GLOBAL CHANGES OF THE PAST

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Global Change: The Last 2000 Years

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Relevance of Climate over the Last 2000 Years to the Next 100 Years

Whatever anthropogenic impacts on climate occur in the future, they will be superimposed on a background of natural climatic processes that may mask, or magnify, such impacts. To understand and anticipate what lies ahead, we must improve our understanding of climatic variations in the past. This requires data with seasonal or annual resolution for as wide a geographic area as possible. The only time period for which there is the possibility of reconstructing season-by-season, detailed maps of global climatic anomalies is the last 2000 years. Such detail is needed to understand the effects of particular forcing factors and the interactions (teleconnections) between one region and another. The longer time frame provides the necessary record length to evaluate the significance of recurrent periodic phenomena.

Climatic variations of the last 2000 years are of particular relevance to contemporary human endeavors. Although climatic fluctuations over this time period were small (e.g., generally <2°C decadal mean seasonal anomalies in any one region) in comparison with those expected from a doubling of greenhouse gases (4–8°C), the last 2000 years have witnessed the most extreme conditions of the Holocene period. There is abundant

19th century. The proposed mapping will provide the first global view of how the natural climate system operates on these time scales. This will be a key contribution to anticipating future changes and to separating the effects of anthropogenically induced change (i.e., greenhouse warming) from the natural baseline.

2. To characterize definitively the nature of climatic events that have long been debated, such as the Little Ice Age and the Medieval Warm Period. Were these events of global significance and could similar events occur in the future?

3. To provide a global framework for testing hypotheses regarding the causes of decade- to century-scale climatic variability. The goal is to test the role of various forcing mechanisms by comparing global maps of observed paleoclimatic anomalies with those simulated in climate model experiments where boundary conditions have been altered to reflect changes in hypothesized forcing (e.g., a major explosive volcanic eruption, an extended period of such eruptions, or a change in solar constant). Later in this chapter, we identify a number of possible climatic forcing mechanisms, both natural and anthropogenic, and propose that detailed record for each of these possible mechanisms be developed.

4. To identify key areas of the globe where we currently lack needed information. Hypotheses generated via the data-model framework can be tested through the acquisition of data from key, climatically sensitive sites. The proposed program may also help to identify those regions and proxy types that might serve to characterize *hemispheric-scale* change over longer time scales, e.g., the high-latitude tree-ring record (Jacoby and D'Arrigo, 1989) or the Chinese documentary records (Bradley et al., 1987). The successes of global mapping-modeling programs over longer time scales—e.g., CLIMAP (1976) and COHMAP (1989)—illustrate the potential that exists for mapping and modeling of decade- to century-scale climatic variability on a global scale.

To accomplish these goals, a multiproxy mapping program should specifically include:

- The integration of a global array of paleoclimate records from multiple proxies. The use of may data types will overcome the geographic and temporal limitations of individual proxies.
- The archiving of all paleoenvironmental time series that cover all or part of the past 2000 years. Many of these time series will have seasonal to annual resolution.
- The construction of a series of global maps, season by season, for each of the past 200 years. Maps will portray multiple climatic fields.

