshore SST is warm and eastern Indian Ocean SST is cool, with implications for zonal atmospheric circulation over the tropical Indian Ocean. SST data are from the Global Sea Ice and Sea Surface Temperature (GISST) data set (Parker *et al.* 1995) and the coastal rainfall data represent 7 coastal sites in Kenya and Tanzania from the Global Historical Climatology network (available at http://cdiac.esd.ornl.gov/cdiac). Analysis spans the period 1950-1990. From Cole, Clark, and Webster, in preparation.



not been well defined. Figure 6 maps the correlation between Indian Ocean SST and East African coastal rainfall, suggesting that rainfall responds positively to warm anomalies in the western Indian Ocean and that cool anomalies in the eastern portion of the basin are also involved, likely as a component of a zonal ocean-atmosphere circulation system (Webster *et al.* 1999; Cole, Clark, and Webster, unpublished results).

The potential exists to test proposed forcings and mechanisms of monsoon variability with concurrent records of both surface ocean and land conditions from annually resolved paleoclimate archives. For example, SST reconstructions from Indian Ocean corals reveal substantial variability on decadal time scales, which is poorly documented by the very limited instrumental SST record. In a Seychelles coral, the decadal patterns of variation correspond with Indian monsoon rainfall indices, suggesting that long-term regional rainfall variability may originate at least in part from the ocean (Charles *et al.* 1997).This and other coral records spanning 1800–1995 AD (R. Dunbar and J. Cole, unpublished) also indicate a long-term warming trend leading up to 1986–1995 as the decade with the warmest SST's in the past two centuries.This trend was identified from the much shorter instrumental record but dismissed due to possible biases in the data (Terray 1995).

## 1.3 Atlantic Ocean/Caribbean/West Africa: The Atlantic Dipole

In the tropical Atlantic, regionally coherent SST anomalies north and south of the equator govern the strength and position of the ITCZ and influence the variability of rainfall on adjacent continents, particularly in the Nordeste region of Brazil (Figure 7) and to a lesser extent, the African Sahel (Hastenrath and Heller 1977; Hastenrath and Lamb 1983; Moura and Shukla 1981; Folland *et al.* 1986; Hastenrath 1990; Servain 1991; Hastenrath and Greischar 1993; Enfield and Mayer 1997). Hastenrath has identified the interhemispheric tropical SST gradient as especially important in this regard: when the northern tropical Atlantic is anomalously warm and the south anomalously cool, the ITCZ is displaced northwards and rainfall is increased in the Sahel and decreased in the Nordeste. When the opposite SST configuration prevails, the Sahel suffers from lack of rain and the Nordeste is unusually wet. Although on interannual time scales, the variability in northern and southern tropical Atlantic SST appears uncoupled

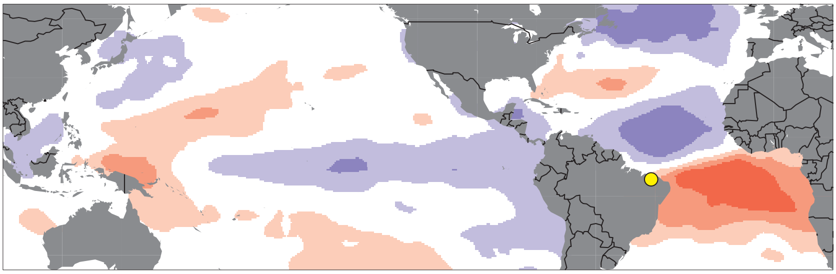


*Figure 7*
Correlation between average Feb-May precipitation in northeast Brazil and sea surface temperature. Red (blue) shading indicates regions in which above-normal SSTs tend to be observed in conjunction with above (below) normal rainfall in Northeast Brazil. The strongest correlations are on the order of 0.7. Northeast Brazil rainfall tends to be more strongly correlated with Atlantic sea surface temperatures than with Pacific sea-surface temperatures. The precipitation time series is the average of 6 stations from northeastern Brazil (including Fortaleza and Quixiramobim) and the SST is from COADS. The analysis period is 1946-1985. From "Pan American Climate Studies: Prospectus and Implementation Plan", available at http://www.atmos.washington.edu/gcg/PACS2/newPACS/pacs.new.pdf.

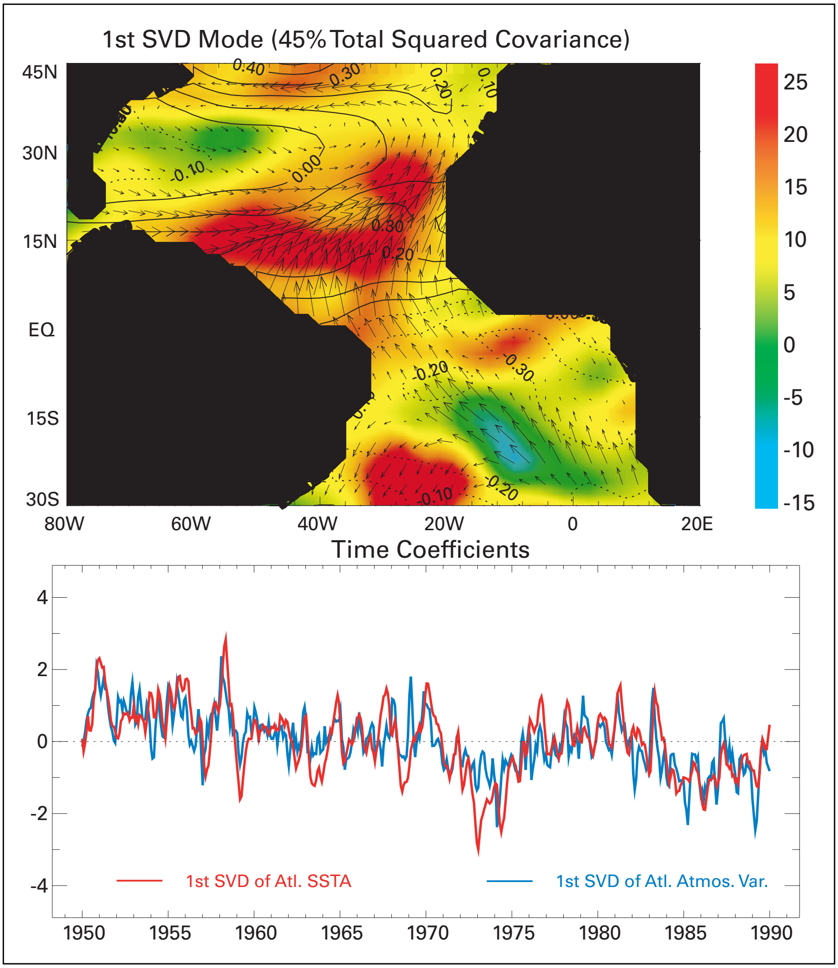


*Figure 8*
The Atlantic dipole-like variability as illustrated by a joint singular value decomposition (SVD) analysis of monthly mean ocean surface data from 1950–1989 AD. The data source is the reprocessed Comprehensive Ocean-Atmosphere Data Set (COADS). The upper panel shows the spatial structure of the first SVD mode. Contours show SST anomaly in °C. Vectors depict wind stress anomalies. Colors indicate the strength of surface heat flux anomalies in $W/m^2$. The first SVD mode explains about 45% of the total squared variance in this coupled system and has a dipole-like SST pattern with maximum amplitudes at about 15°S and 15°N. The lower panel shows two associated time series (in red, the first SVD of Atlantic SST anomalies; in blue, the first SVD of Atlantic atmospheric variation. The time coefficients have been normalized by their own standard deviations. From Figures 1a and 1b of Chang *et al.*(1997). Reprinted by permission from Nature 385:516–518, copyright 1997 Macmillan Magazines Ltd.

(Houghton and Tourre 1992), on decadal scales the interhemispheric SST gradient appears to reflect a dipole, with inversely correlated anomalies on either side of the equator.

Chang *et al.* (1997, 1998) use singular value decomposition of SST and wind data to describe this decadal SST dipole (Figure 8). Based on a series of model experiments, they propose a mechanism by which ocean-atmosphere interaction maintains this oscillation on a decadal time scale. The proposed mechanism involves a balance between SST anomalies reinforced by anomalous winds and negative feedback associated with the cross-equatorial transport of heat by ocean currents. One explicit conclusion of this study is that the Atlantic dipole is not strongly influenced by remote or global patterns but depends on local mechanisms. However, other studies have indicated that at least in the southern tropical Atlantic, SST anomalies are correlated with ENSO interannually (Enfield and Mayer 1997; Hastenrath *et al.* 1987; Curtis and Hastenrath 1995), and in the northern tropics, links to the North Atlantic Oscillation are possible (Lamb and Peppler 1992; Kawamura 1994). The mechanism proposed by Chang *et al.* (1997, 1998) also requires that shifts between phases of the dipole are trig-

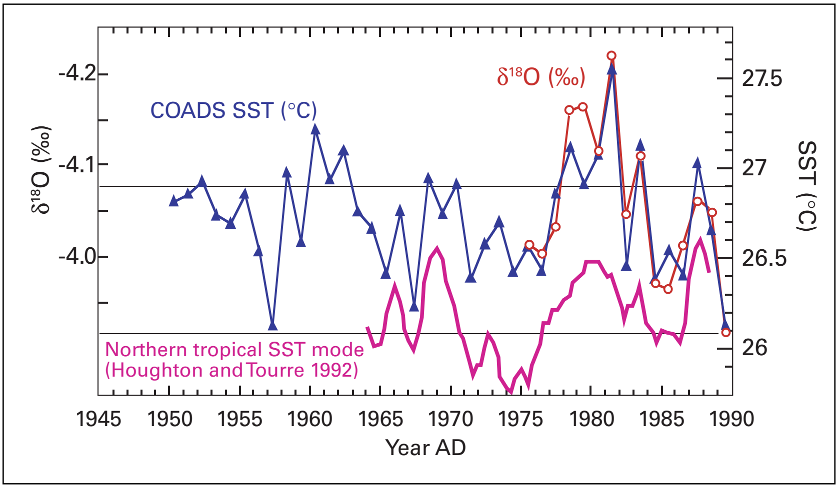


*Figure 9*
Comparison of a composite annual $\delta^{18}O$ record from two Venezuela corals (red line) with the Comprehensive Ocean-Atmosphere Data Set (COADS) SST from the relevant 2x4° grid (blue line) and the time series of the northern mode of tropical North Atlantic SST (Houghton and Tourre 1992; magenta line). The coral data appear to reflect regional SST variability, which in turn correlates with the northern mode of the Atlantic "dipole." Although few reefs exist within regions influenced by the dipole, these data suggest that corals from Venezuela may contain information needed to reconstruct at least the northern component of this pattern (Cole 1996).

gered by circulation changes that alter cross-equatorial heat transport. Testing these hypotheses is an intriguing target for coral-based paleoceanography (Figure 9), which can provide reconstructions of the dipole over longer time frames than used by the studies cited here and perhaps suggest or rule out mechanisms of long-term variation.

## 1.4 Tropical Variability under Altered Background Climates and Boundary Conditions

Well dated, seasonally resolved paleoclimate records extracted from fossil archives may be uniquely suited for documenting seasonal to interannual changes in important climatic systems under altered boundary conditions or during different background climate states. Targets for such investigation could include ENSO, the monsoons, trade winds, and coastal upwelling systems. Seasonal surface temperature gradients across the ocean basins drive atmospheric circulation; these may have been very different in the past. Corals are capable of revealing subtle changes in SST, rainfall, and evaporation within the annual cycle, and can provide clues about how seasonal climate responds to large-scale forcings and background changes. These data sets will be particularly useful for understanding the sensitivity of climatic processes to global climate change, at time scales that are relevant to society.

The nature of tropical involvement in past climate change remains poorly understood but may provide clues about the potential importance of the tropics in future changes via feedback or amplification mechanisms. Addressing this issue requires robust estimates of both past mean conditions and past variability. Several outstanding issues in paleoclimate research are particularly well suited to investigation using fossil corals. For instance, reconstructing tropical SST is a classic problem in paleoceanography. This condition holds today; the precise measurement of the Sr/Ca ratio in coral aragonite by thermal ionization mass spectrometry (TIMS) or inductively-coupled plasma atomic emission spectroscopy (ICP-AES) offers a promising thermometer for reconstructing SST of the distant past (Beck *et al.* 1992; Guilderson *et al.* 1994; Shen *et al.* 1996, Alibert and McCulloch 1997; Gagan *et al.* 1998; Schrag 1999). The applicability of this technique to fossil corals depends to a large degree on the stability of the Sr/Ca ratio of seawater through time. This condition holds today because high-precision measurements of Sr/Ca in modern reef waters show little variability, equivalent to offsets of only 0.2°C in reconstructed SST (de Villiers *et al.* 1994; Shen *et al.* 1996). However, recent models by Stoll and Schrag (1998) suggest that dissolution of Sr-enriched aragonite exposed on continental shelves during sea-level low stands (i.e. the LGM) will increase the Sr/Ca ratio of glacial seawater, potentially producing "cool" artifacts of 1–2°C in reconstructed SST. Nevertheless, the Sr/Ca ratio of seawater should remain sufficiently stable during interglacial sea level high-stands to provide paleo-SST reliable to ±0.5°C.

Paleotemperature estimates from the Sr/Ca ratio of corals from the Caribbean and western Pacific indicate that tropical SST was 5–6°C cooler than today during the late stages of the last glacial maximum (LGM) (Guilderson *et al.* 1994; Beck *et al.* 1997). Although more coral paleotemperature data are needed, these early results suggest that the envelope of potential SST change in the tropics may be large, in contrast to the CLIMAP LGM SST reconstruction for the tropics, which indicates little or no change (CLIMAP 1976). Paleoclimate data for temperate and polar regions suggest that the ensuing Holocene climate may have been complex, with abrupt alternation between cool and warm periods at high latitudes and substantial hydrologic variability at low to mid-latitudes (Sirocko *et al.* 1993; Fisher *et al.* 1995; Lamb *et al.* 1995; O'Brien *et al.* 1995; Overpeck 1995; Alley *et al.* 1997; Stager and Mayewski 1997; Woodhouse and Overpeck 1998). The global climatic expression of these events, and the potential role of the tropics in their forcing, remains unclear and needs to be investigated. Key time slices for exploring potentially rapid cooling, followed by abrupt warming, in the tropics include the Younger Dryas (10.5 ka $^{14}$C yrs), the 8.2ka cooling (Alley *et al.* 1997), the mid-Holocene (ca 5 to 7 ka; Lamb *et al.* 1995), the beginning of the Medieval Warm Epoch (ca 1000 AD; Keigwin 1996), and the Little Ice Age (ca 1500 to 1900 AD; Bradley and Jones 1993). High-resolution records from fossil corals will allow us to check the global extent of these events and the response of important climate systems such as the ENSO and monsoon.

Fossil coral paleotemperature data could also shed light on the debate about self-regulation of SST in the tropical warm pool regions. Previous studies have suggested that the long-term mean SST in the tropics cannot warm beyond about 30°C because of negative feedbacks in the radiation balance of the surface ocean and atmosphere (Ramanathan *et al.* 1989; Ramanathan and Collins 1993; Waliser and Graham 1993). Coral SST reconstructions from periods when the earth may have been warmer than today could provide hard evidence on whether or not this apparent SST maximum can be exceeded. Key time slices that could shed light on this important question might include the last interglacial (125 ka), and the mid-Holocene (8 to 5 ka).

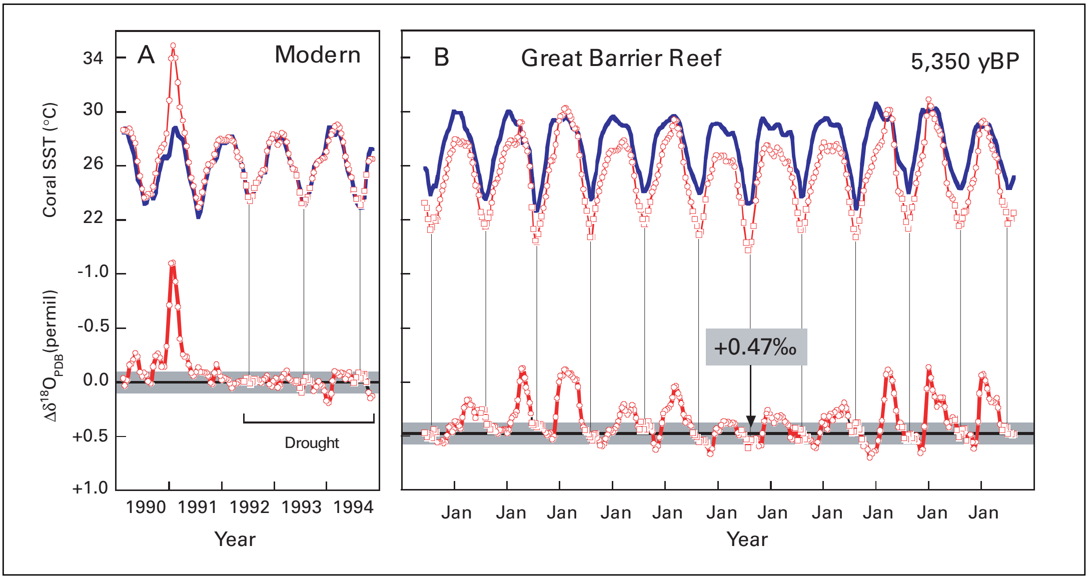


*Figure 10*
Comparison between sea surface temperatures calculated from coral Sr/Ca ratio (blue curves) and $\delta^{18}O$ (upper red curve) for modern (left) and 5,350 yrs BP (right) *Porites* corals from Orpheus Island, central Great Barrier Reef, Australia. Differences in seawater $\delta^{18}O$ (lower red curves), relative to the modern mean, are obtained by removal of the temperature component of the $\delta^{18}O$ signal ($\Delta\delta^{18}O$). The horizontal lines show the mean $\Delta\delta^{18}O$ of seawater, as defined by the seven $\Delta\delta^{18}O$ values (squares) falling in the austral winters (vertical lines). Relative to the mid-Holocene, the modern coral indicates cooler average water temperatures (by 1.2°C and the characteristic interannual variability in salinity ($\sim\delta^{18}O_{seawater}$) that accompanies the ENSO cycle (from Gagan *et al.* 1998).

In addition to their use as ocean thermometers, the correlations observed between the ratios of coral Sr/Ca (Beck *et al.* 1992), U/Ca (Shen and Dunbar 1995; Min *et al.* 1995), Mg/Ca (Mitsuguchi *et al.* 1996) and $\delta^{18}O$ may also make it possible to determine sea-surface $\delta^{18}O$, by removal of the temperature component of the coral $\delta^{18}O$ signal (Figure 10). Maps of sea-surface $\delta^{18}O$ could be produced to estimate variations in the volume of the planetary ice caps. If the strong correlation between seawater $\delta^{18}O$ and salinity holds through time (Rohling and Bigg 1998), it may be possible to produce maps of sea surface salinity that can be used to track changes in water balance over the tropical oceans (cf Gagan *et al.* 1998) as well as varying surface circulation patterns.

Such records are important, particularly for periods when the tropics may have been warmer than today. For instance, recent work has shown that even a small increase in tropical SST (on the order of 0.5°C) leads to a marked increase in oceanic evaporation and precipitable water in the atmosphere, both on the order of 20% (Flohn *et al.* 1990). Model simulations show that the tropical hydrological cycle and latitudinal gradients in SST may drive changes in the mid-latitude atmospheric circulation (Rind 1998). Coral records of the distant past could yield new insights into the links between the hydrological cycle and tropical SST and the degree to which water vapor in the tropics may contribute to the recent warming trend.

Figure 10 shows an example of changed tropical ocean mean temperatures and variability reconstructed from a Great Barrier Reef coral. A 12-year coral record from 5,350 $^{14}C$ years ago provides evidence that relative to today, background SST were warmer by about 1.2°C and that continental runoff was much less variable (Gagan *et al.* 1998). The pattern of cooler SST and reduced runoff associated with ENSO anomalies in this region today is not seen in any portion of this record. These data, although preliminary, are consistent with archeological and paleoclimatic data from South America suggesting a very different pattern of ENSO influence prior to 5,000 years ago (Sandweiss *et al.* 1996, Rodbell *et al.* 1999). Pollen data from Australia also support this interpretation; taxa adapted to the intermittent drought associated with the modern ENSO today are not present before about 5,000 yr BP (Shulmeister and Lees 1995; McGlone *et al.* 1992).

