GLOBAL CHANGE

IGBP

REPORT No. 19

PAGES

PAST GLOBAL CHANGES PROJECT:

PROPOSED IMPLEMENTATION PLANS FOR RESEARCH ACTIVITIES

The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP) of the International Council of Scientific Unions

Stockholm, 1992

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THE PAGES PROJECT: PROPOSED IMPLEMENTATION PLANS FOR RESEARCH ACTIVITIES

An Expanded Explanation of the PAGES Project Plan
Described in IGBP Report No. 12

Based upon the Deliberations of the First Meeting
of the PAGES Scientific Steering Committee
Mainz Academy of Arts and Literature
March 11–13, 1991

Edited by John A. Eddy

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I. EXPLANATION

The evolving plans for the Past Global Changes (PAGES) Project of the IGBP have been described in two earlier IGBP publications. The rationale for a major "palaeo" component of the global change programme, with initial recommendations for programme emphases, was first described in Report No. 6, of 1989. In 1990, in Chapter 7 of IGBP Report No. 12, a more detailed description of proposed project content was presented, including definition of two proposed *temporal streams* and seven areas of scientific emphasis (*activities*) within them. The first of these reports was the result of initial meetings of the IGBP Working Group on Techniques for Extracting Environmental Data from the Past; the second, which was prepared for the review of the second IGBP Scientific Advisory Council (SAC) in Paris in September 1990, presented the more advanced plans of the first IGBP Scientific Steering Committee (SSC) on Global Changes of the Past which had supplanted the original Working Group.

The result of the 1990 SAC review, and of ensuing review in the Scientific Committee for the IGBP (SC-IGBP), was a strong endorsement for the general research structure that was laid out in Report 12, with recommendations to proceed with plans for *implementation* that would allow a broader segment of the scientific community to become more closely involved in project planning and execution.

This report is directed toward these ends. It is the result of the first meeting of the newly-constituted PAGES SSC, in March of 1991 in Mainz. Participants, including those who contributed as special consultants for the 1991 meeting, are given in Appendix 4. The philosophy at Mainz, and expressed here, is that the PAGES project now stands as the first linked cars of a train in a station, ready to move forward, yet able to change or add elements as required to do its task. For these reasons it is particularly important to establish strong ties between the international PAGES Project and the many national committees that now work toward the goals of the IGBP.

Additional information or suggestions regarding the project or participation in it can be obtained from any of the members of the PAGES SSC, listed in Appendix 3, or by contacting the co-chairmen of that committee: H. Oeschger at the Institute of Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland (telephone (41-31) 65 44 62; Telefax (41-31) 65 44 05, or J. Eddy at CIESIN, Saginaw Valley State University, 2250 Pierce Road, University Center, Michigan 48710, USA (telephone (517) 791-7371; Telefax (517) 790-0735.)

II. GENERAL DESCRIPTION

The Past Global Changes (PAGES) project is directed at securing a better understanding of the natural and human-induced variations of the Earth system in the past, through the organization of coordinated national and international endeavors to obtain and interpret a variety of natural and written records. It is one of five core projects that have been established by the IGBP.

Until recent years, the study of historical records and of natural archives such as those found in tree-rings, lake and ocean sediments, corals and ice-cores has been carried out on a largely individual basis, by single investigators or laboratories, directed at the interpretation of a single historical or proxy record, and most often for a limited region of the globe. Examples are dendroclimatological studies of regional aridity and river flow, the reading of deep-sea cores to determine ocean temperature, or the taking and interpretation of polar and mid-latitude ice cores. These classical methods of inquiry, driven by advances in technology and the application of modern methods of physical and chemical analysis, have developed a set of powerful analytical techniques. From these has come the ability to recover changes in surface temperature, air and ocean chemistry, volcanic events, and the distribution of vegetation from the distant past — with temporal resolution that is sometimes adequate to distinguish seasonal changes in the local or regional environment.

New information gleaned from the reading of these natural diaries in the past few years has been largely responsible for our present awareness of the coupled nature of the global system. It has also provided the only data which can be used for the validation of models of climatic and environmental change on time scales of decades to centuries.

It is obvious to any who work in the field of palaeo-records that we have only begun to exploit what is possible. It is also clear that through the coordination of such efforts — particularly through the combination of data secured through a variety of methods — the power of any of these techniques could be vastly increased. This has already been demonstrated through organized activities such as the CLIMAP project, the international effort to produce a Palaeoclimate Atlas, and international activities to coordinate securing of various kinds of data such as lacustrine sediments and tree-rings.

The opportunity to do this, through the IGBP PAGES project, comes at a time when the recovery and interpretation of past data have taken on a sense of urgency. Environmental changes of 10,000 or 100,000 yr ago, and the processes through which they were brought about, are of more than academic interest to a world that faces the possible prospect of dramatic changes of climate in the near future. It would greatly improve our understanding of impending changes were we able to answer questions such as the following:

- In what sequence, in episodes of glaciation and deglaciation, do changes in greenhouse gases and surface temperature occur?
- How has the surface temperature of the Earth changed, regionally and globally, through the last 1000 yr?
- To what extent do natural feedbacks in the Earth system contribute to greenhouse gas forcing?
- To what extent have the activities of man modified climate and the global environment in the past?

To understand global changes of the past, or to predict the changes expected in the future, one would like to know a detailed history of environmental changes throughout the full reach of the past, and for every region of the globe. Practical considerations regarding human and financial resources, the limits of what data are potentially available and where, and the press for answers to specific questions regarding impending changes, demand instead that a project aimed at illuminating the past concentrate first on those periods and places where the most needed information will be

found. Thus the PAGES project will focus on agreed-upon "slices of time" selected to sample critical periods in the longer run of changing processes and where necessary on the coordinated recovery of information regarding regions that are most likely to yield insights into the operation of the Earth system. Following the guidelines of the IGBP, emphasis in choosing these times and places will be guided by the need to understand global changes of decade-to-century scale and that most affect the biosphere and climate.

Toward this end the initial efforts of the PAGES project will focus on two *temporal streams*, each of which addresses a set of common research themes to define a multi-element matrix organization (Table 1). Within each element of the matrix are specific research tasks. Each will be organized to address key scientific questions that are defined by the overarching needs of the IGBP, through other core activities of the programme, as well as associated projects of the WCRP.

Table 1
PAGES Project Organization

Research Themes	Research Tasks: STREAM I	Research Tasks: STREAM II
A. Solar and orbital forcing and response	A.1 Solar Variations of the Last 2 ka A.2 Forcing Mechanisms	A.2 Forcing Mechanisms A.3 Response of the Ocean A.4 Past Insolation Calculations
B. Fundamental Earth System Processes		
1. Trace-gas composition and climate	B1.1 Role of Trace Gases in the Last 2 ka	B1.2 Trace Gases in Glacial-Interglacial Changes B1.3 Trace Gases in the Late Pleistocene
2. Global impacts of volcanic activity	B2.1 Volcanic Events during the Last 2 ka B2.2 Climatic Variations at Times of Major Eruptions B2.4 Role of Vulcanism in Climate Change	B2.3 Volcanic Events during the Late Pleistocene
3. Ice-sheet mass balance and global sea-level change	B3.1 Ice-Sheets & Sea-Level during the Last 2 ka	B3.2 Response of Ice-Sheets to External Forcing B3.3 Long-Term History of Sea-Level Change
4. Biosphere dynamics and environmental change	B4.1 Effects of Climate & Human Impacts on the Biosphere	B4.1 Effects of Climate & Human Impacts on the Biosphere
C. Rapid and Abrupt Global Changes	C.1 Causes of Abrupt Climatic Changes	C.1 Causes of Abrupt Climatic Changes
D. Multi-Proxy Mapping	D.1 Maunder Minimum Pilot Study	

Cross-Project Activities	Research Tasks: STREAM I	Research Tasks: STREAM II
E. Palaeoclimatic and Palaeoenvironmental Modelling	E.1 Climate Simulation of the Last 2 ka E.4 Reduced Models of Climate System Behavior E.5 Biogeochemical, Vegetation and Tracer Models	E.2 Simulation of Glacial-Interglacial E.3 Changes in Ocean Circulation E.4 Reduced Models of Climate System Behavior E.5 Biogeochemical, Vegetation and Tracer Models
F. Advances in Technology		
G. Management of Palaeodata	G.1 International Palaeodata System	G.1 International Palaeodata System
H. Chronologies for Palaeoenvironmental Research	H.1 Improved Chronologies	H.1 Improved Chronologies
I. PANASH Pilot Project		

Stream I will concentrate on the last 2000 yr of Earth history: the period of man's greatest impacts on the planet and the era of significant overlap between instrumental records and the environmental information stored in natural archives. A better understanding of the climatic and environmental changes that occurred during this period (including the Little Ice Age and preceding warmer intervals, such as the so-called "Medieval Warm Interval") should provide important insights into the rates of regional-to-global-scale changes that are expected to occur within the Earth system in the next 50–100 yr.

A clearer illumination of the global and regional changes that have occurred in the last 2000 yr has many potential pay-offs. The period of most reliable climate history, now limited to at most a few centuries, will be extended at least fivefold; the sources and sinks of trace gases as agents of greenhouse warming can be investigated; a more extensive global record of land-use changes will allow us to begin to assess the effects of past human impacts on the Earth system; it may be possible to distinguish human-induced changes in this period from natural responses to external forcing mechanisms and internal system dynamics, allowing calibration and estimation of anticipated anthropogenic impacts; and, by focusing on the period of overlap between written history and natural records, Stream I research can provide a Rosetta stone which can be used to validate and interpret data from the much more distant past.

> The objective of Stream I of the PAGES project is *to reconstruct the detailed history of climatic and environmental change for the entire globe for the period since 2000 BP, with temporal resolution that is at least decadal and ideally, annual or seasonal.*

Stream II will focus on glacial-interglacial cycles of the last several hundred thousand years of the late Quaternary. It will concentrate on understanding the dynamics that cause glacial-interglacial variations, including the roles of atmospheric chemistry and ocean circulation, and that of biota, to illuminate the interactive feedbacks among various components of the Earth system that control the response of the system to climatic forcing. The objectives are to understand both the causes of change and the way the Earth system functions during times of glacial maximum and minimum conditions; to document the onset and nature of the transitions from warm to cold and cold to warm periods; and to define the causes and characteristics of the more abrupt changes that punctuate these periods and the transitions between them.

A clearer understanding of the forcing mechanisms and natural feedbacks of the glacial-interglacial cycles of the Quaternary period, including the role of hydrology, ocean circulation and the role of biota, will clarify our understanding of the response of the Earth system to changes in radiative forcing — an issue that is at the center of modern-day concerns about greenhouse warming. A much clearer picture of the rapid and abrupt (century scale) changes that are noted in north polar records, in features such as the Younger Dryas cooling, about 11,000 yr BP and the preceding Bølling-Allerød warming episodes, will directly address the natural responses of the Earth system to "rapid" climatic changes and illuminate the inherent stability or instability of the climate system.

> The objective of Stream II is *to reconstruct a history of climatic and environmental change through a full glacial cycle, in order to improve our understanding of the natural processes that invoke global climatic changes.*

The two streams concentrate on periods of Earth history that are very recent in geological terms. Data and insights from the more distant past are obviously necessary to define the background on which the changes addressed in Streams I and II are imposed, and to illuminate processes of longer term that link elements of the Earth system together. Other efforts, not organized within the IGBP, are now directed at understanding this longer run of Earth history. Research within the PAGES Project is meant to complement these other existing efforts, and to be conducted in close communication with them.

Coordinated studies within each of the two streams will be directed toward four **research themes**:

A. Solar and orbital forcing and response;

B. Fundamental Earth system processes, including

1. Trace-gas composition and climate,
2. Global impacts of volcanic activity,
3 Ice-sheet mass balance and global sea-level change, and
4. Biosphere dynamics and environmental change;

C. Rapid and abrupt global changes; and

D. Multi-proxy mapping.

The fourth of these is of a different nature in being an all-embracing activity of the PAGES project that is aimed at the systematic collection and intercomparison of a variety of data from the spectrum of historical and proxy sources that are available. The ability to integrate information extracted from different natural and historical archives is a prerequisite for constructing a composite picture of climatic anomalies and trends in all of the activities of the PAGES project. It defines the needed contribution of PAGES to modelling activities of the IGBP and WCRP. It will also transcend the immediate goals of the IGBP in making available to future generations of Earth scientists a fuller and more organized record of the recent history of the Earth system.