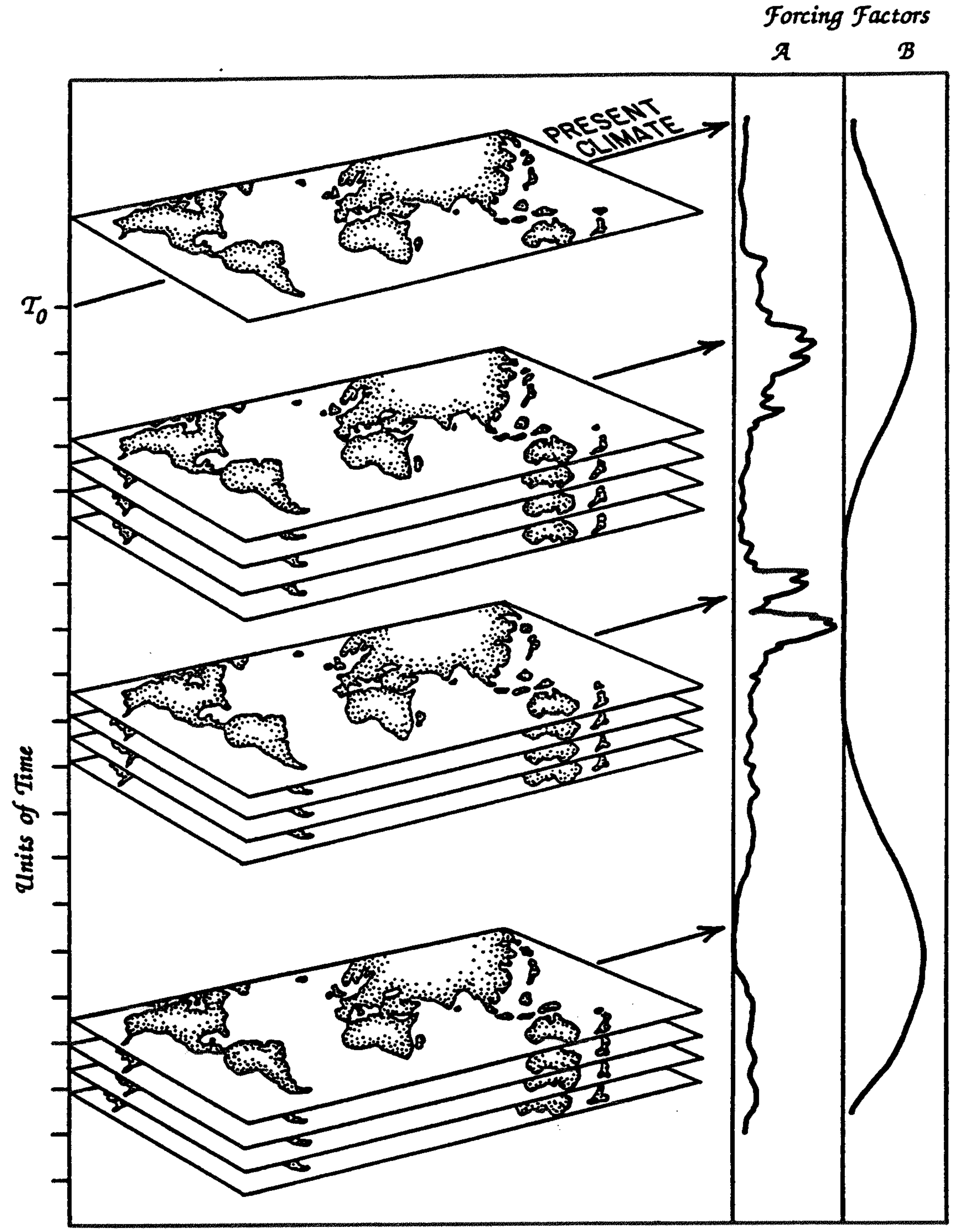

Figure 1. Schematic representations of research strategy to examine climatic conditions associated with particular forcing factors at intervals during the last millennium.

- The construction of global maps for selected earlier time intervals (Figure 1), including: intervals associated with hypothesized volcanic forcing (e.g., the A.D. 1783 Laki eruption) or with a lack of volcanic activity (e.g., A.D. 1100–1200); intervals associated with hypothesized solar forcing (e.g., the Maunder and Spörer sunspot minima); intervals such as the Medieval Warm Period; intervals associated with other forcing factors (see below).

Reconstruction of Key Climatic Systems

We propose a project for the reconstruction of time series of key climatic systems. In picking areas for special study there are two considerations. First, the climate of a particular geographic area should represent a major subsystem within the global climate system. Second, there must be a range of proxy records available now (or available in the near future) that will allow key characteristics of the subsystem to be reconstructed. It should also be possible to compare the relative merits of each proxy to be evaluated and to estimate the lags within and between individual proxies. At a later stage these pilot areas can be linked with similar studies of the parts of other climate system in order to determine teleconnections between the regions.

We suggest that three climatically sensitive regions (which have existing or developing proxy records from multiple sources) be investigated. Each project should involve intensive intercalibration and comparison of how climate signals are recorded by various proxies.

The Asian Monsoon Region

The first region selected is the Tibetan Plateau, the center of the intense summer low pressure cell that drives the Asian monsoons. The monsoons constitute a dominate source of yearly climate variation over an enormous region and affect a large portion of the world's population. Past records of climate variability on the Tibetan Plateau will allow us to address annual to century-scale variation in the monsoons, as well as possible causes of this variation (e.g., snow cover). As high-resolution proxy records become available, other regions such as India and East Africa may also be compared.