# 2. The Tools for ARTS

## 2.1 Corals

Massive corals from the tropical ocean are the only known paleoclimate archive that offer both the annual resolution and multicentury record length needed for quantification of seasonal-centennial changes in the tropical surface ocean (summary in Dunbar and Cole 1993). Most reef corals live at depths <20 m and grow continuously at rates of 6–20 mm/yr, with most species producing annual density bands that provide time markers for the development of long chronologies (Figure 11). Coral skel-

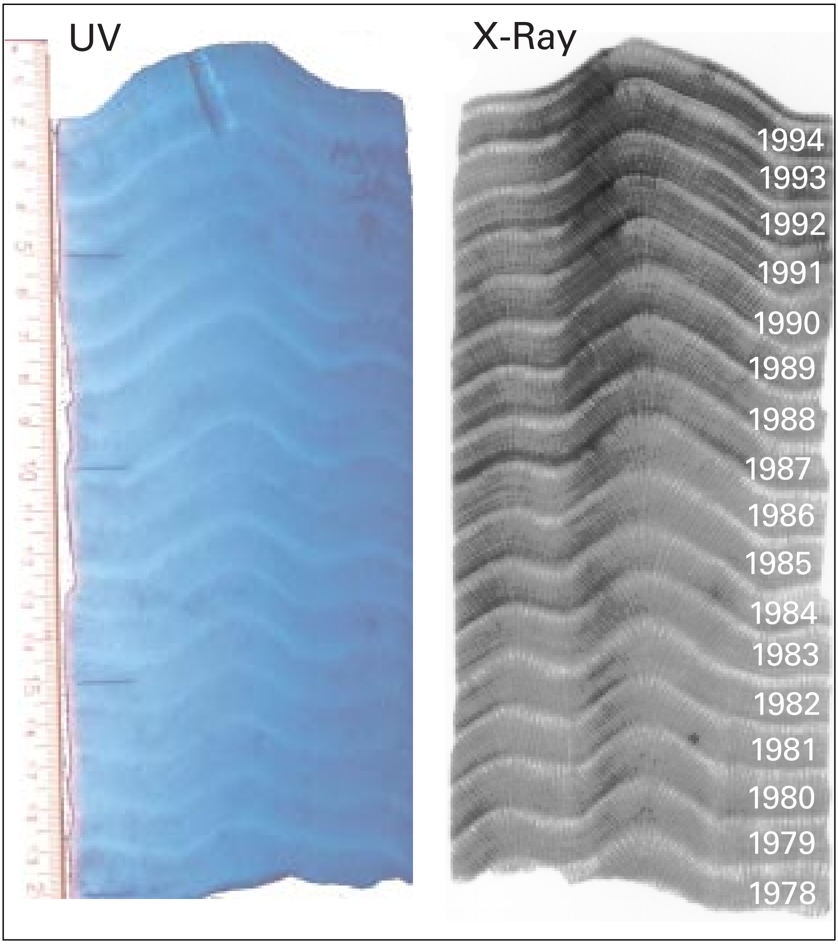


*Figure 11*
X-radiograph (left) and photograph of a coral slab illuminated under ultraviolet light. White numbers indicate assigned year of growth. The coral core was collected from a 4 meter high specimen of *Porites lutea* from Malindi Marine Park, Kenya. This photograph shows the upper 20 cm (1994 to 1978 AD) of a chronology that extends back to 1692 AD. Centimeter ruler is at left. The X-radiograph reveals annual variations in coral skeletal density that result from small changes in the relative magnitude of extension rate versus calcification rate. The bright bands that result from visual wavelength fluorescence under excitation with ultraviolet light most likely result from terrestrial organic substances that are incorporated into the coral skeleton during the annual pulses of river runoff. Both X-ray and UV bands can be correlated between cores from a single head and between cores from within a site and thus comprise useful chronologic and cross-dating tools. From R. Dunbar and J. Cole.

etons have provided new information on environmental changes in surface ocean conditions over the past several centuries in many regions of the tropics (Druffel 1982; Isdale 1984; Isdale *et al.* 1998; Shen *et al.* 1991, 1992a; Cole *et al.* 1993; Quinn *et al.* 1993, 1998; Dunbar *et al.* 1994, 1996; Linsley *et al.* 1994; Tudhope *et al.* 1995, Charles *et al.* 1997; Crowley *et al.* 1997). A summary of highlights is given below.

1) Worldwide, 15 to 20 coral-based climate records extending back to at least the mid 1800's AD are currently available or nearing completion (Figure 12). An additional 20 to 30 records extend back 50 to 100 years from the present. Since reliable instrumental records of past SST variability in the tropics rarely extend prior to about 1940, these coral records are highly useful for studies of decadal climate variability as well as stability and linkages within the climate system at interannual time scales.
2) Many coral records have absolute annual chronologies, wherein annual age assignments are based on multiple independent and consistent age-dating criteria. However, many other coral records are assigned age accuracies of about 1%, based on uncertainties in the parameters used to assign ages. Application of cross-dating and multiple age-specific tracers should allow most coral records to achieve true annual chronologic precision. Many coral records provide sub-annual resolution, on the order of bimonthly to seasonal.
3) The aragonite skeleton of reef-building corals carries a diverse suite of isotopic and chemical indicators that track water temperature, salinity, and isotopic composition as well as site-specific features including turbidity, runoff, and upwelling intensity. At this early stage in the exploration of coral records of climate, few have been calibrated by multi-year *in-situ* monitoring studies. Investigators typically rely on correlations (both near-field and far-field) between their proxies and gridded data sets of SST or rainfall, or with standardized indices of phenomena such as ENSO.

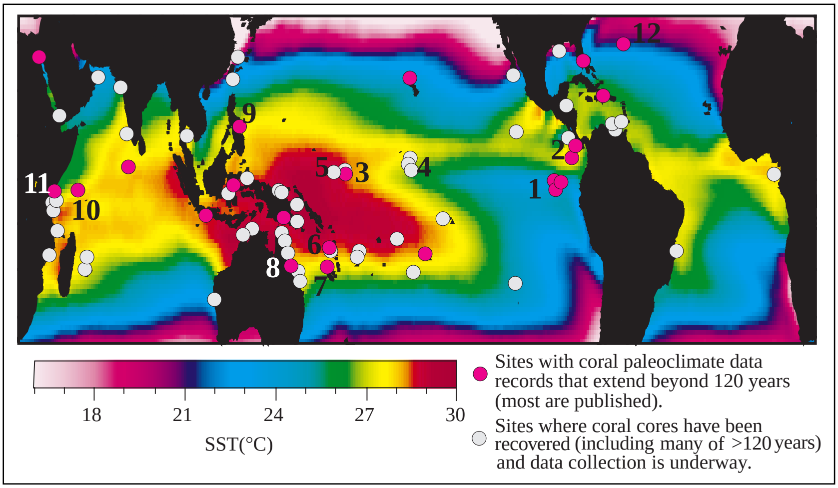


*Figure 12*
Tropical SST's and locations of current coral paleoclimate research. Mean January SST map from NMC SST data available at http://ingrid.ldgo.columbia.edu; coral sites represent the work of many investigators and may be incomplete. Records that extend beyond about 120 years are shown in magenta; gray circles represent both sites where long records are in progress and shorter published records. Numbered sites are mentioned in text:
1. Galápagos; 2. Panamá (Chiriquí); 3. Tarawa (Kiribati); 4. Kiritimati Island (Line Islands, Kiribati);
5. Nauru; 6. Vanuatu;
7. New Caledonia;
8. Abraham Reef, Great Barrier Reef; 9. Cebu, Philippines; 10. Seychelles;
11. Malindi, Kenya;
12. Bermuda.

4) Corals from equatorial and near-equatorial sites in the Pacific basin and central Indian Ocean record past ENSO variability, through ENSO's impact on SST, SSS or a combination of the two. Most coral records show changes in dominant periods of variance going back through time at time scales ranging from annual to multidecadal.
5) Most of these records reveal surprisingly large variability at decade to century time scales. Most are consistent with long-term warming of SST by 0.5 to 2°C since the early 1800's. Rainfall-sensitive sites also suggest long-term variability in tropical precipitation.
6) Some western Pacific records show SST variability related to volcanic events during the past 3 centuries (Crowley *et al.* 1997).
7) Coral records from a few sites (including published records from Tarawa, Galápagos, Christmas, and Seychelles, and unpublished records from the central Pacific islands of Fanning, Aranuka, Maiana, and Nauru) exhibit exceptionally strong correlations to instrumental ENSO and/or SST indices. These sites also indicate changes in the strength of the annual cycle of either rainfall or SST through time.

### 2.1.1 Stable Isotopes

Many coral studies have relied on oxygen isotopic measurements because they are easy to obtain and relatively straightforward to interpret. The stable isotopic content (particularly $\delta^{18}O$, the $^{18}O/^{16}O$ ratio) of coral carbonate provides a useful history of environmental variability. Coral aragonite $\delta^{18}O$ records SST variability, usually according to the standard paleotemperature relationship for carbonates. The isotopic composition is offset by a biological non-equilibrium component that appears to be stable through time, as long as a consistent (and maximum) growth axis is sampled (Weber and Woodhead 1972; Dunbar and Wellington 1981; Pätzold 1984; Mc Connaughey 1989; Winter *et al.* 1991; Shen *et al.* 1992a; Gagan *et al.* 1994; Leder *et al.* 1996; Swart *et al.* 1996; Wellington *et al.* 1996). When seawater $\delta^{18}O$ is variable (a function of hydrologic balance: precipitation, evaporation, and runoff), this component is also incorporated into the skeletal $\delta^{18}O$ (Dunbar and Wellington 1981; Swart and Coleman 1980; Cole and Fairbanks 1990; Gagan *et al.* 1994; Linsley *et al.* 1994). Long records of coral $\delta^{18}O$ have been used to develop precipitation reconstructions from sites where seawater $\delta^{18}O$ correlates with rainfall (Cole *et al.* 1993; Linsley *et al.* 1994)

The carbon isotopic signal in corals is less straightforward to interpret in climatic terms, due to interactions with physiological processes that involve large fractionations (Swart 1983). In some cases, correlation between $\delta^{13}C$ and light intensity has been interpreted to reflect insolation (cloudiness) variability (Fairbanks and Dodge 1979; Weil *et al.* 1981; McConnaughey 1989) or water clarity (Wellington and Dunbar 1995; Grottoli-Everett and Wellington 1999). In other cases, $\delta^{13}C$ correlates poorly with environmental variables, and the signal may differ greatly among adjacent corals or even different sampling transects within a core [J. Cole, R. Dunbar, B. Linsley, unpublished data]. Spawning may also cause skeletal $\delta^{13}C$ variations (Gagan *et al.* 1996). A potential linkage between $\delta^{13}C$ variability and nutrient or food availability has been noted (Grottoli-Everett and Wellington 1999; Felis *et al.* 1998). At present, there are few published indications that highly useful climate information can be derived from carbon isotopic time series in corals. Nevertheless, $^{13}C/^{12}C$ data is normally collected simultaneously with $^{18}O/^{16}O$ ratios during coral analysis and a large body of archived $\delta^{13}C$ data is currently available (although often not in publicly accessible electronic archives). At a few sites, $\delta^{13}C$ information will likely contribute semi-quantitative information on water column or atmospheric properties. At many other sites, $\delta^{13}C$ may be useful in resolving or cross-checking coral chronologies.

### 2.1.2 Elemental Indicators

Development of elemental indicators in corals continues to accelerate. Skeletal constituents known to cycle seasonally in response to environmental forcing include Sr, Mg, U, Ba, Cd, Mn, Cu, B, and F. The concentrations of these elements in coralline aragonite have been variously proposed as proxies for temperature, salinity, vertical mixing, lateral advection, and wind events. Whether these tracers ultimately meet the needs of ARTS depends on our understanding of their controls, their sensitivity to signals of interest, and our analytical capability to deliver sufficient amounts of high quality chemical data. In spite of remaining uncertainties on details related to these indicators, independent crystallographic, thermodynamic, and oceanographic studies are ongoing and specific environmental controls and incorporation mechanisms are being identified and quantified. For example, inroads are being made in the determination of tracer incorporation at the crystal level: x-ray absorption fine structure (XAFS) spectroscopy has revealed that $Ba^{2+}$ appears to substitute for $Ca^{2+}$ in the aragonite lattice (Reeder 1996) – a pivotal but unproven hypothesis of Lea *et al.* (1989).

In terms of environmental controls, perhaps the best characterized is the behavior of Sr in aragonite - a system that has recaptured much attention over the last five years as precise measurement techniques enable SST reconstruction with sufficient accuracy for key climate questions (Beck *et al.* 1992; de Villiers *et al.* 1994; McCulloch *et al.* 1994; Shen *et al.* 1996; Mitsuguchi *et al.* 1996; Gagan *et al.* 1998; Schrag 1999). With the exception of the de Villiers *et al.* study, Sr/Ca appears to be a robust thermometer in reef corals (Figure 13). In combination with $\delta^{18}O$, surprisingly subtle variations in temperature and hydrologic balance can be discerned (Figure 10; Gagan *et al.* 1998). The apparent influence of growth rate on Sr/Ca (de Villiers *et al.* 1995) has not been seen by other groups (C. Alibert, M. McCulloch, pers. comm.; T. Lee, pers. comm.). Temperature-Sr/Ca calibrations from a variety of oceanic environments are converging on a common paleotemperature relationship (Shen *et al.* 1996; M. Gagan, pers. comm. 1996); the main complications appear to be variable Sr/Ca of seawater and interspecies offsets (de Villiers *et al.* 1993; Shen *et al.* 1996) - both of which can be controlled sufficiently for paleoclimatic studies. A new high precision (±0.1%) method of Sr/Ca determination via inductively coupled plasma atomic emission spectroscopy (ICP-AES) using frequent comparison of sample unknowns to a reference solution (Schrag 1999) greatly increases sample throughput and may catapult this tracer to the forefront of coral paleoclimate analytical strategies.

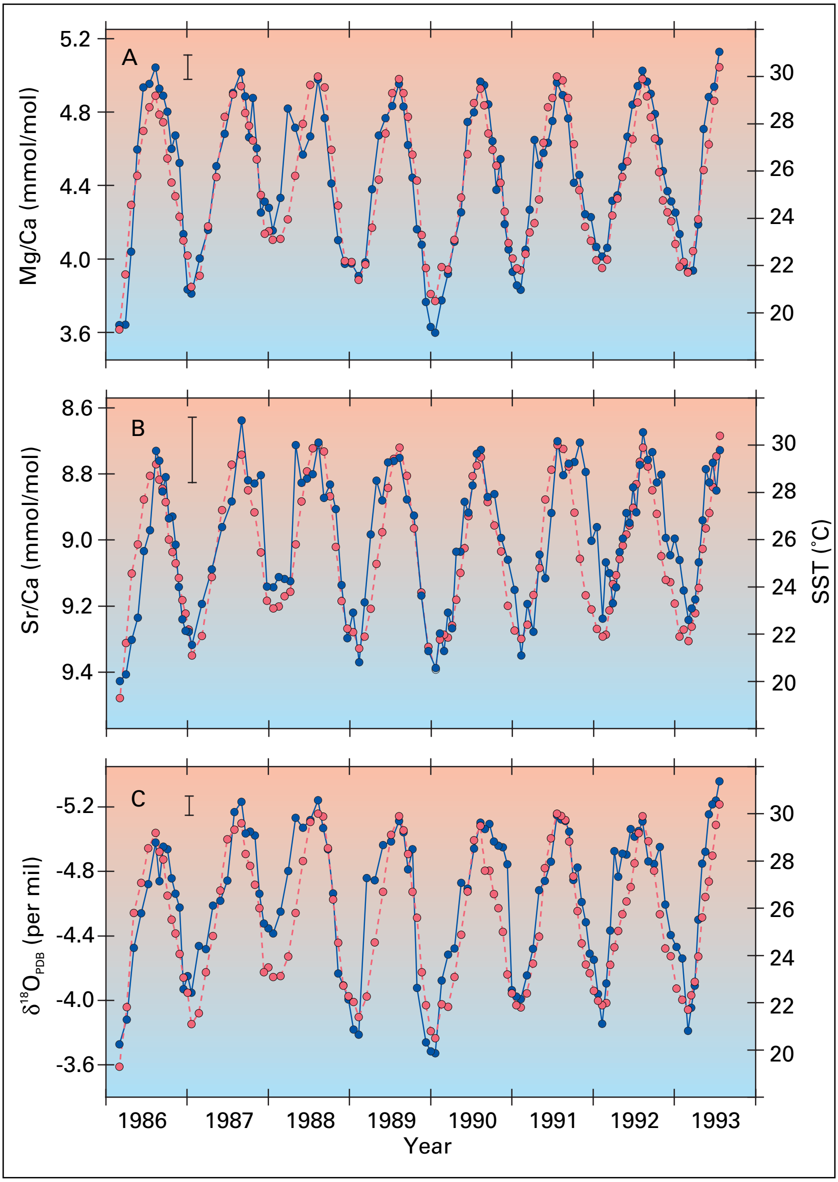


*Figure 13*
Comparison between SST (dashed line) and variations of Mg/Ca and Sr/Ca ratios and $\delta^{18}O$ (solid lines) in a specimen of *Porites lutea* collected from Yasurazaki, Ishigaki Island, Ryukyu Islands, Japan over the period 1986–93. The time resolution for SST and these tracers is 3 weeks.
(A) The Mg/Ca-SST linear correlation is $r = 0.923$. Analytical error bars correspond to an uncertainty of ±0.5°C.
(B) The Sr/Ca-SST linear correlation is $r = 0.853$). Analytical error bars correspond to an uncertainty of ±1.6°C.
(C) The $^{18}O$-SST linear correlation is $r = 0.877$. Analytical error bars correspond to an uncertainty of ±0.4°C.
Modified from Mitsuguchi *et al.* (1996).

Other temperature-sensitive elements include U, Mg, and potentially B and F. Of these, Mg, although not completely free of additional influences, shows the greatest promise as an additional temperature proxy (Figure 13; Mitsuguchi *et al.* 1996). Nevertheless, additional calibration work is needed on all elemental tracers. Shen and Dunbar (1995) suggest that coral U/Ca ratio may depend on both temperature as well as seawater U concentration - thus this indicator should also record salinity. Concentrations of Cd, Ba, and Mn in corals reflect elemental concentrations of seawater associated with upwelling in the eastern equatorial Pacific (Linn *et al.* 1990; Shen *et al.* 1987, 1991, 1992a). Mn/Ca ratios atTarawa correspond to anomalous westerly winds, an important ENSO forcing factor in the central and western equatorial Pacific (Shen *et al.* 1992b). The mechanism of this recording system, however, suggests strong site specificity, as westerly winds remobilize Mn from Tarawa lagoon sediments and disperse it towards portions of the atoll's living coral communities.

New tracers raise intriguing possibilities. Coralline F may offer a new salinity tracer if it responds with a cubic dependence on salinity as hypothesized for foraminiferal calcite (Rosenthal and Boyle 1993). This dependence could account for the 50% variability observed in F/Ca by Hart and Cohen (1996) at Two-Mile Reef, South Africa. A geochemical basis for B isotope variability can be readily argued; if corals take up B as $HBO_3^{2-}$ (Hemming *et al.* 1995) the coral skeletal isotopic Ratio of B could reflect pH and $\Sigma\delta CO_2$ of reef waters (Gaillardet and Allegre 1995). Although the rapid increase in numbers of known and potential environmental proxies in corals has outpaced our understanding of the underlying physics and chemistry, it is nonetheless clear that more paleoenvironmental information is available than can be inferred from $\delta^{18}O$ alone.

Optimally, by combining as many of the above proxies as possible, temperature and salinity can be reconstructed with multiple redundancy for both parameters. For SST reconstruction to within ±0.5°C, using these potential thermometers we need to be able to measure elemental ratios with the following precisions: Sr/Ca: 0.35%; U/Ca: 2%; Mg/Ca: 1.5%; B/Ca: 2%; F/Ca: 2%. Estimates for B and F are based on the relation between their seasonality and $\delta^{18}O$, however these new tracers may also be dependent on other aspects of seawater chemistry such as salinity and/or alkalinity. For example, if U/Ca records SST and salinity (Shen and Dunbar 1995), a 1‰ salinity change should appear as a U/Ca decrease of 3%. If a cubic dependence of F on salinity holds true in corals, a 1‰ salinity change (34‰ to 35‰ = 3%) would be reflected as a 27% change in skeletal F/Ca! The above elements have been measured in corals by the following techniques: thermal ionization mass spectrometry [TIMS] (Sr), inductively coupled plasma mass spectrometry [ICP-MS] (U, Ba, Sr, Mg), inductively coupled plasma atomic emission spectroscopy [ICP-AES] (Sr, Mg), graphite furnace atomic absorption spectroscopy [GFAAS] (Cd, Mn) and ion microprobe [IM] (Ba, Mg, Sr, F, B). These techniques all have advantages and drawbacks in terms of precision, analytical expense, and throughput. For example, analyses that use TIMS and GFAAS are time consuming and may not be the method of choice for most ARTS data acquisition efforts (compare the average TIMS throughput of 6-10 samples/day with isotopes and ICP-based metal analyses at 40-200/day).