The PAGES project will also address five **cross-project activities**:

E. Palaeoclimatic and palaeoenvironmental modelling;

F. Advances in the technology of the recovery and interpretation of proxy data;

G. Management of palaeodata;

H. The development of improved chronologies for palaeoenvironmental research; and

I. The PANASH Pilot Project.

Activities and eventual products of the PAGES project will include the following:

1. Assessing and compiling what is now known of past environmental changes, to identify temporal and spatial gaps where information is particularly needed or deemed to provide the greatest insight into the operation of the Earth system.

2. Organizing coordinated activities and field campaigns, focused upon selected time slices and sensitive regions of the globe, involving many sources of instrumental and proxy data.

3. Enlisting scientists and technicians to strengthen the cadre of researchers who now work in the acquisition and interpretation of palaeodata and in palaeomodelling, and the national funding needed to support their activities.

4. Synthesizing data that now exists and that will be acquired in the course of PAGES project activities, with the aim of addressing particular questions and evolving needs for these data.

5. Providing synthesized information to validate climatic and Earth system models.

6. Establishing archives of palaeodata for ready worldwide access.

The span of historical and natural records that are now available to answer these and other questions are summarized in Table 2, including the span over which they can be read, their temporal resolution, and some of the information that they provide.

Table 2

Characteristics of Proxy Records

Archive	Resolution	Extent (yr)	Information
Historical records	day/hr	2000	B H L M S T V
Tree-rings	yr/season	14,000	B Ca H L M S T V
Lake sediments	yr	1,000,000	B Cs Cw H M T V
Polar ice cores	yr	100,000	A B Ca H M S T V
Mid-latitude glaciers	yr	10,000	A B H M S T V
Coral deposits	yr	100,000	A Cw L T
Loess	10 yr	3,000,000	B Cs H M T V
Pollen	10 yr	10,000,000	B H T
Ocean cores	100 yr	10,000,000	A B Cw M L T V
Palaeosols	100 yr	10,000,000	A Cs H M T V
Sedimentary rock	yr	10,000,000	Cs H L M V

Legend:

A atmosphere-ocean dynamics
B information on biomass
C chemical composition of air (a), water (w), soils (s)
H humidity and precipitation
L sea level
M geomagnetic field
S solar activity
T temperature
V volcanic eruptions

III. IMPLEMENTATION PLANS FOR SCIENCE COMPONENTS

A. SOLAR AND ORBITAL FORCING AND RESPONSE

Tasks within this activity address the two major climatic forcing mechanisms that are external to the Earth system: (1) the modulation due to *intrinsic* variations of the Sun as a star; and (2) effects of *orbitally-induced* variations in insolation through the Milankovitch effect and related feedback mechanisms. The first has long been considered a potential climate forcing factor on time scales of decades to centuries — a qualification that is imposed largely by our ignorance of solar variations in any era earlier than the Holocene; the second, dealing with the effects of changes in the orbit and the axis of rotation of the Earth, is the most commonly-accepted driver of the glacial-interglacial cycles of the late Pleistocene. Data concerning past variations of the Sun itself are derived from historical records of various kinds and from proxy records in tree-ring ^{14}C and ice-borne ^{10}Be.

1. Intrinsic Solar Forcing and Response

TASK A.1:	**Solar variations in the last 2000 yr**	Stream I
GOAL:	*To establish a decade-by-decade history of change in total solar irradiance (solar constant) and in solar spectral irradiance (particularly in near ultraviolet wavelengths that relate to stratospheric chemistry and ozone concentrations) through the last 2000 yr.*	

The hope of achieving this considerable improvement in what is known of terrestrially-important solar behavior in the past rests largely on comparisons of historical data (direct, written records) with the ^{14}C and ^{10}Be proxies, and on the extension and/or improvement of data in all three of these categories. Each has its own advantages and limitations; taken together, however, much more can be learned.

Proposed Steps for Implementation:

- Recovery of ^{10}Be measurements of high temporal resolution from available and planned mid-latitude cores, for comparison with ^{10}Be data from polar cores and with tree-ring ^{14}C records. Analyzed ^{10}Be records that tell of past changes in solar activity are now restricted to those taken from Greenland and Antarctica. Similar data from mid-latitude cores, as from the Tibetan plateau and the high Andes, can help in separating solar modulation of ^{10}Be production from that due to geomagnetic modulation and to regional or local precipitation effects. PAGES should seek to ensure that ^{10}Be measurements are made in these cores for comparison with high-latitude data, especially that from the high-resolution data sets that will be forthcoming from the current GRIP and GISP II cores from Greenland. From these analyses, and similar comparisons with the now-available high-precision ^{14}C data from tree-rings it should be possible to reconstruct a history of solar activity variations through the complete Holocene epoch.

- Combined analysis of data from tree-ring ^{14}C, ice-borne ^{10}Be (from mid- and high-latitude sites) and historical records. Initial emphasis should be placed on the period of overlap with historical data (the last 370 yr) to provide a kind of Rosetta stone comparison. For the earlier part of this span (before about AD 1750) the proxy data from ^{10}Be is more objective and hence more reliable than the available historical data.

- Multi-proxy comparisons of periods of anomalous solar behavior with concurrent regional and global climate. Of initial interest are the so-called Dalton Minimum (ca. AD 1790–1830), the Maunder and Spörer Minima of solar activity, and the Medieval Climatic Optimum.

2. Orbital Forcing and Responses

TASK A.2:	**Forcing mechanisms**	Streams I and II
GOAL:	*To improve our understanding of the mechanisms through which orbitally-induced variations in insolation pace the major ice ages.*	

A number of critical issues still remain regarding the methods of response of the climate system to orbital forcing. Examples of such responses include the pacing of the glacial cycles of the Late Quaternary and the modulation of monsoonal circulation. Two competing models now endeavor to explain how orbital modulation of insolation drives glacial cycles, one ice-centered and the other ocean-centered. Critical tests may be found through more detailed knowledge of times of transition in glacial-interglacial patterns.

Proposed Steps for Implementation:

- Investigations focused on the mid-Pleistocene climate transition (ca. 900 ka BP) to better characterize this sharp break in climate system behavior. These coordinated studies of this particularly interesting "time slice" of the past would involve the collection and use of a variety of different proxy records such as $\delta^{18}O$ records from deep-sea cores and loess records — particularly those high-resolution data sets from China's loess plateau.

- Complimentary investigations of the termination of the last major glaciation, ca. 15 ka BP. No existing climate model has been able to provide a fully satisfactory explanation of the physical processes involved in such events. We need improved time-resolved data sets to distinguish the relative contributions of solar insolation changes, CO_2 forcing, changes in deep ocean circulation, and other effects.

- A major international workshop to address Glacial Cycles and Forcing Mechanisms, to follow the NATO Advanced Research Workshop held in Majorca in 1991 on Glacial-Interglacial change. These organized endeavors can help to identify the major unknowns in our present understanding, including the pressing question of whether glacial-interglacial transitions are gradual or step-wise features, and to define data sets that are most needed.

Ocean response to external forcing

The oceans play a major role in climate, both on short and long time scales. This is realized through a number of processes, including:

- transfer of heat from low to high latitudes and between hemispheres (both at the ocean surface and deep within it),

- transfer of latent heat by evaporation from the ocean surface,

- changes in high latitude albedo and in heat transfer by sea ice formation and melting, and

- storage of a major fraction of the global carbon budget and regulation of atmospheric pCO_2.

Only low-latitude surface-ocean changes may be easily monitored over the time scale of Stream I, because resolution is blurred in most ocean sediments by bioturbation. The chemical and isotopic study of annual growth layers in coral (the first through relative amounts of Cd and Ba; the second through $^{18}O/^{16}O$, $^{13}C/^{12}C$, and $\delta^{14}C$ ratios) offer good opportunities to collect long time series of the variability of the tropical surface oceans. Within Stream II, different proxies may be analyzed in sediment cores to quantify the ocean response to changes in insolation over thousand year time scales. These include:

- high latitude diatom floral changes associated with sea ice

- dependence of planktonic foraminifera species distribution on surface water temperature (the CLIMAP approach)

- spatial gradients in planktonic and benthic foraminifera $\delta^{18}O$, as a function of ocean temperature and salinity

- spatial gradients in foraminifera $\delta^{13}C$, $\Delta^{14}C$, and the Cd/Ca ratio, which serve as proxies for dissolved nutrient and carbon distributions. Indirectly, these are tracers of ocean circulation and deep convection.

TASK A.3 **Response of the ocean** Stream II

GOAL: *To improve our understanding of the chaining of the different mechanisms by which the ocean responds to insolation changes and affects air temperature, humidity, and trace gases in the atmosphere, with particular attention to* CO_2*,*

and

to document the changes in distribution of surface and deep ocean temperature, salinity, and the changes in circulation at critical times of the last climatic cycle, including

- *the initiation of the last glacial cycle, ca 120 ka BP*
- *the first drastic cooling and ice extension, ca 70 ka BP*
- *the last glacial maximum, ca 18 ka BP*
- *the last deglaciation and Younger Dryas*
- *the apparently critical period of change, ca 400 ka BP, when drastic changes occurred in the long term oscillatory patterns of climate.*

Finding answers to these key questions will require:

- a significant increase in the number of high sedimentation rate cores to be analyzed, so as to cover the full depth range in the different oceanic basins and along the major tracks of the main water masses. The most useful sediment cores for this purpose should be taken along continental margins, within the 200 mile limit of coastal countries. International support may be helpful in obtaining the necessary working permits. The addition of special equipment to the coring ships must be encouraged, to allow 30 to 50 m long cores to be collected in these

areas, to cover the last few hundred thousand years. The study of major changes on longer time scales (millions of years) would benefit from new vessels offering hydraulic piston coring facilities for 200 to 300 m length cores, as proposed for example in the European project NEREIS.

- continuous sampling of these cores in order to follow the evolution of the oceanic system within appropriate time scales (several hundred year resolution). This implies a considerable number of analyses, which may be implemented only with automated systems. These are now available for isotopic studies, but have to be developed in micropalaeontology using digital shape analysis and artificial intelligence software.

- a precise intercalibration of the different techniques within participating laboratories, to ensure precision and accuracy of palaeo-oceanographic reconstructions, by:

- creation of one or several reference global collections of micropalaeontological samples characteristic of modern environments (from high sedimentation rate core tops), in the most representative state of preservation, so that each reference collection can be exactly compared in terms of species distribution and preservation state. Such collections should be established for diatoms, foraminifera and radiolaria, the most common families used for palaeo-oceanographic reconstructions; and

- standardization and intercalibration of oxygen and carbon isotopic ratio measurements in foraminifera. Differences larger than 0.2‰ exist between the specialized laboratories, when mass spectrometer reproducibility is better than ±0.05‰.

Both intercalibration processes could be managed through SCOR working groups.

Specific Tasks:

3.1 Determine precisely, in relation to insolation forcing and evolution of the ice sheets, when and how much high latitude surface waters warm or cool, when and how much the boundaries between the surface water masses shift (especially those corresponding to the zero wind stress curl), and when and how much surface water productivity changes.

3.2 Determine when and how deep water reacts to surface water changes, and the implications on heat transport and the carbon cycle.

3.3 Determine when and how much carbonate is accumulated or dissolved in sediments and the associated implications for ocean alkalinity and atmospheric pCO_2.

3.4 Provide a set of well constrained reference stratigraphic markers tying closely the continental, ice, and oceanic palaeoclimatic signals (including, for example, volcanic ashes, pollen, dust, magnetic secular changes, and cosmogenic isotopes).

TASK A.4:	**Theoretical calculations of past insolation changes**	Stream II
GOAL:	*To provide more accurate and detailed calculations of past changes in insolation due to orbital modulation.*	

Recently completed analyses of the evolution of the orbits of the 9 planets by Quinn *et al.* (1991) and by Berger (1991) and others have provided information of increased precision on the evolution of Earth orbit changes over the past 3 million years. These new orbital solutions, derived from improved calculations in celestial mechanics, need to be made more generally available to the community of scientists that study Milankovitch forcing.

Proposed Steps for Implementation:

- A PAGES Data Management and Distribution Center (see Section E.3 below) will assist in making these and other data sets available to interested scientists around the world.

General Recommendation:

The PAGES project may need to consider an additional activity, parallel to that for external forcing, devoted to the compilation and analysis of palaeo-records of *internal* climate system variability. This is addressed only in part in the PAGES focus on Rapid and Abrupt Global Changes. A good example of the additional kinds of data that are needed are records of the interannual variability that results through the ENSO phenomenon (for which palaeodata are available in various archives) and (orbitally-modulated) monsoonal circulation.