The El Niño–Southern Oscillation Region

The second pilot area for multiproxy paleoclimatic reconstruction is chosen to reflect the El Niño–Southern Oscillation (ENSO) phenomenon. ENSO fluctuations are a dominant source of today's interannual climate variability, even in temperate regions. Monitoring the behavior of this system over the past several centuries is therefore important to understanding past climate variability on a global scale. The impact of ENSO conditions is felt primarily in the equatorial Pacific, where several proxy records of ENSO fluctuations are (or soon will be) available. To supplement existing land-based monitors of past conditions (including historical records and an ice core), it may be possible to obtain long coral records, which reflect ocean conditions directly. Moreover, records of both ENSO and monsoon conditions spanning several centuries will enable us to investigate the degree of coupling between these important climate systems.

The North Atlantic Region

The North Atlantic is of crucial importance since it is associated with changes in the location and intensity of one of the major "centers of action" in the global climate system, the Icelandic Low, and because it is a key node in the oceanic thermohaline circulation. Because of the wealth of existing proxies around the North Atlantic, including historical sea ice records, the potential for reconstructing the variability of this system over long periods (at least 500 years) is excellent. The region contains the widest range of available, well-dated proxies and therefore provides an excellent test area for comparing a range of proxies and linking them to models.

Causes of Decade- to Century-Scale Climate Variability

We propose that a project be initiated to identify, characterize, and test the possible causes of decade- to century-scale climate variability. In sharp contrast to the Milankovitch scale of climatic variability, little is known about the mechanisms responsible for the climatic changes of the past 2000 years. Hypotheses regarding possible mechanisms must be defined and tested. Central to this objective is the development of time series that characterize the temporal and spatial aspects of each deterministic mechanism that is believed to affect the global climate system. These time series can then be used in conjunction with paleoclimatic time series and maps (see above) to begin the description of how decadal to century-scale climate variability is forced. Observed climatic changes not associated with the hypothesized deterministic forcing mechanisms may be forced by stochastic variations generated internally by the climate system itself. Hence, a major effort is needed to compile the following records of potential climatic forcing (which are either internal or external to the climate system) and to examine the climatic record for evidence of how these factors may be reflected in climatic variations of the past.

Mechanisms External to the Climate System

- *Volcanic forcing.* The existing historical and tephra records of volcanic eruptions should be improved. A global record of volcanic activity needs to be developed using sulfate (acidity) and volcanic dust records from a global array of ice cores. This goal will require a concentrated effort from the ice-core community. Atmospheric modeling experiments should be carried out in parallel, to determine the dimensions of the ice-core array needed to characterize the magnitude and extent of atmospheric aerosol loading by individual (or multiple) eruptions. In addition, the modeling work (involving dust loading experiments) can be used to identify possible biases that individual ice-core records might have in characterizing long-term variations in the distribution and chemistry of large-scale atmospheric volcanic aerosol loading. Ice-core records should be calibrated against the observed record of recent eruptions.

- *Solar forcing.* A global high-resolution time series of past solar activity is now available in the form of the ^{14}C secular variation record of the past 10,000 years. The utility of this time series as a proxy for past solar activity is evidenced by recent spacecraft observations, the correlation with sunspot activity and a broad agreement with ice-core ^{10}Be determinations (see Stuiver, this volume). Additional high-resolution ^{10}Be data are needed to confirm the ^{14}C record as a solar proxy, and work should be carried out to examine the possible relationship between ^{14}C variations and variations in ultraviolet radiation.

- *Orbital forcing.* Just as the orbital influences on insolation over the globe can be calculated for Milankovitch time scales, it is possible to calculate how the planets and moons influence the patterns of insolation over shorter time scales. These influences could be of the same magnitude as possible solar constant changes that are discussed below.

Mechanisms Internal to the Climate System

- *Nonvolcanic aerosols (dust).* Careful chemical studies and a methodology similar to that described above for volcanic aerosols may enable us to use historical data and an ice-core array to derive a global record of nonvolcanic dust variability.

- *Atmospheric trace gases.* A high-resolution global record of radiatively active trace gases (e.g., carbon dioxide, nitrous oxide, methane) needs to be developed using air trapped in ice cores.

- *Variations in ocean upwelling and thermohaline circulation.* A history of these variations may be preserved in coral and varved-sediment records from marginal marine basins. It may also be possible to use historical sea-ice records and isotopic data from Greenland ice cores to gain insight into thermohaline circulation variations.

- *Variations in ENSO.* Time series are available from historical sources and should be extended using records from Pacific corals, ice cores, and tropical tree-ring series.

