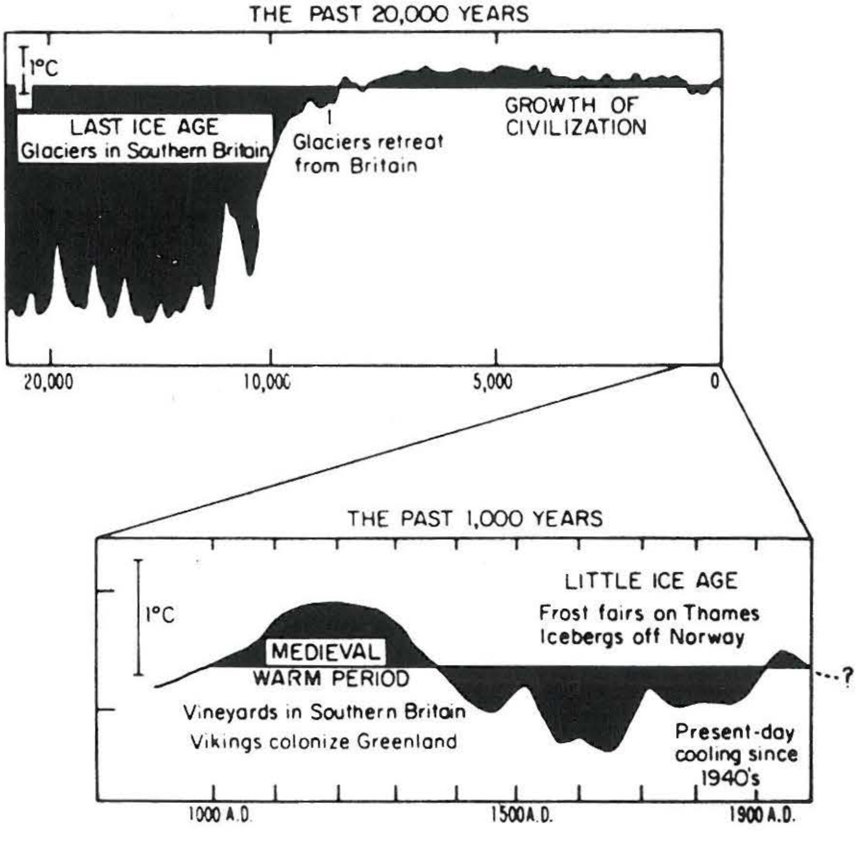
GLOBAL IGBP CHANGE

REPORT No. 6



Global Changes of the Past

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

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Report of a Meeting of the IGBP Working Group on
Techniques for Extracting Environmental Data from the Past
held at the University of Berne, Switzerland
6–8 July, 1988

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The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP)
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I. INTRODUCTION AND ORGANIZATIONAL RECOMMENDATION

Studies of the physical, chemical and biological parameters found in natural archives such as ice cores and tree-rings, and in ocean, lake and terrestrial sediments, have revealed a wealth of information on both the "natural" and perturbed behaviour of the coupled Earth system. Breakthroughs in this area, more than any other, have been responsible for the dawn of Earth system science. Quantitative information on global changes of the past can be used to put observed trends in contemporary data in broader context, to evaluate Earth system models, and to identify unknown and often important interconnections between physical, chemical and biological processes.

We need to realize at the outset that the cross-disciplinary endeavours that have contributed these fundamental insights are now modest and mostly new upon the scene. The first deep ice cores were taken about 20 years ago. Accelerator mass spectroscopy, on which some of this branch of science now depends, is a child of the late 1970s. The number of scientists and of scientific institutions who work at the forefront in taking or interpreting past environmental data, be it tree-rings or ice cores or lacustrine sediments, is surprisingly small; nor has progress in the gathering of new data - as in the case of deep ice cores - been as steady or as comprehensive as it must be to meet the needs and the challenge of an international programme whose goal is a new understanding of a complex, living planet. A new emphasis within the International Geosphere-Biosphere Programme (IGBP) on the recovery and interpretation of records of the past environment can do many things to strengthen the discipline. It can recruit new students and encourage new workers, mobilize new resources, and advance the state of the art across a broad front of field and laboratory work. Equally important, it can coordinate activities that are now disparate and isolated, to focus on regions or slices of time that are of particular promise or concern. It can also identify gaps and stimulate new directions of research in field studies, laboratory techniques and data interpretation.

The analysis of environmental data found in natural archives has revealed a wealth of useful information on the operation of Earth systems. Examples include:

1) The general nature of climate change from glacial to inter-glacial in the Northern and Southern hemispheres, including the record of surface temperature and precipitation through the last 150000 years, and a detailed temperature history of the last 1000 years in polar ice sheets and in mid-temperate latitude glaciers;

2) The documentation of extreme climatic and environmental changes in the last 1000 years;

3) The identification of the Milankovich cycles and higher frequency climatic oscillations in both the ocean and continental archives;

4) Changes in patterns of terrestrial vegetation coincident with major climate variations;

5) Changes in the basic nature of ocean circulation and in deep-water formation that are also linked to changes in the climate;

6) Variations in the chemical composition of the atmosphere, particularly in CO_2 and CH_4;

7) Significant temporal changes in the abundance of cosmic-ray produced isotopes, such as ^{14}C, ^{10}Be, and ^{36}Cl;

8) Fluctuations in a broad spectrum of ions deposited in polar ice;

9) Major variations, linked with climatic change, in the particulate content of ice, and hence in the transport of dust in the atmosphere;

10) Significant variations in the extent of aridity, derived from lake sediments.

These findings document the internal and external forcing mechanisms, biogeochemical feedbacks, and the general response of the geosphere-biosphere system. They also relate directly to the spectrum of interactive Earth-system processes that are addressed in the four key areas of the IGBP:

- Terrestrial Biosphere-Atmospheric Chemistry Interactions (specifically 5, 7 and 8 above);

- Marine Biosphere-Atmosphere Interactions (4, 5 and 7);

- Biospheric Aspects of the Hydrological Cycle (3); and

- Effects of Climate Change on Terrestrial Ecosystems (3, 5).

At the July Workshop in Berne the group concluded that securing resolution information on global changes of the past is a prerequisite for the success of the IGBP. As noted above, the study of environmental information stored in natural archives pervades all of the present activities of the programme. At the same time, because of its importance, and because of the limited number of scientists and institutions working in the field, the group proposes that the SC-IGBP reform the present Working Group on Extracting Environmental Data of the Past" as a Coordinating Panel on "Global Changes of the Past", to ensure that efforts in this area are given high priority in the planning and future conduct of the programme, and that efforts are not unnecessarily divided nor spread so thin as to be less effective.

During the past years it has become more and more evident that scientists involved in studies of global change focus increasingly on the natural evolution of the Earth system and hence on the evidence of past changes in the palaeo-environment of the planet. Examples of this growing interest include the 1987 and 1988 Dahlem Conferences on "The Changing Atmosphere" and on "The Environmental Record in Glaciers", the formation of a European scientific consortium to pursue polar-ice drilling (EUROCORE), a new Japanese plan to carry out deep drilling projects in Queen Maud Land in 1993-1995, and recent initiatives toward similar ends in the U.S. National Science Foundation.

Of special significance is the fact that the four classes of Earth-system interactions defined in panels of the IGBP owe much of their impetus to findings of past global changes that were derived from the study of ice and ocean cores. There can be little doubt that new information yet to be found in these and other natural archives will continue to drive the directions of research in Earth system science, and continue to provide critical tests of analytical models. It is essential, therefore, that the proposed 5th panel keep in close contact and exchange information with the four existing panels.

II. PRESENT TECHNIQUES

Environmental data of the past are preserved in natural archives of many types. The principal sources are listed in Table 1, with optimum temporal precision, length of record, and an indication of the environmental parameters that have been derived. T = temperature; H = humidity or precipitation; C = chemical composition of the air (a), water (w) or soils (s); B = information on biomass, as in pollen samples; V = volcanic eruptions; M = geomagnetic field; L = sea level; and S = solar activity. Table 2 summarizes the techniques presently used to glean Earth system information from these records.

Tree-ring studies offer an absolute chronology with annual resolution; moreover, the distinction between early and late wood allows seasonal (spring-summer) resolution for certain studies. The most environmentally-sensitive trees are found in arid high-latitude and high-altitude sites, and it is in these areas of the Earth where most usable tree-ring series have been compiled.

A handful of such collections span several thousand years, notably the bristlecone pine in the White Mountains of California (8.5 kyr long) and oaks in Ireland and Germany (7.27 kyr). There are now prospects to extend the first and longest of these series to perhaps 10000 years, covering the full span of the Holocene, though for a very limited geographical area.

Isolated instances of older wood can be found as "floating chronologies", without absolute dating reference. Ring widths of many species in dry regions show clear, simple and well-understood relationships with water availability.

Tree-ring widths are a convolved measure of soil moisture, temperature, nutrients and other growing conditions. The ring-width in certain high-latitude species has been demonstrated to be a direct measure of summer temperature, as has the maximum density of late-wood growth in more general cases.

Large networks of these various tree-ring data have been used to reconstruct a variety of aspects of regional climate variability and circulation anomalies. In certain cases ring-widths and ring-structure may also be interpreted in terms of volcanic-dust veils and the incidence of forest fires.