B. FUNDAMENTAL EARTH SYSTEM PROCESSES

For the purposes of PAGES organization we consider four internal processes within the Earth system for which palaeodata hold important information on the operation of the coupled Earth system.

1. Trace-Gas Composition and Climate

Over the last 200 yr human activities have seriously altered the concentration of trace gases in the atmosphere. Many of these gases are radiatively active, and thus directly affect the course of future climate change. To be able to predict the impacts of human intervention we must first understand the natural processes, including feedbacks and limits, against whose background man-made changes will operate. Critical clues to these lie principally in the past behavior of the system, at a time when human impacts were absent or minimal. The research in this field aims to understand the complicated interplay between trace gas cycles and climate. This includes understanding the mechanisms of change and the processes of interaction with other elements of the system, including biota. Reliable palaeodata, with sufficient temporal resolution, can provide insights into leads and lags in the system. The effort now underway concerns mainly radiatively active trace gases: CO_2, CH_4, and to a lesser extent, N_2O, as these are deemed relevant to future greenhouse warming.

TASK B1.1:	**Role of trace gases in the climate changes of the last two millennia**	Stream I
GOAL:	*To document the changes in global atmospheric concentrations of CO_2, CH_4, and N_2O and other trace gases over the last 2000 yr.*	

Proposed Steps for Implementation:

- Determine atmospheric trace gas abundances during the Little Ice Age and Medieval Warm periods in both hemispheres and compare these with climate data for these periods. To be determined are whether significant, rapid changes occurred that give information on global temperature changes during these two extreme periods. During this period trace gas changes may not have played an important role in driving climate change; at the same time knowledge of variations during this time can yield important information on the operation of the Earth system. The onset of the "Little Ice Age" may have occurred before the start of the Industrial Revolution; thus this period, and the entire "Medieval Warm Epoch" (ca. AD 1000–1300) provide opportunities for comparing trace gas variations, if present, with climatic features that are within the range of written records. Comparison of these more rapid climate changes with trace gas abundances will add new information in understanding greenhouse warming, and should elucidate the sources, sinks and feedbacks in these gas cycles in order to predict future impacts of these gases on climate. It will also be necessary to develop a better understanding of other trace gases such as CO, H_2O, and non-methane hydrocarbons (NMHC) which are involved in greenhouse gas cycles, and to measure isotopic compositions of all these gases as source and sink indicators.

The data required to answer these key questions traditionally has come primarily from polar ice cores which provide a direct sample of the atmosphere of the past. Modern techniques for their recovery and analysis make it possible to achieve a temporal resolution of about 1% of the actual age, or ± 10–20 yr in the period of Stream I. In terms of changes in the carbon cycle, we should re-evaluate the use of $\delta^{13}C$ values in tree-rings, peat bogs and lacustrine sediments as proxies for carbon fluxes in and out of the biosphere. Important oceanic fluxes can be addressed through coral reconstructions of ENSO cycles.

Existing multi-national efforts include ice coring projects in Greenland (GISP II and GRIP), past vegetational histories from pollen distributions (COHMAP, EPOCH) and regional scale studies of human impact on climate (ESF Palaeoclimate and Man Project). Individual initiatives abound, and PAGES can contribute by coordinating these efforts.

TASK B1.2:	**Role of trace gases in glacial-interglacial changes**	Stream II
GOAL:	*To quantify the role of trace gases as forcing factors for climate change during glacial-interglacial changes and changes that were more rapid and abrupt.*	

Specific Tasks:

2.1 Determine the importance of trace gases as forcing factors relative to insolation changes (Milankovitch effect), ice volume feedback and atmospheric aerosol content.

2.2 Establish the phase relationship between changes in trace gas concentrations and climate parameters, including ice volume and surface temperature.

2.3 Determine whether changes in trace gases accompanied the rapid and abrupt changes that are found during the last glaciation and during the onset of the present interglacial.

2.4 Document trace gas changes through as many climatic cycles as possible during the late Pleistocene to determine the period of the Quaternary through which climate and greenhouse gases were closely connected.

2.5 Compare trace gas and climate data taken from Antarctic ice cores with the same data from the Arctic (Greenland cores) in order to synchronize Arctic and Antarctic records and to compare climatic evolution in the two hemispheres.

TASK B1.3:	**Trace gas variations through the late Pleistocene**	Stream II
GOAL:	*To determine the causes of natural variations in trace gas concentrations during the glacial-interglacial cycles of the late Pleistocene.*	

Proposed Steps for Implementation:

3.1 Document changes in atmospheric CO_2, CH_4, N_2O, and H_2O with high resolution during this period.

3.2 Establish the phase relationships that have applied in the past between changes in concentrations of different radiatively active gases.

Data needed to answer the questions in Task 3 have come primarily from marine sediment cores and ice cores. Improvements need to be made in understanding marine carbon budgets (for the $\delta^{13}C$ / pCO_2 calculation) and in the absolute and relative dating of ice cores, marine sediment cores, and other proxy data recorders. Considerable unknowns exist regarding changing amounts of water vapour. These can be resolved in part through reconstructing former large-scale water budgets.

Existing efforts include the GISP II and GRIP ice coring projects currently underway in Greenland, the SPECMAP project, and the German Climate Research Project.

Specific PAGES Activities:

The project-wide PANASH initiative described in Section IV of this report can do much to promote needed intercomparisons of Northern Hemisphere and Southern Hemisphere ice, marine, and land records of trace gas compositions.

Workshops on the following topics would aid in palaeostudies of trace gases and climate:

1. Correlating ice core records from different hemispheres and latitudes.

2. The past global carbon budget derived from CO_2 abundance (ice cores) and isotopic changes (ocean and lake sediments and tree-rings) and from vegetation mapping, including a comparison with models of climate and of vegetation.

3. Techniques of ice core drilling.

Relationships with Other IGBP and WCRP Projects:

PAGES activities in this area will work closely with the PAGES palaeo-modelling activity (Section E1 below), including modelling of the sources and sinks and of the climatic impact of past changes in trace gas abundances. They will need also to collaborate actively with other IGBP projects including IGAC, JGOFS, GCTE and GAIM. Specific activities within IGAC, which is the most relevant IGBP Core Project, are listed below for cross-reference. Connection with the WCRP should also be emphasized.

IGAC studies of particular relevance to PAGES:

- IGAC Focus No. 3: The role of polar regions in changing atmospheric composition, including Activity 1 [Polar atmospheric chemistry: Task 2 (Long-range transport of air pollution into the Arctic)] and Activity 2 [Polar air-snow experiment: Task 1 (model development) and Task 2 (chemical analysis of current snow, trace gas and aerosol composition)]. China has also undertaken a major research project for emphasis in 1991–1995 on Modern Environment Background and Climate and Environment Evolution in the Antarctic Region since the Late Pleistocene.

- IGAC Focus No. 5: Global distributions, transformations, trends and modelling, specifically Activity 3 (Development of global emission inventories). Any information that ice cores or sediments may give on the deposition and atmospheric concentrations of CO, CH_4, N_2O, NO_3^-, $SO_4^=$, etc. are very important to aid in estimating natural sources of these compounds and as a check on model calculations of the chemical composition of past atmospheres. It would be also desirable to emphasize the potential information in lake sediments, ombrogenous peats, and ice cores on biomass burning of the past, which was previously the only important source of air pollution.

• IGAC Focus No. 8: Cloud condensation nuclei as controllers of cloud properties. Information on $SO_4^=$, DMS, and particulate matter deposited in ice cores would be of potentially great importance in relation to climatic changes of the past.

2. Global Impacts of Volcanic Activity

Ice-core records from Greenland and Antarctica have revealed the occurrences of widespread volcanic activity throughout the Quaternary period. This is detected by varying levels of sulfuric and other aerosols in stratigraphically discrete layers. Although it has been postulated for years that aerosols may cause climatic change, the availability of records of explosive volcanism in ice-core data has heightened this interest. Still, the influence of aerosols as a forcing mechanism has not been evaluated satisfactorily. Three present obstacles are: (1) the chronology, distribution and character of volcanic eruptions are not well understood; (2) the relative importance of aerosols, compared to solar activity and greenhouse gases as forcing mechanisms; and (3) the role of changing patterns of atmospheric circulation that distribute volcanic effluents latitudinally.

A relationship has been established between the presence of aerosols, particularly sulfuric aerosols from volcanism, and global surface temperature in the short term. Sulfuric aerosols, mainly H_2SO_4 derived from SO_2, appear to lower the temperature of the lower troposphere through back-scattering of solar radiation. This has been concluded from observations and empirical studies of eruptions over the last 100–200 yr. The magnitude and composition of an explosion determines the influence of volcanic eruptions on climate and whether the effect is local or worldwide. Temperatures may be lowered on the order of 0.2 to 1.0°C for a period of up to two years.

High acidity levels are recorded at various depths in ice-cores in Greenland and Antarctica. Greenland records provide

resolution on the order of $\pm$ one year for the past few hundred years from the Crete core, whereas the more than 100,000 year old record from Camp Century is well dated through the Holocene. Resolution decreases in all ice cores more or less exponentially with depth; however, the Camp Century cores clearly show more volcanic activity at the beginning and at the end of this time span. The source of volcanism is commonly determined from historical data or geological evidence. High energy eruptions recorded in Greenland ice-cores have sources north of latitude 20°S whereas Antarctica ice cores contain aerosols from south of 20°N. Comparison of the two data sets show that some high energy eruptions, such as Tambora in 1815, show up in both records and may have had a global impact on climate.

Various factors inhibit translating volcanic activity into regional or worldwide temperature changes. However, climatic effects of volcanism have been investigated by comparing continental temperature data from the Northern Hemisphere with the timing of major explosive eruptions. This comparison indicates that the largest eruptions are associated with significant drops in summer and fall temperatures but the effects are short-lived, lasting on the order of 2 to 3 months and then diminishing thereafter for up to 2–3 years. Location and magnitude of the eruption determines the effect on surface air temperature, but temperature depressions associated with some of the largest eruptions may be as much as 0.4°C.

Attention has also been focused on highly sensitive short term (decadal scale) alpine glacier fluctuations that have occurred in the past few hundred years in North America. Causes of these fluctuations have been attributed to solar variability, volcanic aerosols and CO_2 loading. Comparing glacial data with the Greenland ice-core records, an argument can be made that volcanic activity is connected to glacial activity. Further, acidity values may be related to the degree or size of the advance. Multiple or closely spaced eruptions may cause longer periods of cooling, as, for example, during certain decades within the "Little Ice Age," when global surface temperature may have been 0.5 to 1.2°C lower than during the present century. Climatic effects of volcanism have also been tested by studies of tree-ring growth. For example, studies of tree-rings from the Sierra Nevada Mountains suggest that major volcanic explosions may be responsible for a 1–2 year temperature depression with a 1°C drop after the first year. The same seems true for the widely known Laacher See eruption of late glacial time in Europe. In addition, clusters of significant volcanic events may have produced longer term effects.

To understand better the influence of volcanic and non-volcanic aerosols on climate, we must first improve our knowledge of the chronology, magnitude and character of volcanic eruptions. More analyses of acids in ice-cores are needed to detect what is volcanically-related and to establish temperature variations in relation to the amount of aerosol loading. Finally, we need to supply modellers with more reliable data on volcanic aerosols, particularly size distribution, optical characteristics, and half-lives in the atmosphere.

TASK B2.1:	**Volcanic events during the last 2000 yr**	Stream I
GOAL:	*To improve the chronology and description of volcanic eruptions during the last 2000 yr.*	

Specific Tasks:

1.1 From existing data, compile descriptions of individual volcanic events utilizing ice cores, tree-rings, documentary records, high-resolution lacustrine and marine sediments, and continental and marine tephra occurrences.

1.2 Compare Northern and Southern Hemisphere records of volcanic effects to establish global vs regional impacts.

1.3 Specify the temporal resolution of each of the records mentioned above to aid in establishing more precise chronologies.

Proposed Steps for Implementation:

- Organize a multidisciplinary workshop including ice core and tree-ring experts, volcanologists, historians and high-resolution stratigraphers to evaluate existing records and to identify gaps in the record. A possibility is a NATO Advanced Research Workshop.

- Compile and make available a digital data set of volcanic events.

TASK B2.2:	**Climatic variation at times of major eruptions**	Stream I
GOAL:	*To establish climatic conditions at times of known volcanic events in order to elucidate detailed forcing mechanisms.*	

To accomplish this it will be necessary to identify, collate and evaluate records of past climate for years before and after known major volcanic eruptions and for periods of clusters of eruptions, for the last 2000 yr. It will also be necessary to compare records within similar belts of latitude in the Northern and Southern Hemispheres.