### 2.1.3 Radiocarbon as a Tracer of Ocean Circulation

Radiocarbon ($^{14}C$) contained in dissolved inorganic carbon in seawater (DIC) is a transient tracer useful for determining past changes in ocean circulation. Radiocarbon is produced both naturally in the upper atmosphere and as a result of thermonuclear testing which peaked in the 1950's and early 1960's. During pre-bomb and post-1970 periods, the main controls on $\Delta^{14}C$ in the surface ocean are horizontal advection and vertical mixing. Immediately following the onset of nuclear testing, $^{14}C$ levels in the upper ocean dissolved carbon pool increased by 150 to 250‰, producing

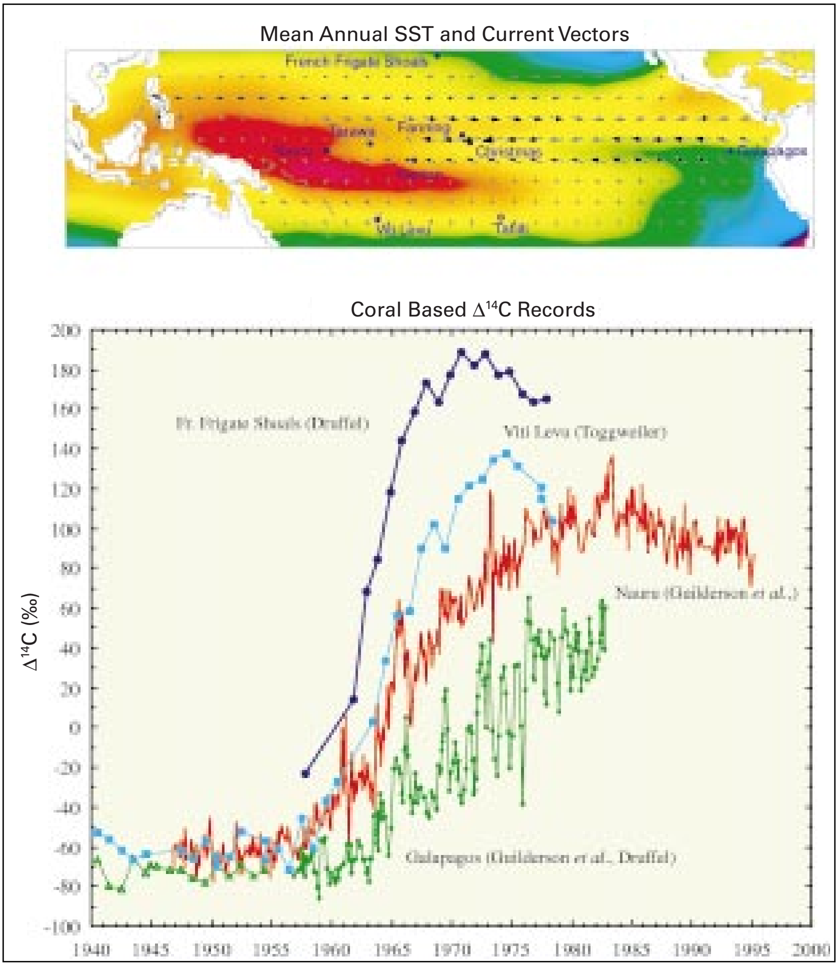


*Figure 14*

Locations of coral based $\Delta^{14}C$ records in relation to the mean annual SST and surface currents. The longitudinal changes in $\Delta^{14}C$ correlate with SST. Upwelling in the eastern equatorial Pacific brings cold, low $^{14}C$ water to the surface. This water is then advected to the warm pool where it mixes with high $^{14}C$ water from the sub-tropics. The records from French Frigate Shoals and Viti Levu (Fiji) are from the literature and are the source of high $^{14}C$ water to the warm pool. New AMS-$^{14}C$ (±4‰) records from Nauru and the post-bomb Galapagos are also shown. The long-term trend in the individual records reflects the uptake of bomb $^{14}C$ in the ocean. The Nauru $\Delta^{14}C$ record is dominated by interannual variability (up to 80‰) in concert with the oceanic manifestation of ENSO. During the warm phase of ENSO (El Niño), the western equatorial Pacific has higher $\Delta^{14}C$ indicative of a larger component of subtropical origin water. During the cold phase of ENSO (La Niña), stronger than average trade winds increase the upwelling in the eastern equatorial Pacific and decrease the time that it takes to advect the newly upwelled water across the Pacific, resulting in low $\Delta^{14}C$ in the western equatorial Pacific. Maximum $\Delta^{14}C$ during El Niño events tend to lag the corresponding Niño-3 SST anomaly by 3–4 months whereas the return to more negative $\Delta^{14}C$ is in phase. This implies that during the termination of El Niño events there is rapid transport of water across the equatorial Pacific in as little as several months. From Guilderson *et al.* (1998), Druffel (1987), and data from Toggweiler *et al.* (1991) and Guilderson and Schrag (1999) with M. Kashgarian and J. Southon.

a steep gradient in $\Delta^{14}C$ that is preserved in coral skeletons and can be used to track water mass movements (Figure 14). $\Delta^{14}C$ is influenced to some extent by air-sea exchange but the equilibration time is on the order of a decade. Only when bomb $^{14}C$ was increasing rapidly in the 1960's was gas exchange a primary controller of surface ocean $\Delta^{14}C$. Biological processes have a negligible effect on $DI^{14}C$. Thus, unlike temperature and salinity, $\Delta^{14}C$ is a nearly conservative tracer in surface waters. Coral $\Delta^{14}C$ data augments an instrumental record that contains significant spatial and temporal biases. The bomb-induced $^{14}C$ transient is providing exciting views into the dynamics of the modern ocean (e.g. Toggweiler *et al.* 1991). For example, Guilderson and Schrag (1998) used subannual $\Delta^{14}C$ measurements from a Galápagos coral to argue that the important 1976 "Pacific climate shift" was unrelated to subsurface advection of a warm North Pacific thermal anomaly as has been postulated by Zhang *et al.* (1998).

In another study, Bermuda coral $\Delta^{14}C$ measurements revealed a factor of 3 decrease in water mass renewal (ventilation) rates in the Sargasso Sea during the 1970's (Druffel 1989, 1997). In these types of studies, coral $\delta^{18}O$ or other temperature records may be used to distinguish between two types of ocean mixing. For example, a change in SST would suggest a change in upwelling rate as the cause of a $\Delta^{14}C$ shift. Circulation changes associated with ENSO across the tropical Pacific can also be readily distinguished at many sites (e.g. Druffel 1981; Guilderson *et al.* 1998). The long half-life of this tracer also permits its use further back in time. Annual and seasonal $\Delta^{14}C$ records have been reconstructed from banded corals for the past few centuries from several sites (e.g. Druffel 1981, 1982; Nozaki *et al.* 1978; Druffel and Griffin 1993).

### 2.1.4 Existing Records from the Pacific

The tropical Pacific has been a common focus of many coral paleoclimate studies (labeled sites in Figure 12), due to the importance of ENSO in global climate variability and the presence of long-lived coral heads. In the eastern Pacific, a comprehensive network of coral climate reconstructions is developing (Druffel 1981; Druffel *et al.* 1990; Linn *et al.* 1990; Shen 1996; Shen *et al.* 1991, 1992a; Dunbar *et al.* 1994, 1996; Linsley *et al.* 1994, 1999; Wellington and Dunbar 1995; Wellington *et al.* 1996; Carriquiry *et al.* 1988, 1994, 1998). A 370-yr $\delta^{18}O$ record from the Galápagos Islands reveals strong interannual through multi-decadal variability in eastern Pacific SST in a fashion that suggests that ENSO-like processes are operative at decadal and longer periods. In Panamá, a 280-yr $\delta^{18}O$ record from a rainfall-sensitive site indicates decadal periods in the strength and/or position of ITCZ-related precipitation and a long-term increase in either rainfall or SST. Decade to century variance in these Galápagos and Panamá records appears to be anticorrelated, consistent with a southward displacement of the ITCZ during warmer periods in the Galápagos (Dunbar *et al.* 1996).

Previous work on corals in the central Pacific has focused on the islands of central/north Kiribati (near 1°N, 172°E; Cole and Fairbanks 1990; Cole *et al.* 1993, Shen *et al.* 1992b) and the Line Islands (~160°W; Druffel 1985; Evans *et al.* 1999; Dunbar and Linsley, in preparation). In this region, the combination of warm and wet anomalies during ENSO warm phases works in phase to generate lower coral skeletal $\delta^{18}O$. Simple calculations based on observed variability indicate that local rainfall variations can produce a seawater $\delta^{18}O$ signal sufficient to yield the observed coral $\delta^{18}O$ variability (Cole and Fairbanks 1990; Cole 1992). The $\delta^{18}O$ record from Tarawa corals (to 1894 AD) correlates with instrumental ENSO indices at levels similar to instrumental data from individual Pacific sites (Cole *et al.* 1993), a result also seen in *Porites* corals at Christmas Island (Evans *et al.* 1999). The Tarawa record shows that seasonal and interannual variability have varied together over the past century, with stronger seasonal cycles accompanying periods of reduced ENSO amplitude within and beyond the tropical Pacific, and that the recent warm period since 1976 is unprecedented in the past century. Comparison of the Tarawa records with isotopic data from cores from nearby atolls reveals regional reproducibility of the ENSO signal in the $\delta^{18}O$ data over tens of kilometers and several decades (Urban *et al.* 1998).

In the western Pacific, decadal variability of SST or rainfall is implicated at Vanuatu by a persistent 14-yr period in a $\delta^{18}O$ record (Quinn *et al.* 1993). A 3-century record from New Caledonia shows evidence for SST variability related to volcanic activity (Crowley *et al.* 1997). Indonesian corals reveal interannual variability in $\delta^{18}O$ that is strongly correlated with the Southern Oscillation (Fairbanks *et al.* 1997). A 3-century record from Abraham Reef (Great Barrier Reef) has been interpreted as reflecting changes in ocean circulation off NE Australia (Druffel and Griffin 1993). Other records are available or are being developed in the Philippines, Thailand, Taiwan, Fiji, New Guinea, Tahiti, and the Cook Islands (Pätzold 1984; Moore 1995; Boiseau *et al.* 1998; Cole 1998; Lee, Tudhope, Linsley/Wellington, Cole/Shen, personal communications).

Some regional isotopic events and trends can be explained in terms of variability in key climatic systems of the Pacific. For example, the driest/coolest interval at Tarawa (1955–56) corresponds with a very dry/cool period at Espiritu Santo (southwest Pacific) and a warm/wet period at Cebu (Philippines). These observations are consistent with a westward contraction of the warm pool and consequent local anchoring of the Indonesian Low during a strong La Niña (1955 through early 1957). Cook (1995) discusses another multi-decadal inverse relationship between SST's derived from the Urvina Bay record, a Great Barrier Reef SST index derived from coral growth band thickness (Lough *et al.* 1996), and the Abraham reef $\delta^{18}O$ record (Druffel and Griffin 1993). These results are consistent with ENSO warm mode conditions raising eastern Pacific SST's but causing drought and slight cooling in northeast Australia and suggest that ENSO-type variability may operate over long time scales. Most of these long coral time series have only recently become available and this short discussion is not meant to forecast the results of comprehensive synthesis effort. However, the results thus far are intriguing enough to warrant further data acquisition and initial attempts at quantitative synthesis.

Outside the Pacific, long-term records are emerging from the Indian Ocean that appear to reflect large-scale variability. In the Seychelles, interannual variability in a $\delta^{18}O$ record is strongly linked to ENSO, and decadal variations may be related to long-term monsoon variability (Charles *et al.*

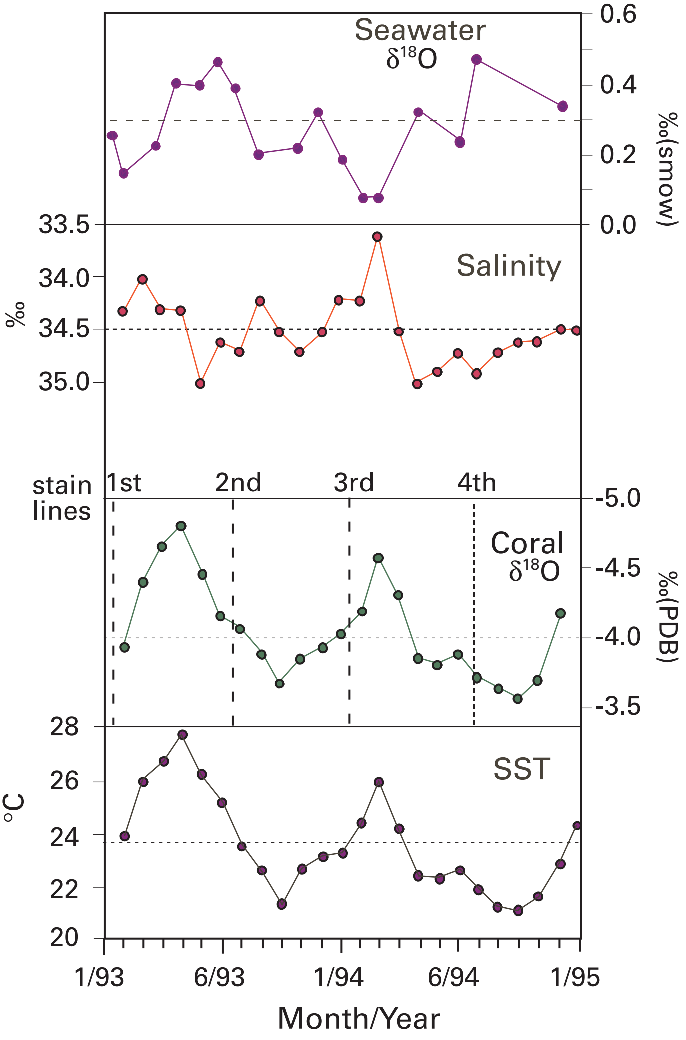
1997). A 200-yr record from Kenya (Dunbar and Cole, unpublished) exhibits strong decadal variability and agrees with the Seychelles record in displaying a long-term warming trend up to the present.

### 2.1.5 Remaining Issues and Challenges in Utilizing Recent Coral Records

Despite past successes in the use of corals for paleoclimate reconstruction, many issues regarding their utility remain to be resolved. These include:

1) *Chronology:* Many key applications of coral paleoclimate records depend on establishing accurate annual chronologies. Most long time series are initially dated via the use of annual density bands. The annual periodicity of density banding has been documented in many species of corals over a wide geographic range (Weber *et al.* 1975; Knutson *et al.* 1972; Dodge and Thomson 1974; Wellington and Glynn 1983). The exact causes of this banding are under ongoing investigation; an understanding of many relevant details is emerging from recent work (Barnes and Lough 1993 and references therein; Dodge *et al.* 1994). Some corals have such clear banding that chronology development is relatively straightforward, but at many sites, growth bands are indistinct. In addition, because density banding derives from changes in growth and calcification rates, often related to reproduction and seasonal changes in productivity, possibilities exist for more or less than 1 band per year in settings where the annual cycle is weak. Methods adapted from dendrochronology, especially cross-dating of multiple cores from a site, are essential for achieving annual and absolute chronologic precision over long time scales. In addition to density bands, any physical or chemical tracer that exhibits regular seasonal cycling can be used for chronology development, including $\delta^{18}O$, $\delta^{13}C$, many trace elements, and fluorescent banding.
2) *Calibration:* Few sites have been calibrated via *in situ* monitoring of SST and SSS, and regular water sampling for $\delta^{18}O$ and chemistry. Although empirical relationships have been established between various isotopic and trace element proxies and regional climate indices, uncertainties remain about the partitioning of the coral-derived signals among specific climate forcing mechanisms. Even after *in situ* calibrations are accomplished, we cannot be certain that the modern partitioning we observe (e.g. between salinity and temperature in a $\delta^{18}O$ record) also applies several centuries in the past. Nevertheless, calibration studies help establish the causal mechanisms for both isotopic and elemental variability in coral time series and serve to improve the accuracy of our climate reconstructions. An example of a multi-sample calibration study from Galápagos is shown in Figure 15 (Wellington *et al.* 1996).
3) *Coral Growth Issues:* Recent anecdotal suggestions of biological causes of long-term variability in coral $\delta^{18}O$ and trace element content have yet to be documented via observation or experiment. There are no *a priori* reasons to expect a strictly biological "aging" effect that would produce spurious results at multi-decadal to century time scales, but signals at these scales are generally small and this possibility should be investigated by replication studies using corals of different ages (Linsley *et al.* 1999). A non-biological, yet local, cause of low frequency variability may

*Figure 15*
Profiles of $\delta^{18}O_{seawater}$, SSS, $\delta^{18}O_{coral}$, and SST from a calibration study site in the Galápagos Islands. Data shown is for a specimen of *Porites lobata* from Bartolome Island, one of 9 coral specimens used in 4 *in situ* calibration exercises throughout the archipelago. Water samples were collected monthly and analyzed for salinity and seawater isotopic composition. Corals were stained with alizarin red dye in January 1993, June 1993, January 1994, and June 1994, to provide visible time marks on the coral skeleton to allow correlation of coral isotopic data with seawater information. Dashed lines represent the means. In this example, SST alone accounts for greater than 89% of the variance in coral $\delta^{18}O$. Similar results were observed at 3 other sites in Galápagos. From Wellington *et al.* (1996).



be the accreting coral surface growing at shallower depths (by several meters) as a colony ages. This may expose the coral growth surface to waters of slightly different temperature, salinity, and light intensity at some locations. A second growth issue is seasonal-annual "smoothing" of the climate signal by calcification at depth below the surface of the coral. Some calcification must occur within and at the base of the living tissue layer (typically 3 to 10 mm thick). Since corals usually grow at annual rates of 5 to 20 mm/yr, there is a possibility of signal attenuation, especially in specimens with low growth rates and thick tissue layers. Understanding this process is necessary for selecting an appropriate sampling resolution as well as establishing the time scale over which the climate reconstruction is accurate - e.g. monthly vs. seasonal vs. annual vs. interannual. For example, McCulloch *et al.* (1994) demonstrate that this effect is likely minimal in a coral sampled at 50 samples/yr with a growth rate of ~1.3 cm/yr.

4) *Replication:* There are several published and unpublished examples of replication of isotopic and elemental time series in corals using cores from within the same colony or within adjacent heads. Most show very similar results; others show disturbing disagreement. It seems clear that greater reliability should be given to climate reconstructions from sites where multiple records show agreement and allow signal precision to be established based on differences between the records. This has not yet been accomplished for most records over 100 years in length. Multiple coring (and subsequent analysis) will also aid in the development of accurate age assignments based on cross-dating. Replication will also allow us to distinguish long-term variations in coral records that are due to large-scale climate changes from those that may be due to either localized or biological artifacts.
5) *Species issues:* The utility of many coral species has not been fully explored; investigators have concentrated on developing climate records from just a few species. In some cases, different taxa appear to yield very similar results (e.g. compare records in Cole and Fairbanks 1990 and Cole *et al.* 1993; Dunbar *et al.* 1994; Urban *et al.* 1998). In other cases, records from certain species have proven difficult to reproduce even among adjacent colonies (e.g. *Siderastrea siderea*: Smith 1995; Guzman and Tudhope 1998). Some species require very specific sampling procedures for best results (Leder *et al.* 1996). In general, the *Porites* species used in most Pacific and Indian Ocean studies appear to provide very reproducible results if reasonable care is taken in sampling (Tudhope *et al.* 1995; Linsley *et al.* 1999; Urban *et al.* 1998). A better understanding of coral growth processes may be the key to developing specific sampling procedures for "difficult" species - e.g. sampling specific skeletal growth elements may yield more accurate records of climate (Leder *et al.* 1996).
6) *Tracer calibration and incorporation:* in many cases, a promising tracer that appears to track environmental variability reliably in one setting or over a few years may exhibit bizarre behavior in other regions or over longer time periods. Based on widespread application, some tracers are known to be more reliable than others. Our present understanding of how geochemical tracers in corals record environmental variability is often driven by observed correlations between records, rather than by a full understanding of the relevant thermodynamic and physiological constraints. More calibration and process studies will improve the potential for multivariate reconstructions and will enable us to evaluate which tracers should work best in specific situations.

In summary, there are several issues that remain to be addressed before we can assign accurate error estimates to most coral climate records. Calibration and coral growth studies will help us understand what actually produces the proxy signal at each site. Replication of longer records from promising sites is essential for age-control and establishing the reliability of the reconstruction. Existing strong empirical relationships and successful calibration studies lead us to expect that at some locations, high-accuracy, subannually resolved, multi-century climate reconstructions will be forthcoming. Current data also suggests that corals from some sites will remain difficult to interpret, for as yet mostly unknown reasons.

It is not too early to begin large-scale data syntheses, but such efforts must recognize that each individual coral record comes with its own set of uncertainties that are often site-specific. The impact of small chronology errors can be minimized by looking at interannual or longer variability. However, the reliability of isotopic and elemental tracers at each site may also vary as a function of site-specific factors. The best approach for an initial spatial synthesis may be to assign a reliability weighting according to the degree of site-specific replication, calibration and/or agreement with modern (post-1950 AD) instrumental indices. However, even if this is done, such syntheses should remain flexible to include new data sets and reliability rankings. We anticipate many developments during the next 5 years and recommend that the acquisition of new, multi-century records at climatically important sites continue in parallel with calibration, replication, and synthesis exercises.