Isotopic examination of dated tree-ring cellulose can yield information on root-water temperature and ^{14}C abundance; measurements of the latter, from the long bristlecone pine series, now provide the primary index of solar activity before the time of the introduction of the telescope. Existing tree-ring materials are limited to the temperate zone land masses and so can provide only a partial description of global changes or high-frequency changes. Nevertheless, their potential as an environmental indicator has yet to be fully utilized.

Lake sediments provide another high-resolution archive that can be used to establish local conditions, in some cases as far as a million years into the past. As such they can be used to test various climate models and to understand feedback processes on a regional scale.

Lithology and sedimentation rates both change in response to environmental conditions. In order to properly interpret the proxy climatic signal in lake sequences, it is imperative to understand how environmental signals are stored in lake sediments. Pollen and plankton biota have been traditional tools; the former to establish the density and extent of trees and other vegetation in the region, the latter to derive physical and chemical conditions in the lake water. Biogenically precipitated carbonates carry the oxygen isotopic signal

TABLE 1. CHARACTERISTICS OF NATURAL ARCHIVES

Archive	Temporal precision	Extent	Derived parameters
Tree-rings	yr/season	10^4yrs	T H C_A B V M L S
Lake sediments	yr	10^4-10^6	T B M
Polar ice cores	yr	10^5	T H C_A B V M S
Mid-latitude ice cores	yr	10^3	T H B V M S
Coral deposits	yr	10^5	T C_W L
Loess	10 yr	10^6	H C_S B M
Ocean cores	100 yr	10^7	T C_W B M
Pollen	1000 yr	10^5	T H B
Paleosoils	100 yr	10^5	T H C_S V
Sedimentary rock	2 yr	10^7	H C_S V M L
Historical records	day/hr	10^3	T H B V M L S

T = temperature
H = humidity or precipitation
C = chemical composition of the air (a), water (w) or soils (s)
B = information on biomass, as in pollen samples
V = volcanic eruptions
M = geomagnetic field
L = sea level
S = solar activity

TABLE 2. INFORMATION GLEANED FROM NATURAL ARCHIVES

	ICE				SEDIMENTS/PEAT				TREE - RINGS	
	^2H ^{18}O (H_2O)	Dust/Chem	Gases	Radio Isotopes	Comp.	Faunal	Plants	Isotopes	Structure	Isotopes
<u>SUN</u>		X		XX						XX
<u>ATMOSPHERE</u>										
aerosols		XX			XX			XX		
circulation	X	XX		XX	X			XX	XX	
gas composition			XX					XX		XX
humidity	XX	XX		XX	X			X	XX	X
temperature	XX							XX	XX	X
<u>OCEAN</u>										
circulation	XX	XX	XX	XX	XX			XX		XX
bio-pump		X	XX	X	XX			XX		X
sea-level	XX	X	X		XX			XX		X
sea-ice	X	X	X		XX			XX		X
<u>BIOSPHERE</u>										
vegetation		XX	XX	X	X	XX	XX		XX	XX
<u>LITHOSPHERE</u>										
volcanoes / erosion		XX	X	X	XX				X	
<u>BIOGEOCHEMICAL CYCLES</u>										
Carbon, N, S		XX	XX	XX	X		X	XX	XX	XX
<u>ICE SHEETS</u>										
mass, height, sea ice	XX	XX	X	XX	XX			XX		
<u>ANTHROSHPERE</u>	X	XX	XX	XX	XX	X	X		X	XX
<u>DATING</u>	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

of the lake water which is related to precipitation and evaporation.

Analyses of such archive sequences can also provide a proxy record of biotic/abiotic interactions within the lake, and supply information on the magnitude and rate of environmental change within a lacustrine system. Detrital carbonates can be used to map sources of clastic input and resedimentation processes; surface and littoral precipitates may record seasonal productivity and temperature changes as well as changing water composition. Lake sediments are also a principal source of palaeo-magnetic data.

Ice cores from polar regions (specifically Antarctica, Greenland and Arctic Canada) have yielded the richest lode of data on the environmental conditions of the Quaternary, reaching as far as 150000 years into the past. This reach should be at least doubled in deep cores of bedrock that are now planned in both Greenland and Antarctica. A resolution of one year is possible in recent (<10000 years) ice, through the identification of annual layers of snowfall and the measurement of seasonal temperature differences. Dating degrades in older material and depends on geochemical dating and on models of compression and ice flow.

Information derived from polar cores includes a direct measure of precipitation temperature, atmospheric composition, aerosol loading, volcanic sulphate and other dust, as well as a record of the deposition of cosmogenic nuclides, including ^{14}C and ^{10}Be which promise to extend the history of solar and geomagnetic variations well into the Pleistocene. The quantitative analysis of air bubbles entrapped in Arctic and Antarctic ice allow the direct measurement of the abundance of greenhouse gases in ancient air. These data provide evidence for changes in atmospheric CO_2 and CH_4 that track the air temperature through a full glacial cycle, and indicate that the concentrations of both of these greenhouse gases have already exceeded the global concentrations reached at any time in the last 150000 years.

Polar cores have established the range of precipitation temperature beginning with the last interglacial (3°C warmer than the present) and through the last glacial maximum (10°C cooler). There is evidence, especially from Greenland ice cores, of abrupt climatic changes (several °C in a few decades) both during the last ice age and during the last deglaciation, with concurrent changes in CO_2. Periods of Milankovich (orbital) forcing appear in the 150000-years Antarctic data. All along the last glacial cycle there is a close association between climatic-physical parameters (temperature, precipitation) and environ-mental-chemical parameters (CO_2, CH_4, aerosols from marine, continental and biospheric surfaces). From these has come the principal evidence for a fundamental link between climate and biospheric processes.

Ice cores drawn from high altitude glaciers in the Andes, Alps and on the Tibet Plateau have extended the sampling of past environmental data to mid-latitude sites. The heavy snowfall and seasonal melting that characterizes the mid-latitude glaciers allows annual resolution throughout the extent of the two deep cores that have thus far been taken. These features, however, seem to preclude the sampling of atmospheric CO_2 and probably CH_4.

From the Quelccaya glacier in the Andes has come a detailed record of temperature, precipitation, and aerosol loading through the last 1000 years, including the clear marks of the Medieval Climatic Optimum, the Little Ice Age, and the gradual warming that has characterized the globe since the mid-19th Century. An ice core from Monte Rosa, Switzerland enabled A. O. to reconstruct Sahara dust deposition patterns, melt layers, indications of warm summers, and the anthropogenic increases of NO_3^-, $SO_4^=$, and Cl^-.

Coral deposits provide an annually-laminated record of climate and sea conditions in tropical or semi-tropical waters, not unlike the tree-ring record of temperate latitudes. A recent year-by-year analysis of coral cores from the Galapagos, for example, has provided a clear record of El Niño/Southern Oscillation (ENSO) events for the last several hundred years, through

the quantitative analysis of cadmium in the coral material. Cadmium has been shown to follow the nutrient cycle; the cadmium content of coral is a measure of nutrient upwelling in coastal waters, and is significantly reduced during El Niño events when the nutrient supply declines in coastal oceans.

Temperature information can also be gleaned from measurements of the $^{18}O/^{16}O$ ratio in the calcium carbonate of coral. Coral deposits have also been used as archives of information on past sea-level changes in tropical waters, since certain species grow only within the upper meter of ocean water. It has been shown by this method that sea-level was about 5 meters higher than at present during the last interglacial, leading to the claim that the West Antarctic ice sheet had at that time largely melted.

Loess is a geological sediment of aeolian origin. In places it can accumulate to an appreciable thickness, providing a sedimentary archive that is not unlike that available in glaciers. In the extensive Loess Plateau in west-central China the deposits reach a thickness of as much as 400 meters, providing a continuous record more than 2.5 million years long. Similar deposits may be found in almost any other continent; loess beds in Central Europe, for example, have been demonstrated to extend more than two million years into the past.

Loess beds are primarily a record of wind erosion, vegetation, and atmospheric circulation for the continental region of origin for the wind-blown dust, which is carried at heights of up to 10 km and which can deposit as much as 1 mm of loess in a single dust-storm. Studies of the loess deposits in China have demonstrated an episode of heavy deposition at about 120000 years B.P. as well as shorter and more recent episodes in about 9900-8100, 7400-4600, and 3000-2000 B.P.. In the most recent era, epochs of heavy dust-fall are found that correspond with historical accounts of "dust rain" in Chinese annals, as in A.D. 1060-1090, 1160-1270, 1470-1560, 1610-1710, and 1820-1890. Loess deposits have also provided a terrestrial record of reversals of the Earth's magnetic field.

Ocean sediment cores have now been taken from many regions of the Earth's ocean, providing, through derived continental ice volume and temperature histories, the principal evidence for the orbital forcing of the Earth's climate (Milankovich effect) through the last one million years. Most cores are drawn from ocean depths of 2500 to 4000 meters, to a sediment depth that is limited by the extent of soft sedimentary material; some go as deep as 200 meters, although conventional piston coring is limited to about 40 meters. At the bottom of the deepest cores material is retrieved that fell to the floor of the ocean as long as 20 million years ago.