Specific Tasks:

2.1 Utilizing information from Task 1, above, identify times of key volcanic eruptions for climate-response analyses.

2.2 In parallel, collate available data and identify areas where data are particularly needed.

2.3 Critically evaluate records of climate history in selected latitudes and of the entire globe for periods of enhanced volcanic activity.

Proposed Steps for Implementation:

- Organize a multidisciplinary group including ice-core specialists, glacial geologists, tree-ring specialists, climatologists, and geochronologists to carry out above tasks.

- Establish INQUA working groups to carry out Tasks 2.1 and 2.2.

TASK B2.3:	**Major volcanic events during the late Pleistocene**	Stream II
GOAL:	*To improve the chronology and the understanding of the major volcanic eruptions and sequences during the late Pleistocene, to determine their role in climatic changes of the period.*	

Specific Tasks:

3.1 From existing data, compile key volcanic and non-volcanic dust events utilizing ice-cores, tree-rings, lacustrine,

aeolian and marine sediments, and continental and marine tephra occurrences, from the Northern and Southern hemispheres.

3.2 Critically examine the temporal resolution and spatial distribution of each of the above.

3.3 Critically evaluate records of climate history in selected latitudes and of the entire globe for periods of enhanced volcanic activity.

Proposed Steps for Implementation:

- Organize a multidisciplinary workshop, including appropriate specialists, to evaluate existing records, to identify gaps in the records, and to assess their possible climatological impacts.

- Negotiate with an INQUA commission such as the Tephra Commission to carry out Tasks 3.1 and 3.2.

TASK B2.4:	**Relative role of volcanism in climatic change**	Stream I
GOAL:	*To determine the relative role of volcanic forcing and dust events,compared to the effects of greenhouse gases and solar variability.*	

Specific Tasks:

4.1 Apply models utilizing the results of Tasks 1, 2, and 3 and available data on other possible forcing mechanisms.

3. Ice-Sheet Mass Balance and Global Sea-Level Change

Global sea-level rise is acknowledged as a potentially important result of greenhouse warming, although the amount of the increase to be expected over the next 50–100 yr is as yet uncertain. The uncertainty in identifying the cause of the observed rise over the last century and in forecasting future changes stems in part from incomplete knowledge of the mass balance of the major ice sheets with the contributions to the uncertainty from the Antarctic and Greenland ice sheets and local glaciers decreasing in magnitude in the order mentioned. An uncertainty of ±20% in the estimated snow accumulation in Antarctica is e.g. equivalent to a change in sea-level of about 10 cm/century. Enhanced greenhouse warming may significantly increase the yearly amount of water stored in the Antarctic ice sheet, which would result in lowered sea-level, whereas the warming is believed to increase melting of the Greenland ice sheet to such an extent that a positive contribution to sea-level rise is expected from this ice sheet. A much better knowledge of the mass-balance parameters, including melting from below ice shelves and iceberg calving, is needed in order to resolve these uncertainties. This information is needed to evaluate the importance of ice-sheet mass balance relative to other factors that alter sea-level (e.g., tectonic-glacial isostatic, eustatic, and human intervention) and to estimate more accurately both past and predicted variations.

The stable oxygen isotopic record from deep-sea cores shows the long-period changes in the ice sheets and glaciers of the globe. The waxing and waning of the great ice sheets of the Northern Hemisphere has transformed the landscapes of Northern Australia, North America, and Western Europe. As ice spread, sea-level fell and vice versa; this can be measured along coastlines, provided they are stable. The modern great ice sheets of the Antarctic and of Greenland continue to hold the keys to the size of future sea-level change that might result from enhanced greenhouse conditions.

The global ice budget is therefore a fundamental aspect of the Earth that must be investigated on a range of timescales. Accumulation rates and calving rates need to be known on observational time scales of years. The sea and the ice are, however, still responding to the last glaciation. Modern effects are therefore superimposed on a long-period change. This change can only be investigated using palaeo-sea-level data, coupled with ice-flow modelling constrained by dated ice cores.

The current estimates of the mass balance of the major ice masses of the Earth are accurate to within 10–30%. This is not good enough. In the plan that follows, it is proposed that the best of modern observational methods be combined with the best that the palaeo-records offer to reduce this uncertainty.

Key tasks are given for each temporal stream in order of priority:

TASK B3.1:	**Ice-sheets and sea-level during the last 2000 yr**	Stream I
GOAL:	*To substantially reduce the uncertainties in the mass balance of the major ice masses of the Earth to better understand and explain the current rate of sea level change.*	

Specific Tasks:

1.1 Utilize palaeo sea-level data to both constrain the discharge rate of the Antarctic and Greenland ice sheets during the last few centuries (in Greenland, before the modern construction of coast-protecting dams) and to constrain the parameters of glacial isostatic adjustment models of sea level change.

1.2 Compile existing ice core data and obtain a statistically sound sample of cores to further constrain the accumulation rate of ice sheets. Some of the needed information can be obtained from surface traverses; also needed is information on ablation rates and calving of glaciers.

Proposed Steps for Implementation:

- Organize a workshop to further plan the determination of ice sheet accumulation rates using short ice cores. The rates are to be determined over approximately the last 200 yr with proper attention to a rigorous analysis of the statistics of the sampling. The output of this workshop will provide ground truth for remote sensed estimates of accumulation rates and input to ice sheet modelling and important information about atmospheric chemistry, surface temperature, and relationship between climate and accumulation rates during the few centuries. Priority will be first Antarctica, followed by Greenland and finally mountain glaciers.

Existing Efforts:

NOAA/NASA Satellite altimetry programme; International Trans-Antarctic Scientific Expedition; ANARE/CSIRO/CNRS Accumulation Rate Estimates; University of Melbourne mountain glacier balance re-assessment; Australia/UK/NZ tripartite study of New Zealand glacier mass balance; EPOCH programme on Climate Change, Sea-Level Rise, and Associated Impacts in Europe; GISP II and GRIP ice coring projects in Greenland. The WCRP is also becoming involved.

TASK B3.2:	**Response of ice sheets to external forcing**	Stream II
GOAL:	*To determine the response of ice sheets to external forcing and the contributions that changes in trace atmospheric gases may make to this response, using ice core analysis and models of mass balance and ice-sheet dynamics.*	

Specific Tasks:

2.1 Secure data from ice cores to cover the last two glacial-interglacial cycles for purposes of correlating ice volume with the marine record and with calculations of astronomical forcing; include detailed ice records of the period since the Last Glacial Maximum to study the controls of abrupt climate changes.

2.2 Investigate the velocity and amplitude of episodes of sea-level rise during the beginnings of the Holocene and the last interglacial, and the timing and velocity of late interglacial regressions.

2.3 Develop relationships between accumulation rates, temperature and precipitation in data from Antarctic cores.

Existing Efforts:

GRIP/GISP II Deep Drilling initiatives in Greenland; Ice Sheet Modelling by many groups; Ongoing Vostok drilling and analysis; University of Melbourne/ANARE/CSIRO estimates of controls on accumulation rates; the ESF ice-sheet dynamic modelling workshop in Cambridge (UK) of April 1991; and geologic coast surveys in many countries. The WCRP is becoming involved and there are reasons to pursue a working connection with GEWEX.

TASK B3.3:	**Long-term history of sea-level change**	Stream II
GOAL:	*To determine constraining values for the long-term history of net sea-level rise during the transition from glacial to interglacial conditions.*	

Accomplishment of this goal will depend chiefly upon further examination of coral records of sea-level, since these provide the principal data that fix the maximum volume of continental ice that existed at the times of glacial maxima.

Specific Tasks:

3.1 Secure additional records of sea-level change during several glacial-interglacial transitions from the Huon Peninsula and elsewhere.

Existing Efforts:

Examples are coral coring by Lamont-Doherty and Gif-sur-Yvette groups; analyses being carried out by Caltech/ANU/Nagoya University; proposed drilling by Nagoya University in Ryukyu Islands.

Considerable additional information may be obtained on this and other questions dealing with ice sheets and sea-level from the history of lake basins, such as, for example from the study of existing extinct lakes on various continents.

4. Biosphere Dynamics and Environmental Change

Biospheric dynamics are closely related to climatic changes of the Earth. This applies to ocean planktonic productivity as well as terrestrial biological communities. There has been a rhythm of changes following glacial and interglacial periods which is well documented for the last million years. However, some interactions are not completely understood, such as time-lag between physical climate change and worldwide biome displacements during the Holocene. One fundamental question is how CO_2 variations are controlled on the glacial/interglacial scale. Nor do we have access to quantified data on biomass, carbon storage and other matters related to the major biogeochemical cycles.

The situation during the Holocene differs from all other interglacials because of the human exploitation of the biosphere. The agricultural economy had already been introduced on some continents by 10,000 yr BP, with its impact accelerating until the present. Ecologically this brought deleterious local effects including deforestation, soil erosion, and peat exploitation. Indirectly this affected the albedo, the hydrology, the carbon cycle, and the climate. Among palaeoecologists and climatologists there are two contrasting views: some hold that human disturbance played a major role in climate and hydrology throughout prehistoric time; others contend that these interventions constituted a minor factor until the global population explosion of the last 200 yr. This conflict probably has its background in the scale (time and space) within which different processes act but this has to be clarified and the different effects of the disturbances quantified.

It has been assumed that the terrestrial biosphere has been composed of major biomes with predictable responses to the global climate. It has been shown from broad-scale vegetation and faunal reconstructions that taxa respond in an individualistic way, which means that communities present today are unique and that other combinations of taxa occurred in the past. Techniques such as pollen and micro-fossil mapping have confirmed the long-term dynamic response of the biosphere to broad-scale environmental change. The record of past vegetation will therefore provide important indications as to how biomes will respond to the changed climate of the future and help test models of climate change and the response of biomes to climate change.

Of importance for a better understanding of global biogeochemical cycles is the documentation of past vegetation as well as storage of organic carbon and other components in peatlands and soils. Until now only the broad-scale relative changes during the last glacial/interglacial cycle are known. It is now urgent to quantify the biomass and the organic carbon in vegetation, peat deposits, soils, etc., for selected time slices. Such work has to start with the dynamics of modern vegetation and soil systems.

TASK B4.1:	**Effects of climate and human impacts on the biosphere**	Streams I and II
GOAL:	*To quantify climatic and human impacts since the last glacial maximum on biomass, carbon storage and related parameters of marine and terrestrial ecosystems, including marine biota, terrestrial vegetation, peatlands, and soils.*	

Key Questions:

1) What are the global biospheric responses to climatic changes, as expressed in changes of biomass, CO_2, CH_4, etc.?

2) What is the relation between marine and terrestrial biological production during a glacial/interglacial cycle?

3) Are there variations in the marine/ocean productivity during Holocene?

4) Do there exist major biotic changes in parts of the biosphere which are more or less independent of climatic changes, and how important are they?

5) How does human impact transform ecosystems; e.g., deforestation, soil erosion and peat exploitation?

6) How and when does human disturbance have an impact on biogeochemical cycles, climate and hydrology?

7) How long are the lag-times between human perturbations and the resulting impacts on various components of the biosphere?

8) How is the climate influenced by natural or human-induced changes in the biosphere?

New research should follow two different approaches in order to answer the key questions above:

i. obtaining well-dated time-series at selected sites; and

ii. global mapping of available data.

Specific Tasks:

1.1 Identify key areas and transects in climatically-sensitive areas as well as areas for which data are currently lacking, such as Central Asia, tropical areas, and polar areas. The cross-correlation of different types of palaeodata, including that from high-resolution ice-cores, is important within these and other areas.

1.2 Identify key tree-ring and varved lake sediment palaeoecological sites or regions with annual time resolution and correlate annual increments taken from these. The search should extend to at least late glacial times in various parts of the world.

1.3 Identify key areas for studies of long-term human impact on vegetation and soils with the purpose of quantifying ecosystem changes, such as Central Europe, the Middle East, the Far East, Southern Africa and Australia.

1.4 Identify and quantify the consequences of long-lasting impacts on terrestrial ecosystems in view of an entrophication of shelf seas and their bioproduction and hydrologic functioning.

1.5 Quantify the response of biomass and carbon storage to changes in CO_2 and CH_4 and the resulting changes in marine biota, terrestrial vegetation, peatlands and soils, including peat and soils in permafrost regions.