### 2.1.6 Fossil corals

Fossil corals offer a unique source of information on tropical climate variability throughout the late Quaternary. Several studies have used these archives to provide information about past changes in tropical SST (Beck *et al.* 1992, 1997; Guilderson *et al.* 1994; McCulloch *et al.* 1996, 1999), global ice volume (Guilderson *et al.* 1994), hydrologic balance (Klein *et al.* 1990; Gagan *et al.* 1998), and ocean mixing (Edwards *et al.* 1993). The reconstruction of past variability from fossil coral samples benefits from the diversity of known geochemical paleoenvironmental tracers and from the ability of corals to provide seasonal reconstructions of sea-surface conditions. Seasonally resolved paleoclimate data are particularly important for reconstructing ENSO, monsoon systems, and seasonal oceanic upwelling. Many fossil corals can be accurately dated (to within 1 to 3 percent of their total age) by precise measurement of their $^{230}Th/^{234}U$ ratios (Edwards *et al.* 1987). Annual density bands, or annually varying geochemical tracers, can then be used to achieve annual chronological control within individual records.

Chronologically accurate, high-resolution, multivariate data sets extracted from fossil corals offer the promise of answering questions about tropical climates that cannot be answered in any other way. New coral paleothermometers, combined with oxygen and carbon isotope ratios, are allowing us to explore the natural bounds in tropical SST's, the hydrological cycle, and ocean circulation during the last full glacial cycle. The global climate change debate has led to renewed interest in analyzing corals that grew during times when the earth was warmer than today, or warming rapidly. Although these climates of the past are not perfect analogues for a $CO_2$-warmed Earth (Crowley 1990), such records will certainly yield perspectives on processes driving the climate system (Rind 1993).

## 2.2 Tree Rings

Although corals provide substantial information on past variability in tropical marine areas, information on how this variability translates onto the continents is also required. Are the linkages between tropical ocean-atmosphere variations and extratropical climate, such as ENSO teleconnections, consistent through time? Are they sensitive to changes in background climate, external forcings, and/or extratropical systems? Do these linkages vary stochastically? Annually dated records of continental climate are required to address these questions. Tree-rings offer one of the best-documented and most extensively applied methods for annual climate reconstruction, particularly in the temperate latitudes. Subtropical tree-ring studies, particularly in monsoon regions, are expanding into regions where strong seasonality in precipitation or (in alpine areas) temperature provide the seasonal stimulus for ring formation. Low-latitude tree-ring analysis is in its infancy, but is potentially of tremendous value to ARTS.

### 2.2.1 Temperate Tree-Ring Records

Tree-rings offer a long-standing and powerful technique for the reconstruction of climate in temperate and highly seasonal locations. Trees form annual band couplets of early- and late-wood in response to seasonal stimuli. At sites where climatic aspects are limiting to tree growth, the width, density, and other aspects of these annual bands have been correlated to climate variability with remarkable success. Physiological studies confirm that tree-ring formation responds to climatic inputs, in site-specific ways depending on the limiting climate variable. For example, trees growing in the arid southwestern US are likely to be limited by water availability and thus are promising candidates for drought reconstruction; trees growing at Arctic treeline are likely limited by cold and thus provide better records of temperature.

Site selection is a critical initial component of dendroclimate reconstruction; a well-developed set of chronological and statistical procedures is employed subsequently to confirm the presence of a climate signal in a dendroclimatic study (e.g. Fritts 1976; Cook and Kariukstis 1991). First, cores from many trees are compared, using standard cross-dating techniques, to identify and eliminate age errors associated with extra or missing rings. This process ensures absolute annual dating of the final chronology, composed of many individual cores, and enhances the climatic signal over potential biological noise. Conservative standardization procedures are usually applied to remove biological influences and persistence. Climatic signals in ring-width, density, or other core-derived parameters are then evaluated using standard calibration-verification techniques, by which a statistical model is developed to relate climate to tree-ring parameters over a limited calibration interval and then tested over an independent period during which observational climate data are also available. If the model verifies (performs as well in the verification interval as it did in the calibration period), it is considered sufficiently robust for the quantitative reconstruction of climate variability. These techniques produce precisely dated and quantifiable climate reconstructions based on the statistical relationship between climate and tree growth.

Although ARTS has a tropical focus, our goals will benefit tremendously from the wealth of existing dendroclimatic reconstructions in temperate climates. These records are being compiled and incorporated into reconstructions that enable evaluation of broad patterns of change in temperature and moisture availability. We can use these to evaluate the changing influence of tropical systems on the extratropics (e.g. ENSO teleconnections or monsoon penetration) and to develop gridded fields of climate reconstructions that can be directly compared with model output for validation purposes (e.g. Cook *et al.* 1999; see Section 4 ). For example, Cole and Cook (1998) use drought reconstructions from tree-rings to evaluate the stability of teleconnected climate patterns over the past 140 years (Figure 5). In regions where teleconnections to tropical phenomena are clearly stable, we can develop reconstructions of tropical systems based on their extratropical influences. Stahle *et al.* (1998) present a reconstruction of ENSO based on drought-sensitive trees from the southwestern US, where ENSO's effects are reasonably consistent.

More direct reconstruction of tropical phenomena from tree-rings has begun, for example in Indonesia (D'Arrigo *et al.* 1994). Widespread application of this approach will require advancements in our ability to develop tropical and subtropical dendroclimate studies, a process that faces challenges described in the following section.

### 2.2.2 Tropical Tree-Rings

The extreme scarcity of long, exactly dated tree-ring chronologies from tropical forests is the fundamental problem preventing the widespread application of dendroclimatology in the tropics. The vast majority of tropical forest species do not produce anatomically distinct annual growth rings, and therefore cannot be used for paleoclimate reconstruction given our present understanding and technology. However, a small subset of tree species native to the tropics has been conclusively shown to form reliable annual growth rings, and a very few species within this subset are also long-lived and sensitive to tropical climate variability. The key challenge is to discover additional species that produce annual growth rings in as many tropical climate regions as possible.

The absence of strong temperature seasonality, and thus no winter dormant season, largely explains the lack of annual growth rings in most tropical tree species. The legendary diversity of many tropical forests is both a potential advantage and impediment to the search for species useful to dendroclimatology. Tropical rainforests are the most diverse forests on earth, and as many as 700 tree species have been counted on 10 selected hectares in Borneo, the same number of tree species native to all of North America (Wilson 1986). Finding the very few species that are suitable for dendroclimatology within this cascade of diversity can be like searching for a needle in a haystack. Effective strategies for expediting this search need to be developed. Two simple strategies can be suggested. First, in spite of the absence of strong temperature seasonality,

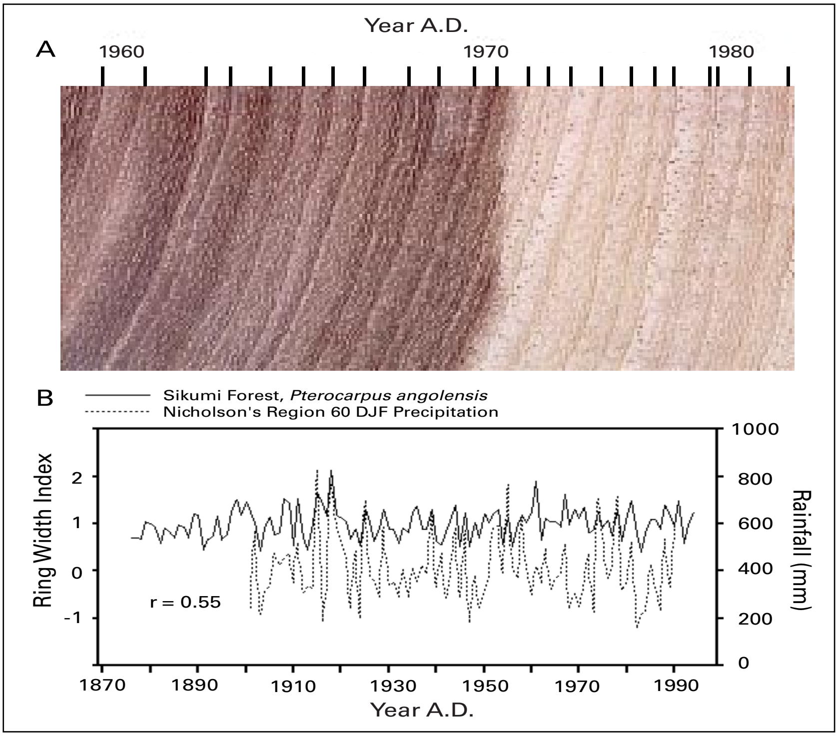


*Figure 16*
A) Photograph of annual growth bands in *Pterocarpus angolensis* from Sikumi Forest, Zimbabwe.
B) Time series comparison of *Pterocarpus angolensis* chronology from Sikumi Forest, Zimbabwe, with Sharon Nicholson's region 60 precipitation for the wet season (DJF; Nicholson 1994). Region 60 includes parts of Zimbabwe, Zambia, Botswana, and South Africa. The precipitation data extends from 1900-1990. The tree ring chronology extends from 1874 to 1994. During the common interval, the data sets correlate at r = 0.55. From Stahle *et al.* (1999).

there is dramatic seasonality of precipitation in many tropical climates, and this rainfall variability is often imprinted on the phenology of native plants. Many tree species in unimodal rainfall regimes of the tropics are deciduous and shed their entire canopy of leaves during the extended dry season. This deciduous habit is a major physiological event and does appear to be associated with the formation of distinctive anatomical structures in the xylem of certain trees, which can be used to identify the boundaries of annual growth layers. *Canthium burttii* in western Zimbabwe, for example, sheds all leaves during the extended winter dry season, and produces faint microscopic structures that identify annual growth ring boundaries. Ring width time series in *C. burttii* can be exactly synchronized among different trees (i.e., cross-dated), and are significantly correlated with total rainfall amounts during the wet season. Other tropical and subtropical species also show promise; Figure 16 shows an example of variability in ring widths of *Pterocarpus angolensis* compared with a regional precipitation index from Zimbabwe (Stahle *et al.* 1999).

A second strategy for locating tropical species with annual growth rings will be to simply expand upon previous successes, and evaluate other species within a particular botanical family (or genus) that has already produced one species suitable for tree-ring analysis. *Tectona grandis* (teak) has been known for some time to produce annual growth rings under certain tropical climate conditions. We now know that *Vitex keniensis* (Meru oak) and *Premna maxima*, which along with *T. grandis* are members of the family Verbenaceae, also produce annual growth rings under certain circumstances in Kenya. Other botanical families that include tropical species suitable for dendroclimatology include Pinaceae (e.g., *Pinus kesiya* and *P. merkusii* in Thailand; *P. montezumae* and *Abies religiosa* in Mexico), Taxodiaceae (*Taxodium mucronatum* in Mexico), and Rubiaceae (*C. burttii* in Zimbabwe).

Long, exactly dated tree-ring chronologies that are sensitive to climate variability in the tropics will provide an essential historical perspective on several important climatological questions, including the decadal variability of ENSO and its suite of climate teleconnections. One obvious priority for tropical tree-ring research will be to target chronology development within the centers of action of the Southern Oscillation, and within the tropical and extratropical regions where strong and consistent climate teleconnections to ENSO have been demonstrated in analyses of modern instrumental data. For example, a significant fraction of the interannual climate variability in the Gulf of Mexico sector may be directly linked to the zonal position of equatorial convection over the central and eastern Pacific via an enhanced and displaced low-level subtropical jet stream (Mo and Higgins 1998). Apart from the ENSO system, long tree-ring chronologies should be developed in other areas where climate teleconnections between the tropics and extratropics have been demonstrated [e.g., the Asian monsoon; and the summer precipitation teleconnection between northern Mexico and the central USA Corn Belt (Douglas and Englehart 1996)]. Also, tropical regions where climate prediction schemes have been most successful (e.g. northeastern Brazil, southern Africa) should be networked wherever possible with long tree-ring chronologies to extend the time span of proxy climate data in these key areas of opportunity for socioeconomically useful climate applications.

To facilitate development of monsoon-sensitive tree-ring chronologies from Asia, the Southeast Asian Dendrochronology meeting was convened by R. D'Arrigo and B. Buckley in Chiang Mai, Thailand in February 1998, sponsored by the U.S. National Science Foundation and PAGES. The meeting promoted collaboration between western and Asian scientists interested in the dendrochronology of southeast Asia and vicinity (see PAGES Newsletter 98–2).

## 2.3 Ice Cores

Ice cores typically provide annual resolution in their uppermost sections, through layer counting based on regular annual cycles in specific physical or chemical properties of the accumulating snow and ice. Ice cores from tropical and subtropical sites are especially useful for ARTS research as they directly monitor a hydrologic response to climate change, and they do so in a high elevation region of the atmosphere for which no long-term instrumental data exist and where other paleoclimate archives are unavailable. The number of tropical and subtropical sites where useful ice cores may be retrieved is limited, yet many of these sites are in regions with moderate ENSO responses (Figure 17). ENSO signals are apparent in a series of ice cores from the Peruvian and Bolivian Andes (Quelccaya, Huas-

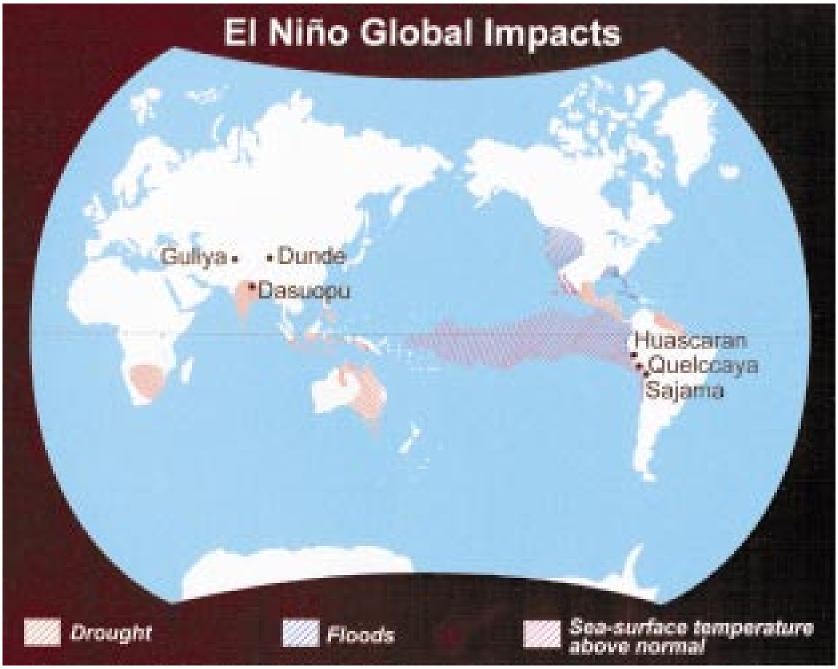


*Figure 17*
Location of high altitude subtropical ice cores in Asia and South America relative to known ENSO forcing (equatorial Pacific SST's) and terrestrial hydrologic responses (from Thompson *et al.*, 1999).

carán, Sajáma: Thompson *et al.* 1984, 1992, 1995, 1997, 1998, 1999). New results from Huascarán reveal a strong concordance between monthly zonal wind anomalies at the 500 mb level in the atmosphere over Brazil and Peru (e.g. the approximate height of the Huascarán cores) and monthly anomalies in $\delta^{18}O$ of the ice (Thompson *et al.* 1999). The result is an ENSO signal in the Huascarán ice cores that stems from changes in the near-equatorial upper tropospheric zonal winds, linked to variability in the east-to-west SST gradient across the equatorial Pacific. Similarly, drought indicators, such as increased particulate concentration and enriched $\delta^{18}O$ values are apparent during ENSO events in an ice core from Dasuopu, a Himalayan site that also records variability in the Indian Monsoon (Thompson 1999).

At most ice core sites the late Holocene sections consist of snow and firn that is relatively uncompressed by burial. The resulting annual layers are relatively thick (10 to 50 cm or more) and easily resolved, satisfying an ARTS requirement of annual chronologic precision. A particularly fruitful region for new ARTS-related ice core recovery is the Cordilleran belt of North, Central, and South America where a nearly continuous array of ice-covered plateaus and summits is available. Ice cores recovered from this transect will allow the examination of cross-equatorial symmetry in the climate system and also provide information about latitudinal gradients in greenhouse-forced warming at high altitude. The principal tracers of annual climate variability preserved in ice cores include the snow accumulation rate, $\delta^{18}O$ and $\delta D$ of the ice, and the concentrations of dust, water soluble ions ($H^+$, $Ca^{++}$, $SO4^=$, $Cl^-$, $NH4^+$) and trapped atmospheric gases ($O_2$, $CO_2$, $CH_4$). These indicators provide information about provenance of the water reaching the coring site, degree of atmospheric distillation, temperature at the precipitation site, and a time-integrated measure of atmospheric composition near the time of bubble close-off within the firn layer.

Recent observations document the urgency of recovering ice cores from high altitude sites in the tropics. Ice caps and glaciers in the region are rapidly melting and retreating, at a rate that threatens to destroy unique paleoenvironmental records (Hastenrath and Kruss 1992; Schubert 1992; Thompson *et al.* 1993). Freezing-level heights have been rising in the lower latitudes, apparently in response to decadal-scale changes in tropical sea-surface temperatures (Diaz and Graham 1996). There is also the suggestion, based on general circulation model experiments, that high elevations in the tropics may be particularly vulnerable to greenhouse-gas induced warming (Mitchell *et al.* 1990), providing additional pressure to develop a coordinated, international high altitude ice core research program. At the same time, models project that high latitudes will ultimately witness the largest changes in temperature. A transect of ice cores from high southern latitudes (Chile/Argentina) to high latitudes of the northern hemisphere (Alaska/Yukon Territory) would provide a valuable perspective on the underlying climate variability throughout the Americas, and on inter-hemispheric linkages in the timing and mechanisms of climate change at a time when greenhouse gases are rising exponentially.

## 2.4 Other Archives

### 2.4.1 Sclerosponges

Sclerosponges are slowly growing marine organisms that inhabit a wide range of water depths in the tropical ocean (Figure 18; Goreau 1959; Dustan *et al.* 1976). They secrete a dense calcareous skeleton that also contains siliceous spicules. New stable isotopic studies as well as analysis of skeletal color variation combined with radiometric dating shows signals that are probably annual in nature (Swart *et al.* 1998). Although typical growth rates of 0.2 to 0.4 mm/yr are low compared to reef-building corals, annual and sub-annual sampling is possible in some samples using micro-drilling procedures. Sclerosponges appear to precipitate carbonate in isotopic equi-

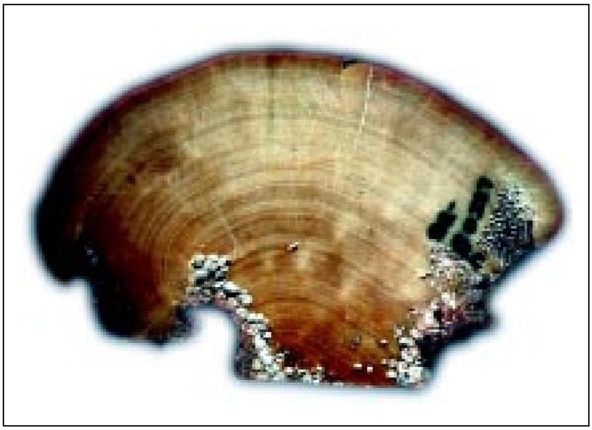


*Figure 18*
Polished slab of a section of a sclerosponge (*Ceratoporella nicholsoni*) from Lee Stocking Island in the Bahamas. The variation in banding can be clearly seen. The age of this specimen is about 400 years based on preliminary U/Th dates. The sample is 10 cm high (photograph by L. Grammer; from Swart *et al.* 1999).

librium with seawater (Druffel and Benavides 1986), an essential attribute that enhances their utility for paleoclimate studies. Sclerosponges are relative newcomers to paleoclimatic applications, however, and will require calibration and replication in a variety of environments.

Sclerosponge records 150 to 800 years long show long-term trends in $\delta^{13}C$, interpreted as the impact of fossil fuel $CO_2$ input to the atmosphere on the $\delta^{13}C$ of seawater $\Sigma CO_2$ over the past 150 years (Druffel and Benavides 1986; Bohm *et al.* 1996). Although there have been no *in situ* calibration studies of sensitivity of sclerosponge $\delta^{18}O$ to variability in water temperature, several investigators have correlated bulk skeletal $\delta^{18}O$ with mean annual water temperatures over a 6°C range and found equilibrium behavior (Swart *et al.* 1998). Long-term $\delta^{18}O$ records also appear to correlate with instrumental SST compilations and in one instance, a seasonal cycle in $\delta^{18}O$ was inferred using closely-spaced sampling (Swart *et al.* 1998). Sclerosponges will likely yield stable isotopic records similar in utility to those from corals, with the following differences: 1) Sclerosponges can provide environmental reconstructions from subsurface regions of the water column. 2) Lower growth rates will result in lower resolution records than for corals. 3) The apparent absence of a metabolic offset from equilibrium makes interpretation of sclerosponge $\delta^{18}O$ relatively straightforward.