- *Anthropogenic change.* Time series of human land use and industrial activity are needed to separate natural from anthropogenic climate variability. We propose an effort to map the detailed spread of land clearance and land drainage, and, where possible, land-use patterns of the past 2000 years. These records can be used in conjunction with atmospheric CO_2 and ^{13}C records to separate the anthropogenic signal in the trace-gas records.

- *Changes in the biosphere.* In addition to human-induced change in the biosphere (see above), it is likely that other changes in the biosphere will affect the climate system. We propose that an effort be made to use data from historical records, tree rings, treeline, and sediments (e.g., pollen and macrofossils) to map the global patterns of vegetation and fire frequency changes over the past 2000 years.

- *Changes in ice cover.* Changes in the extent of snow and sea-ice cover could explain some of the observed patterns of past decadal to century-scale regional climatic change. Historical, glacial, and ice-core data should be used to reconstruct changes in snow and ice cover.

- *DMS/CCN.* Dimethylsulfide (DMS) excreted by marine micro-organisms may be an important contributor to cloud condensation nuclei (CCN) and hence play a role in the formation of clouds. Because of the significance of clouds to the global energy balance, long-term variations in DMS based on ice-core records should be developed.

Modeling Experiments

Given time series of hypothesized forcing, several strategies must be pursued to test how these forcings relate to observed climate variability. Superimposed epoch analysis (e.g., Kelly and Sear, 1986; Bradley, 1988) has proven to be one useful approach. We propose a more systematic approach via comparisons of observed climatic fields or time series (see projects described above) with those simulated in climate model experiments. If a forcing can be hypothesized, then the hypothesis can be represented by a climate model experiment with altered boundary conditions. Examples are provided here for volcanic, solar, and trace-gas forcing; similar experiments should be set up to test the effects of the other possible forcing mechanisms. We recommend that a series of experiments be carried out with multiple climate models to permit model comparison and to involve a range of transient and equilibrium modeling approaches.

- *Volcanic forcing.* In many cases, it will be possible to know the point source and timing of a particular eruption (from historical data), the associated distribution of volcanic aerosols over the globe (from ice core data), and the observed climate fields (and time series) for the period postdating the eruption (see above). Using the recent observed record of aerosol characteristics (e.g., optical depth) as a guide, transient climate model experiments can be used to produce simulated aerosol deposition and climatic patterns over the globe. These can then be compared with the observed patterns. A series of climate model sensitivity experiments may be necessary to explore the effects of variable aerosol optical depth and cumulative atmospheric loading from a series of explosive eruptions closely spaced in time.

- *Solar and trace gas forcing.* Climate model experiments with different values of the solar constant and altered trace-gas concentrations will produce similar simulated climatic patterns. In the case of hypothesized solar forcing during the Maunder Sunspot Minimum (~A.D. 1645–1715) it will be necessary to investigate how a relatively small change in the solar constant can be amplified by atmospheric mechanisms to produce a recognizable climatic anomaly.[1]

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[1]The reasoning behind this Maunder Minimum conclusion is as follows: The measured decrease of 0.06% in the solar constant at the end of the last 11-year solar cycle was associated with a reduction of ca. 120 in sunspot number. On a longer time scale, the absence of sunspots during the 70-year Maunder Minimum can be compared to an average sunspot number of 51 for the recent A.D. 1880–1965 period. By analogy, the solar constant change between these periods would be 0.026% (51/120 x 0.06%). The instrumental record of geomagnetic Aa indices, reflecting cosmic ray modulation and therefore changes in the solar wind, has been used to calculate how much more solar activity diminishes after the sunspot signal "runs out" at zero. During the Maunder Minimum, solar modulation of cosmic rays was twice what the sunspot record alone shows and so the difference in solar constant from recent levels was about –0.05% (2 x –0.026%). These calculations suggest that the magnitudes of solar constant change during the Maunder Minimum and the last solar cycle are comparable but of different durations, and this conclusion is supported by studies with global ^{14}C models which show that similar ^{14}C production rate changes are associated with these different phenomena. A solar constant change of 0.05% corresponds to a global temperature forcing of only 0.1°C, which seems insufficient to account for the environmental changes recorded during the Little Ice Age in many parts of the world. It would seem that an amplification mechanism is required, and the recent solar-climate link pursued by van Loon and Labitzke (1988) appears to be promising.

