The International Geosphere-Biosphere Programme: A Study of Global Change

The Initial Core Projects
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IGBP

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The planning phase of the IGBP has been supported by ICSU, the governments of Sweden (especially in support of the Secretariat) and other nations (particularly those with established IGBP National Committees), UNEP, Unesco, the Commission of the European Communities, the African Biosciences Network, the Commonwealth Science Council, and the Third World Academy of Sciences, the Andrew W. Mellon Foundation, Wissenschaftskolleg zu Berlin, Shell Netherlands and IBM Sweden.

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Overview

"Today the scale of our interventions in nature is increasing and the physical effects of our decisions spill across national frontiers. The growth in economic interaction between nations amplifies the wider consequences of national decisions. Economics and ecology bind us in ever-tightening networks. Today many regions face risks of irreversible damage to the human environment that threaten the basis for human progress."

Our Common Future
The World Commission on Environment and Development 1987
IGRF: A STUDY OF GLOBAL CHANGE

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1. Overview

Mankind today is in an unprecedented position. In the span of a single human generation, the Earth’s life sustaining environment is expected to change more rapidly than it has over any comparable period of human history. Much of this change will be of our own making. Worldwide economic and technological activities are contributing to rapid and potentially stressful changes in our global environment in ways that we are only now beginning to understand. The effects of these changes may profoundly impact generations to come.

Natural forces have influenced and shaped the environment of our planet over the course of its lifetime. The uniqueness and challenge posed by the changes facing us today lie not only in the magnitude and rate at which these changes are occurring, but also in mankind’s ability to inadvertently affect such changes. Increasing atmospheric concentrations of greenhouse gases, due in part to the burning of fossil fuels, may significantly alter our climate. Agriculture, forestry, and other land-use practices, industrial activities, waste disposal, and transportation have altered terrestrial and coastal ocean ecosystems; thus affecting, for example, biological productivity, water resources, and the chemistry of the global atmosphere. These fundamental changes, evident also in the decline of stratospheric ozone and in acid precipitation, transcend the traditional boundaries of scientific disciplines and have potential impacts that reach beyond the domains of individual nations.

World population growth and increase in greenhouse gases.

The IGBP is an interdisciplinary research endeavour, carried out within the framework of the International Council of Scientific Unions (ICSU), that is focused on a set of key research questions. Along with the World Climate Research Programme (WCRP) and other international research efforts it addresses critical unknowns related to global environmental change. The extent of intergovernmental endorsement of the programme is reflected in the UN General Assembly resolution of 17 December 1989 (A/C.2/44/L.40/Rev.1), which "Recommends that Governments, with due consideration of the need for increased scientific knowledge of the sources, causes and impact of climate change and of global, regional and local climates, continue and, wherever possible,"
increase their activities in support of the World Climate Research Programme and International Geosphere-Biosphere Programme, including the monitoring of atmospheric composition and climate conditions, and further recommends that the international community supports efforts by developing countries to participate in these scientific activities. In addition, the Intergovernmental Panel on Climate Change (IPCC) has identified IGBP and WCRP as the two major research programmes devoted to decreasing our uncertainty in relation to global climate change.

The IGBP and WCRP are complementary programmes of research, under the aegis of ICSU (and for WCRP, the WMO), that together address the scientific issues of global environmental change. The research focus of the IGBP is on the biogeochemical aspects of global change phenomena, on Earth-system models, the recovery and interpretation of data dealing with global changes of the past; the WCRP addresses the physical aspects of the climate system. A schematic depiction of the areas of concern to the IGBP, including the connections addressed in some of the key research questions and the relation of the programme to companion activities of the WCRP, is shown in Figure 1.

Three developments make the IGBP and WCRP possible:

1. Progress in the individual disciplines that are involved has evolved to the stage that truly interdisciplinary studies of global problems are now tractable.
2. Modern tools of research are now available that are capable of global-scale observations, theoretical constructs and predictive models. Remote-sensing spacecraft allow global measurements of key parameters of Earth-system behavior, including the detection of global environmental change. Modern computers allow, for the first time, the collection and rapid dissemination of global data sets and permit the construction and operation of global models of coupled systems.
3. National and international infrastructure and communications capabilities make possible the planning and effective administration of research programmes that are interdisciplinary in nature and global in scale.