Ocean cores are analyzed chemically for many parameters and classically examined for the number and distribution of various foraminifera - primitive shelled fauna - whose abundance in the surface layers of the ocean is at any time a function of surface-water temperature and other environmental conditions. Radiocarbon analyses of the same organisms provide a method of dating the associated core material, to a limit of about the last 40000 years.

Sediment studies (including sedimentology, geology, geomorphology, pedology, and pollen analysis) offer many tools and a long experience to those who would read the history of the Earth and its environment. The record of global change is written most indelibly in geomorphic processes and the strata of rock and sand and soil that exist today in all parts of the world. Absolute chronology of such records is provided by geochemical analysis.

The reading of these records in rock has yielded a wealth of information on hydrological and biological changes, the rise and fall of sea-level and the shifts and flexure of the Earth's surface in response to earthquakes and volcanic activity, changes in palaeosols, glacial loading and unloading, and the motions and evolution of continental plates. A knowledge of changes in the figure of the Earth is essential to interpret the apparent rise and fall of sea-level; a knowledge of the changes in the orientation and moment of the Earth's magnetic field is essential to interpret the records of the cosmogenic nuclides, including ^{14}C.

Written or historical records, together with contemporary measurements, provide the "ground truth" and "Rosetta stones" through which the natural archives are read. They are also a source of information in their own right. Quantitative records of temperature and other meteorological parameters are available for at most 250 years, and in but a few areas of the globe. Descriptions and diaries in Europe and the Americas, often in the records of trade or in religious orders, can provide a more subjective record for another 500 years into the past.

In ancient China, Korea and Japan, where traditions of government and of judicial astrology demanded the keeping of official and provincial diaries, these annals reach back, more or less continuously for 22 centuries into the past. For almost all of this time span the Oriental accounts are more extensive, more detailed, and more valuable than those from anywhere else on Earth. Coupled with natural archives for the same region, including the deep loess beds of China, they identify the Asian continent as an area of particular promise for the reconstruction of natural and anthropogenic environmental changes in the last 2000 years.

III. RECOMMENDED PROGRAMME EMPHASES

In what follows we describe seven themes, developed at a workshop in Berne, Switzerland in July 1988 for recommended emphasis in the IGBP. These are:

A. Year-to-Year, Decadal and Century-Scale Changes

B. Palaeo Records of El Niño - Southern Oscillation (ENSO) Phenomena

C. Past Effects of Man on Climate and Environment

D. Global Changes in the Holocene

E. The Last 150000 Years: Global Changes through a Glacial-Interglacial Cycle

F. Needs in Ocean and Terrestrial Data

G. Requirements for Modelling Palaeo Data

As noted in Section I, these themes are intimately connected to related programme initiatives in Terrestrial Biosphere - Atmospheric Chemistry Interactions, Marine Biosphere-Atmosphere Interactions, Biospheric Aspects of the Hydrologic Cycle, and Effects of Climate Change on Ecosystems, and were chosen with these basic programme directions in mind. They also bear upon broader areas of Geosphere-Biosphere Modelling and on Data and Information needs for the IGBP. It is obvious that an IGBP initiative in **Global Changes of the Past** must be developed parallel to and in close contact with all of these other areas of emphasis.

A. *Year-to-year, Decadal and Century-Scale Changes*

1. Problem statement

The expression of Earth system behaviour that is most readily perceived is the high frequency variation in climate: the year-to-year and decadal changes. Yet our knowledge of past variations on these time scales is very limited. This is chiefly a consequence of the restricted temporal and spatial concentration of instrumental records; most begin with the Industrial Age and are limited to major centers of population. There are, however, a number of other indirect sources of relevant information that can be effectively integrated with one another to extend our knowledge of past climate. These include, for example, early instrumental records, annual ice-layers, tree-rings, corals, varves, and cosmogenic isotope records.

The following issues limit our present understanding and need to be addressed:

- How well can climate variability on sub-century time-scales be characterized in the space, time, and frequency domains?

- To what extent can such year-to-year, decadal and century-scale variability be accounted for by identifiable forcing factors?

- Which of the trends and forcing factors are global in scale?

2. Background issues

Substantial climatic variance is found on widely different time scales. For instance, long-term components lasting tens of thousand of years have been tied to the Milankovich insolation changes whereas much shorter annual variability is induced by El Niño oceanic change. On decades to century time scales there are the Little Ice Age, the Medieval Climatic Optimum, and the present 20th Century warming. The causes for these century-scale variations are not well understood. Nor is there, as yet, a sufficiently detailed record of trace gas variations during the last 1000 years. An improved understanding of the forcing functions and the phasing of changes in temperature, CO_2 and CH_4 abundance is essential for understanding the past and predicting future global change. Decadal and century-scale variations are part of the natural background against which the climatic influence of greenhouse gases have to be measured.

Volcanic emissions, solar variability, and increased frequency of El Niño events have been proposed as possible causes for the century-scale variations. Although much previous work has been focussed on the Little Ice Age and Climatic Optimum, a precise record is lacking. The regional extent and chronology of these events is not well established. A more precise record of climate variability would improve the identification of climatic forcing factors. At least one potential forcing factor, solar variability, is chronologically much better defined through the atmospheric ^{14}C record in dated tree-rings. The Greenland ice core record also provides a ^{10}Be record and offers a chronology of major Northern Hemispheric volcanic eruptions, with much better time resolution than most climate records.

Historical data, proxy records of tree-ring indices, of oxygen and hydrogen isotopic ratios in ice cores, and of pollen distribution in lacustrine sediments play an important role. Much more information seems deducible from studies of ^{10}Be, ^{14}C and total CO_2 in ice cores; such studies would help to disentangle climatic influences on ^{10}Be distribution and to investigate the several ppm natural variability in total atmospheric CO_2 content. Further studies on changes in ocean circulation (such as El Niño history in corals) are also essential.

Whereas the above approach improves the correlation procedures essential for identifying possible causes, much more has to be known about the physical and chemical processes tied to these causes. For example, although the sun's modulation of the cosmic ray flux has been known for the past 1000 years, its direct influence on solar radiative output is much less understood. Similarly, the record of Northern Hemispheric volcanic eruptions is chronologically precise for that period, but provides only limited information on the atmospheric distribution of the gaseous components and dust particles.

The nature and causes of inter-annual and decadal climatic variability are not well known and constitute an obvious gap in our understanding of the climate system. Surely, the best known feature of decadal change is the warming that has characterized the Northern Hemisphere in the last 100 years. Beyond this global trend, little more is known with certainty about even the last century. No one source of data can provide the geographic coverage or climate sensitivity to study global patterns of multivariate climate change. The spatial and temporal applicability of the various records, coupled with their often complex or ill-defined responses to climate, must all be recognized. A strategy for reconstructing short-term climate must:

- be based on as many different kinds of record as possible, to allow cross-validation;

- incorporate or encourage improvements in understanding the responses of the various records to climate change, e.g. biological mechanisms in the cases of corals or tree-rings; and

- involve specialists in synoptic climatology and climate modelling at every stage to ensure that the data taken are applicable to tractable mechanistic problems.

The strategy proposed to meet these requirements is to organize the collection and integration of annual resolution climate records for specific eras in the last 1000 years. The project must also include

interpretation, and models of year-to-year and decadal climate change. This must be done using the full range of available natural and human records, from marine and freshwater as well as terrestrial and cryospheric sources. It is important to have the best possible geographical distribution, including low, middle and high latitudes in the Southern as well as Northern Hemispheres.

3. Other related programmes and activities

Many agencies and individual scientists are engaged in developing year-to-year and decadal climate records, but there have been few organized attempts to integrate them on a continental or larger scale. Some notable exceptions are a) the European Climate Programme, b) several separate joint initiatives between bilateral signatories, and c) programmes or joint projects initiated by national or multinational groups of individual scientists. The last group includes:

- a recent meeting on Climate in the Year 1816, the year without a summer, organized by the National Museum of Canada;

- a project called "Analysis of Recent and Rapid Climate Change" being planned by a group of US scientists. They hope to link a global palaeoclimate database with General Circulation Model (GCM) experiments, focussing first on the years 1680-1715 A.D. and 1790-1825 A.D. and then extending to several centuries and perhaps eventually the whole Holocene;

- the International Project in Dendroclimatology (IPID) in which scientists from eight countries pooled tree-ring data and are seeking strategies to reconstruct high-frequency climate variability, particularly since A.D. 1700.

- a proposed circumpolar tree-ring density network, designed to record summer temperature, proposed by the Eidg. Anstalt für das Forstliche Versuchswesen, Switzerland; and

- a proposed Central-Asian tree-ring network proposed by the Laboratory of Tree-Ring Research, University of Arizona, USA.

4. Proposed IGBP activities

The goals of a sub-century climate initiative for the IGBP are to characterize climate variability on sub-century time scales and to identify mechanisms responsible for these changes and to assess global implications through modelling. The specific objectives are:

- to establish a global inventory and database of palaeoclimate data for the last 1000 years with at least annual resolution;

- to set up a related global directory of data on possible climate forcing functions (e.g. volcanic, trace gas, solar variations, major oceanic oscillations);

- to develop strategies for comparing various records and integrating them into global reconstructions and annual or seasonal maps;

- to expand the available proxy data by encouraging new collections in regions that are ill-represented or of particular climatic interest;

- to test hypotheses on the possible causes of high-frequency changes identified in the proxy data through climate-model experiments, by comparing simulated and observed changes;

- to encourage efforts to understand the mechanisms that control variability in proxy climate records, especially tree-rings (width, density, micro-anatomy, isotopic composition), coral layers and laminated aquatic sediments.