Sclerosponges also incorporate a variety of other elemental tracers into their skeletons. Some of these, such as Sr, U, Ba, Mn, and Cd, may be useful adjunct tracers of water temperature and circulation. Other trace components such as U, Th, and $^{14}C$ are useful for radiometric dating to establish the overall age of a specimen and to verify whether visible band structures are annual in nature. This new archive can be used to augment coral records of surface ocean variability as they exist in a wider latitudinal range, and in some cases provide longer records.

### 2.4.2 Varved Sediments

Sediments are rich sources of paleoclimate data, and in fact remain an important source of information about past environmental variability over decadal to centennial scales. Annually resolved sediment layers (varves) offer potential archives of information on past interannual climate variability, but demonstrably annual layering in sediments is a rare and, in most cases, discontinuous phenomenon. Laminated (layered) sediments are common in marine sedimentary basins of the continental margin and in some lacustrine systems. Distinct sediment layers form in response to changes in the composition and flux of particles to the sediment-water interface. They are preserved either due to very rapid accumulation rates or because of the absence of post-depositional disturbance by physical or biological mechanisms. But although layering (laminae) may be common, the attribution of layer formation to discrete units of time is not. At most locations, the annual cycles of climate and primary production are sufficient to produce a resolvable annual signal, but water column and sedimentary processes obscure the annual signature. When varves are present, they are often discontinuous in time, so that although annual sedimentary layers can be documented, continuous multi-century chronologies with absolute dating are not available. Most varve records are in fact short, annually resolved chronologies that are floating with respect to absolute age assignment, similar in some ways to short annually-banded coral sections recovered from a long borehole (e.g. Hughen *et al.* 1996).

Sedimentary systems record climate events through changes in sediment accumulation rate and composition. Terrestrial sedimentary systems are typically sensitive to changes in water balance and often act to integrate precipitation minus evaporation over large areas. Both lacustrine and marine sediments may contain microfossils or inorganic precipitates that act as carriers for isotopic, chemical, and ecological information about the environment. Sediments also collect pollen and other indicators of terrestrial vegetation.

Varved sediment systems will likely play a small but important role in acquiring annually resolved records of tropical climate variability. Even without absolute time control, these systems often record links to distant phenomena at interannual time scales. For example Rodbell *et al.* (1999) use a radiocarbon-dated turbidite chronology from Lago Pallcacocha in Ecuador to infer the onset of periodic strong ENSO warm-mode events at about 5000 years BP, following a period with flood-event turbidite sedimentation decidedly different from the modern system. This result is similar to indications from molluscan assemblages in Peru and Ecuador that suggest a fundamentally different ENSO state during the middle Holocene (Sandweiss *et al.* 1996). In a tropical marine example, Hughen *et al.* (1996) have shown that variability in laminae thickness and color in anoxic sediments of the Cariaco Basin of Venezuela is nearly identical to the pattern of $\delta^{18}O$ variability in the GRIP ice core in Greenland at the scale of a single decade. This close correspondence indicates an essentially synchronous response to climate forcing, one that would seem only possible via an atmospheric mechanism, in this case, stronger trade winds during colder intervals in the North Atlantic. Black *et al.* (1998) analyze the past several centuries of varves in the Cariaco Basin and find strong correlation between regional SST and sedimentary indicators that include foraminiferal abundances and $\delta^{18}O$.

Additional promising targets for sediment records of annual variability within the tropics and subtropics include crater lakes of Central America, rift valley lakes of Africa, and shelf-slope deposits beneath the highly productive upwelling systems of California, Peru, and SW Africa.

### 2.4.3 Historical Documents

Historical archives are a proven source of valuable information concerning the long-period variation of ENSO. Bill Quinn's lifelong work made outstanding use of the Spanish colonial records from Ecuador and Peru (Quinn *et al.* 1987; also see an extensive compilation by Ortlieb 1999), but many additional archives in the western Pacific and other regions influenced by ENSO should be analyzed for references to past climatic conditions. As well, historical archives from Asia offer a potentially important source of information on monsoon strength. Japanese and Chinese records have been somewhat explored in this vein (e.g. Zhang and Crowley 1989). Additional archives from southeast and southern Asia are also likely to contain information on climate that will benefit ARTS. Quantification of these records is needed if they are to be integrated with other sources of information in ARTS.

## 2.5 Numerical Methods

Among the most critical requirements for ARTS data is that they be developed as quantitative indicators of specific aspects of climate, suitable for robust error analysis and quantitative comparison and integration with other records and with model output. Techniques common in instrumental climate dynamics research, including various spectral analysis approaches, empirical orthogonal function analysis, singular value decomposition, and others, are being increasingly applied to annual, quantitative proxy data, with results that clearly extend the instrumental perspective on recent climate variations (e.g. Mann *et al.* 1998). Workshop participants discussed several numerical approaches, with a focus on two methods that scale up single-site records to a broader context: 1) data assimilation and integration into spatial fields, and 2) modeling and model/data comparisons. These have formed the basis for continuing discussions and presentations at workshops following the Kauai meeting (e.g. the "Cross-Validation of Proxy Climate Data and the Instrumental Record" workshop in Seattle, June 1997, and the "PEP I Synthesis" meeting in Merida, Venezuela, March 1998).

Recent applications of optimal interpolation methods for the infilling of sparse instrumental data sets (Kaplan *et al.* 1998a) provide useful road maps for developing pre-instrumental fields of SST using only paleoclimate data (Evans *et al.* 1998b). These techniques are based on modern relationships among SST anomalies worldwide and use increasingly greater reliance on these relationships when *in situ* data become sparse. The techniques work well as long as the spatial relationships remain consistent. One technique for climate field reconstruction from a sparse observational network makes use of reduced-space objective analysis (Kaplan *et al.* 1998a). The procedure produces theoretical errors for the reconstructions and permits several verification procedures. As an example, these authors use tree ring chronologies from the Pacific coast of the Americas to reconstruct the SST anomaly field for the period AD 1–1990 (Kaplan *et al.* 1998b). Analysis of theoretical errors suggests that the NINO3 index estimated from this analysis may be useful for about the last three centuries, although the authors note that further proxy development and more robust error analysis are needed to constrain the reconstruction. Correlation between the tree-ring-derived NINO3 and one based on sparse historical observations (Kaplan *et al.* 1998a) reach about 0.4–0.5 in the equatorial Pacific over the period 1856–1990. These kinds of approaches provide a useful matrix into which new paleoclimate data sets can be placed as they come on-line. New annual records from ENSO centers of action, rather than teleconnected sites in the extratropics, will yield improved reconstructions of ENSO.

The second area of numerical analysis discussed at the ARTS workshop is the application of GCMs to derive greater understanding of the relationships among tropical variability, extratropical teleconnections, and global climate forcings. One application that drew particular interest was the development of a multicentury gridded SST dataset for use in driving transient simulations with atmospheric GCMs (see section 4 for more details). A realistic representation of interannual variability in transient model experiments requires that observed, rather than climatological, SSTs be used to drive the simulation. Simulations spanning the past few decades driven by observed SST fields demonstrate that atmospheric GCMs will respond in a fairly consistent manner to imposed SST anomalies. In particular, the source of this predictability appears to arise from fairly consistent responses to tropical Pacific variability. Many observed aspects of anomalous tropical atmospheric circulation can be reproduced in models driven by observed SST fields, as can certain mid-latitude anomalies. The latter arises from ENSO teleconnection patterns that appear to be reasonably consistent.

Of course, not all interannual variability, even in the tropics, can be linked to SST changes in the tropical Pacific. The Asian monsoon provides one example of a critically important tropical system with an intermittent and variable connection to ENSO. However, reconstructing global fields of SST over the past few centuries will allow for regional patterns related to SST to emerge from the simulations. Long model experiments that incorporate additional known forcings (e.g. changing $CO_2$ concentrations, solar insolation, and tropospheric and stratospheric aerosol levels) will allow us to evaluate the interactions among tropical variability and background climate changes. We can also use long paleoclimatic records of atmospheric phenomena as a testbed against which to compare GCM results. A framework project that integrates these modeling elements with a focused data collection effort is described in section 4.

# 3. ARTS Science Priorities

Paleoclimatic records of high fidelity and with annual resolution can contribute to resolving key uncertainties in our knowledge of tropical climate dynamics and impacts on two main fronts. First, continuous, seasonal-annual records over the past several centuries can tell us about the range of natural variability of tropical systems and their extratropical impacts. By understanding the natural behavior of these systems over the span of several centuries, we can assess the sensitivity of these systems to various forcings, including natural phenomena (e.g. solar and volcanic changes) and anthropogenic inputs (e.g. increasing greenhouse gas concentrations and land-use changes). We can assess the degree to which the tropics play a role generating or feeding back on observed changes (or alternatively, whether they are relatively stable). Reconstructed fields for past centuries can be compared with model output to assess model performance. Thus in addition to expanding our observational baseline, annual paleoclimate records can play important roles in climate change detection and attribution, in model evaluation, and in impact assessment.

A second front on which ARTS science can contribute important climate understanding is through the reconstruction of tropical variability during times of altered background climates (e.g. the last ice age or the mid-Holocene). These reconstructions will likely be shorter (a few decades) and not form a global picture at any given interval, due to sample recovery constraints. Continuous coral cores from ancient periods when climate means and forcings were different are not straightforward to find or sample. Often such samples are recovered fortuitously during drilling of reefs for other purposes, or in outcrop at locations where tectonic uplift has brought them above modern sea level. Nonetheless, these samples offer a unique source of climate observations bearing on the relationship of tropical variability to climate mean state. Understanding this relationship offers obvious relevance to our attempts to predict future changes in variability that may occur in a greenhouse-warmed world.

Along both of these fronts, continuous recent records and isolated “windows” deeper in the past, ARTS science can contribute to improving climate predictability. Climate prediction is accomplished through numerical modeling approaches of varying complexity. An important way for ARTS to contribute to improved climate predictability will be to produce data that is compatible with numerical models - either as interpolated fields of SST that can be used to drive atmospheric GCMs or as fields or indices of large-scale phenomena that can be compared with GCM output. ARTS participants recognized this need and identified several science priorities that will contribute to these efforts. A major outcome of the ARTS planning meeting was the integration of individual efforts to varying degrees into regional projects as outlined here; many of these projects are actively being pursued by those at the meeting.

## 3.1 Multicentury Tropical SST Fields

Recent studies have established that the tropical atmosphere responds in a fairly deterministic way to variability in tropical SST fields. Given observed SST fields, therefore, many aspects of variability in the tropical atmospheric circulation can be reproduced in models. In many cases, aspects of mid-latitude circulation can also be reproduced, as teleconnection patterns associated with ENSO are invoked. Thus, reconstructing tropical SST fields for the past few centuries will provide an important key to understanding both tropical and extratropical climate variability and may provide insight into the interaction among global natural forcings (volcanic and solar variability, as well as the generally cooler temperatures of the sixteenth–nineteenth centuries) and ENSO variability and teleconnections.

The primary source of tropical SST variability (and the main source of the atmospheric response) lies in the tropical Pacific. Reconstructing low-latitude Pacific SST's is therefore a major priority for ARTS. Participants outlined the current status of Pacific SST reconstruction efforts and defined a sampling scheme to fill critical existing holes in data coverage. The main approach for this project will be the recovery and multivariate geochemical analysis of multicentury coral cores from key Pacific sites. A major byproduct of this effort will be (through the combined use of oxygen isotopes and trace elements) the concurrent mapping of rainfall anomalies that signal atmospheric convection. Samples will also be available for radiocarbon and other geochemical analyses. Data coverage and gaps were also identified for the tropical Indian and Atlantic Oceans, which play key roles in regional climate anomalies whose connection to ENSO may be weak, variable, or nonexistent.

Top priority for new sampling is a transect of islands in the central Pacific (Figure 19), with second priority given jointly to a similar transect in the western Pacific warm pool and to filling in between meridional transects of existing samples near the equator. A third priority is identified in integrating and filling in gaps among eastern Pacific reconstructions and in Indian and Atlantic domains.

### Priority 1: Central Pacific Transect (170°E – 170°W, 20°N – 20°S)

The warmest open ocean temperatures on Earth occur in the far western tropical Pacific. The extent of the warm pool, a major source of atmospheric water vapor and latent heat, is defined by the east-west SST gradient near the dateline. Interannual expansion and contraction of the warm pool are related to ENSO, and long-term base state changes in warm pool size and position would also have a profound worldwide impact. As this transect bisects the surface Pacific warm pool and extends north and south into cooler waters, the changes of the borders of the warm pool will be used

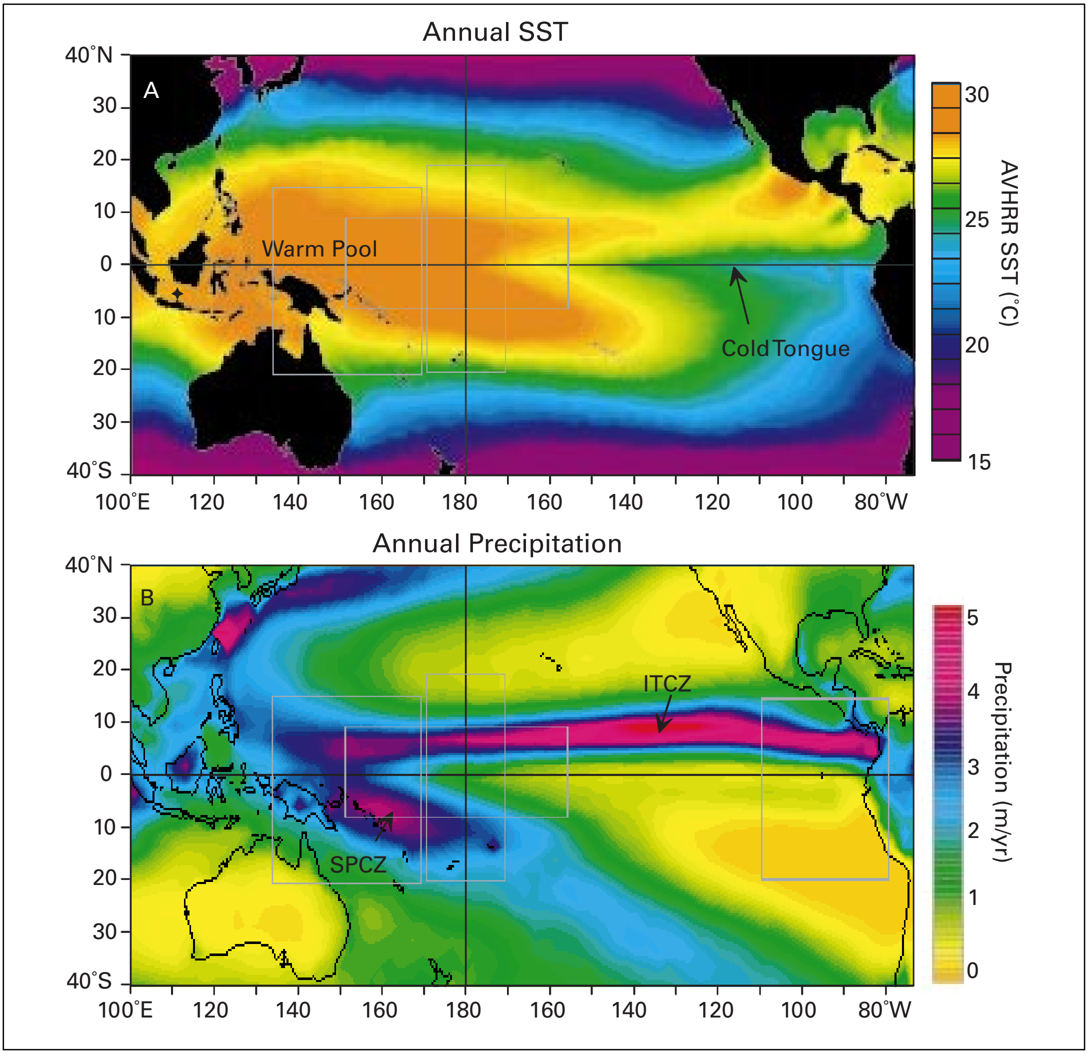


*Figure 19*
Modern average annual SST (upper) and precipitation for the tropical and subtropical Pacific basin. Gray boxes show locations of prioritized transects discussed in this section. Priority 1: Central Pacific Transect (170°E – 170°W, 20°N – 20°S). Priority 2a: Western Tropical Pacific (135°E – 170°E, 15°N – 20°S). Priority 2b: Low-latitude Zonal Transect (155°W – 150°E, 10°N – 10°S). Priority 3a: Eastern Tropical Pacific (110°W – 80°W, 15°N – 20°S).

to track the movement and the overall size of the warm pool as a function of ENSO. The frequency of sampling proposed is a site every 3° of latitude, or 14 sites for collection of coral cores. Several cores (5–10) will be taken at each site to ensure that adequate material is on hand for future analyses. A dedicated research vessel capable of supporting teams of divers, drillers, and core processors, should be used in order to maximize efficiency. Participants agreed that in this remote region of the world, with minimal infrastructure locally available, the typical small-program approach to sample recovery, using local boats and single dive teams of 2–3 people, would be at best inefficient and most likely impossible.

### Priority 2a: Western Tropical Pacific (140°E – 170°E, 15°N – 20°S)

The Western Pacific Transect has been chosen to reflect changes of the South Pacific Convergence Zone (SPCZ) and the hydrologic cycle in the warm pool of the western tropical Pacific. Reconstructions from this region should bear on past water vapor fluxes as well as regional convective rainfall. The same frequency of sampling will be needed as for the Central Pacific (every 3° of latitude). Ongoing field efforts have yielded coral collections sufficient for this level of analysis, jointly among several investigators.

### Priority 2b: Low-Latitude Zonal Transect (155°W – 150°E, 10°N – 10°S)

Sites between the meridional transects close to the equator are needed to track east-west movement of SST and rainfall gradients in the region between the warm pool and the eastern Pacific cold tongue, particularly across the NINO3 region (spanning 5°N to 5°S and 90°W to 150°W). In this remote region, with sites stretched across several thousand kilometers of ocean, coral cores and water column samples for calibration purposes will be collected using local facilities and a few short cruises on a dedicated vessel.

### Priority 3a: Eastern Tropical Pacific (110°W – 80°W, 15°N – 20°S)

In this region, ENSO-related SST anomalies reach their largest excursions and existing coral collections are beginning to provide insight into variability over the past few centuries. Ongoing efforts from Mexico to the Galápagos are producing coral-based SST reconstructions, and additional efforts are needed to integrate these records (held among several investigators) into a regional picture. An integrated record of El Niño activity in this transect should reveal the variability and mechanisms of teleconnections between Pacific climate and the Americas.

### Priority 3b: Indian Ocean Records

In the tropical Indian Ocean, many investigators are independently pursuing the development of long coral records from several sites. Networks of records are underway along the African coast, in the offshore islands of the western Indian Ocean, and along the western coast of Australia. As these and other records become available, and as further analysis is performed to assess the spatial scales of relevance of these records, we will be better able to identify gaps that require filling. For example, short records from islands in Indian waters show great promise for long reconstructions, although long cores are not yet recovered (Chakraborty and Ramesh 1992 and pers. commun.).

### Priority 3c: Atlantic Ocean/Caribbean Records

In the Atlantic and Caribbean, networks of records are also under development, particularly around Florida and in the southeastern Caribbean. Once these records are available, gaps for future sampling will be more readily identified. Many of the continental coastlines in the Atlantic provide unfavorable habitats for corals growth, due to the presence of large, sediment-laden rivers (e.g. the Amazon, Orinoco, Niger and Congo); there are fewer offshore islands remote from river influence, than in the Pacific and Indian Oceans. However, many Caribbean coastlines (continent and well as island) support healthy reefs that have not been sampled. Islands off of Africa, such as Sao Tome/Principe, also offer promise; their lack of infrastructure may require dedicated research vessel support as in the central Pacific. Workshop participants also discussed a theme for coordinating Caribbean research efforts around analysis of past patterns of water throughflow from the equatorial Atlantic to the Gulf Stream (CASE – Caribbean Salinity Experiment). The main focus of this effort is to determine the extent to which variability in the influence of equatorial waters in the Caribbean impacts the transport of heat and salt to the North Atlantic.

## 3.2 Reconstructing Ocean Circulation from $^{14}C$ in Corals - Seasons to Centuries

The distribution of radiocarbon in the ocean is a powerful tracer of ocean circulation. By measuring radiocarbon in corals and other carbonate organisms that form skeletons with annual or sub-annual banding, time series records allow for study of long-term variability in ocean circulation patterns (e.g. Druffel 1987, 1989), complementing recent water-sampling efforts. Through the collection of additional radiocarbon time series and the incorporation of these data into ocean circulation models, these techniques can be used to study variability in ocean circulation over a range of time scales.