1.6 Map the broad-scale patterns of vegetation and biomass for selected time-slices (see Multi-Proxy Mapping, Section III D, below): 18, 11, 9, 6 ka and during the last two millennia.

1.7 Develop and test models of the interaction between climate and the biosphere.

Proposed Workshops:

1) Inventory of Available Palaeo-data. This should include development of a sampling strategy for a few key areas, considering climate as well as human impact. Particular emphasis should be given to important sites with datable chronologies. Needed are innovative techniques and strategies for separating human from natural impacts.

2) Quantification Methods for Reconstructing Past Biosphere Dynamics including the Carbon Cycle. The following data sources should be included: (a) marine, (b) terrestrial vegetation, (c) peat, and (d) soils.

Existing Efforts and Related Programmes:

IDEAL

The IDEAL Project (International Decade for the East African Lakes) is a nascent multi-national, multidisciplinary study of East African rift lakes whose primary goals are to obtain long, high-resolution records of climatic change in tropical East Africa and to provide a comprehensive training programme for African students and scientists. IDEAL will at the same time strengthen African institutional capabilities in the aquatic sciences and establish research partnerships between African and Northern Hemisphere limnologists and palaeoclimatologists.

The IDEAL project is an obvious contributor to PAGES, in both Stream I and Stream II, and has been designed internationally with the needs of the IGBP and the PAGES project in mind. It has particular relevance to biosphere dynamics and particular value in providing data from a region of Earth from which palaeodata are in short supply.

The large lakes of the East African rift valley are among the oldest on Earth, containing an invaluable record of climatic change in underlying sediments that extends back several million years in time. The record is unique, because it is the only one of tropical climatic change on the African continent that is both of sufficient temporal resolution to be compared directly to proxy records in tree-rings and ice cores and of sufficient temporal longevity and continuity to be compared directly to proxy records in deep-sea sediments. It can also be directly connected with written records of low and high water levels of the river Nile since about 3000 B.C. Through the increased understanding of how large lakes at low latitudes respond to climatic forcing one can gain insight into how complex natural systems interact.

Four or five of the major East African lakes will be selected for long term study. Each will be occupied by a research vessel for a year to understand and monitor seasonal variability in the physical and biological processes related to climatic forcing. Most of these lakes will be occupied for a second year to assess interannual variability. Additionally long-term monitoring arrays that include thermistor chains, current meters, transmissometers and time-series sediment traps will be deployed in each lake. These limnological studies will be designed primarily to establish the linkage between climatic and other forcing functions with sediment composition.

Over four kilometers of sediment underlie some of the rift valley lakes, and it is hoped to acquire from these and smaller lakes continuous records that extend back at least through the last two glacial-interglacial cycles, including the seasonal variability of climate (temperature, wind intensity and direction and other parameters), changes in the hydrological budgets of the lakes, and changes in the distribution of vegetation in the vicinity of the lakes that are studied.

Other Related Programmes

Many Quaternary palaeoecologists are involved in research on past biotic changes and their relation to different environmental factors. There are also several attempts to coordinate available data, for example, COHMAP (with a global approach for the last 18 ka), ESF/EPC for the study of the human influence on climate and ecosystems since approximately 6500 BP in Europe, various INQUA commissions including the Holocene Commission, pollen data bases in North America (such as the work of Webb *et al.* at Brown University) and Europe (EPD at Arles, France). The COHMAP and ESF/EPC projects include palaeoecological data of different kinds; the other projects and databases are concentrated on pollen data. However, most of these data are descriptive and in general give no direct information on biomass and carbon storage of vegetation, with the exception of the EPOCH programme. Work on

vegetation dynamic models has been initiated by scientists linked to IIASA, and we can hope that estimates of past biomass can be calculated from a pollen-analog approach. Phytomass estimates for parts of Eurasia have been performed at the USSR Academy of Sciences for the last glacial/interglacial cycle.

Within China, a major research activity for the 1991–1995 period concerns Dynamic Processes and Developing Trends of Environmental Change in Arid and Semi-Arid Areas of China in the Past 150 ka.

The US National Geophysical Data Center (NGDC) and the German research project on terrestrial palaeoclimates will be available for the coordination of palaeodata through their Palaeoclimate programmes.

Most Quaternary palaeoecologists are linked to INQUA and its commissions. The Holocene commission has subcommissions for each continent. Through this organization it may be possible to fill the gaps in the geographical coverage of palaeoecological data.

C. RAPID AND ABRUPT GLOBAL CHANGES

Abrupt climatic changes of decades to centuries duration have been identified in a number of palaeorecords from the late Pleistocene, including ice cores and lake sediments. Such changes are possible analogues of the greenhouse induced warming that is now anticipated in the first decades of the next century. Most of these changes seem to be the result of combined internal and external forcings of the Earth system. Of special interest are the responses in chemistry (e.g., atmospheric composition) and in biota as recorded in pollen composition in peat and sediments to changes in the physical climate system, as these changes are determined through isotope studies in ice, lake and ocean sediments.

Main emphasis is given to the last glacial-interglacial transition (Oldest Dryas - Bølling, Allerød - Younger Dryas, Younger Dryas - Preboreal) and the rapid changes between cold and mild climate states observed in the Greenland ice cores for the period from 80 to 30 ka BP. Rapid changes during the Holocene are also of interest in this context provided they are at least regional in extent.

The recovery of Earth system parameters, primarily those linked to rapid changes during the glacial-interglacial transition, but also during the last 2000 yr, will develop the data base needed for major modelling emphases of the PAGES project.

In present estimates of the future evolution of climate, the biological feedbacks leading, for example, to internally induced changes in CO_2 and CH_4, cannot be adequately included because of their complexity. A knowledge of past biological responses to climatic changes, including the role of greenhouse gases, may at least give indications regarding the direction and magnitude of these feedbacks.

Key Questions:

- What does the spectrum of climatic and environmental parameters tell us about rapid Earth system changes? How were these changes distributed over the globe? What were the rates of change?

- What can we learn about the relationships of chemical and biological changes to concurrent physical changes? What were the phase relationships between these changes?

- What indications can we find regarding the possible causes of the changes? Are they due to external or internal forcing (e.g., switching between two modes of system operation)?

- How can we improve the absolute and relative dating [annual layer counting, tree-ring chronologies, reference horizons, radioactive dating (e.g., ^{14}C)] of the different types of information? How can, for example, the rapid changes observed in the Greenland ice cores be synchronized with climatic variations observed in the Antarctic ice cores?

TASK C.1:	**Causes of abrupt climatic changes**	Streams I and II
GOAL:	*To determine the causes and characteristics of abrupt changes in a global perspective, comparing particularly events and patterns of change in both the Northern and Southern Hemispheres.*	

Specific attention should be directed at comparing abrupt changes in the last glacial period in ice cores from both polar regions, and in other comparable high-resolution records, to determine the global nature of these signals and to obtain rates of change. The PANASH pilot project, described in Section IV below, can initiate work in this regard.

Specific Tasks:

1.1 Map surface conditions during the Younger Dryas cold period (10,500 ±500 ^{14}C yr BP) and during the preceding and following warm periods (ca. 12,000 and ca. 9,000 ^{14}C yr BP).

1.2 Determine the rates of rapid climatic and environmental change using high resolution and well-dated records such as ice cores, varved sediments and tree-rings.

1.3 Examine the interactions of the biosphere-atmosphere-ocean-cryosphere system by modelling the various processes which can induce abrupt changes in parts of the Earth system.

Proposed Steps for Implementation:

- A planning workshop to focus on (a) mapping of selected time intervals and (b) rates of change and modelling of processes leading to abrupt climatic and environmental change.

- A workshop on analytical methods (both existing and envisioned) which provide high-resolution information for absolute and relative dating of records relevant to rapid changes.

Existing Efforts and Related Programmes:

Several international initiatives are either planned or are underway concerning aspects of the Younger Dryas interval.

These include:

1. IGCP project 253 — Termination of the Pleistocene — concerned with various aspects of several temporal features of the Younger Dryas.

2. IGCP projects such as the Quaternary Climate of South America that touch upon aspects of the Younger Dryas.

3. The EPOCH programme, which reconstructs the history of climate and of changes in biomass in Europe since 30 ka BP.

4. Various INQUA commissions involved in the study of abrupt changes including the Younger Dryas. These include, among others, the Commission on the Quaternary of South America, Stratigraphy, and the Shoreline Commission.

5. The IUGS global change programme which includes a project on abrupt global changes.

6. The IDEAL Project, described in Section B.4 above.

7. Several projects of the Geological Survey of Canada (mostly mapping) concerning the termination of the last ice age, involving both the Laurentide and mountain ice.

8. The German Climate Research Project, devoted to studies of the greenhouse effect.

9. GISP II and GRIP ice-coring projects in Greenland, which have now penetrated the depth of the last glacial/interglacial transition.

Recent interest in the Younger Dryas has resulted in considerable attention to rapid changes in climate. Efforts to define the geographical extent of the cooling event have begun or are continuing in South America, where investigations are currently reconstructing the deglacial history of lake levels, mountain glaciation and vegetation; in the mountain region of the western United States; in the North Atlantic, with efforts to identify and date the meltwater diversion; in Northern Eurasia and Central Asia; and in the Pacific Ocean Basin and surrounding region. Detailed studies of rapid variations during the Wisconsin glaciation, of which the Bølling-Allerød-Younger Dryas changes may be but the most recent of a series of similar events, are also important. Within several years, a rigorous evaluation of the geographic extent of this event should be possible, as well as the first attempts at quantifying the magnitude of climate change that is associated with the event in various parts of the globe.

D. MULTI-PROXY MAPPING

Applying various types of palaeodata to the focussed study of specific regions or slices of time offers the greatest promise of the organized PAGES project. By combining, for example, the full spectrum of information from ice cores (including atmospheric composition, sea and continental dust, atmospheric dynamics, ocean temperatures) with related continental and ocean records, one can assemble a fuller picture of Earth system states and information on their dynamics.

Stream I

The last 2000 yr provide the most diverse and detailed records available for palaeoclimatic reconstruction. For many regions of the world, there is the potential of using certain proxy records to reconstruct climate on a seasonal or annual basis, year by year, for the entire 2000 year period. However, only occasionally has more than one type of proxy record been employed to produce composite maps of past climate. By combining more than one proxy record, it should be possible to reconstruct climate for selected time intervals for extensive geographical regions, ideally in both hemispheres. This should enable us to address important questions regarding the effects of particular forcing factors. By focusing initial efforts on a key period of time (such as the period of the Maunder Solar Minimum, AD 1645–1715) methodological problems of combining diverse data sets can be resolved and the efficacy of this approach to understanding a period of particular interest can be assessed.

TASK D.1:	**Maunder Minimum pilot study**	Stream I
GOAL:	*To investigate possible solar forcing during cold periods within the "Little Ice Age," to test the feasibility of multi-proxy mapping on a relatively restricted period.*	

We propose a pilot project to address climatic variations during the Little Ice Age period of the Maunder Minimum (AD 1675–1715 ±15 yr).

Specific Tasks:

1.1 To produce maps of seasonal climatic anomalies for each year of this period making use of precisely dated records including historical documents, tree-rings, instrumental data, laminated sediments of various kinds and ice core records.

Proposed Steps for Implementation:

- To facilitate progress on the complex problem of merging quite diverse data sets, global or regional workshops should be held to examine methodological problems and to identify potentially important data sets. Such endeavors have already begun under auspices of the ESF, concentrating on Europe. A by-product of this meeting should be the identification of potentially important data sets which need additional effort, and funding, to generate new information. This must involve aggressive steps to maximize high quality data from tropical regions and from the Southern Hemisphere.

Existing Efforts and Related Programmes:

A number of mapping projects, using one or two types of proxy data are in progress. At present, the following maps have been produced:

1. Using tree-rings: maps of summer temperature for W. Europe to AD 1700 (for Scandinavia to AD 1650); maps for Western & North Western North America to AD 1750.

2. Using primarily historical documents, plus some tree-ring information, selected maps for Central Europe from AD 1076–1515. A standardized coding system has been developed to facilitate mapping procedures. This could be easily adapted for other regions of the world.

3. In the U.S., a project has begun to develop maps of seasonal climatic anomalies for selected intervals in the last 500 yr (Project ARRCC: Analysis of Rapid and Recent Climatic Change). This project intends to combine tree-ring, ice core, sediment, coral, historical and instrumental data, but no results are expected before late 1992.

4. In China, a major research project for emphasis in 1991–1995 addresses variations in the Palaeomonsoon and its impact on the climate change in North China.