Priority should be given to:

- Establishing global inventories and databases of high-resolution palaeo-climate data and forcing function records;

- Expanding the available data to new regions for example, through new tree-ring collections for ring-width, density and other measurements in a) the high latitudes of the Northern Hemisphere and b) the heart of Asia, the region surrounding the Tibetan massif;

- Developing new annual resolution records in low latitudes, for example in coral layers in the West and East Pacific basins;

- Securing a number of "short-term" ice cores, including lower latitude cores (1 to 2 kyr with clear annual resolution) from as many geographical regions and with as much local replication as possible;

- Improving mechanistic understanding of the processes creating annual resolution environmental records, by experimental and simulation approaches;

- Rescuing or protecting endangered records (dying or destroyed coral, mined, felled forests, housing ancient trees;

- Linking GCM experiments with palaeo-climate data for relatively well-recorded periods for which there is prima facie evidence for possible major forcing factors, such as the Maunder Minimum and the 1790-1825 A.D. period.

B. *Palaeo Records of ENSO Phenomena*

The palaeo-record of arid region variability can add much to our knowledge of episodic ocean-climate anomalies (ENSO/Monsoon/ and Others).

1. Problem statement

Proxy records of climate variability on time scales of seasons to years are needed to define and test both climate models and models of vegetational change. Of particular promise are records of past variations in the extent of arid regions and their fringes.

2. Background issues

The atmosphere, biosphere and geosphere are linked and interact by exchanges of radiation, heat, momentum, and notably water. The connections are particularly evident in arid regions which make up more than 26% of the land surface of the Earth. Climatic-hydrologic conditions in such areas, particularly on their fringes, are of special relevance to the habitability of the planet. How sensitive are arid-zone fringes to slight shifts or abrupt feedback - responses, or to continuing anthropogenic impact?

Small changes in the ocean and atmospheric circulation appear to control the expansion and contraction of arid regions. More importantly, we have recently realized that there may be a link between recurring natural oceanic-climate anomalies (such as the Monsoons and El Niño/Southern Oscillations) which abruptly affect critical seasonal rainfall patterns. Monsoons for example, are driven by seasonal heat and moisture-budget differences. Even small shifts add a tragic burden to the agricultural potential of arid fringes dependent on, for example, monsoon recurrence.

We need to understand the high-frequency record of past variability of episodic climatic anomalies; this can be done in part by documenting and analyzing arid-zone responses.

Arid-region changes have occurred on a variety of time scales including those of recurrent glaciations, of decadal time scales, thought to link interactions between the North Atlantic Oscillation and drought in North Africa and on scales of several years, such as the El Niño/Southern Oscillation and Monsoons.

Models predicting the past and future changes of insolation and monsoons need to be validated for time spans back to 180000 years B.P. The models suggest smooth transitions with monsoon maxima near 9000 B.P.. What fragmentary information we have suggests that the natural record is punctuated with a complex pattern of higher frequency events. Natural archives provide

the key to defining the important recurrence rates of extreme environmental events.

3. Other related programmes and activities

Various national and international programmes are in progress to collect and study proxy archives. Ocean cores, for example, are available along a monsoon transect of the Arabian Sea. These ocean data are limited by relative sedimentation rates and bioturbation. Non-marine palaeo-environment transects have been devised for Europe, North Africa, USA, USSR and northern South America, and Australia. Most of these are aimed at a single proxy archive for major late glacial to post-glacial transitions. Such programmes can also act as foci for analyses of short- term episodic climatic anomalies.

4. Proposed IGBP activities

A focussed study of lake sediments and other records in regions presently affected by climate changes of the ENSO type can do much toward understanding and predicting this fundamental interaction. We propose the investigation of selected time-window transects across swaths or belts that link arid zones to the oceans. These provide a means of extending and improving the resolution of proxy archives and should focus on quantifiable geosphere-biosphere interactions including vegetation, seasonality, and the hydrological cycle. The concept of time-window-transects on the continents implies a close correlation of proxy records with ocean core and polar ice core results.

Methods and techniques. Reconstruction of time-window transects for temporal variation requires integration of continuous archives such as historical records, tree-rings, lake bog cores, palaeosoils, ocean cores, ice cores, loess cores, and other more punctuated data sets such as lake levels, soils, middens, and volcanic residue.

Much individual work is in progress but the IGBP can do much to fill gaps, identify sites and integrate the use of various methodologies to understand past changes on decadal to centuries scales. The IGBP can help to define time windows which spotlight specific mechanisms of feedback responses. It is essential to encourage collaboration between groups, coordinate site selection, and define quality control of data. The quality and integration of the records are determined by the availability and quality of the samples. The IGBP can, for example, ensure the development and availability of sampling techniques for high resolution in undisturbed lake and land-core archives. The IGBP must also help ensure the availability of the facilities for the large increase in precision dating that will be needed to define a high resolution study.

Large-scale multi-national transect studies which can define the variability of episodic climate anomalies include:

a) a transect along the monsoon path from the Arabian Sea across India, Tibet, Mongolia, to the USSR and back through China to the China Sea. Closed-basin lakes that are found along this path are particularly sensitive to variations in excess moisture and transport. They also document landscape and vegetation changes. A range of other valuable archives is also available along this swath. This transect can also serve as a critical test of the palaeo-insolation-monsoon models that are now being developed. The IGBP can be of most value where transects cross national boundaries.

b) Transects to test the Palaeo-ENSO variability across the Pacific margins of the Galapagos to the Andes, or eastern Australia. These need to link long records of coral growth rings with tree-rings, historical records, lake sediments, and offshore varves in upwelling zones.

c) A north-south Equator-to-Mediterranean transect through Africa to define shifts in vegetation and palaeoclimate with a focus on interactions with the Atlantic Ocean, linked to work in progress on shifts in tropical-forest regions associated with warm and cold climatic phases form the basis for integrated variability studies.

d) A Tasmania-Australia transect to match Southern and Northern Hemisphere records. Programmes in progress on Late Glacial records can be encouraged to expand their scope to meet this need.

e) An Eastern Pacific-to-Colorado Plateau-Gulf of Mexico transect to provide an unparalleled opportunity, since within this swath there are a wealth of proxy environmental records. These cover time scales as long as 100000 years and are found in coastal and lake laminated sediments, well-dated fluvial events, pack rat middens, and the world's largest concentration of well-understood tree-ring chronologies. A number of well-tested reconstructions of climate aspects for the last 400 to 5000 years already exists; an integrated approach to at least the last 1500 years seems entirely feasible with annual resolution.

The IGBP should help organize panels for each transect to help to coordinate ongoing work, focus on scientific questions for site selection, and initiate complimentary research projects.

C. Past Effects of Mankind on Climate and Environment

1. Problem statement

It has become evident that the effects of human activities have grown so much as to influence climate and the environment in a significant way on a global scale. The increase in atmospheric CO_2 and of other trace gases is an obvious case in point. The emission of man-made gases is almost certainly the cause for the observed dramatic decrease of stratospheric ozone over Antarctica ("ozone hole"). The surface of the continents has been modified by human activities through agriculture, industry, and construction. These land-surface modifications have involved the emission of CO_2 and other greenhouse gases such as methane and N_2O, and they have changed the boundary conditions for atmospheric processes (including albedo, surface roughness and change of evapotranspiration due to deforestation).

2. Background issues

Reliable, direct atmospheric measurements of concentrations of greenhouse gases are available for only the past 20 to 30 years. For earlier periods, the main source of information is analyses of bubbles trapped in polar ice. These have provided evidence of increasing concentrations of CO_2, CH_4 and N_2O in the past centuries, obviously, as a consequence of human activities. The increase in carbon dioxide has also been identified by means of carbon-13 analyses in tree rings, but the natural variability of this isotope in trees is so large that it is difficult to isolate the atmospheric signal.

3. Proposed IGBP activities

The CO_2 increase is caused by the burning of fossil fuels as well as by deforestation, and agricultural use of soils. There is still much debate on the relative contributions from the two sources. To clarify this question, which is important as a basis for predictions for the future, research in several areas is necessary:

- The variations in CO_2 (concentration and isotopic composition) in the past must be established with better precision for the industrial era as well as for the whole Holocene, since it is important to know the amplitude and character of the natural variability. To achieve this the retrieval and analysis of polar ice cores constitute the most promising methods.

- Data on changes in the terrestrial biomass must be improved by establishing the extent of land-surface changes, the density of the affected biomass (or the carbon density, tons of carbon per hectare) and regrowth processes. These data can be obtained for the present period by IGBP spaceborne mapping and land-use studies. For past periods many types of records and natural archives (such as lake cores and associated pollen studies) will need to be used and coordinated.

- The effect of anthropogenic and natural processes on primary productivity and carbon storage in undisturbed ecosystems, by pollution or inadvertent fertilization with CO_2 and nitrogen compounds, is not at all clear and requires intensive efforts in the field of process studies.

- Existing global carbon-cycle models need to be further refined for the interpretation of the palaeo records obtained, especially towards higher resolution in the ocean submodels and the modelling of the terrestrial as well as the marine biosphere.