### 3.2.1 Pacific Radiocarbon Ocean Circulation Experiment (PROcCiE)

The focus of this specific initiative is on radiocarbon variability at seasonal and interannual time scales over the last 40 years as a constraint on near-surface ocean circulation in the tropical Pacific. Through the use of coral skeletons as stationary monitors of surface radiocarbon content, this program will document how bomb-produced radiocarbon has penetrated into the surface ocean, and then has been redistributed by upwelling and the movement of surface currents. This work will require multiple radiocarbon (and stable carbon and oxygen isotope) records from corals growing across the Pacific with radiocarbon measurements made at approximately bimonthly resolution, as well as some measurements on sclerosponges and deep sea corals growing within the thermocline.

Initial analytical efforts will focus on coral samples collected during past paleoclimatic projects, with additional samples to be collected in coordination with other initiatives within ARTS. Parallel efforts will incorporate radiocarbon as a tracer into ocean circulation models, with an emphasis on sensitivity analysis and model development. The synthesis of modeling and analytical efforts will focus on the question of which circulation patterns in the tropical Pacific are consistent with the radiocarbon distribution as measured in corals, as well as all other available data from water-sampling programs such as GEOSECS, WOCE and monitoring programs such as TOGA. The results of this initiative will lead to greater understanding of seasonal and interannual variability in circulation patterns in the tropical Pacific and to improving the accuracy of ocean circulation models which will benefit a range of other programs, including those concerned with the ocean's role in the global carbon cycle.

### 3.2.2 Decadal Variability in Surface Currents through the 19th Century

Radiocarbon records from corals extending back several centuries can be used to address key questions involving decadal to centennial variations in ocean circulation. In the Pacific, such coral records can be used to determine whether there are links between the intensity and location of major ocean currents and past changes in the Southern Oscillation. Such records from the Atlantic Ocean can address whether changes in the Atlantic dipole are related to changes in water mass renewal (mode water or 18°C-water formation) in the North Atlantic. Finally, records from the Indian Ocean can resolve patterns of monsoon variation over decadal time scales. The main data requirements for these studies are annual and seasonal records of radiocarbon, $\delta^{18}O$, and $\delta^{13}C$ from multicentury cores of recent coral skeletons. Some samples are available now (Indian Ocean Transect, 72°E – 50°E, 30°S – 20°N) and others will need to be collected (Central Pacific Transect, 180°, 20°N – 20°S). Absolute time chronology (±0.5 yr) is needed in some of the records, and larger bounds can be tolerated for others (± several yr), depending on the time scale of interest.

### 3.2.3 Ancient Coral Records of Ocean Circulation

Radiocarbon measurements in corals from the Holocene and recent Pleistocene will reveal past ocean dynamics at times when the climate system may have been radically different from today. Although long coral records are rare in the fossil record, Holocene and Pleistocene samples from uplifted reefs can provide constraints on large-scale shifts in ocean circulation associated with larger climatic changes.

## 3.3 Other Records of Annual Climate Variability

### 3.3.1 Tree-Ring Data

Annually dated tree-ring chronologies that are sensitive to climate have been developed for a few unique species in the tropics, including teak (Tectona grandis) under the western center of action of the Southern Oscillation in Java. The opportunity exists to develop additional chronologies in the tropics, and priority is placed on those areas in the tropics and extratropics where tree-ring chronologies presently do not exist, and where strong and consistent tropical teleconnections have been identified in the instrumental meteorological record. In particular, this should include additional collections from land areas in the western Pacific warm pool (Maoke Mountain Range in New Guinea), the Nordeste of Brazil, Mexico, eastern subtropical South America, India, and eastern and southern Africa. Additional chronologies from Asia should help to identify monsoon variability and potentially variability in hypothesized monsoon forcings such as snow cover.

### 3.3.2 Sclerosponges

Sclerosponges are a newly identified marine proxy indicator of climate change, and additional proxy development work lies ahead. The most important issue for rapid resolution is chronology. It is unlikely that all sclerosponges have the potential to yield annual resolution. How can annual age assignments be verified? Is there potential for an absolute annual chronology throughout a record? Although the stable isotopes of oxygen and carbon are known to be useful in sclerosponges, few additional tracers have been studied and none have been calibrated. Development work on the sclerosponge archive is important as these organisms are long-lived; because they are found over a range of water depths, they can provide information about variability within the thermocline or sub-thermocline, possibly shedding light on proposed mechanisms of tropical surface water variation (e.g. Gu and Philander 1996). The current status of sclerosponges as paleoclimate indicators, and issues remaining in their application, were the focus of a recent workshop (Workshop on the Use of Sclerosponges as Proxy Climate Indicators) and are summarized by Swart *et al.* (1998).

### 3.3.3 Ice Cores and Sediments

Ice cores and marine/terrestrial sediment sequences have long been key archives of past climate variability. They will continue to provide insights on annual to 100 kyr timescales and certain of these archives are of direct interest to ARTS. Ice cores from regions that track moisture fluxes within the tropics or from areas with strong teleconnected responses to large tropical climate systems are of most obvious interest. Specific targets discussed at the ARTS workshop include extending a latitudinal transect along the Andes Mountains where this orographic feature intersects moisture derived in part from the convective centers of the western Pacific. We also discussed collecting a series of ice cores from an altitude transect to derive information about high frequency variability in lapse rate and hence moisture content of the sub-tropical atmosphere. In addition, multiple targets exist in Asia that can provide annually resolved information about past variability in the monsoon.

Most sedimentary systems lack the annual resolution required for ARTS research. However exceptions exist in some ocean margin regions and in many lakes. Workshop participants recommended exploratory research in closed-basin lake systems of the tropics, particularly in areas with large seasonal variability in precipitation that might be expected to produce annual signals in sediments. There appear to be few tropical marine sedimentary archives with annual resolution, but the success of coring in drilling in sites such as the Cariaco Basin argues for continuing the search for new targets. In addition, it is desirable for the Ocean Drilling Program to continue to devote resources to the recovery of multiple drill cores from basins containing varved sediments, such as the Santa Barbara Basin, Cariaco Basin, and the Palmer Deep.

# 4. Initial Implementation: Climate of the 19th Century

Many of the primary objectives of ARTS fall within a common time domain of the past few centuries and involve common needs and approaches. As well, important data are becoming available for the past few centuries from individual and small-group efforts, and these records need to be integrated into a broader context. ARTS participants proposed an overarching framework program, tentatively titled Climate of the Nineteenth Century (CNC), for coordinating research objectives that focus on the past two or more centuries. This project aims to develop a better assessment and understanding of climate variability over annual-century time scales, using the most recent centuries as a guide to climate patterns, processes, sensitivity and stability. In particular, the 19th century represents a period relatively unaffected by anthropogenic climate forcings, and thus a reasonable baseline for comparison both with ancient periods and with the late 20th century "greenhouse" world. The 19th century is most accessible in terms of data density and can provide a useful testbed for this approach, but a longer time frame should be considered in this project wherever possible.

This program requires the parallel development of multicentury reconstructions of tropical SST fields, atmospheric and hydrologic variables, and histories of climate forcing factors. CNC will utilize indices, gridded fields, and time series of these parameters to drive atmospheric GCMs and evaluate their results in terms of model performance, climate sensitivity, and pattern stability. The steps needed to implement CNC are detailed here; many of these steps are underway in some form already, among individual researchers and small groups. Existing data are too sparse to attempt CNC model runs at this stage, but coordination of existing data with ongoing field campaigns will, we expect, identify strategies for obtaining maximum paleo-SST information most efficiently (e.g. Evans *et al.* 1998b). We suggest that a follow-up workshop to the ARTS planning meeting be held in the near future to design an implementation plan for CNC.

Here we outline the concept of CNC in the belief that it will encourage the coordination of independent groups and the exchange of data and approaches needed to produce a global synthesis of recent climate variability and its possible causes.

## 4.1 Paleoclimatic Reconstruction:

- Use the annually resolved paleoclimatic record (including data from corals, tree rings, ice cores, and other appropriate archives) to reconstruct, with seasonal resolution, tropical SST's.
- Use the annual paleoclimatic record to reconstruct additional atmospheric, oceanic, and hydrologic aspects of climate, including precipitation, SSS, and ocean currents.
- Conduct field sampling campaigns in undersampled regions known to be important in terms of the spatial and temporal coherency of their variance and the impact of that variance on global climate (e.g. the central Pacific).
- Acquire or develop histories of climate forcing functions for the same period, including insolation, volcanic dust, and greenhouse gases.

## 4.2 Data Processing and Numerical Analysis:

- Design an optimal network of sites for SST reconstruction, based on spatial coherency of patterns in modern SST fields, including iterative analysis of how to expand the existing network in a way that yields the maximum amount of new information.
- Develop, from point reconstructions, interpolated climate fields with explicit error estimates to enable paleoclimatic data to be used to drive AGCM's and to facilitate comparisons among model output and reconstructed fields.
- Develop reconstructed indices of modern climate patterns (e.g. ENSO, the Atlantic tropical dipole, the Asian monsoon) from point reconstructions, with explicit error estimates.

## 4.3 Numerical Modelling

- Force global AGCM's with specified tropical SST's to simulate the evolution of climate since the nineteenth century, incorporating or testing additional known forcings (e.g insolation, greenhouse gases, tropospheric aerosols). Ensemble runs will determine which aspects of the climate are reproducible.
- Apply an iterative strategy to the model-data comparison and to the application of climate forcing functions, as new data become available, to converge on a most-likely global picture of the evolution of climate over the past centuries.

## 4.4 Evaluation and Synthesis

- Compare model results with reconstructions of atmospheric and hydrologic variables to assess both model performance and the consistency of the paleodata.
- Use model results to indicate where additional field sampling for paleoclimate reconstruction would prove most valuable.
- Assess the patterns, processes, sensitivity and stability of climate with respect to external forcings and internal variability over the past two or more centuries.

# 5. Future ARTS Research: Needs and Recommendations

- The strength of ARTS research lies in the intersection among climate scientists with numerical, instrumental, and paleoclimatic perspectives. This meeting generated significant interaction and motivated several subsequent workshops and group interactions, including at least one multidisciplinary group proposal (for central Pacific coral sampling). Such efforts work best when conceived and developed with full participation of scientists from different backgrounds throughout the process. *The interdisciplinary nature of such interactions is a strength that deserves encouragement through support for truly multidisciplinary programs and focused cross-disciplinary working group meetings to address specific ARTS goals.*
- The contribution of ARTS in the reconstruction of ocean variability will lie in the development of multicentury, replicated, high-resolution geochemical records. Production of these time series requires unprecedented analytical throughput. *Expanded availability of instrumentation, and continued support for those facilities (including personnel), is essential for ARTS coral investigators to contribute along the lines described in this report.*
- Although coral fieldwork has typically relied upon locally available logistical support (e.g. local fishing boats), we find such infrastructure increasingly and even wholly inadequate in the remote regions where certain climate signals are strongest (e.g. the central Pacific). Where available, such crafts are often unsuitable for reasons that include safety, efficiency, and basic capabilities; some target islands are uninhabited and offer no local support of any kind. Yet support for a dedicated research vessel for live-coral coring has been difficult to obtain, as it falls outside the usual uses of, e.g., a UNOLS vessel. *Coral drilling field programs will be more successful if dedicated research vessels are supported*
- Support for new drilling technologies and platforms is needed to recover long sections of "fossil" corals for the purpose of paleoclimate variability reconstruction, particularly related to the Holocene initiation/redevelopment of ENSO and tropical variability during periods of altered boundary conditions. The need for such new drilling capabilities has also been recognized by the Ocean Drilling Program and system de-

velopment is in its early stages. *We fully support the development and testing of new drilling technologies required to recover fossil corals in water depths beyond the range of conventional live coral drilling.*

- ARTS priorities extend well beyond coral reconstructions of surface ocean conditions; we require records from land and from the deeper ocean (thermocline) to understand the mechanisms, the teleconnections, and the impacts of tropical variability. *A strong focus needs to be placed on developing new paleoclimatic archives from poorly sampled systems, including tropical and subtropical tree-rings, thermocline-dwelling sclerosponges and non-reef-building corals.*
- ARTS research requires that individual records be made public in a timely way, to promote the synthetic activities we have described. These activities also require careful documentation of uncertainties and errors associated with reconstructions and model simulations. *We encourage the submission of all paleoclimate datasets, derived indices, and model output that are documented in the scientific literature, along with detailed metadata, to the World Data Center-A for Paleoclimatology.*

# 6. References Cited

Allan, R., and R. D'Arrigo, 1999, Persistent ENSO sequences: how unusual was the 1990–1995 El Niño?, The Holocene, in press.

Allan, R., J. Lindesay, and D. Parker, 1997, El Niño Southern Oscillation and climatic variability, CSIRO, Australia, 405 pp.

Alley, R.B., P.A. Mayewski, T. Sowers, M. Stuiver, K.C. Taylor, and P.U. Clark, 1997, Holocene climate instability: a prominent, widespread event 8,200 years ago, Geology, 25, 483–486.

Alibert, C. and M.T. McCulloch, 1997, Strontium/calcium ratios in modern Porites corals from the Great Barrier Reef as a proxy for sea-surface temperature: Calibration of the thermometer and monitoring of ENSO, Paleoceanography, 12, 345–363.

Balmaseda, M.A., M.K. Davey, and D.L.T. Anderson, 1995, Decadal and seasonal dependence of ENSO prediction skill, J. Climate, 8, 2705–2715.

Barnes, D.J., and J.M. Lough, 1993, On the nature and causes of density banding in massive coral skeletons, J. Exp. Mar. Biol. Ecol., 167, 91–108.

Barnett, T.P., N. Graham, M.A. Cane, S.E. Zebiak, S. Dolan, J. O'Brien, and D. Legler, 1988, On the prediction of the El Niño of 1986–87, Science, 241, 192–196.

Barsugli J., P. Sardeshmukh, and S. Zhang, 1996, Identifying the most sensitive areas of tropical SST forcing for midlatitude seasonal prediction, 7th Conference on Climate Variations, Long Beach, CA, 2–7 Feb 1996.

Beck, J.W., R.L. Edwards, E. Ito, F.W. Taylor, J. Recy, F. Rougerie, P. Joannot, and C. Henin, 1992, Sea surface temperature from coral skeletal strontium/calcium ratios, Science, 257, 644–647.

Beck, J.W., J. Recy, F. Taylor, R.L. Edwards, and G. Cabioch, 1997, Abrupt changes in early Holocene tropical sea surface temperature derived from coral records, Nature, 385, 705–707.

Bitz, C.C., and D.S. Battisti, 1999, Interannual to decadal variability in climate and the glacier mass balance in Washington, Western Canada, and Alaska, J. Climate, in press.

Black, D.E., L.C. Peterson, M. Kashgarian, J.T. Overpeck, and K.A. Hughen, 1996, Variability in the ITCZ and trade winds over the southern Caribbean for the last 800 years and during the Bolling-Allerod/Younger Dryas transition, EOS: Trans. Am. Geophys. Union 79, F309.

Bohm, F., M.M. Joachimski, H. Lehnert, G. Morgenroth, W. Kretschmer, J. Vacelet, and W.C. Dullo, 1996, Carbon isotope records from extant Caribbean and South Pacific sponges: Evolution of $\delta^{13}C$ in surface water DIC., Earth Planet. Sci. Lett., 139, 291–303.

Boiseau M., A. Juillet-Leclerc, P. Yiou, B. Salvat, P. Isdale, M. Guillaume, 1998, Atmospheric and oceanic evidences of El Niño-Southern Oscillation events in the south-central Pacific Ocean from coral stable isotopic records over the last 137 years, Paleoceanography 13, 671–686.

Bradley, R.S. and P.D. Jones, 1993, 'Little Ice Age' summary temperature variations: their nature and relevance to recent global warming trends, The Holocene, 3, 367–376.

Cadet, D., 1979, Meteorology of the Indian summer monsoon, Nature, 279, 761–767.

Cadet, D. and G. Reverdin, 1981, Water vapour transport over the Indian Ocean during summer 1975, Tellus, 33, 476–487.

Cane, M.A., A.C. Clement, A. Kaplan, Y. Kushnir, R. Murtugudde, D. Pozdnyakov, R. Seager, and S. Zebiak, 1997, Twentieth-century sea surface temperature trends, Science, 275, 957–960.

Carriquiry, J.D., M.J. Risk and H.P. Schwarcz, 1994, Stable isotope geochemistry of corals from Costa Rica as proxy indicator of El Niño (ENSO), Geochim. Cosmochim. Acta, 58, 335–351.

Carriquiry, J.D., M.J. Risk, and H.P. Schwarcz, 1988, Timing and temperature record from stable isotopes of the 1982–1983 El Niño warming event in eastern Pacific corals, Palaios, 3, 359–364.

Carriquiry J.D., J.F. Soto-Castro, C.D. Charles, and M. Moore, 1998, Stable isotope records and trace element records in coral growth bands as tracers of ENSO activity in the Mexican Pacific, Proc. Am. Quat. Assoc., 12–13.

Chakraborty, S., and R. Ramesh, 1992, Climatic significance of $\delta^{18}O$ and $\delta^{13}C$ variations in a banded coral (Porites) from Kavaratti, Lakshadweep Islands, In: Desai, B.N. (ed.), Oceanography of the Indian Ocean, Oxford & IBH, New Delhi, India, 473–478.

Chang, P., L. Ji, and H. Li, 1997, A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions, Nature, 385, 516–518.

Chang, P., L. Ji, H. Li, C. Penland, and L. Matrosova, 1998, Prediction of tropical Atlantic sea surface temperature, Geophys. Res. Lett., 25, 1193–1196.

Charles, C.D., D.E. Hunter, and R.G. Fairbanks, 1997, Interaction between the ENSO and the Asian monsoon in a coral record of tropical climate. Science, 277, 925–928.

Chen, D., S.E. Zebiak, A.J. Busalacchi, and M.A. Cane, 1995, An improved procedure for El Niño forecasting: Implications for predictability, Science, 269, 1699–1702.

CLIMAP Members, 1976, The surface of the ice-age earth, Science, 191, 1131–1137.

Cole, J.E., 1992, Interannual-decadal variability in tropical climate systems: stable isotope records and general circulation model experiments, Ph.D. thesis, Columbia Univ., 302 pp.

Cole, J.E., 1996, Coral records of climate change: Understanding past variability in the tropical ocean-atmosphere, in Climatic variations and forcing mechanisms over the last 2000 Years, P.D. Jones, R.S. Bradley, and J. Jouzel. (editors), Springer-Verlag, New York, 331–354.

Cole, J.E., 1998, The changing pulse of warm pool variability during the past 220 years: New oxygen isotopic results from a Gulf of Papua coral, EOS: Trans. Am. Geophys. Union, 79, F493.

Cole, J.E., and R.G. Fairbanks, 1990, The Southern Oscillation recorded in the oxygen isotopes of corals from Tarawa Atoll, Paleoceanography, 5, 669–683.

Cole, J.E., and E.R. Cook, 1998, The changing relationship between ENSO variability and moisture balance in the continental United States, Geophys. Res. Lett., 25 , 4529–4532.

Cole, J.E., R.G. Fairbanks and G.T. Shen, 1993, Recent variability in the Southern Oscillation: Isotopic results from a Tarawa Atoll coral, Science, 260, 1790–1793.

Cook, E.R., D.M. Meko, D.W. Stahle, and M.K. Cleaveland, 1999, Drought reconstructions for the continental United States, J. Climate, 12, 1145–1162.

Cook, E.R., 1995, Temperature histories from tree-rings and corals, Climate Dynamics, 11, 211–222.

Cook, E.R., and L. Kairiukstis, 1991, Methods of dendrochronology: applications in the environmental sciences, Kluwer, Dordrecht, 408 pp.

Crowley, T.J., 1990, Are there any satisfactory geologic analogues for a future greenhouse warming?, J. Climate, 3, 1282–1292.

Crowley, T.J., T.M. Quinn, and F.W. Taylor, 1997, Evidence for a volcanic cooling signal in a 335 year coral record from New Caledonia, Paleoceanography, 12, 633–639.

Curtis, S., and S. Hastenrath, 1995, Forcing of anomalous sea surface temperature evolution in the tropical Atlantic during Pacific warm events, J. Geophys. Res., 100, 15,835–15,847.

D'Arrigo, R.D., G.C. Jacoby, and P.J. Krusic, 1994, Progress in dendroclimatic studies in Indonesia, Terr. Atmos. Oceanic Sci., 5, 349–363.

de Villiers, S., G.T. Shen, and B.K. Nelson, 1994, The Sr/Ca-temperature relationship in coralline aragonite: Influence of variability in $(Sr/Ca)_{seawater}$ and skeletal growth parameters, Geochim. Cosmochim. Acta, 58, 197–208.

de Villiers, S., B.K. Nelson, and A.R. Chivas, 1995, Biological controls on coral Sr/Ca and $\delta^{18}O$ reconstructions of sea surface temperatures, Science, 269, 1247–1249.

Diaz, H.F. and N.E. Graham, 1996, Recent changes in tropical freezing heights and the role of sea surface temperature, Nature, 383, 152–155.

Dodge, R.E., and J. Thomson, 1974, The natural radiochemical and growth records in contemporary hermatypic corals from the Atlantic and Caribbean, Earth Planet. Sci. Lett., 23, 313–322.