Stream II

The development of maps based on many different proxy records can help address a number of important questions on the time scale of the glacial-interglacial oscillations of the late Pleistocene:

Key Questions:

1. Can global circulation models accurately simulate climate radically different from the present and thereby demonstrate their usefulness for prediction?

2. How does the climate system behave on time scales of 10^3 to 10^4 yr?

3. How have the storages of carbon changed over time scales of 10^3 to 10^4 yr?

4. Can warm periods in the past be used as analogues of future warm conditions?

5. How can information obtained from palaeodata regarding atmosphere-biosphere interactions be used to predict biospheric responses to impending greenhouse warming?

Proposed Steps for Implementation:

There are several INQUA Commissions and Subcommissions and IGCP projects which could support the objectives of the PAGES Multi-proxy Mapping activity, in both streams I and II. Contacts need to be developed or strengthened with the officers of these groups, aimed at developing mutual collaborations.

Cooperation between INQUA/IGCP and the PAGES project could be developed through all of the following:

1. Organization of visits of scientists from one country to another, in the same region, especially in developing countries, and outside the region.

2. Organization of joint scientific events as meetings, symposium, workshops, seminars or field meetings and/or co-sponsoring activities.

3. Joint publications of proceedings or special volumes in leading journals.

4. Publication of joint newsletters, at the regional or the global scale.

5. Organization of large-scale and long-term mail inquiries and/or postal distribution of information.

6. Exchange of scientists' directories, with their respective areas of scientific interest and geographical areas of field work.

Relevant INQUA commissions and projects include, *inter alia*, commissions on the Holocene, on Loess, on the Quaternary of Africa, on the Quaternary of South America, on Neotectonics, and on the Palaeogeographical Atlas.

Existing Efforts and Related Programmes:

At present, the following projects are underway:

1. Palaeoclimatic reconstructions for selected periods over the last 130 ka, largely based on palaeobotanical data for land areas and on foraminiferal assemblages and O^{18}/O^{16} ratios in carbonate fossils, for ocean areas. Most effort has so far focused on 6, 18 and 125 ka BP.

2. "Landscape components" reconstructions for selected geographic regions (e.g., the Soviet Atlas of the Palaeogeography of Europe and the western Soviet Union for the last glaciation). These spatial reconstructions include sets of maps (climate, vegetation, soil, permafrost, glaciers, albedo, hydrologic balance) for critical time intervals: 125 ka, 18 ka, 6 ka BP). However, each of

these maps is incomplete and requires additional work to expand coverage to a global scale. Included are maps on Formation of Glacial Deposits, on Tephras, on Stratigraphy, on Palaeopedology, and on Palaeoecology of Early Man.

3. The recently-published Atlas on Palaeoclimates and Palaeoenvironments which comprises the last 170 ka. Later refinements are intended to reach farther back in time.

E. PALAEOCLIMATIC AND PALAEOENVIRONMENTAL MODELLING

An important goal of the PAGES project is the incorporation of appropriately-synthesized palaeodata in mathematical models that describe the climate and other aspects of the Earth system. The role of the palaeomodelling effort in the PAGES project includes all of the following:

1. Testing climate models through comparison of palaeodata with model output.

2. Estimating the sensitivity of climate to various climatic forcings operating in the past.

3. Helping the interpretation of palaeodata in going from regional to global depictions, defining key areas, and using tracer models.

4. Providing insight into how the climatic system functions, using a hierarchy of time-dependent models.

5. Understanding long-term variations and rapid changes in CO_2 and CH_4 and their interactions with the climatic system.

6. Developing models of vegetation changes that establish the linkages between climate and the response of biota.

TASK E.1:	**Climate simulation of the last 2000 yr**	Stream I
GOAL:	*To construct a complete and reliable simulation of the full climate system from 2000 yr BP to the present.*	

Within the next few years we shall have high quality records of the variation of radiatively-active trace gas concentrations through at least this interval of time (using, for example, data from the GRIP and GISP II Greenland cores), useful information on solar output (from $^{14}C/^{10}Be$ comparisons), and helpful data on volcanic eruptions and aerosol concentrations. These palaeo data should be employed as forcing functions even in the absence of similar information on the time variation of SSTs, in a sequence of GCM simulations of the evolution of climate over this interval of time. Initially these will probably be run in coarse temporal steps. A main purpose would be to establish whether or not climate system response to proposed forcing mechanisms is above model noise. Because this interval of time includes the time of onset of pronounced anthropogenic impact the results will be especially useful in formulating future global change scenarios.

TASK E.2:	**Simulation of glacial-interglacial transitions**	Stream II
GOAL:.	*To construct a complete and reliable simulation of the most recent glacial-interglacial transitions.*	

Current Atmosphere-Ocean-GCMs are particularly deficient in their ability to reproduce many aspects of the modern hydrological cycle. Clearly the most stringent test that one can apply to this crucial component of the climate system is the reproduction of the last glacial-interglacial transition. Contributing factors to the last "termination" of the present ice-age included (i) orbital forcing; (ii) feedback due to variations of greenhouse gas concentrations; (iii) feedback to variations in the strength of the thermohaline circulation in the oceans; and (iv) feedback associated with marine instability of the ice sheets

themselves. In order to make further progress in understanding the glacial-interglacial cycles of the late Pleistocene era a more detailed understanding is needed of the relative importance of these various feedback mechanisms. Whether such understanding will follow from detailed AO-GCM synchronously-coupled ice-sheet simulations is not clear, but in our view the experiment must be performed. The comparison of the processes acting during the most recent and preceding transitions will help to differentiate between general and more individualistic trends.

TASK E.3:	**Changes in ocean circulation**	Stream II
GOAL:.	*To reconstruct reliable simulations of selected periods ("snapshots") of the general pattern of ocean circulation across the last glacial-interglacial transition.*	

Although several Atmosphere-Ocean-GCM experiments have been performed reconstructing the general circulation at discrete intervals of time beginning at glacial maximum, a number of recent advances strongly suggest that these experiments need to be repeated. Firstly, new constraints on the variation of the thicknesses of the major ice masses through time have delivered models which differ significantly from those of the CLIMAP study, on which the earlier model simulations were based. Secondly, the last glacial maximum may have been reached more nearly 21,500 (sidereal) yr BP than the 18,000 yr BP that was previously assumed. There are therefore mismatches between the timing of the orbital variations and changes in ice sheet thickness in the earlier snapshot computations. Extensive snapshot studies should be performed for other periods suited for model-data comparison.

TASK E.4	**Reduced models of climate system behavior**	Streams I and II
GOAL:	*To construct reliable, reduced models of general climate system behavior.*	

Various reduced models of the evolution of the climate system are available, including 1-D and 2-D time dependent and steady state, zonally-averaged systems, 2-D versions with realistic geography (land ice contrast), and including or excluding representations of the effects of atmospheric circulation. Each of these has some role in the development of understanding of climate system behavior. For example, 1-D time dependent models can be useful as conceptual tools for understanding the major climate events recorded in deep ice cores (e.g., the mid-Pleistocene climate transition in $\delta^{18}O$ records). 2-D energy balance models provide a very useful explanation of the amplitude and phase of the annual cycle, and may be used when coupled asynchronously to an ice sheet model, as an aid to understanding of glacial cycles. Similarly, box type reservoir models of the carbon cycle continue to play a useful role in helping to come to grips with significant issues in this vital area, although they may not be appropriate for fully resolving them. Work should continue in the development and application of these important theoretical tools.

TASK E.5:	**Biogeochemical, vegetation, and tracer models**	Streams I and II
GOAL:	*To develop biogeochemical and other models needed in palaeo-studies that deal with non-physical aspects of the Earth system.*	

The tasks explained above focus for the most part on models of *physical* aspects of the palaeoenvironment. It is clearly important that equivalent effort be directed towards the development of integrated system models which include the important biogeochemical cycles. The carbon cycle mentioned above would constitute a concrete example. There is also considerable need to continue to develop vegetation models of a form that makes them applicable in the context of research on past environments. Models of the transport of tracers of interest for the interpretation of palaeorecords (continental and marine aerosols, water isotopes, chemical species) also deserve increased attention. This approach will be also useful for examining the potential climatic role of aerosols of various origin (volcanic aerosols, dust, cloud condensation nuclei) and the air chemistry-climate long term interaction.

General note: Tasks 1 and 2 above describe long-term objectives which will not be achieved during the next five years. Tasks 3, 4, and 5 correspond to research activities to be developed over the next five years.

Existing Efforts and Related Programmes:

Modelling of palaeo-climate and palaeo-environment is an active field in each of the areas described above, either through coordinated programmes such as COHMAP and SPECMAP, or through the research conducted by individual teams. The NATO Palaeoclimate Modelling Intercomparison Project (PMIP) is of obvious relevance to the PAGES Project.

F. ADVANCES IN TECHNOLOGY

A major goal of the PAGES project is to mobilize efforts, worldwide, to advance the state of technology in areas of data acquisition, data analysis, and data interpretation. Resources sufficient to define and develop new techniques in any of the varied facets of palaeodata recovery and interpretation are seldom available to the individual investigator. The PAGES project offers the opportunity to make the first of these — the definition effort — immediately available through the organization of workshops involving a broad representation of the experts who now work in specific areas. Hope for the second goal of securing support for the development and field-testing of these techniques is found in the collective advantages of organized efforts, and through the creation of authoritative descriptions of these needs, in the form of reports that are sponsored by the PAGES project, and through the sharing of technique and expertise through focussed endeavors and field projects.

A plan for organization of this area of effort within PAGES has yet to be defined. Included below, as *examples* of early steps toward definition, are preliminary assessments in three sample areas. A more general description of project aims in each of these areas of technology may be found in the PAGES project description in IGBP Report 12, where a particularly thorough discussion of problems of dating and correlation of data may be found.

1. Sampling and Coring Techniques for Lacustrine Sediments

Lake sediments are among the most important source materials for palaeo-ecological research. Most essential is the coring technique for obtaining reliable results. Particular limitations and problems are encountered in securing cores from deep

lakes, in taking and analyzing long sediment sequences and in dealing with laminated sediments, and most of all, when lakes of interest are situated in severe climates or in badly accessible regions. Techniques and equipment adequate to meet these particular needs have in some cases not yet been developed, and in others are available in only a limited number of laboratories. To date, there have been no community-wide or broad collective efforts of the sort that have brought equipment development support to the allied fields of ice- and deep sea coring. Were a similar effort applied to the field of lacustrine sediments we are confident that these would lead to major if not revolutionary advances in quality and number of records, in the rates at which data are taken, and in derived information.

Valuable experience is available in the USA, France, Switzerland, Germany, Scandinavia, and some other countries. Coring strategy and technology should be further developed at a workshop where scientists with this knowledge are brought in contact with engineers from suitable geotechnical firms. There is a need to develop simple but reliable coring technology for the following situations:

- ancient lakes with deep sediments
- moderately deep lakes
- deep lakes
- lakes with annually-laminated sediments
- recent surface sediments.

2. Radiocarbon Dating

Most PAGES activities rely on correlation between events and proxies or between different proxies. This correlation depends upon accurate time control which is provided in the ideal situation on an annual basis by the counting of tree-rings or laminated sediments. Radiocarbon (^{14}C) dating falls far short of the ideal but may at times be the only option. Routine ^{14}C dating, of the sort that is used, for example, for most applications in archaeology, is not useful for this purpose: the combination of poor sample integrity and poor precision leads to "nearest 1/2 millennium" dating. Only a few laboratories are equipped to carry out high precision analyses.

The resources available to put ^{14}C dating to work in PAGES-related efforts are now apportioned between efforts in Accelerator Mass Spectroscopy (AMS), characterized by poorer dating precision but higher sample specificity, and in high precision dating through conventional decay techniques, which has the opposite traits. There is a major need for better understanding of samples drawn from peats, lake sediments, marine samples, etc. This is a task for ^{14}C lab researchers, which the PAGES project can support. There is an additional need to convince many geologists and vulcanologists of the need for more precise dating. They do not often deal in annual time-scales and are often not acquainted with the need for high-precision, modern ^{14}C technology. This is more a task in education than a funding issue.

In palaeo studies of terrestrial records, dating is generally achieved by annual layer counting, as in tree-rings (which now extend in continuous series back into the last glacial-interglacial transition), varved lake sediments, and annual ice layers. The last of these may be extended back to the time of the Eemian (Sangamon) interglacial through measurements of electric conductivity, dust layers, and other chemical analysis, as, for example, of ammonia. Were data from these techniques taken together, they could serve as a very useful master chronology for Stream I and Stream II studies. The use of reference horizons (as in volcanic dust layers, or the identification of climatically-extreme years) could help to synchronize records which contain less defined dating.