The history of atmospheric methane and N_2O is less well known than that of CO_2, and nothing is known about the other trace gases such as CO for the period before about 1960. Again, ice-core studies appear to be the major if not the only possible source of information. Similarly, such studies may provide information on variations in photochemically active atmospheric components. However, so far little work has been done in this area except for H_2O_2 determination. Indirect evidence for changes in stratospheric chemistry might be found by looking for nitrogen compounds in Antarctic ice. Limited studies toward this end have already been attempted, though for other purposes and with equivocal results.

The growing acidification and general pollution of the atmosphere (especially by heavy metals) can be followed in ice-core records, and in continental deposits (lake sediments). However, a quantitative interpretation requires a better understanding of the processes responsible for atmospheric transport and for deposition of aerosols.

The effects of land-surface changes are primarily local, e.g. soil erosion, or frequency of floods. However, large-scale consequences must be expected as an integral result of the modifications, on a continental scale, carried out by man, e.g. in Europe, Asia or North America in the past, or as is currently occurring in other parts of the world. These changes will ultimately influence the surface water balance (runoff, evapotranspiration) and the radiation budget via albedo changes. These cumulative effects seem to be less important on a global scale than the better documented increase in greenhouse gases, but they certainly cannot be neglected. At present, the extent of the land-surface changes through past centuries and millennia is not well known. A European research programme is now being initiated by the European Science Foundation to study the effect of human activities on climate in Europe during the past 9000 years.

D. Global Changes in the Holocene

1. Problem statement

The last 10000 years of the Earth's history is the period in which the present ecological conditions, including our present life-support systems, were developed and in which human impact on these systems became obvious, first as a result of rapidly expanding agriculture and later through wide spread industrialization and urbanization.

It is important to analyze the changes that took place during this period, both in order to understand the present and to anticipate the future. Of particular relevance is the medieval climatic optimum (A.D. 1100-1200) in which a global warming of 1°C must have been accompanied by significant changes in the circulation of the atmosphere and the oceans. Resultant changes in the terrestrial structure and zonation of ecosystems offers an appropriate scenario for the first decade of the next century. For this purpose, we need to intensify research to obtain a more complete description of the changes that took place in key indicators and key processes during global changes throughout the Holocene.

2. IGBP emphases

Temperature and precipitation. Our knowledge of the evolution of climate through the Holocene (in terms of surface temperature, precipitation, atmosphere and ocean circulation, and the responses of the environment) is far from complete. Nor can we model it reliably, without a better understanding of the global climate system. As is the case today, changes of temperature and precipitation were not globally uniform. In the high latitudes changes in temperature were predominant; in the middle latitudes there were significant changes in both temperature and precipitation; at low latitudes changes in precipitation were more important. Of special interest is a comparison between conditions in the Northern and the Southern Hemispheres, because we do not yet know whether the processes were synchronous. Nor do we understand the various time lags between significant changes in atmospheric and oceanic circulation that occurred in the Northern and Southern Hemispheres.

Arid and semi-arid land. The arid and semi-arid regions of the Earth describe the most sensitive ecosystems between the humid extratropical and tropical zones. The smallest changes in humidity (even 100 to 200 mm per year) had not only a very strong effect on the hydrological (lake formation, fluvial systems), biological (vegetation cover, wild life migration), and pedological (soil) formation systems, but also on the development of adapted cultures and land- use systems. The combination of many of these indirect climatic indicators allows us to reconstruct the circulation patterns in the atmosphere for this period in time. The systematic advance of the monsoon, as humid tropical air masses move towards and into today's arid zones, must be taken into account in any future scenario of global warming. Therefore, we need intensified efforts to recover data on past occurrences in the arid zones, through studies on lake sediments, palynology, palaeosoils, groundwater dating, the analysis of geomorphic processes, etc. These data are needed if we are to understand the spatial and temporal changes that took place.

Of particular relevance is the International Geological Correlation Programme (IGCP) Project No. 252 on the "Past and Future Evolution of Deserts."

Loess. Desert and loess usually developed side by side during the Holocene in arid and semi-arid regions. For this reason a marginal shift between the desert and the loess constitutes a sensitive indicator of changes in regional aridity. An appropriate IGBP effort in this area would pay particular attention to:

- the shifts of Holocene desert and loess areas, particularly at their transition zones, in both the Northern and Southern Hemispheres;

- changes in vegetation and land formation in the desert and loess regions since the beginning of agrarianism in the Holocene.

Middle latitudes. In this zone smaller changes occurred in both temperature and humidity. Certain impacts occurred on vegetation, soils, water balance, glacier extent, etc. The study of climate and ecosystems in the Holocene will reveal important interactions as well as providing us with indications about possible future changes in climatic conditions in the most important and most intensely used agroecosystems. Changes in precipitation quantity, regional distribution and variability could influence the water balance and the water content in the soils, which would have serious consequences on worldwide agricultural production in the next century.

High latitudes. The climatic changes during the Holocene had pronounced effects on the dynamics of the glacier and the permafrost systems in the high latitudes. During the thermic optimum of the Holocene there was an active retreat of the high latitude and mountain glacial systems. The extent of permafrost was closely related to thermal changes.

There are several practical reasons for studying the past dynamics of the permafrost zone:

- Evaluations of surface temperature and of the change in depth of the seasonal (active) layer, in response to global climatic change, can influence present economic and other human activities in permafrost regions of the globe.

- Present-day investigations of biogeochemistry have shown that systematic melting of the permafrost during the climatic optimum of the Holocene may have provoked an increase in atmospheric methane as a positive climatic feedback factor.

Sea level changes in the Holocene. The warming that follows an increase in greenhouse gases may lead to the melting of polar and continental ice sheets and ultimately to the possible submergence of some coastal cities. Relationships between climate and the volume of sea-water changes must be determined more accurately. Palaeo sea levels recorded in coastal landforms are indicators of changes in seawater volume and in isostatic (glacio- and hydro-) and local tectonic movements. For this reason, we need to collect sea-level data from tectonically stable coasts, take the isostatic adjustments into consideration, and then obtain data on water-volume changes. This knowledge from the past is essential if we are to predict future sea-level rises. Present uncertainties in this area are reflected in the range of predictions that are made, ranging from a few meters to several tens of meters. The IGCP-Project No. 61 on Holocene Sea-Level Changes and Project No. 260 on Sea-Level Correlation and Application provide some past sea-level data. However, we need more extensive Holocene sea-level data of a higher degree of accuracy in order to predict future sea-level rises. We also need to improve isostatic modelling.

Phytomass. The biomass of the terrestrial ecosystems has shown clear responses to climatic evolution during the Holocene. The preliminary investigations show that an increase in the present mean global temperature by 1°C corresponds to an increase in the terrestrial phytomass of between 10% and 20% (from data in regions of Eurasia). But, more important than the change in quantity of the terrestrial biomass were the accompanying shifts in the boundaries of climatic zones (such as those in the tropical and moderate forest zones, and the tundra zone in the north). An IGBP effort in this area should aim at improving the record of biomass changes throughout the Holocene, by the recovery and interpretation of various proxy indicators.

Orbital and cosmic ray effects. Cycles of Milankovich orbital frequencies are clearly observed throughout the oceanic and the continental stratigraphic record in climate sensitive facies. However, very little is known as to how this subtle external forcing works. It is manifest that the "climate" is an end product of the combined external forcing and internal responses of the system such as changes in atmospheric CO_2, ice cover, and ocean circulation.

The Holocene period provides an excellent time segment of the global climate system for detailed multivariate study. Documented changes in trace gases and the aerosol content of the atmosphere at the close of the Pleistocene and throughout the Holocene can illuminate the role of the factors that apparently amplify Milankovitch forcing of the climate system.

Although many of the climatic parameters have remained within a narrow range of variability during the Holocene, the variations are still measurable, and some have even varied significantly. Attempts should be made to study the more variable parameters throughout the Holocene, with as much accuracy as possible, including $CaCO_3$ preservation, ocean circulation, precipitation, aeolian transport and grain size. Of particular significance during the Holocene would be the study of the effects of volcanic eruptions in changing the climate.

The ^{14}C record in tree-rings also deserves special mention since it shows large variations in decadal, century and millennia time scales. It has been believed for a long time that these changes primarily reflect changes in the cosmic-ray flux. A competing view that has recently emerged is that changes in oceanic circulation and chemistry may be the main cause of the observed ^{14}C changes in tree-rings.

Another recorder of cosmic-ray flux is cosmogenic ^{10}Be, for which a long time-series has been measured in ice cores. The record is however difficult to interpret, chiefly because its rate of deposition is not only an index of its mean global production rate, but also of the amount of local precipitation (rain and snow). These effects need to be deconvolved. It would be most significant if the question of the time variation of ^{14}C and ^{10}Be production during the Holocene could be resolved.

The tree-ring isotopic record could then reveal more exact information on changes in air sea exchange, land/ocean carbon inventories and small changes in ocean circulation.