Recommendations

In addition to the specific action plans outlined above, the Working Group makes the following more general recommendations:

Data Exchange and Archiving

A high-priority initial step to accomplishing the project goals outlined above is the acquisition of proxy data sets from many different parts of the world. Although this will involve the recovery of new records, much progress can by achieved by integrating existing data sets. This requires international collaboration in data exchange and data base management. As noted in Report No. 4 of the International Geosphere-Biosphere Programme (IGBP):

> It would be of value to establish a global inventory and data base of paleoenvironmental data, as a lasting feature of the IGBP, to facilitate the exchange of information between field research and modeling efforts, and the exchange of data between different disciplines.

We strongly endorse this idea and recommend that a plan be developed and implemented as soon as possible to create a widely accessible computer-based archive of fully documented paleoenvironmental data. This should be accompanied by a major effort in developing comprehensive bibliographies of work already undertaken and, most importantly, by initiating a program of translation into one or two common languages. Much important work remains essentially unknown to the larger scientific community because of language barriers. Translation is a cost-effective way of enlarging the worldwide data base of paleoenvironmental information.

Improvements in Dating Precision

Annual and decadal time-scale information on global change will have to come from historical records, tree rings, ice cores, corals, and laminated sediments where yearly signals can be proven. High-precision radiocarbon dating (^{14}C years) is the method of choice when annual dating methods cannot be applied. Much attention will have to be given to sample type as well as ^{14}C reservoir deficiency and bioturbation in lake and marine sediments. Precise radiocarbon ages must then be converted to calendar years. In many but not all instances, the precision will suffer from the time-scale calibration process and it will be difficult to obtain errors below ~40 yr for the 2000-year time interval under discussion. Routine radiocarbon dating (i.e., dates not obtained by accelerator mass spectrometry, or AMS) will generally be of limited use in this time span as calibrated age ranges are often >200 years. Meeting the needs will require increased AMS dating capabilities. High precision and accuracy will only be possible if ^{14}C laboratories adhere to rigorous intercalibration procedures.

Secular variations in paleomagnetic signals can be used for correlation and can be calibrated to absolute ages. Tephra layers are probably our most precise time lines over wide areas and in some cases may be absolutely dated. To determine recent sedimentation rates in uppermost lake sediments, ^{210}Pb is commonly used.

Other methods that may eventually prove useful with increased efforts are uranium/thorium (U/Th) series dating, thermoluminescence, electron spin resonance (ESR), lichenometry, and obsidian hydration dating. Finally, dating amino acid records may be useful in providing an integrated temperature record over selected time intervals.

Proxy Calibration and Validation

A better understanding of how a climatic or environmental signal is recorded in a natural proxy record is required. Often, processes in modern systems are not understood well enough to allow us to convert numerous forms of proxy data into climate-relevant parameters for models. Improvement requires a four-step strategy:

- *Environmental monitoring.* Seasonal signal parameters must be monitored at key proxy sites in order to determine the reproducibility or faithfulness of an archive parameter. The monitoring programs should be targeted at specific problems related to converting proxy information into climate parameters.

- *Process studies on environmental signals.* Process studies are essential to understand how the environmental condition is transferred into an archive signal. These studies should include both laboratory and field experiments and the development of new techniques. For example, a proxy record of sea ice would be extremely valuable, but it is not clear at present what the optimum environmental indicator of the presence of sea ice might be.

- *Validation of proxy records.* In many parts of the world, time series of instrumental climatic data going back over a century are available near to the sites of several different proxy archives. It is recommended that cross validation among different proxies be carried out as a step towards developing calibrated transfer functions and understanding the differential response times and sensitivity of different proxies.

Maintenance and enhancement of environmental monitoring networks. Maintaining climate data coverage with high quality poses serious difficulties. The advent of satellite observations has unfortunately led to closing remote weather stations which are essential to link with proxy records. For example, in the Arctic such remote stations are needed to provide background records for key ice-core areas. Similarly, long-term monitoring of oceanic sites by weather ships has been reduced. Satellite observations should be used to supplement, not replace, ground-based observations. Calibration of proxy climate records demands the maintenance of existing climate monitoring stations. Expansion of this network, to improve coverage in regions of paleoclimatic interest, is an important goal and will require the development of new instruments and techniques (with the aid of engineers) to monitor environmental conditions. New developments in equipment design and instrumentation are also needed to procure and analyze the high-quality cores and samples that are necessary to understand the climatic record of the last 2000 years.