Dodge, R.E., A.M. Szmant, R. Garcia, P.K. Swart, A. Forester, and J.J. Leder, 1994, Skeletal structural basis of density banding in the reef coral *Montastrea annularis*, Proc. 7th Coral Reef Symposium, 186–195.

Douglas, A.V. and P.J. Englehart, 1996, Variability of the summer monsoon in Mexico and relationships with drought in the United States, Proc. 21st Annual Climate Diagnostics Workshop, Huntsville, AL, Climate Prediction Center, 296–299.

Druffel, E.M., 1981, Radiocarbon in annual coral rings from the eastern tropical Pacific Ocean, Geophys. Res. Lett., 8, 59–62.

Druffel E.R.M., 1982, Banded corals: Changes in oceanic $^{14}C$ levels during the Little Ice Age, Science, 218, 13–19.

Druffel, E.R.M., 1985, Detection of El Niño and decade time scale variations of sea surface temperature from banded coral records: implications for the carbon dioxide cycle, in The Carbon Cycle and Atmospheric $CO_2$: Natural Variations Archean to Present, W.S. Broecker and E.T. Sundquist (editors), American Geophysical Union, Washington DC, 111–122.

Druffel, E.R.M., 1987, Bomb radiocarbon in the Pacific: annual and seasonal timescale variations, J. Mar. Res., 45, 667–698.

Druffel, E.R.M., 1989, Decade time scale variability of ventilation in the north Atlantic: high-precision measurements of bomb radiocarbon in banded corals, J. Geophys. Res., 94, 3271–3285.

Druffel, E.R.M., 1997, Pulses of rapid ventilation in the North Atlantic surface ocean during the past century, Science, 275, 1454–1457.

Druffel, E.R.M., and L. Benavides, 1986, Input of excess $CO_2$ to the surface ocean based on $^{13}C/^{12}C$ ratios in a banded sclerosponge, Nature, 321, 58–61.

Druffel, E.R.M., and S. Griffin, 1993, Large variations of surface ocean radiocarbon: evidence of circulation changes in the southwestern Pacific, J. Geophys. Res., 98, 20,249–20,259.

Druffel, E R.M., R.B. Dunbar, G.M. Wellington, and S.A. Minnis, 1990, Reef-building corals and identification of warming episodes, in Global Ecological Consequences of the 1982–83 El Niño-Southern Oscillation, P.W. Glynn (editor), Elsevier, New York, 233–254.

Dunbar, R.B., and G.M. Wellington, 1981, Stable isotopes in a branching coral monitor seasonal temperature variation, Nature, 293, 453–455.

Dunbar, R.B., and J.E. Cole, 1993, Coral Records of Ocean-Atmosphere Variability, NOAA Climate and Global Change Program Special Report #10, 38 pp..

Dunbar, R.B., G.M. Wellington, M.W. Colgan, and P.W. Glynn, 1994, Eastern Pacific sea surface temperature since 1600 AD: the $\delta^{18}O$ record of climate variability in Galapagos corals, Paleoceanography, 9, 291–316.

Dunbar, R.B., B.K. Linsley, and G.M. Wellington, 1996, Eastern Pacific corals monitor El Niño/Southern Oscillation, precipitation, and sea surface temperature variability over the past three centuries, in Climatic fluctuations and forcing mechanisms of the last 2000 years, P.D. Jones, R.S. Bradley, and J. Jouzel (editors), Springer-Verlag, Berlin, 375–407.

Dustan, P., W. Jaap, and J. Halas, 1976, The distribution of the class Sclerospongia, Lethaia, 9, 419–420.

Ebbesmeyer, C.C., D.R. Cayan, D.R. McClain, F.H. Nichols, D.H. Peterson and K.T. Redmond, 1991, 1976 step in Pacific climate: Forty environmental changes between 1968–1975 and 1977–1984, In: Proc. 7th Annual Pacific Climate (PACLIM) Workshop, April, 1990, California Department of Water Resources, J.L. Betancourt and V.L. Tharp (editors), Interagency Ecological Study Program Technical Report 26, 115–126.

Edwards, R.L., Chen, J.H. and Wasserburg, G.J., 1987, $^{238}U$-$^{234}Th$-$^{230}Th$-$^{232}Th$ systematics and the precise measurement of time over the past 500,000 years, Earth Planet. Sci. Lett., 81, 175–192.

Edwards, R.L., J.W. Beck, G.S. Burr, D.J. Donahue, J.M.A. Chappell, A.L. Bloom, E.R.M. Druffel, and F.W. Taylor, 1993, A large drop in atmospheric $^{14}C/^{12}C$ and reduced melting in the Younger Dryas, documented with $^{230}Th$ ages of coral, Science, 260, 962–968.

Enfield, D.B., and D.A. Mayer, 1997, Tropical Atlantic sea surface temperature variability and its relation to El Nino-Southern Oscillation, J. Geophys. Res., 102, 929–945.

Evans, M., R.G. Fairbanks, and J.L. Rubenstone, 1998a, A proxy index of ENSO teleconnections, Nature, 394, 732–733.

Evans, M.N., A. Kaplan, M.A. Cane, 1998b, Optimal sites for coral-based reconstruction of global sea surface temperature, Paleoceanography, 13, 502–516.

Evans, M. N., R.G. Fairbanks, and J.L. Rubenstone, 1999, The thermal oceanographic signal of ENSO reconstructed from a Kiritimati Island coral, J. Geophys. Res., in press.

Fairbanks, R.G., and R.E. Dodge, 1979, Annual periodicity of the O-18/O-16 and C-13/C-12 ratios in the coral *Montastrea annularis*, Geochim. Cosmochim. Acta, 43, 1009–1020.

Fairbanks, R.G., M.N. Evans, J.L. Rubenstone, R. A. Mortlock, K. Broad, M. D. Moore, and C. D. Charles, 1997, Evaluating climate indices and their geochemical proxies measured in corals, Coral Reefs, 16, S93-S100.

Felis T., J. Pätzold, Y. Loya, and G. Wefer, 1998, Vertical water mass mixing and plankton blooms recorded in skeletal stable carbon isotopes of a Red Sea coral, J. Geophys. Res., 103, 30,731–30,740.

Fisher, D.A., R.M. Koemer, and N. Reeh, 1995, Holocene climatic records from Agassiz ice cap, Ellesmere Island, NWT, Canada, The Holocene, 5, 19–24.

Flohn, H., A. Kapala, H.-R. Knoche, and H. Machel, 1990, Recent changes of the tropical water and energy budget and of midlatitude circulations. Climate Dynamics, 4, 237–252.

Folland, C.K., T.N. Palmer, and D.E. Parker, 1986, Sahel rainfall and worldwide sea temperatures, 1900–85, Nature, 320, 602–607.

Fritts, H.C. 1976, Tree Rings and Climate, Academic Press, London, 567 pp.

Gagan, M.K., L.K. Ayliffe, D. Hopley, J.A. Cali, G.E. Mortimer, J. Chappell, M.T. McCulloch, and M.J. Head, 1998, Temperature and surface-ocean water balance of the mid-Holocene tropical western Pacific, Science, 279, 1014–1018.

Gagan, M.K., A.R. Chivas, and P.J. Isdale, 1994, High-resolution isotopic records from corals using ocean temperature and mass spawning chronometers, Earth Planet. Sci. Lett., 121, 549–558.

Gagan, M.K., A.R. Chivas, and P.J. Isdale, 1996, Timing coral-based climatic histories using $^{13}$C enrichments driven by sychronized spawning. Geology, 24, 1009–1012.

Gaillardet, J., and C.J. Allegre, 1995, Boron isotopic compositions of corals: seawater or diagenesis record?, Earth Planet. Sci. Lett., 136, 665–676.

Gershunov, A., T.P. Barnett, 1998, Interdecadal modulation of ENSO teleconnections, Bull. Am. Met. Soc. 79, 2715–2726.

Goreau, T.F., 1959, The ecology of Jamaican reefs. I. Species composition and zonation, Ecology, 40, 67–90.

Graham, N.E., 1994, Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: observations and model results, Climate Dynamics, 10, 135–162.

Graham, N.E., 1995, Simulation of recent global temperature trends, Science, 267, 686–671.

Grottoli-Everett, A. and G. Wellington, 1999, Effect of light and zooplankton on skeletal $\delta^{13}$C values in the eastern Pacific corals Pavona clavus and Pavona gigantea, Coral Reefs, in press.

Gu, D., and S.G.H. Philander, 1997, Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics, Science, 275, 805–807.

Guilderson, T.P., and D.P. Schrag, 1998, Abrupt shift in subsurface temperatures in the tropical Pacific associated with changes in El Niño, Science, 281, 240–243.

Guilderson, T.P. and D. P. Schrag, 1999, Reliability of coral records from the western Pacific warm pool, Paleoceanography, in press.

Guilderson, T.P., R.G. Fairbanks, and J.L. Rubenstone, 1994, Tropical temperature variations since 20,000 years ago: Modulating interhemispheric climate change, Science, 263, 663–665.

Guilderson, T.P., D.P. Schrag, M. Kashgarian, and J. Southon, 1998, Radiocarbon variability in the western equatorial Pacific inferred from a high-resolution coral record from Nauru Island, J. Geophys. Res., 103, 24,641–24,650.

Guzman, H., and A.W. Tudhope, 1998, Seasonal variation in skeletal extension rate and stable isotopic ($^{13}$C/$^{12}$C and $^{18}$O/$^{16}$O) composition in response to several environmental variables in the Caribbean reef coral *Siderastrea siderea*, Mar. Ecol. Prog. Ser., 166, 109–121.

Hart, S.R., and A.L. Cohen, 1996, An ion probe study of annual cycles of Sr/Ca and other trace elements in corals, Geochim. Cosmochim. Acta, 60, 3075–3084.

Hastenrath, S., 1990, Decadal-scale changes of the circulation in the tropical Atlantic sector associated with Sahel drought, Int. J. Climatology, 10, 459–472.

Hastenrath, S., and L. Heller, 1977, Dynamics of climatic hazards in northeast Brazil, Quart. J. Royal Met. Soc., 103, 77–92.

Hastenrath, S., and P.J. Lamb, 1983, Some aspects of circulation and climate over the eastern equatorial Atlantic, Mon. Weather Rev., 106, 1280–1287.

Hastenrath, S., and P.D. Kruss, 1992, The dramatic retreat of Mount Kenya's glaciers 1963–87: greenhouse forcing, Ann. Glaciol., 16, 127–133.

Hastenrath, S., and L. Greischar, 1993, Circulation mechanisms related to Northeast Brazil rainfall anomalies, J. Geophys. Res., 98, 5093–5102.

Hastenrath, S., L. Castro, and P. Aceituno, 1987, The Southern Oscillation in the tropical Atlantic Sector, Contrib. Atmos. Physics, 60, 447–463.

Hastenrath, S., A. Nicklis, and L. Greischar, 1993, Atmospheric-hydrospheric mechanisms of climate anomalies in the western equatorial Indian Ocean, J. Geophys. Res., 98, 20,219–20,235.

Hemming, N.G., R.J. Reeder, and G.N. Hanson, 1995, Mineral-fluid and isotopic fractionation of boron in synthetic calcium carbonate, Geochim. Cosmochim. Acta, 59, 371–379.

Houghton, R.W., and Y. Tourre, 1992, Characteristics of low-frequency sea surface temperature fluctuations in the tropical Atlantic, J. Climate, 5, 765–771.

Hughen, K.A., J.T. Overpeck, L.C. Peterson, and S. Trumbore, 1996, Abrupt deglacial climatic change in the tropical Atlantic, Nature, 380, 51–54.

Isdale, P., 1984, Fluorescent bands in massive corals record centuries of coastal rainfall, Nature, 310, 578–9.

Isdale, P.J., B.J. Stewart, and J.M. Lough, 1998, Palaeohydrological variation in a tropical river catchment: a reconstruction using fluorescent bands in corals of the Great Barrier Reef, Australia, The Holocene, 8, 1–8.

Kaplan, A., M.A. Cane, Y. Kushnir, A.C. Clement, M.B. Blumenthal, and B. Rajagopalan, 1998a, Analyses of global sea surface temperature 1856–1991, J. Geophy. Res., 103, 18,567–18,589.

Kaplan, A., M. Evans, M.A. Cane, and R. Villalba, 1998b, Globality and optimality in SST field reconstructions from tree rings: ENSO and more, extended abstract for Pole-Equator-Pole Paleoclimate of Americas (PEP1) Conference, Merida, Venezuela, March 16–20, 1998, on line at http://rainbow.ldeo.columbia.edu/~alexeyk/work/.

Kawamura, R., 1994, A rotated EOF analysis of global sea surface temperature variability with interannual and interdecadal scales, J. Phys. Oceanog., 24, 707–715.

Keigwin, L.D., 1996, The little ice age and medieval warm periods in the Sargasso Sea, Science, 274, 1504–1508.

Klein, R., Y. Loya, G. Svistzman, P.J. Isdale, and M. Susic, 1990, Seasonal rainfall in the Sinai Desert during the late Quaternary inferred from fluorescent bands in fossil corals, Nature, 345, 145–147.

Knutson D.W., R.W. Buddemeier, and S.V. Smith, 1972, Coral chronologies: seasonal growth bands in reef corals, Science, 177, 270–272.

Kumar, A., and M.P. Hoerling, 1997, Interpretations and implications of the observed inter-El Niño variability, J. Climate, 10, 83–91.

Lamb, H.F., F. Gasse, A. Benkaddour, N. El Hamouti, S. van der Kaars, W.T. Perkins, N.J. Pearce, and C.N. Roberts, 1995, Relation between century-scale Holocene intervals in tropical and temperate zones, Nature, 373, 134–137.

Lamb, P.J., and R.A. Peppler, 1992, Further case studies of tropical Atlantic surface atmospheric and oceanic patterns associated with sub-Saharan drought, J. Climate, 5, 476–488.

Latif, M., D. Anderson, T. Barnett, M. Cane, R. Kleeman, A. Leetmaa, J. O'Brien, A. Rosati, E. Schneider, 1998, A review of the predictability and prediction of ENSO, J. Geophys. Res., 103, 14,375–14,394.

Lea, D.W., E.A. Boyle, and G.T. Shen, 1989, Coralline barium records temporal variability in equatorial Pacific upwelling, Nature, 340, 373–376.

Leder, J.J., P.K. Swart, A. Szmant, and R.E. Dodge, 1996, The origin of variations in the isotopic record of scleractinian corals: I. Oxygen, Geochim. Cosmochim. Acta, 60, 2857–2870.

Linn, L.J., M.J. Delaney, and E.R.M. Druffel, 1990, Trace metals in contemporary and seventeenth-century Galápagos coral: records of seasonal and annual variations, Geochim. Cosmochim. Acta, 54, 387–394.

Linsley, B.K., R.B. Dunbar, G.M. Wellington, and D.A. Mucciarone, 1994, A coral-based reconstruction of Intertropical Convergence Zone variability over Central America since 1707, J. Geophys. Res., 99, 9977–9994.

Linsley, B.K., R.G. Messier, and R.B. Dunbar, 1999, Assessing between colony oxygen isotope variability in the coral *Porites lobata* at Clipperton Atoll, Coral Reefs, in press.

Lough J.M., D. J. Barnes, and R.B. Taylor, 1996, The potential of massive corals for the study of high-resolution climate variation of the past millennium, in Climatic fluctuations and forcing mechanisms of the last 2000 years, Jones, P.D., R.S. Bradley, and J. Jouzel (editors), Springer-Verlag, Berlin, 355–372.

Mann, M.E., R.S. Bradley, and M.K. Hughes, 1998, Global-scale temperature patterns and climate forcing over the past six centuries, Nature, 392, 779–787.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997, A Pacific interdecadal climate oscillation with impacts on salmon production, Bull. Amer. Meteorol. Soc., 78, 1069–1079.

McConnaughey, T.A., 1989, C-13 and O-18 isotopic disequilibria in biological carbonates: I. Patterns, Geochim. Cosmochim. Acta, 53, 151–162.

McCulloch, M.T., M.K. Gagan, G.E. Mortimer, A.R. Chivas, and P.J. Isdale, 1994, A high resolution Sr/Ca and $\delta^{18}$O coral record from the Great Barrier Reef, Australia, and the 1982–1983 El Niño, Geochim. Cosmochim. Acta., 58, 2747–2754.

McCulloch, M.T., G. Mortimer, T. Esat, L. Xianhua, B. Pillans, and J. Chappell, 1996, High resolution windows into early Holocene climate: Sr/Ca coral records from the Huon Peninsula, Earth Planet. Sci. Lett., 138, 169–178.

McCulloch, M.T., A. W. Tudhope, T. M. Esat, G.E. Mortimer, J. Chappell, B. Pillans, A. R. Chivas, and A. Omura, 1999, Coral record of equatorial sea-surface temperatures during the penultimate deglaciation at Huon Peninsula, Science, 283, 202–204.

McGlone, M.S., A.P. Kershaw, and V. Markgraf, 1992, El Niño/Southern Oscillation and climatic variability in Australasian and South American paleoenvironmental records, In: El Niño: Historical and paleoclimatic aspects of the Southern Oscillation, H.F. Diaz and V. Markgraf (editors), Cambridge University Press, Cambridge, 435–462.

Meehl, G.A., and G.W. Branstator, 1992, Coupled climate model simulation of El Niño/Southern Oscillation: implications for paleoclimate, in El Niño: Historical and paleoclimatic aspects of the Southern Oscillation, H.F. Diaz and V. Markgraf (editors), Cambridge University Press, Cambridge, 69–91.

Min, R.G., R.L. Edwards, F.W. Taylor, J. Recy, C.D. Gallup, and J.W. Beck, 1995, Annual cycles of U/Ca in coral skeletons and U/Ca thermometry, Geochim. Cosmochim. Acta, 59, 2025–2042.

Mitchell, J.F.B., S. Manabe, V. Meleshko and T. Tokioka, 1990, Equilibrium climate change - and its implications for the future, in Climate Change: The IPCC Assessment, J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (editors) Cambridge University Press, Cambridge, 131–172.

Mitsuguchi, T., E. Matsumoto, O. Abe, T. Uchida, T. and P.J. Isdale, 1996, Mg/Ca thermometry in coral skeletons, Science, 274, 961–963.

Mo, K.C., and R.W. Higgins, 1998. Tropical convection and precipitation regimes in the western United States, J. Climate, 11, 2404–2423.

Moore, M.D., 1995, Proxy records of the Indonesian Low and the El Niño-Southern Oscillation from stable isotope measurements of reef corals, unpublished Ph.D. dissertation, University of California at Berkeley.

Moura, A., and J. Shukla, 1981, On the dynamics of droughts in northeast Brazil: observations, theory, and numerical experiments with a general circulation model, J. Atmos. Sci., 38, 2653–2675.

Nicholson, S., 1994, Recent rainfall fluctuations in Africa and their relationships to past conditions over the continent, The Holocene, 4, 121–131

Nozaki, Y., D.M. Rye, K.K. Turekian, and R.E. Dodge, 1978, A 200 year record of carbon-13 and carbon-14 variations in a Bermuda coral, Geophys. Res. Lett., 5, 825–828.

O'Brien, S.R., P.A. Mayewski, L.D. Meeker, D.A. Meese, M.S. Twickler, and S.I. Whitlow, 1995, Complexity of Holocene climate as reconstructed from a Greenland ice core, Science, 270, 1962–1964.

Ortlieb, L., 1999, The documentary historical record of El Niño events in Peru: An update of the Quinn record (sixteenth through nineteenth centuries), in El Niño and the Southern Oscillation: Multiscale Variability, Global and Regional Impacts, H.F. Diaz and V. Markgraf (editors) Cambridge University Press, in press.

Overpeck, J.T., 1996, Warm climate surprises, Science, 271, 1820–1821.

Parker, D.E., M. Jackson, and E.B. Horton, 1995, The GISST2.2 sea surface temperature and sea-ice climatology, Technical report, CRTN 63, Hadley Centre for Climate Prediction and Research, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SY, 35 pp.

Pätzold, J., 1984, Growth rhythms recorded in stable isotopes and density bands in the reef coral *Porites lobata* (Cebu, Philippines), Coral Reefs, 3, 87–90.

Quinn, T.M., T.J. Crowley, F.W. Taylor, C. Henin, P. Joannot, and Y. Join, 1998, A multi-century stable isotope record from a New Caledonia coral: Interannual and decadal sea-surface temperature variability in the southwest Pacific since 1657 AD, Paleoceanography, 13, 412–426.

Quinn, T.M., F. Taylor, and T. Crowley, 1993, A 173 year stable isotope records from a tropical South Pacific coral, Quat. Sci. Rev., 12, 407–418.

Quinn, W.H., V.T. Neal, and S.E. Antunez de Mayolo, 1987, El Niño occurrences over the past four and a half centuries, J. Geophys. Res., 92, 14,449–14,461.

Rajagopalan, B., U. Lall, and M.A. Cane, 1997, Anomalous ENSO occurrences: an alternate view, J. Climate, 10, 2351–2357.