E. The Last 150000 Years: Global Change Changes Through a Glacial-Interglacial Cycle

1. Problem statement

Recent marine and continental records have allowed us to characterize large global changes of climate parameters through a complete glacial cycle. These glacial/interglacial changes have had a large impact on land-surface characteristics and on the biosphere. Perhaps more important, ice core results have provided evidence of concurrent large chemical changes in the atmosphere. In particular, concentration changes in atmospheric CO_2 and CH_4 during a glacial cycle are comparable to the changes now observed in response to human activities. The reconstructed temperature changes through glacial-interglacial cycles are also of the same order as those predicted by modelled effects of human impact on climate in the next 50-100 years.

Abrupt climate changes, lasting decades to centuries are another feature of the ice-core record. Ice cores, marine and lake sediments, and continental pollen records show evidence, at least in the Northern Hemisphere, of abrupt climatic changes of significant amplitude on time scales from decades to centuries.

These palaeo-data reveal important Earth system processes. Taken together they show the evolution of climate and environment. This permits a critical evaluation of existing models of climate and environment. It should also stimulate new model experiments that deal with complex Earth system interactions. Such an understanding of Earth system evolution requires additional quantitative, high resolution data from ice cores and from marine and continental records.

2. Background issues

Over the last few years proxy data of past climates have provided evidence for important changes in the coupled Earth system. These data indicate changes in air and sea temperatures, distribution of ice sheets, glaciers, permafrost, sea level, ocean circulation, land-surface characteristics, continental vegetation and biomass, and in the chemical composition of the atmosphere. Long-term climatic and environmental records allow us to characterize various climatic stages, starting with the last interglacial, culminating about 125000 years ago, and through a long, cold climatic period interrupted by stages of slightly warmer conditions. Full glacial to interglacial conditions are characterized by large precipitation and temperature changes (2° to 4°C globally, but up to 10°C in polar areas) with large increases of greenhouse- gas concentrations (CO_2 + 50%, CH_4 X2), and changes in continental dust (up to X30), and in marine and biospheric (e.g. dimethyl-sulphide derived) aerosols.

The few longer quaternary cores available from lakes, peat bogs and loess show a first-order correlation with the marine and ice-core records. These archives document the timing of vegetation changes in response to regional glaciation and deglaciation processes.

The long-term temperature trends found in palaeo records are well correlated with calculated changes of solar insolation in the Northern Hemisphere (Milankovitch mechanism) which probably induced the build up and destruction of continental ice.

Portions of the Milankovitch signal in the Southern Hemisphere are out of phase with those for the Northern Hemisphere. Moreover, the possible albedo change due to the building up of continental ice is much smaller than in the Northern Hemisphere. It is therefore difficult to explain why climatic changes as pronounced as the transition from the last glacial to the postglacial occurred at almost the same time.

Model calculations indicate that inter-hemisphere coupling cannot be accomplished by atmospheric heat transport between the hemispheres. Possible mechanisms include:

- A reduced global greenhouse effect due to reduced atmospheric CO_2 and CH_4 concentrations during the glacial;
- The transport of the cold signal from the Northern to the Southern Hemisphere by ocean circulation;
- Increased cloud cover due to a higher aerosol concentration, leading to globally increased albedo;
- Changes in ocean circulation, i.e. fluctuations in the extension of the North Atlantic cold surface water.

Long-term variations in the atmospheric composition and of cosmic-ray produced isotopes. Atmospheric trace-gas and cosmogenic-nuclide content undergo substantial changes during a full glacial cycle. The changes are recorded in ice cores and tree-rings (^{14}C). Trace gases such as methane and carbon dioxide determine the greenhouse contribution to climatic change. Cosmogenic nuclides such as ^{14}C and ^{10}Be provide information on possible changes in Earth geomagnetic dipole intensity, on variations in the exchange rate of the Earth-carbon reservoirs, and on the changes in the extended magnetic field of the sun.

Because substantial change in carbon reservoir properties took place at the glacial-interglacial transition, the ^{14}C record in tree-rings should be extended, in whatever way possible, beyond the 8500-year interval currently available in the bristlecone pine. This work should preferably be done for at least two independent tree-ring chronologies.

The presence of ^{14}C and ^{10}Be in ice cores provides information on the solar and geomagnetic modulation of the high-energy cosmic ray flux. The two isotopes show different geochemical behaviour, e.g. ^{10}Be is removed from the troposphere by precipitation within a few weeks, whereas $^{14}CO_2$ is continuously cycled between the ocean and the atmosphere. The combined study of the two isotopes makes it possible to distinguish between the history of production-rate changes and the influence of the geochemical processes. The ^{10}Be signal in ice cores may also provide stratigraphic markers for dating and intercomparison of ice-core samples.

Analysis of deep polar-ice cores have clearly demonstrated that the concentration of atmospheric CO_2 has varied in step with climate during the past 150000 years, within a factor of about 1.5. Model calculations suggest that these variations have contributed significantly to the glacial-interglacial temperature difference. Recent results have shown that the methane concentration at the glacial maximum was about 50% of the Holocene level. It seems certain that changes in oceanic, physical, or biological state must have been responsible for the CO_2 variations, but the processes are not yet known.

Methane changes are probably linked to terrestrial ecosystems (wetlands), but our understanding of the processes and controls are not well developed. Rather surprisingly, methane and CO_2 seem to have varied in parallel, although the chemical processes involved are fundamentally different.

More detailed records of gas concentrations are needed, especially to identify cause-effect relationships between air temperature (^{18}O) and gas concentrations. Of special interest are the variations (magnitude and rate) that characterize the Alleröd-Younger Dryas variation. Answers to these questions are needed to understand what controls the natural trace-gas levels and what changes might be expected in the future.

The long-term trend in climate over the last 150000 years is clearly documented in the $\delta^{18}O$ record which changes in the continental ice mass and in ocean sediments. A very similar trend is observed in the ice core from Vostok Station, Antarctica, for the hydrogen-deuterium ratio, δD, which also reflects regional atmospheric temperature.

The ice cores from Greenland and from Antarctica, exhibit a more complex $\delta^{18}O$ record. The transition from low glacial to higher postglacial values occurs in two distinct steps. Around 13000 years B.P. a first warming occurred which lasted about 2000 years. This initial warm period has long been established in pollen profiles taken from peat bogs. It was followed by the cold Younger Dryas period with temperatures (from $\delta^{18}O$ values) as cold as those during the preceding glacial period . Around 10000 years B.P. the final warming occurred, leading to climatic conditions which have been essentially constant during the past 10000 years.

Another feature observed in the Greenland ice is a series of rapid climatic changes in the period from 70000 to 30000 years B.P. All parameters measured in the ice cores show significant changes for these periods including $\delta^{18}O$, major ions, dust, CO_2, and from first indications CH_4. Similar changes, though less definite, are also observed in the faunal composition of ocean sediments, and pollen distributions in European peat bogs.

Terrestrial ecosystems reacted emphatically to these documented climatic changes. The first attempts to calculate the change of continental phytomass (for the territory in the northern half of Eurasia) had shown, that during the optimum of Eemian time (the last interglacial period, when mean global temperature was 2°C higher than at present) the phytomass had increased by more than 50% above the present amount. In contrast, at times of increased cooling in the intervening ice age the value of phytomass decreased; during the maximum of last glaciation (18000 to 20000-years ago) phytomass was 30% of the present value. With size of phytomass the composition of vegetational formations also changed. In the Eemian, an increase in the different forest formations was typical in the tropics as well as in the middle latitude regions. During the cold periods, the amount of steppe and semi-desert areas increased.

The short-term climate changes observed in the Greenland ice cores. Rapid climatic oscillations were found in the Greenland ice core in the time interval from 70000 to 30000 years B.P., accompanied by CO_2 concentration changes between 200 and 240 ppmV. Since CO_2 is globally well mixed, these temperature changes are assumed to be global in extent, and should also appear in the Antarctic ice cores. So far, changes of similar nature have yet to be identified in the Byrd core, in spite of a detailed analysis of a possible attenuation due to the lower Antarctic accumulation rate. It remains an open question whether rapid CO_2 changes did in fact occur or whether they could be an artifact of melt-layers in the somewhat warmer Greenland ice sheet.

New measurements of CH_4 planned in Arctic and Antarctic ice cores promise to give new insights regarding the existence of rapid (50-year) changes in atmospheric trace concentrations. Tests are planned to determine whether the CH_4 concentrations follow the general trends of CO_2 and $\delta^{18}O$, and whether high CH_4 concentrations are found in Greenland and Antarctica at the time of a warm interval during the glacial period. A detailed CH_4 study on Greenland and Antarctic ice cores might enable us not only to reconstruct the atmospheric CH_4 history but also to closely match the time scales (detailed chronologies) of the ice cores from the two hemispheres.

3. *Other related programs and activities*

Several existing programs and activities are directly related to IGBP efforts to examine the glacial-interglacial cycle. The International Geological Correlation Programme (IGCP) of the United Nations Educational, Scientific and Cultural Organization (Unesco), and the International Union of Geological Sciences (IUGS)

includes several projects related to environmental changes, in particular its subprogramme on Quaternary Geosciences and Human Survival, and the Man and Biosphere Programme (MAB). The International Hydrological Programme (IHP) provides data on water balances; activities of Intergovernmental Oceanographic Commission (IOC) and some of the related programmes (e.g. Coastal Marine Project (COMAR)) provide data on sea-level changes and sea evolution. The activities of the International Union for Quaternary Research (INQUA) deal with the study of the Quaternary period and the work of some of its Commissions or Committees (Commission on Palaeographical Mapping of the World, Committee on Global Changes), etc. are directly related to the above subject. Some projects and activities of the World Meteorological Organization (WMO) may contribute to the study of very long-term climatic changes.