The study of marine records could be improved through the organized development of a master chronology from ice volume information from $\delta^{18}O$ in foraminifera and other parameters.

It is also necessary to establish a generally agreed-upon set of reference horizons to synchronize terrestrial and oceanic chronologies. These could include times of rapid changes in the North Atlantic Ocean, volcanic dust layers; and $\delta^{13}C$ in foraminifera, which reflect variations in the so-called biological pump in the ocean, which may in turn affect the atmospheric abundance of CO_2.

3. Methods in Dendrochronology

The science of dendrochronology has developed very fast in the last two decades, although all new methods are still based on cross-dating techniques. State of the art reviews and expositions of new techniques have been given by Fritts (1976), Cook and Kairiukstis (1990), and Schweingruber (1988).

In spite of a long history of research and the excellent time control provided by tree-rings, dendroclimatic results that are applicable to PAGES are still very limited in temporal and geographical extent. A large part of tree-ring research effort has been directed to archaeological and other non-climate oriented projects and the chronologies produced are of limited value as climate proxies. The new techniques summarized in the table below may enable more information to be extracted from these existing and new materials. In many areas chronologies produced in the 1960s and 1970s need to be brought up to date to take full advantage of the longer instrumental record available for calibration and verification of reconstructions. In other areas new techniques are still needed to derive climate reconstructions that have sufficient skill to be useful for PAGES activities. Particularly promising are ongoing projects involving stable isotopes in wood.

The following table summarizes current techniques that are now in use.

Method	Recorded Parameters	Material	State of Calibration	Ready for Routine Data Producing	Possible Technical Progress in Future	Remarks
Skeleton plot (pointer years)	Extreme values; not continuous time series	Cores	Partially Subjective	Now		Much information in trees from temperate climates
Ring width measurements	Ring width (latewood width)	Cores	OK	Now	New systems with light reflection (Canada)	Climatologic information is in many cases limited
Mechanical resistance (F. Rinn method)	Ring width; latewood width; densities	Living trees; beams	Vague	Probably never for climatology	?	Much information for growth studies and wood technology
Sandblast	Ring width and densities	Dry cross-sections	Width OK; densities vague	Probably never for dendro-climatology	?	New information: wood-architecture
Light-reflection and light absorption (Vaganov method)	Cell size; No. of cells; cell wall thickness	Micro-sections of conifers	?	No	Faster proceeding	New information: hydrological conditions
Image analysis	Tissue-parameter: No. of cells; cell size; cell type; cell wall thickness	Micro-sections of conifers and broadleaf trees	Developing slowly	No	Speeding up procedures and the unification systems	Applicable to conifers and deciduous trees
X-ray densitometry	Width and densities	Cores	OK in some labs	Now (system is on the market)	Interlaboratory tests; better software	Almost all conifers are comparable
Stable Isotopes	C^{12}/C^{13}, D, O^{16}/O^{18}	Discs and cores	In process	In a few years	Speeding up procedure	New information expected: air humidity
Tissue chemistry	Heavy metals and others	Cores and discs	?	?	?	Signals are difficult to understand

G. MANAGEMENT OF PALAEODATA

Data are the fuel of palaeoenvironmental research — a resource that must be managed in a way that provides the entire global change research community with the tools to find, access, and manipulate quickly the data needed for a particular investigation. At present, few sets of palaeodata are widely available in easy-to-use formats. Notable exceptions exist, but these data sets are limited geographically and in the type of data they contain. An important goal of PAGES is to help coordinate the design and implementation of a *global* science-driven data management system that integrates all types of needed data for the use by the global change community. Without this global array of freely shared data, many of the broader objectives of the IGBP cannot be met. The data component of the PAGES project is its most important product and the principal link to other projects of the IGBP and WCRP.

Types and Sources of Data to be Managed and Used in the PAGES Programme:

Many of the PAGES project goals require the availability of large high-quality sets of data. PAGES will make an important contribution by moving quickly to begin the design of an international data management system and to acquire for these systems as much of the needed data as possible. Several types of data are to be given high priority:

1) Original "raw" or <u>primary</u> palaeoclimatic, palaeoecologic, and palaeoceanographic data, including associated chronological information. These raw data are the foundation of palaeoenvironmental research. Examples of this type include raw tree-ring width measurements, counts of fossil pollen data versus depth in a sediment core, data from historical documents, and original radiocarbon dates.

2) Secondary data developed from the primary data. These include, for example, tree-ring chronologies developed from multiple tree cores, pollen percentages as a function of inferred age, synthesized documentary data, and radiocarbon dates corrected for secular variations in atmospheric ^{14}C.

3) Tertiary information inferred from the primary and secondary data, such as palaeoclimate estimates or vegetation reconstructions. These data would be managed in both time series and in the form of maps.

4) Calibration data, which are primarily the modern environmental data sets needed to convert primary and secondary data into quantitative estimates of past climate, ocean, or biosphere conditions.

5) Time series of known or hypothesized climate forcing functions (such as solar, volcanic, trace gas, or orbital parameters).

6) Climate boundary conditions through time (e.g., ice extent and height, or land surface characteristics).

7) Output from models (including GCMs for atmosphere and/or ocean behavior, vegetation models and tracer models).

These types of data are those that will be needed to meet the scientific goals of the PAGES programme. Although the primary data may not always be used, it is crucial that these data are available. As methods and calibration data sets improve, so will the secondary and tertiary data that are derived from the primary data. Primary data will always serve as the ultimate source of palaeoenvironmental information. Individual scientists seldom have the time or support to archive their data in safe and accessible form; the PAGES project can work to make quality data archiving a priority.

Much of the needed palaeoenvironmental data will come from one of the following sources:

- cave calcite
- corals
- fluvial deposits
- fossil insects
- fossil pollen
- glacier mass balance
- historical documents
- ice cores
- lake level variations
- loess
- long instrumental records
- noble gases in ground water
- ocean sediments
- other eolian deposits
- packrat middens
- palaeolimnological data
- palaeosols
- plant macrofossils
- sea level variations
- tree-rings
- treeline movement

TASK G.1: **International palaeodata system** Streams I and II

GOAL: *To establish an easily accessible international data system devoted to the acquisition, management, and distribution of palaeoenvironmental data.*

To accomplish this end, the PAGES data management plan must build on existing regional and topical efforts. Existing efforts now include ARRCC, COHMAP, EDP, ESF/EPC, European Working Group on Historical Climate, German Palaeoclimate Research Project, Soviet Palaeoclimate Research Project, ITRDB, LIGA, NGDC Palaeoclimate Programme, North American Pollen Database, Oak Ridge Carbon Dioxide Programme, Oxford Lake-Level Data Bank, European Pollen Data Bank, NORDMAP Data Bank, SPECMAP, and the US/China Historical Documentation Project.

Proposed Steps for Implementation:

- A PAGES Data Management Working Group will meet to establish an agreed-upon protocol for data sharing. This protocol will be distributed for comment and ratification. This Working Group will also work on the details of the PAGES data management effort.

- PAGES will encourage funding agencies and national research communities to require the archiving and sharing of all palaeoenvironmental data. In general, published data should be shared as should unpublished data in cases where the data producer is willing to allow its unrestricted use. Policies regarding the sharing of data need take into account the prerogatives of the original investigator regarding data synthesis and the often considerable investment expended in collecting data.

- The PAGES Project Office and the U.S. National Geophysical Data Center (NGDC) will coordinate the international sharing of data. NGDC has the long-term commitment of support that is necessary to ensure availability of data to the research community for years to come. The coordinated system will consist of many regional and topical database efforts feeding into a centralized database management system at NGDC. Of utmost importance is the responsibility for data quality, utility, and reliability. Regional and/or topical groups will be established to:

1. inventory sites,
2. set guidelines for data acquisition,
3. assemble data (primary, secondary, and tertiary),
4. document the data, and
5. distribute available data.

- A PAGES Data Management and Distribution Center at NGDC will work with the PAGES Project Office to:

1. integrate data sets into common formats for display, querying, and accessing,
2. coordinate individual data banks,
3. provide user friendly software for data display and access via personal computer magnetic diskettes, compact disk ROMs and electronic networks,
4. assist in setting up regional distribution nodes where deemed necessary by PAGES,
5. explore the possibility of establishing World Data Centers for Palaeoclimatology as part of the existing World Data Center System, and
6. work with the PAGES community to ensure that the data are acquired, managed, and distributed in the way that best serves the global change community.

- In addition to the initial planning/protocol workshop, PAGES will also endorse workshops where needed to coordinate data groups and database development plans. All other PAGES workshops will also work to keep track of their data management needs and coordinate these with the PAGES Project Office and NGDC.

PAGES data management must begin immediately since other PAGES activities will depend on the easy and free exchange of data. Guidelines for coordinating individual databanks are of highest priority. Several regional or topical database efforts are already underway, as is the integration effort at NGDC. The initial PAGES data management planning/protocol workshop will be held in 1992–1993 to ensure that these ongoing efforts are coordinated and that a universal protocol for the exchange of palaeoenvironmental data is established rapidly enough to serve all of the PAGES activities.

Related Programmes:

The PAGES data management effort is closely linked to all of the other PAGES efforts and will be required for their successful completion. The PAGES Programme Office will work to ensure that the PAGES data management effort serves all of the PAGES activities and that these activities communicate their data management needs, maintaining appropriate communication with the IGBP-DIS.

H. IMPROVED CHRONOLOGIES FOR PALAEOENVIRONMENTAL RESEARCH

Success of the PAGES programme will depend to a considerable degree on the establishment and availability of a rigorous chronostratigraphic framework. Investigations of the past 2000 yr (Stream I) will require an annual time control that can be obtained from sources such as annually banded trees, corals, ice cores, and sediments. Investigations of century to millennium-scale variability (Stream II) will usually be based on less accurate methods (e.g., ^{14}C), but high-resolution studies will be possible if care is taken to obtain the best time control possible. PAGES is committed to doing what it can to ensure that the time control for palaeoenvironmental time series is the best available.

An example of what is needed is the recently constructed continental master chronology that was based on seasonal variations in Greenland ice cores and linked to an ocean core master chronology through studies of ^{18}O in O_2, reflecting essentially ice volume changes.

TASK H.1:	**Improved chronologies**	Streams I and II
GOAL:	*To construct improved chronologies for palaeoenvironmental research.*	

Proposed Steps for Implementation:

- In all cases possible, palaeoclimatic data should be reported and archived with a complete documentation of how a chronology was derived. In many cases, time control is inherently inaccurate and subject to improvement. For this reason, data should be placed in public archives with the chronologic and non-chronologic data separated. Both types of data should be well documented.

- High priority should be given to the goal of placing all chronologies on the same absolute time scale. For example, most climate models use insolation values calculated in absolute time and geological boundary conditions (e.g., ice sheets) dated in radiocarbon time, even though the two time scales may differ by as much as 2500 yr during some time periods. PAGES will endorse efforts to (a) exploit whenever possible the use of annually-dated records, and (b) extend the ^{14}C calibration via trees and U-series dating. Special attention must be given to the last deglaciation where the ^{14}C time scale may be most problematic. An additional benefit of extending the ^{14}C calibration is that it will help, in connection with analyses of ^{10}Be, to put limits on possible past variations in solar irradiance.

- Efforts should be made to find and use reference isochronous horizons to correlate between land and sea and between Northern and Southern hemispheres. Possible examples that should be explored include extraordinary ^{10}Be events, ashes, methane peaks, and dust layers.

- PAGES will encourage the development of guidelines for how to best date different types of palaeoenvironmental time series. These guidelines can then be distributed to the global palaeoenvironmental research community to ensure that all time series being produced will be of use in meeting PAGES goals.

- PAGES will also conduct a survey to make sure that the necessary resources (e.g., dating facilities and funds) are available to meet the chronology guidelines. There is a real concern that the existing international AMS ^{14}C capacity will be insufficient to meet the research goals as set forth by PAGES. A high priority

must be placed on making time control as good as possible. This means that many dates must be made available to researchers at low cost and with minimum waiting time.

IV. PANASH: AN INITIAL PILOT PROJECT

Many of the activities described in this report share common goals; many involve the same data sets and call for efforts to expand them through common strategies and to fill similar gaps in time and space. They all involve, in large measure, the same limited numbers of scientists and groups of scientists who *now work* in collecting various kinds of palaeo-data, in interpreting and modelling them, in advancing techniques of data recovery and analysis, and in efforts now underway to bring palaeo-data together to make them more widely available to a broader spectrum of scientists in all parts of the world.