Ramanathan, V., R.D. Cess, E.F. Harrison, P. Minnis, B.R. Barkstrom, E. Ahmed, and D. Hartmann, 1989, Cloud-radiative forcing and climate: Results from the Earth Radiation Budget Experiment, Science, 243, 57–63.

Ramanathan, V., and Collins, V., 1993, A thermostat in the tropics?, Nature, 361, 410–411.

Reeder, R.J., 1996, Interaction of divalent cobalt, zinc, cadmium, and barium with the calcite surface during layer growth, Geochim. Cosmochim. Acta, 60, 1543–1552.

Rind, D., 1993, How will future climate changes differ from those of the past?, in Global changes in the perspective of the past, J.A. Eddy and H. Oeschger (editors), John Wiley & Sons Ltd., 39–49.

Rind, D., 1998, Latitudinal temperature gradients and climate change, J. Geophys. Res., 103, 5943–5971.

Rodbell, D.T., G.O. Seltzer, D.M. Anderson, M.B. Abbott, D.B. Enfield, and J.H. Newman, 1999, A high-resolution ~15,000-yr record of El Niño-driven alluviation in southwestern Ecuador, Science, 283, 516–520.

Rohling, E.J., and G.R. Bigg, 1998, Paleosalinity and $\delta^{18}O$: A critical assessment, J. Geophys. Res., 103, 1307–1318.

Rosenthal, Y., and E.A. Boyle, 1993, Factors controlling the fluoride content of planktonic foraminifera: An evaluation of its paleoceanographic applicability, Geochim. Cosmochim. Acta, 57, 335–345.

Sandweiss, D.H., J.B. Richardson, E.J. Reitz, H.B. Rollins, and K.A. Maasch, 1996, Geoarchaeological evidence from Peru for a 5000 years BP onset of El Niño, Science, 273, 1531–1533.

Schrag, D.P., 1999, Rapid analysis of high-precision Sr/Ca ratios in scleractinian corals and other marine carbonates, Paleoceanography, 14, 97–102

Schubert, C., 1992. The glaciers of the Sierra Nevada de Mérida (Venezuela): a photographic comparison of recent deglaciation, Erdkunde, 46, 58–64.

Servain, J., 1991, Simple climatic indices for the tropical Atlantic and some applications, J. Geophys. Res., 96, 15,137–15,146.

Shen, C.-C., T. Lee, C.-Y. Chen., C.-H. Wang, C.-F. Dai, and L.-A. Li, 1996, The calibration of D[Sr/Ca] versus sea-surface temperature relationship for *Porites* corals, Geochim. Cosmochim. Acta, 60, 3849–3858.

Shen, G.T., 1996, Rapid change in the tropical ocean and the use of corals as monitoring systems, in Geoindicators: Assessing Rapid Environmental Changes in Earth Systems, A.R. Berger and W.J. Iams (editors), Balkema Press, Rotterdam, 155–169.

Shen, G.T., and R.B. Dunbar, 1995, Environmental controls on uranium in reef corals, Geochim. Cosmochim. Acta, 59, 2009–2024.

Shen, G.T., E.A. Boyle, and D.W. Lea, 1987, Cadmium in corals as a tracer of historical upwelling and industrial fallout, Nature, 328, 794–796.

Shen, G.T., T.M. Campbell, R.B. Dunbar, G.M. Wellington, M.W. Colgan, and P.W. Glynn, 1991, Paleochemistry of manganese in corals from the Galapagos Islands, Coral Reefs, 10, 91–101.

Shen, G.T., J. E. Cole, D. W. Lea, L. J. Linn, T. A. McConnaughey, and R. G. Fairbanks, 1992a, Surface ocean variability at Galápagos from 1936–1982: Calibration of geochemical tracers in corals, Paleoceanography, 563–588.

Shen, G.T., L.J. Linn, T.M. Campbell, J.E. Cole, and R.G. Fairbanks, 1992b, A chemical indicator of trade wind reversal in corals from the western tropical Pacific, J. Geophys. Res., 97, 12,689–12,698.

Shukla, J., 1987, Interannual variability of monsoons, In: J.S. Fein and P.L. Stephens (editors), Monsoons, John Wiley, New York, 399–464.

Shulmeister, J., and B.G. Lees, 1995, Pollen evidence from tropical Australia for the onset of an ENSO-dominated climate at c. 4000 BP, The Holocene, 5, 10–18.

Simmons, A.J., J.M. Wallace, and G. Branstator, 1983, Barotropic wave propagation and instability, and atmospheric teleconnection patterns, J. Atmos. Sci., 40, 1363–1392.

Sirocko, F., M. Sarnthein, H. Erlenkeuser, H. Lang, M. Arnold, and J.-C. Duplessy, 1993, Century-scale events in monsoonal climate over the past 24,000 years. Nature, 364, 322–324.

Smith, N.E., 1995, Decadal climate variability in the western tropical Atlantic and the potential for proxy records from the coral *Siderastrea siderea*, unpublished Masters thesis, Univ. of Colorado, 100 pp.

Stager, J.C., and Mayewski, P.A., 1997, Abrupt early to mid-Holocene climatic transition registered at the equator and the poles, Science, 276, 1834–1836.

Stahle, D.W., R. D'Arrigo, *et al.* (14 authors), 1998, Experimental dendroclimatic reconstruction of the Southern Oscillation, Bull. Am. Meteorol. Soc., 79, 2137–2152.

Stahle, D.W., P.T. Mushove, M.K. Cleaveland, F. Roig, G.A. Haynes, 1999, Management implications of annual growth rings in *Pterocarpus angolensis* from Zimbabwe, Forest Ecology and Management, in press.

Stoll, H.M., and D.P. Schrag, 1998, Effects of Quaternary sea level cycles on strontium in seawater, Geochim. Cosmochim. Acta, 62, 1107–1118.

Swart, P.K., 1983, Carbon and oxygen isotope fractionation in scleractinian corals: a review, Earth Sci. Rev., 19, 51–80.

Swart, P.K., and M.L. Coleman, 1980, Isotopic data for scleractinian corals explain their palaeotemperature uncertainties, Nature, 283, 557–559.

Swart, P.K., J.J. Leder, A.M. Szmant, and R.E. Dodge, 1996, The origin of variations in the isotopic record of scleractinian corals: II. Carbon, Geochim. Cosmochim. Acta, 60, 2871–2885.

Swart, P.K., J.L. Rubenstone, C. Charles, and J. Reitner, 1999, Sclerosponges: A new proxy indicator of climate, Report from the Workshop on the Use of Sclerosponges as Proxy Climate Indicators, 20 pp., in press, preprint available at http://mgg.rsmas.miami.edu/mgg.htg/groups/sil/report.pdf.

Swart P.K., K.S. White, D. Enfield, R.E. Dodge, P. Milne, 1998, Stable oxygen isotopic composition of corals from the Gulf of Guinea as indicators of periods of extreme precipitation conditions in the sub-Sahara, J. Geophys. Res, 103, 27,885–27,892.

Terray, P., 1995, Space-time structure of interannual monsoon variability, J. Climate, 8, 2595–2619.

Thompson. L.G., 1999, Ice core evidence for climate change in the tropics: implications for our future, Quat. Sci. Rev., in press.

Thompson, L.G., and E. Mosley-Thompson, 1992, Reconstructing the history of interannual climate variability from tropical and subtropical ice-core records, in El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation, H.F. Diaz and V. Markgraf (editors), Cambridge University Press, Cambridge, 295–322.

Thompson, L.G., E. Mosley-Thompson, and B.M. Arnao, 1984, El Niño-Southern Oscillation events recorded in the stratigraphy of the tropical Quelccaya ice cap, Peru, Science, 226, 50–53.

Thompson, L.G., E. Mosley-Thompson, M. Davis, P.N. Lin, T. Yao, M. Dyurgerov, and J. Dai, 1993, "Recent warming:" Ice core evidence from tropical ice cores, with emphasis on Central Asia, Glob. Planet. Change, 7, 145–156.

Thompson, L.G., E. Mosley-Thompson, M.E. Davis, P.-N. Lin, K.A. Henderson, J. Cole-Dai, J.F. Bolzan, and K.-B. Liu, 1995, Late glacial stage and Holocene tropical ice core records from Huascarán, Peru, Science, 269, 46–50.

Thompson, L.G., T. Yao, M.E. Davis, K.A. Henderson, E. Mosley-Thompson, P.-N. Lin, J. Beer, H.-A. Synal, J. Cole-Dai, and J. Bolzan, 1997, Tropical climate instability: The last glacial cycle from a Qinghai-Tibetan ice core, Science, 276, 1821–1825.

Thompson, L.G., M.E. Davis, E. Mosley-Thompson, T.A. Sowers, K.A. Henderson, V.S. Zagorodnov, P.-N.Lin, V.N. Mikhalenko, R.K. Campen, J.F. Bolzan, J. Cole-Dai, and B. Francou, 1998, A 25,000-year tropical climate history from Bolivian ice cores, Science, 282, 1858–1864.

Thompson, L.G., K.A. Henderson, E. Mosley-Thompson and P.-N. Lin, 1999, The tropical ice core record of ENSO, in El Niño and the Southern Oscillation: Multiscale Variability, Global and Regional Impacts, H.F. Diaz and V. Markgraf (editors), Cambridge Univ. Press, in press.

Toggweiler, J.R., K. Dixon, and W.S. Broecker, 1991, The Peru upwelling and the ventilation of the south Pacific thermocline, J. Geophys. Res., 96, 20,467–20,497.

Trenberth, K. E., G.W. Branstator, D. Karoly, A. Kumar, N.-C. Lau, and C. Ropelewski, 1998, Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures, J. Geophys. Res.,103, 14,291–14,324.

Trenberth, K., and T. Hoar, 1996, The 1990–1995 El Niño-Southern Oscillation event: Longest on record, Geophys. Res. Lett., 23, 57–60.

Trenberth, K.E., and J.W. Hurrell, 1994, Decadal atmosphere-ocean variations in the Pacific, Clim. Dynamics, 9, 303–319.

Tudhope, A.W., G.B. Shimmield, C.P. Chilcott, M. Jebb, A.E. Fallick, and A.N. Dalgleish, 1995, Recent changes in climate in the far western equatorial Pacific and their relationship to the Southern Oscillation: oxygen isotope records from massive corals, Papua New Guinea, Earth Planet. Sci. Lett., 136, 575–590.

Urban, F.E., J.E. Cole, J.T. Overpeck, and J. Kelleher, 1998, A new index of ENSO derived from multiple central Pacific corals, EOS: Trans. Am. Geophys. Union , 79, F493.

Vernekar, A.D, Zhou, J., and J. Shukla, 1995, The effect of Eurasian snow cover on the Indian Monsoon, J. Climate, 8, 248–266.

Walker, G.T., 1923, Correlations in seasonal variations of weather, VIII, A preliminary study of world weather I. Memoirs of India Meteorological Department, 24, 75–131.

Walker, G.T., 1924, Correlations in seasonal variations of weather, IX, A further study of world weather (world weather II), Memoirs of India Meteorological Department, 24, 275–332.

Waliser, D.E., and N.E. Graham, 1993, Convective cloud systems and Warm-Pool sea surface temperatures: Coupled interactions and self-regulation, J. Geophys. Res., 98, 12,881–12,893.

Weber, J.N., E.W. White, and P.H. Weber, 1975, Correlation of density banding in reef coral skeletons with environmental parameters: the basis for interpretations of chronological records preserved in the coralla of corals, Paleobiology, 1, 137–149.

Weber, J.N., and P.M.J. Woodhead, 1972, Temperature dependence of oxygen-18 concentration in reef coral carbonates, J. Geophys. Res., 77, 463–473.

Webster, P. J., and S. Yang, 1992, Monsoon and ENSO: selectively interactive systems, Quart. J. Royal Met. Soc., 118, 877–926.

Webster, P.J., V.O. Magaña, T.N. Palmer, J. Shukla, R.A. Tomas, M. Yanai, and T. Yasunari, 1998, Monsoons: Processes, predictability, and the prospects for prediction, J. Geophys. Res., 103, 14,451–14,510.

Webster, P. J., J. Loschnigg, A. Moore, and M. Reban, 1999, Evidence of prolonged coupled ocean-atmosphere instabilities in the Indian Ocean, Nature, in press.

Weil, S.M., R.W. Buddemeier, S.V. Smith, and P.M. Kroopnick, 1981, The stable isotopic composition of coral skeletons: control by environmental variables, Geochim. Cosmochim. Acta, 45, 1147–1153.

Wellington, G.M., and P.W. Glynn, 1983, Environmental influences on sketetal banding in eastern Pacific (Panamá) corals, Corals Reefs, 1, 2315–2322.

Wellington, G.M., and R.B. Dunbar, 1995, Stable isotopic signatures of ENSO in eastern tropical Pacific reef corals, Coral Reefs, 14, 5–25.

Wellington, G.M., G. Merlen, and R.B. Dunbar, 1996, Calibration of stable oxygen isotope signatures in Galapagos corals, Paleoceanography, 11, 467–480.

Wilson, E.O., 1986, The current state of biological diversity. in Biodiversity, E.O. Wilson (editor), National Academy Press, Washington, D.C., 3–18.

Winter, A., C. Goenaga, and G.A. Maul, 1991, Carbon and oxygen isotope time series from an 18-year Caribbean reef coral, J. Geophys. Res., 96, 16,673–16,678.

Woodhouse, C.A., and J.T. Overpeck, 1998, 2000 years of drought variability in the central United States, Bull. Am. Met. Soc., 79, 2693–2714.

Zebiak, S.E., and M.A. Cane, 1987, A model El Niño/Southern Oscillation, Mon. Wea. Rev., 115, 2262–2278.

Zhang, J., and T.J. Crowley, 1989, Historical climate records in China and reconstruction of past climates, J. Climate, 2, 833–849.

Zhang, Y., J.M. Wallace and D.S. Battisti, 1997, ENSO-like decade-to-century scale variability, 1900–93, J. Climate, 10, 1004–20.

Zhang, R.-H., L.M. Rothstein, A.J. Busalacchi, 1998, Origin of upper-ocean warming and El Niño change on decadal scales in the tropical Pacific Ocean, Nature, 391, 879–883.

# 7. Participant List

Rob Allan
CSIRO, Division of Atmospheric Research
Private Bag 1
Aspendale, Victoria, Australia, 3195
rjs@dar.csiro.au

David Battisti
Dept. of Atmospheric Sciences
University of Washington
P.O. Box 351640
Seattle WA 98195-1640, USA
david@atmos.washington.edu

Warren Beck
Department of Physics
University of Arizona
PAS 255, Tucson, AZ 85721, USA
wbeck@physics.arizona.edu

Jose Carriquiry
Instituto de Investigaciones Oceanologicos
Universidad Autonoma de Baja California
Ensenada, Mexico
jdcarriq@faro.ens.uabc.mx

Supriya Chakraborty
Department of Chemistry
University of California San Diego
La Jolla CA 92093, USA
schakrab@chem.ucsd.edu

Chris Charles
Scripps Institution of Oceanography
University of California San Diego
La Jolla CA 92093, USA
ccharles@ucsd.edu

Anne Cohen
Woods Hole Oceanographic Institution
Woods Hole MA 02543, USA
acohen@whoi.edu

Julia E. Cole
INSTAAR, Campus Box 450
University of Colorado
Boulder CO 80309, USA
coleje@spot.colorado.edu

Ed Cook
Tree Ring Laboratory
Lamont-Doherty Earth Observatory
Palisades NY 10964, USA
drdendro@ldeo.columbia.edu

Ellen Druffel
Department of Earth System Science
University of California, PSRF-207
Irvine CA 92717-3100, USA
edruffel@uci.edu

Robert B. Dunbar
Department of Geological and Environmental Sciences
Stanford University
Stanford CA 94305-2115, USA
dunbar@stanford.edu

Mark Eakin
Office of Global Programs
National Oceanic and Atmospheric Administration
Silver Spring MD 20910-5603, USA
eakin@ogp.noaa.gov

Michael Gagan
Australian National University
Environmental Geochemistry, RSES
Canberra ACT 0200, Australia
michael.gagan@anu.edu.au

Georg Heiss
Karlstalweg 2/1
D–69412 Eberbach, Germany
gheiss@gmx.de

Wayhoe Hantoro
Indonesian Institute of Sciences
Jalan Cisitu - 21/154D
Bandung 40135, Indonesia
hantoro@geotek.lipi.go.id

Typhoon Lee
Institute of Earth Sciences
Academia Sinica
Nangkang, Taiwan
typhoon@biaa.sinica.edu.tw

Brad Linsley
Department of Earth and
Atmospheric Sciences ES 351
University at Albany–SUNY
Albany, NY 12222, USA
blinsley@cnsunix.albany.edu

Eiji Matsumoto
Institute for Hydrospheric-
Atmospheric Sciences
Nagoya University
Nagoya 464-01, Japan
oabe@ihas.nagoya-u.ac.jp

Mike Patterson
NOAA Office of Global Programs
Silver Spring MD 20910-5603, USA
patterson@ogp.noaa.gov

Terry Quinn
Department of Geology
University of South Florida
Tampa FL 33620-5200, USA
quinn@chuma.cas.usf.edu

Jacques Recy
Observatoire Océanologique
Villefranche-sur-Mer, France
recy@ccrx.obs-vlfr.fr

Dan Schrag
Department of Earth and Planetary Sciences
Harvard University
Cambridge, MA 02138, USA
schrag@eps.harvard.edu

Glen Shen
School of Oceanography, WB-10
University of Washington
Seattle WA 98195, USA
glenshen@u.washington.edu

Uli Schotterer
Climate and Environmental Physics
University of Bern
Sidlerstrasse 5
CH-3012 Bern, Switzerland
schotterer@climate.unibe.ch

David Stahle
Department of Geography
Ozark Hall 108A
University of Arkansas
Fayetteville AR 72701, USA
stahle@comp.uark.edu

Peter Swart
RSMAS
University of Miami
4600 Rickenbacker Causeway
Miami FL 33149, USA
swart@oj.rsmas.miami.edu

Fred Taylor
Institute of Geophysics
University of Texas
8701 N. MOPAC Blvd.
Austin TX 78759, USA
fred@utig.ig.utexas.edu

Lonnie Thompson
Byrd Polar Research Center
Ohio State University
1090 Carmack Road
Columbus OH 43210, USA
thompson.3@osu.edu

Kevin Trenberth
Climate Analysis Section
NCAR, ML
1850 Table Mesa Drive
P.O. Box 3000
Boulder CO 80307, USA
trenbert@ncar.ucar.edu

Sandy Tudhope
Grant Institute of Geology and Geophysics
University of Edinburgh
Edinburgh, Scotland
studhope@ed.ac.uk

Peter J. Webster
PAOS
University of Colorado
Campus Box 311
Boulder CO 80309, USA
pjw@willywilly.colorado.edu

Gerard Wellington
Department of Biology
University of Houston
Houston TX 77004, USA
wellington@uh.edu

Herman Zimmerman
Division of Earth Sciences
National Science Foundation
4201 Wilson Blvd.
Arlington VA 22230, USA
hzimmerm@nsf.gov

# 8. List of Acronyms

| | |
|---|---|
| AGCM | Atmospheric General Circulation Model |
| AMS | Atomic Mass Spectroscopy |
| CASE | Caribbean Salinity Experiment |
| CLIMAP | Climate Mapping Project |
| CNC | Climate of the Nineteenth Century |
| COADS | Comprehensive Ocean Atmosphere Data Set |
| CT | Cold Tongue |
| DIC | Dissolved Inorganic Carbon |
| ENSO | El Niño/Southern Oscillation |
| GCM | General Circulation Model |
| GEOSECS | Geochemical Ocean Sections |
| GISST | Global Sea Ice and Sea Surface Temperature |
| GFAAS | Graphite Furnace Atomic Absorption Spectroscopy |
| GR | Global Regression |
| IAWA | International Association of Wood Anatomists |
| ICP-AES | Inductively Coupled Plasma Atomic Emission Spectroscopy |
| ICP-MS | Inductively Coupled Plasma Mass Spectroscopy |
| IM | Ion Microprobe |
| ITCZ | Inter Tropical Convergence Zone |
| LGM | Last Glacial Maximum |
| NOAA | National Oceanic and Atmospheric Administration |
| NSF | National Science Foundation |
| ODP | Ocean Drilling Program |
| PDO | Pacific Decadal Oscillation |
| PDSI | Palmer Drought Severity Index |
| PMEL | Pacific Marine Environmental Laboratory |
| PNA | Pacific North American |
| PROcCiE | Pacific Radiocarbon Ocean Circulation Experiment |
| SLP | Sea Level Pressure |
| SOI | Southern Oscillation Index |
| SPCZ | South Pacific Convergence Zone |
| SSS | Sea Surface Salinity |
| SST | Sea Surface Temperature |
| TIMS | Thermal Ionization Mass Spectrometry |
| TOGA | Tropical Ocean Global Atmosphere |
| TAO | Tropical Atmosphere Ocean |
| WOCE | World Ocean Circulation Experiment |
| XAFS | x-ray absorption fine structure |