4. *Proposed IGBP activities*

Understanding the scale and the interrelated processes affected during a Glacial-Interglacial cycle is a key link in determining the natural range of past global changes. To achieve this understanding and unravelling the complex nature of the proxy data, priority should be given to projects addressing the following issues.

- The combination of various proxy records should allow one to document the physical, chemical and biological states of the Earth over glacial and interglacial stages. Within this very large objective, priority studies should focus on transitions from glacial to interglacial, from interglacial to glacial, and on abrupt climatic changes such as those already found during the last ice age and subsequent deglaciation. It is of particular importance to obtain high resolution records describing the sequence of events of different nature (such as temperature, precipitation, gases and dust) to help identify causal mechanisms.

- Of particular interest is also the study of the previous interglacial and the conditions that brought it to a close. The optimum part of the Eemian is characterized by somewhat warmer conditions (+2° to 3°C) and a higher sea level (possibly up to 5m) which may represent a useful analog for future changes in the present interglacial epoch.

- Time scales employed in analysing proxy records are independent and based on a variety of different techniques. It is of primary importance to develop approaches to correlate the various records by using large-scale atmospheric events which should be globally simultaneous. Cosmogenic ^{10}Be events, rapid changes in greenhouse gas concentration, and volcanic and aerosol events are possible candidates.

- There are only limited data to document geographical changes in the biosphere with climatic changes of the past. It would be of great value to collect sufficient data to compile maps of vegetation changes for different climatic stages in order to identify important connections and interactions.

The finding that significant changes in atmospheric chemistry accompany major climatic changes opens up a broad spectrum of questions that are closely related to the objectives of the IGBP.

- Are the atmospheric CO_2 changes accompanied or caused by changes in ocean circulation, affecting the biological pump? What happens to the uptake or release of CO_2 during a climate-induced change in ocean circulation?

- What is the origin of global CH_4 variations? Do they reflect a reduced CH_4 source, or a general change in atmospheric chemistry? Is higher decomposition and increased CH_4 production with rising temperature a significant feedback?

- Can we detect an effect on cloud cover of a changing aerosol content such as those that are known to characterize major periods of cold?

- How did past ecosystems respond to changes in the physical climate system as reflected, e.g. in the $\delta^{18}O$ profiles determined in lake marl?

For such studies it will be very important to determine the phase relations between the parameters measured in the ice cores ($\delta^{18}O$, CO_2, CH_4, etc.) and to synchronise Northern and Southern Hemisphere records, if possible within decades, through periods such as the last glacial-postglacial transition.

To improve our knowledge about the Earth-system evolution during the last 150000 years, concerted efforts will be needed to extract information on the changes in the marine and continental records, as has been emphasized in a great number of scientific programmes, e.g. in the IUGS Task Group Report on Global Change. We especially emphasize the development of more intensive ice core studies including field programmes, analytical developments, and modelling.

The ice drilling projects presently planned for Greenland and later Antarctica deserve highest priority support. In addition to the existing equipment, new fast drills should be developed which will provide the uncontaminated ice cores of high quality which are needed for gas analysis. In order to extract the maximum information recorded in ice cores techniques should be developed for continuous and quasi-continuous high-depth-resolution measurements of a broad spectrum of parameters including ^{18}O, ^{2}H, ^{18}O (O_2), CO_2, CH_4 (including isotopes), ^{10}Be, H_2O_2, CHOH, and dust. Important new information is expected from ^{14}C and ^{81}Kr.

Most promising analytical techniques include accelerator mass spectrometry, ion chromatography, GC/MS fluid injection analysis and resonance ionisation spectrometry.

F. Needs in Ocean and Terrestrial Data

1. Problem statement

The manner in which the ocean circulates is important to the Earth climate in two ways: (1) large amounts of heat are transported from low to high latitudes by ocean currents; and (2) the strength of the Earth's biological pump (and hence the CO_2 content of the atmosphere) is influenced by the pattern and rate of ocean mixing. Based on the record of cadmium to calcium and carbon isotope ratios in foraminifera from deep-sea sediments, we now know that the pattern of deep-ocean ventilation during glacial time was fundamentally different from that of today. One important aspect of this difference is that the strong conveyor-belt system, which currently dumps enormous amounts of heat into the atmosphere over the North Atlantic, appears to have been inoperative during glacial time. In addition, the transition from the glacial mode to today's mode of ocean operation occurred abruptly about 13000 years ago. This was quite likely the event which initiated the demise of the Northern Hemisphere Laurentine and Scandinavian ice sheets.

Industrial development has led and is leading to significant changes in the chemistry (trace elements, phosphorus, nitrates, oxygen) and biology (diversity, algal blooms, elimination of certain species of organisms) in many areas. These changes have been well documented in sediments from lakes and waste basins and such studies may serve as analogs for continuing trends of global dimensions.

2. Proposed IGBP activities

It is important that we learn much more about the mode of ocean circulation which existed during glacial time and also about the extent to which contemporary ocean circulation matches that for the full span of the Holocene. Most important to these reconstructions are measurements of cadmium to calcium, $^{13}C/^{12}C$, and $^{14}C/^{12}C$ ratios in benthic and planktonic foraminifera. The first two provide information regarding the pattern of circulation; the third provides information regarding the rate of circulation. Studies of marine sediments designed to reconstruct sea-ice cover, opaline-silica rain rate and calcium-carbonate dissolution rates are also important. These studies should be carried

out on cores drawn from many geographic locations and water depths in the world's oceans.

In addition to the very important studies of ice cores cited in the previous section it is important to improve our knowledge of marine and continental records. Needed particularly are those which are continuous and subject to quantification. For marine cores a way must be found to separate the contributions of ice volume and temperature in the oxygen isotope record. One promising approach is to carry out $^{18}O/^{16}O$ measurements on coexisting opal and calcite. Also, the $\delta^{13}C$ record must be firmly established. This record is important to the understanding of the reason for atmospheric CO_2 change. To do this will require a better knowledge of which planktonic species to use. Finally the record of calcite and aragonite dissolution must be better quantified. Special effort must be made to establish the relative timing of the changes in the above parameters at terminations I and II in the glacial/interglacial cycle.

For the continents three records are of particular interest. Long detailed pollen records, such as those now available for Les Echets and Grande Pile in France, and Phillipi in Greece, should be obtained at ten to twenty sites around the world. The loess records in China, Europe, and Argentina should be studied with the view to establishing the source of the material, and the vegetation cover associated with this source. Finally, lake-level records for closed-basin water bodies in the world's major desert regions need to be obtained. The Great Basin of the US, Patagonia in Argentina, the Saharan region and northwestern China are of particular interest.

Another area of particular promise is that of palaeomagnetic and archaeomagnetic research, with special attention to changes in the strength of the geomagnetic moment and the position of the palaeomagnetic poles throughout the Holocene.

G. Requirements for Modelling Palaeo Data

1. Problem statement

Global geosphere-biosphere models have various advantages for investigating the dynamics of climate. They provide a quantitative and physically consistent treatment of the different components of the climate system. They are an invaluable tool for testing theories of climatic changes and for predicting or suggesting phenomena that can subsequently be studied with observations. They will help to identify the most important climate parameters to be measured and the most sensitive sites where samples must be taken. Models can also give some information on the structure of the environment between widely spaced data.

Conversely, records and reconstructions of palaeoclimates will continue to allow both calibration and validation of geosphere-biosphere models. The models will, in turn, provide useful information about gaps and "failures" in existing palaeoclimate data banks. A "two-way" interaction between data-generating and modeling communities needs to be maintained.

It is important to give priority to further efforts to formulate and test global geosphere-biosphere models, even though such models are now simplistic due to inadequate understanding of the crucial physical, chemical and biological processes that connect the Earth system.

2. Background issues

A wide variety of models are now being usefully applied to palaeoclimatic problems. Because of the large computational costs that are involved, atmospheric general circulation models (GCMs) have only been used to provide "snapshot" views of the climate in equilibrium, under prescribed boundary conditions. These boundary conditions include the seasonal and latitudinal changes of solar radiation at the top of the atmosphere, variations in sea-surface temperatures, major ice-sheet configurations, and atmospheric composition and turbidity derived from geological records. Detailed comparisons have been made between the simulated climates and the geological reconstructions of palaeoclimates.

On the other hand, statistical-dynamical models (which include atmosphere, ocean, sea-ice and land-surface processes in an interactive way) have been coupled to an ice sheet model in order to investigate the transient response of the climate system to orbital forcing. Results of these models have been compared with time-series of ice-volume changes deduced from geological records.

Continued research is now needed to develop models which take into account all the components of the climate system and their interactions in an interactive and time-dependent way. These models could then be used to study the transient response of the climate system to any prescribed "external" forcing. It is also important to continue testing the many computer models with the entire array of palaeoclimatic data that is available. Regarding the objectives of the IGBP it is of interest to identify phases of unstable climate and water balance with higher frequency of extreme events and to study whether they play a leading role in rapid transformations of ecosystems.