Assessment of Climatic Extremes

The proposed detailed reconstruction of paleoenvironmental change over the past 2000 years should provide an ideal baseline data set for the validation of climatic impact studies and for the study of extreme environmental events. For example, the inferred relationship between global climatic warming and increased tropical storm intensity (Emanuel, 1987) should be examined in the context of past warm and cold periods. The physical correlation between atmospheric warmth and convective storm intensity (and thus forest fire frequency; Overpeck et al., 1989) can also be tested using past records of climatic change, forest fire frequency (e.g., from lakes and tree fire-scar records), and mass wastage (e.g., as recorded in lake sediments in sensitive areas such as the Alps). The natural recurrence interval of extreme drought and flood events can only be characterized in some instances by paleoclimatic time series that significantly exceed those available in length. The careful documentation, analysis, and modeling of seasonal to annual environmental change over the past 2000 years will clearly aid in the assessment of future climatic hazards.

IGBP Regional Research Centers

Ecosystem monitoring and process-oriented studies of proxy records should be major activities of the IGBP Regional Research Centers. These centers should be directly involved in the planning, execution, and analysis of projects to secure the necessary global coverage of proxy archives for the IGBP Core Program on Global Changes of the Past. In choosing the Regional Research Centers, careful attention should be given to those areas where paleoclimate records and proxy process monitoring could provide important long-term information about significant components of the global climate system.

The following general areas are suggested for discussion as potentially sensitive regions where existing proxy records can be supplemented by other records or where proxy records are now entirely lacking.

Beringia: Sea-ice variations and Arctic Ocean–Pacific Ocean links, boreal forest changes, and permafrost.

Peru-Ecuador: El Niño–Southern Oscillation variability.

Patagonia: Links with Antarctic records and southern oceans.

West Africa: Links of Sahel zone with Atlantic monsoon and intertropical convergence zone (ITCZ) fluctuations.

East Africa: Record of biogeochemical cycles and ecosystems in lakes, links to monsoon, and regional hydrological budget.

India: Record of variations of Asian monsoons, links with Himalaya-Tibet records.

East Asia: East Asian monsoon system, volcanoes, terrestrial dust, ocean productivity.

Indonesia–New Guinea: Links to ENSO-Walker systems, volcanic activity, monsoon system.

Southern Australia–New Zealand: Links to southern oceans, Northern and Southern Hemisphere coupling.

Trieste, Italy (Third World Academy and Institute of Environmental Sciences): Links to southern European, North African, and Middle Eastern climate proxy archives; human impact on climate system.

Amazonia: Equatorial forest dynamics and climate significance; role in global hydrological cycle and atmospheric composition changes.

References

Bradley, R.S. 1988. The explosive volcanic eruption signal in northern hemisphere continental temperature records. *Climatic Change 12*, 221–243.

Bradley, R.S. Pre-instrumental climate: how has climate varied during the past 500 years? In *Greenhouse Gas-induced Climatic Change*, M. Schlesinger, ed. Elsevier, New York, in press.

Bradley, R.S., H.F. Diaz, P.D. Jones, and P.M. Kelly. 1982. Secular climatic fluctuations of Northern Hemisphere land areas and mainland China since the mid - 19th century. In *The Climate of China and Global Change*, D. Ye, C. Fu, T. Chao, and M. Yoshino, eds., 76–87. China Ocean Science Press, Beijing.

CLIMAP Project Members. 1976. The surface of the ice age earth. *Science 191*, 1131–1144.

COHMAP Project Members. 1988. Major climatic changes of the last 18,000 years: observations and model simulations. *Science 241*, 1043–1052.

Emanuel, K.A. 1987. The dependence of hurricane intensity on climate. *Nature 326*, 483.

Jacoby, G., R. d'Arrigo. 1989. Reconstructed Northern Hemisphere annual temperatures since 1671 based on high latitude tree-ring data from North America. *Climatic Change 14*, 39–59.

Kelly, P.M., and C.B. Sear. 1984. Climatic impact of explosive volcanic eruptions. *Nature 311*, 740–743.

Overpeck, J.T., L.C. Peterson, N. Kipp, J. Imbrie, and D. Peteet. 1989. Climate change in the circum-North Atlantic region during the last deglaciation. *Nature 338*, 553–557.

van Loon, H., and K. Labitzke. 1988. Association between the 11-year solar cycle, the QBO, and the atmosphere. Part II. Surface and 700mb in the Northern Hemisphere in winter. *Journal of Climate 1*, 905–920.