The research agenda outlined in this report can be best begun and most effectively harnessed, given these commonalities and limitations, by focussing as many elements as possible on an initial pilot project of global scale. Through such an effort the whole can exceed the sum of the parts. Moreover, the impetus of a common initial project can be an effective starting mechanism for subsequent efforts throughout the programme. Finally, practical considerations of the funding that will be available for IGBP PAGES in the initial years of the project dictate that priority themes be identified and first pursued.

An obvious theme that cuts across many of the research elements of the PAGES project plan is that of linking now-disparate data from the Northern and Southern hemispheres for global palaeoclimate reconstruction.

Of interest in regard to Northern-Southern Hemisphere effects are the asymmetry of land and ocean cover; in phase and out of phase solar insolation changes; asymmetry of land-ocean-atmosphere interaction; asymmetry of albedo changes, due to continental ice cover or to extent or changes in vegetation; and differences in anthropogenic emissions to the atmosphere or oceans. A number of issues are of interest in interhemispheric coupling. One involves changes in atmospheric CO_2 and CH_4, which are so-well mixed as to be essentially global in nature; as such they could provide some climatic coupling. Another issue deals with atmospheric transport, which is an unlikely agent in physical coupling due to the short energy memory of air masses in processes of radiative exchange. Oceanic coupling could be an important parameter, through major rearrangements of ocean circulation, or due to significant north-south transport, which should introduce a noticeable lag time.

The need for North-South integration of palaeo-data is common to both of the now identified temporal streams of the PAGES project. Two practical considerations argue for immediate attention to an interhemispheric synthesis of palaeoclimate information.

The first is a present imbalance in the information that is now available on the past history of the climate system. What is known of almost any past fluctuations is weighted all too heavily toward past conditions in Western Europe, parts of China, and North America. The existence of Southern Hemisphere and tropical data gaps has been long acknowledged as a critical weakness in our knowledge of past climate variations. This is immediately true of what is now known of the Little Ice Age, to take one example, and equally applicable to known or suspected fluctuations of earlier times, such as the Younger Dryas cooling of ca 11,000 yr BP. What is known of the glacial-interglacial oscillations of the Pleistocene is derived from deep-sea data whose application to the Earth as a whole is based more on supposition and extrapolation than on any solid buttress of comparative data.

Putting increased emphasis on North-South synthesis carries the added advantage of involving the scientific potential of scientists in countries of the less-developed world, the majority of whom are from nations in the Southern Hemisphere and the Tropics.

The second consideration is the need to distinguish regional or hemispheric effects from truly global changes, and through this process to expand what is known of the global climate system. The rapid climatic fluctuations that are now known, including the Younger Dryas and Bølling-Allerød events of the last deglaciation, and the abrupt changes identified during the last glaciation, are found principally in the Northern Hemisphere, and largely on the strength of data from Greenland ice cores. Nor do we know the sequence and phasing of either the onset or end of the major glaciations, as one might expect through the operation of Milankovitch forcing, nor the extent of hemispheric asymmetry in the magnitude of these major climatic changes. The need to compare data from the two poles of the Earth is a need no less pressing than that of filling the Southern Hemisphere and Tropical data gaps.

Toward this end the PAGES project will organize, as an initial pilot activity, an accelerated global-scale study of Palaeoclimates of the Northern and Southern Hemisphere (PANASH). The goal of the study is to identify the commonalities and interrelationships between known climate fluctuations in the two hemispheres, and through this process to improve our understanding of global climatic change. PANASH will target times of interest in both *temporal streams* of the PAGES project, and involve each of the project's three general *research themes*: solar and orbital forcing and response, fundamental Earth system processes, and rapid and abrupt global changes. It will be based upon and guided by efforts in the fourth major theme of multi-proxy mapping, to which it will give initial definition and organizational structure. PANASH efforts will demand the improvement and, as important, the dissemination of technology in almost every area of data recovery and interpretation. It will also provide an appropriate pilot activity in palaeo-data management.

The PANASH project may be seen as cutting across the PAGES general plan depicted in matrix form in Table 1 of

Section II above, linking temporal streams and scientific activities in a common initial effort.

PANASH efforts in Stream I will focus initially on the more restricted period of the last 1000 yr to promote the extraction of new, high-resolution records including historical documents, tree-rings, ice cores, corals, and layered sediments of various kinds from all parts of the world, with particular attention to the Southern Hemisphere and the Tropics. This period spans the Little Ice Age and the so-called Medieval Warm Period, for which there is still very little in the way of solid evidence. By focusing attention on the intercomparison of detailed records from these intervals, real progress should be made in resolving the relative importance of now-hypothesized forcing factors, including volcanism and solar changes. This time scale also embraces the period of the most intense alteration of the global environment by humankind and so ties the project more immediately to the broader objectives of the IGBP.

Under Stream II, the highest priority for research will be the development of a large number of continuous, land-based proxy records spanning the last glacial-interglacial cycle, with principal emphasis on the late glacial and the whole of the Holocene, to augment what is now known chiefly from deep-sea and polar cores, while expanding and focusing the taking of data in these two areas. This emphasis would promote coring efforts, dating and multi-parameter analytical work on lake and bog sediments and ice-cores, where available, from all continents of the world. The IDEAL project, aimed at recovering data from East African rift lakes, is of particular relevance. With many more of such long records we can hope to resolve current uncertainties regarding leads and lags in the climate system, differences between records in the two hemispheres, the partitioning of carbon in different reservoirs over time, and the frequency and timing of abrupt climatic changes. We propose a particular emphasis on terrestrial records since there are currently so few which span the time period now embraced in marine sedimentary records. At the same time this should not

preclude further collection and analysis of selected marine cores, particularly from those areas where high-resolution and/or better dated records could provide new information.

More specific goals and targeted eras to be emphasized in the PANASH pilot project will be arrived at through the appointment of a small PANASH steering committee which will prepare a phased plan for implementation, after receiving input and review from relevant disciplines and research groups. The input of the WCRP will be particularly sought, given the distinct emphasis of the project on climate and climate change.

A Pole-Equator-Pole (PEP) initiative has been proposed in the U.S. that would systematically examine palaeoclimate data along agreed-upon longitudinal transects in the Western Hemisphere. It is of obvious relevance to the PANASH initiative. The principal goal of PEP is to analyze the dynamics of past pole-to-pole climatic teleconnections in the Americas; it could represent the first step of translating the general recommendations of PANASH into an immediate research agenda.

We plan to initiate the PANASH pilot project in 1992–1993, with responsibility for its execution in the hands of the PAGES Core Project Office, under the periodic review of the PAGES SSC.

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pa nache n. **1.** A bunch of feathers or a plume, especially on a helmet. **2.** Dash; swagger; verve. *"There was a grandeur and panache — and impatience of all constraint — about everything he did."*

Appendix 1

PAGES PROJECT STRUCTURE, MODE OF OPERATIONS, AND RELATION TO OTHER SCIENTIFIC PROGRAMMES

The IGBP PAGES project is now guided by an international Scientific Steering Committee (SSC) appointed by the SC-IGBP. Members (listed in Appendix 3 below) were chosen from active scientists who might represent the major techniques and disciplines that work in gathering and interpreting data from natural and written archives, while at the same time providing regional geographic representation. Meetings of the PAGES Scientific Steering Committee (SSC), which are supported by the IGBP Secretariat from national contributions to the organizational aspects of the IGBP, are held about once per year; special consultants are routinely invited to take part in these meetings to provide additional expertise and to expand geographical representation.

The National Science Foundations of Switzerland and of the U.S.A. have now agreed to support a jointly-funded, international Core Project Office (CPO) for PAGES which will commence operation in Bern in early 1992. At that time it will join and work with corresponding project offices for the other four core projects of the IGBP (IGAC, JGOFS, GCTE, and BAHC), the IGBP-DIS office, and a proposed office for the IGBP START initiative.

The PAGES CPO will perform the following functions, under the review of the SSC:

- Initiate and organize planning meetings and resulting international workshops to implement scientific activities of the project.

- Provide day-to-day scientific oversight, as needed, for organized scientific activities of the PAGES project.

- Publish a periodic newsletter and distribute it internationally.

- Compile and issue scientific reports to report activities and scientific results of the project.

- Advise national funding agencies as appropriate regarding proposed individual and national initiatives that may relate to the project.

- Compose general and review articles for scientific journals that report aims and opportunities to aid in recruiting scientists and technicians to work in the project.

- Act as a multi-national advocate for the project.

- Maintain active contact with national programmes that will work to implement PAGES activities.

- Organize and maintain an active international directory of scientists and institutions relevant to the activities of the PAGES project.

- Assist in establishing data repositories for various types of palaeo-data that can be readily accessed internationally.

- Serve as the point of contact for PAGES activities with the IGBP Secretariat and with the CPOs of other IGBP and WCRP projects.

- Provide facilities, and if possible, salary support for visiting scientist to work on PAGES planning and scientific activities.

- Raise funds to support the continued operation of the Core Project Office.

Specific PAGES activities, such as the PANASH project described in Section IV, will be guided by steering committees appointed by the SSC and coordinated on a day-to-day basis, as needed, through the CPO.

Plans for the PAGES CPO include provision for a visiting scientist or scientists in the office, to be recruited internationally.

The PAGES project, through the Bern CPO, will work to establish close working relations with the WCRP and with INQUA, which share many of the aims of the PAGES project, to insure appropriate collaboration and complementarity. It will also work to complement activities of the proposed "Earth Processes and Global Change" Programme of UNESCO and the IUGS.

Appendix 2

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Appendix 5

ACRONYMS AND ABBREVIATIONS

AMS	accelerator mass spectrometry
ANARE	Australian National Antarctic Research Establishment
ANU	Australian National University
AO	atmosphere-ocean
ARRCC	Analysis of Rapid and Recent Climate Change Project
BP	years before the present
CLIMAP	Climate/Long Range Investigation Mappings and Predictions Project
CNRS	Centre National de la Recherche Scientifique (France)
COHMAP	Cooperative Holocene Mapping Project
CPO	IGBP Core Project Office
CSIRO	Commonwealth Scientific and Industrial Research Organization of Australia
ENSO	El Niño/Southern Oscillation
EPD	European Pollen Database
EPOCH	European Programme on Climate and Hazards (EEC)

ESF/EPC	European Science Foundation/European Palaeoclimate and Man Project (Holocene climate)
GAIM	Global Analysis, Interpretation and Modelling Activity (IGBP)
GCM	general circulation model
GCTE	Global Change and Terrestrial Ecosystems Project (IGBP)
GEWEX	Global Energy and Water Cycle Experiment (WCRP)
GISP II	Second Greenland Ice Sheet Project (US)
GRIP	Greenland Ice Core Project (European)
IDEAL	International Decade for the East African Lakes Project
IGAC	International Global Atmospheric Chemistry Project (IGBP)
IGBP	International Geosphere-Biosphere Programme
IGBP-DIS	Data and Information System Activity of the IGBP
IGCP	International Geological Correlation Programme (IUGS, UNESCO)
IIASA	International Institute for Applied Systems Analysis
INQUA	International Union for Quaternary Research (ICSU)
ITRDB	International Tree-Ring Data Bank

IUGS	International Union of Geological Sciences
JGOFS	Joint Global Ocean Flux Study (IGBP)
ka	thousands of years
LIGA	Last InterGlacial in the Arctic Project
NASA	U.S. National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NEREIS	European deep-sea drilling program (drilling ship, named after genus *Nereis* of marine worms)
NGDC	National Geophysical Data Center (Boulder, Colorado)
NMHC	non-methane hydrocarbons
NOAA	U.S. National Oceanic and Atmospheric Administration
NORDMAP	European Nordic Pollen Data Mapping Project
PAGES	Past Global Changes Project of the IGBP
PANASH	Palaeoclimates of the Northern and Southern Hemispheres proposed pilot project of PAGES
PEP	Pole-Equator-Pole Palaeoclimates Initiative for the Western Hemisphere (proposed in the U.S.)
PMIP	NATO Palaeoclimate Modelling Intercomparison Project

ROM	read-only-memory
SAC	IGBP Scientific Advisory Council
SCOR	Scientific Committee on Oceanic Research (ICSU)
SPECMAP	Mapping Spectral Variability in Global Climate Project
SSC	PAGES Scientific Steering Committee
SST	sea surface temperature
UNESCO	United Nations Educational, Scientific and Cultural Organization
WCRP	World Climate Research Programme
1-D, 2-D	one or two dimensional

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