3. *Other related programmes and activities*

Development of fully-coupled models of the climate system and the comparison of their results with observations are integral parts of the World Climate Research Programme (WCRP) and of activities of the International Union of Geodesy and Geophysics (IUGG). The United States National Science Foundation (US-NSF) Project: Cooperative Holocene Mapping Project (COHMAP) is constructing global maps of palaeoclimatic conditions from 18000 years B.P. to the present at 3000-year intervals by comparing observed palaeoclimates with "snapshot" simulations performed by GCMs.

4. *Proposed IGBP issues*

Priority must be given to:

- The development of more reliable ocean circulation models. We need to be able to include both horizontal and vertical motions in sea-surface circulation, divergences and convergences, deep and bottom-water formation, water-mass advection and distribution, and ocean-sea ice interactions;

- The development of models which simulate the dynamics of ice sheets;

- The development of models of the biosphere and of its interactions with the other component of the climate system;

- The development of 2D (latitude - height) or 3D fully-coupled models, which take into account the complex physical and chemical interactions between the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere, and which allow us to analyse the internal behaviour of the system and its transient response to external forcings;

- The development of regional-scale models, the time-dependent boundary conditions of which are provided by global models. By allowing a more direct comparison of the simulated variables with the recorded proxy-data, regional-scale models will help to improve our understanding of the observed local environmental changes;

- The modelling of surface energy, including hydrological processes and vegetation dynamics. Simulation of certain isotopic fractionations and transports is needed to understand past climate gradients;

- The development of methods to facilitate the comparison of data with model results;

- The transformation of the basic climatic variables available from models into meaningful terrestrial and oceanographic processes or features;

- The formatting of data sets in spatial as well as temporal arrays - i.e., in map view - to facilitate the comparison between model simulations and palaeoclimatic proxy data;

- The development of accelerated integration techniques such as asynchronous coupling of the component models;

- The compilation of a catalogue of palaeoclimatic data of interest to modelers, to include: a) input data, as boundary and/or initial conditions (such as sea-ice and ice sheets extent and elevation, SST, and albedo) or as data potentially useful in the model itself (such as CO_2 or other trace gases contents or dust load of the atmosphere); and b) output data including ground-level temperature, precipitation rate, atmospheric circulation and windspeed changes, and relative humidity over the sea-surface;

- The development of the *in situ* cosmogenic isotope method for quantifying geomorphological processes.

IV. UNDERLYING NEEDS

Recovering information from historical and natural records involves four distinct processes. These are briefly described below.

A. *The Identification of Natural and Historical Archives*

Geomorphological investigations and studies of sediments, ice and organic deposits are well-established disciplines, as are studies of tree-rings, and lacustrine and ocean sediments. Equally valuable, though as yet less studied are other natural diaries, found in deep layers of loess, coral deposits, lake-level variations, and mid-latitude glaciers. Least utilized, yet the most powerful for studies of Earth system behaviour, are combined analyses of these records of the past in specific eras of interest or in the study of long-term trends in regional or global trends of change. The recent suggestion of *in situ* cosmogenic nuclide production offers the potential of quantifying geomorphological processes. Radio-nuclide ^{14}C, ^{36}Cl, ^{26}H and ^{10}Be studies may prove valuable in studies of erosion history and weathering and erosion processes.

Nor has adequate attention been paid to existing historical records of climate and other environmental change and its impact on ecosystems and of man. In the New World these records cover at most a few centuries, but they span the time in which human impacts on an unperturbed environment have been profound. In Europe, written records of climate and environmental change extend as far as about 500 years into the past, and in the Orient, where customs of recording natural events were more advanced and systematic, one can find a continuous record four times as long and far more extensive in terms of temporal and spatial detail. These written sources of environmental history and land use are a valuable resource in their own right. They assume additional importance when read in conjunction with concurrent, natural histories.

B. *Fieldwork*

In principle, the techniques for drilling cores in sediments and ice are now well established. Nevertheless, the taking of cores, for example, through ice sheets is still a major operation, requiring several years and the dedication of highly trained crews. Recent technological advances offer new opportunities. On the one hand new analytical techniques, such as accelerator mass spectrometry, have significantly reduced the size of sample that is needed for the study of a given parameter. These same advance techniques offer the potential of measuring a much larger spectrum of parameters which are needed, in turn, to derive detailed information on the Earth system evolution. Recent studies of ice cores have revealed extremely rapid changes of almost all the parameters that have been measured, within a depth interval of sometimes less than a meter, corresponding to a temporal span of but a few hundred years. In such depth intervals high-resolution measurements of as many parameters as possible are needed to derive phase relationships and to separate short-term variations from long-term trends. Such studies can provide a detailed picture of the change over time of fundamental Earth system processes and the identification of causes and effects.

This calls for improvements in drilling techniques, for the development of continuous or quasi-continuous measuring techniques of a broad spectrum of physical and chemical parameters, and if possible, analytical measurements in the field on newly-drilled cores.

Similar problems and opportunities exist in the acquisition and analysis of other types of natural environmental records. Fieldwork in terrestrial archives must be organized in a more integrated and multidisciplinary manner; studies of geology, pollen, palaeosoils and also fluvial, glacial and marine sediments require a team of specialists to collaborate both in the laboratory and in the field.

C. Laboratory Techniques

New analytical techniques, such as accelerator mass spectrometry, ion chromatography, investigations of palaeosoils, fluid injection analysis, optical spectral analysis, and combined gas chromatography/mass spectrometry, have contributed much to our ability to secure more complete and higher-resolution pictures of past Earth system events. These techniques need to be perfected and adapted to secure rapid analysis of samples of natural records of many kinds.

Other emerging analytical techniques offer additional opportunities. An example is single-atom counting by resonance ionization spectroscopy of ^{81}Kr ($T_{1/2}$ = 210000 years) which would contribute significantly to obtaining more accuracy in the dating of old ice and groundwater. Other examples may be found in stable isotope analysis of elements other than the conventional set of H, C, and O, in the chemical analysis of individual particles and aerosols, and in the application of mass spectroscopy to biological investigations.

D. Data Interpretation

An initial area of needed emphasis is the coordinated analysis of different natural records to obtain an overall view of interacting components of the natural Earth system. The interpretation of these data is not a simple matter, for it involves a deep understanding of the relevant properties and mechanisms of the natural archives themselves. An example is found in the analysis of stable isotope ratios of the elements H, C and O in tree-ring cellulose. The isotopic abundances of these basic elements are determined on the one hand by environmental conditions, such as the isotopic composition of the soil and the water, and of ambient CO_2; they are also fixed by biological and chemical processes in the soil and by the chemical and biological processes in the trees. These influences need to be disentangled if one is to derive information on past environmental conditions. In the process one learns much about the influence of interactive ecosystem processes.

To interpret the records of atmospheric cosmic-ray produced isotopes (cosmogenic nuclides) such as ^{14}C, ^{10}Be, or ^{36}Cl, one needs to understand the pathways from their production, mainly in the stratosphere, into the natural archive. One also needs information on the basic processes by which their production is modulated by solar and geomagnetic effects. These pathways include, among other things, nuclear spallation and subsequent chemical reactions, and the processes by which the nuclides are attached to particles in the atmosphere. Also included are processes of atmospheric mixing and circulation, absorption in ocean reservoirs, and in the case of isotopes such as ^{10}Be that are ultimately attached to aerosols, the processes and rates of removal by precipitation or dry deposition. As an example it has been observed that measurements of the $^{10}Be/^{36}Cl$ ratio in ice samples reflect large variations which are probably best explained by different affinities of attachment of Cl and Be to atmospheric particles.

A second step in the interpretation of the data concerns modelling of the processes that are involved in the production of variations of the reconstructed parameters. Examples are of the solar and geomagnetic shielding of cosmic radiations, transport of isotopes and particles, and attempts to explain the variations of atmospheric gases such as CO_2, CH_4 and N_2O, and of decay products of dimethylsulphide.

The third step is the use of these data in evolving interactive Earth system models. These tests may reveal weaknesses of the models; they will also suggest further process studies which will help improve the integrated understanding of the geosphere-biosphere system.

It would also be of value to establish a global inventory and data base of palaeo-environmental data, as a lasting feature of the IGBP, to facilitate the exchange of information between field research and modelling efforts and the exchange of data between different disciplines. A readily accessible archive of this nature would go a long way toward resolving differences of temporal and spatial scales, terminology, methodology, and the general needs of information flow in multidisciplinary and transdisciplinary research.

APPENDICES

APPENDIX 1. BIBLIOGRAPHY

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APPENDIX 2. ACRONYMS

COHMAP	Cooperative Holocene Mapping Project
COMAR	Coastal Marine Project (Unesco)
ENSO	El Niño - Southern Oscillation
GCM	General Circulation Model
IGBP	International Geosphere-Biosphere Programme
IGCP	International Geological Correlation Programme
IHP	International Hydrological Programme (Unesco)
IOC	Intergovernmental Oceanographic Commission (Unesco)
INQUA	International Union for Quaternary Research
IPID	The International Project in Dendroclimatology
IUGG	International Union of Geodesy and Geophysics
IUGS	International Union of Geological Sciences
MAB	Man and the Biosphere Programme (Unesco)
SC-IGBP	Special Committee for the IGBP
UNESCO	United Nations Educational, Scientific and Cultural Organization
US-NSF	United States National Science Foundation
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

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