The concerns that drive the IGBP are international in character, with causes and effects that transcend national boundaries. The global measurements, observations and synthesis that are required necessitate international cooperation; the human and material resources needed to mount the programme cannot be met without involvement of most countries. All nations have a stake in the consequences of global change; any hope of concerted response strategies requires their involvement in the design and execution of research that must be the basis for recommended policy actions.

Within the decade of the 1990s, the IGBP will launch a world-wide research effort, unprecedented in its comprehensive interdisciplinary scope, to address the functioning of the Earth system and to understand how this system is changing. The body of information generated by the IGBP will form the scientific underpinning for predictions relating to future causes and effects of global changes. Through its observational network and process studies, and the timely communication of the resulting data to scientists in all nations committed to this endeavor, the IGBP will help provide the world's decision makers with input necessary to wisely manage the global environment.

The IGBP will design and implement research projects to produce global data sets on properties and processes central to global change. These will include observations and studies at the Earth's surface as well as from an array of Earth-sensing satellites. This research will make use of a network of Regional Research Centres in forging a new understanding of the interactions among biogeochemical cycles and physical processes of the Earth system. The IGBP will also interpret critical records of global changes of the past - particularly the records of the last 2,000 years, which when compared to the most recent glacial cycle will help us understand the roles of human and natural forces in global change. The unification of global biogeochemical and physical approaches in the study of global change, combined with an understanding of the record of the past, will be used to develop models for predicting future change.

In the course of this endeavour, the IGBP will promote an interdisciplinary approach to studies of the Earth system. This is essential to educate the next generation of scientists, so that they will more fully understand the complexities of this system. This knowledge will be the key to success in the wise use of the Earth's resources for generations to come.

Objective

To describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human activities.

The IGBP is concerned with the significant interactions of biological, chemical, and physical processes that govern changes in the Earth system and that are most susceptible to human perturbation. The primary goal of the IGBP is to develop a predictive understanding of the Earth system, especially in relation to changes that affect the biosphere. To make this goal achievable, emphasis is placed on a time scale of decades to centuries.

As an evolving programme, the IGBP selects from the broad array of subjects that comprise the science of the Earth system, those issues that are deemed to be of greatest importance in contributing to our understanding of the changing nature of the global environment on timescales of decades to centuries, that most affect the biosphere, and that are most susceptible to human perturbations and that will most likely lead to practical, predictive capability.

While the objective of the IGBP is to understand the interactive processes that regulate the total Earth system, for practical reasons, a suite of Core Projects on the important sub-components of the system must be designed: In this context, the IGBP has defined a number of research priority questions, within which core research projects are being developed. Each of these priorities focuses on process linkages where the current state of understanding is insufficient to predict future changes. In addition, consideration of how natural and human forces contribute to global change is included.

The Core Projects focus on the important sub-components of the global Earth system. Each project must be intellectually challenging and scientifically sound, administered with minimal bureaucracy, and designed with provision for rigorous and with flexibility to adapt to changing needs. The success of each of them will depend on the active involvement, in planning and execution, of the best scientists in each of the fields involved. In view of the global focus, a true international approach is necessary with the involvement of scientists throughout the world. Success of the overall effort will require strong national support and international coordination.

Figure 1. Linkages among biological, chemical and physical processes critical to our understanding of global change on a decade to century time scale. Arrows refer to the seven first research priority questions as described in this report.
The research priority questions and the projects that make up the programme are expected to evolve with new insights and understanding, but the initial operational phase of the programme focuses on seven key questions:

1. How is the chemistry of the global atmosphere regulated and what is the role of biological processes in producing and consuming trace gases?
2. How do ocean biogeochemical processes influence and respond to climate change?
3. How changes in land use affect the resources of the coastal zone, and how changes in sea level and climate alter coastal ecosystems?
4. How does vegetation interact with physical processes of the hydrological cycle?
5. How will global changes affect terrestrial ecosystems?
6. What significant climatic and environmental changes have occurred in the past, and what were their causes?
7. How can our knowledge of components of the Earth system be integrated and synthesized in a numerical framework that provides predictive capability?

These questions will be addressed through activities of observation, process studies and modelling in the context of a limited set of Core Projects. Based on the above seven questions, the Core Projects described in the following chapters have been developed during many planning meetings held by the IGBP over the past two years where scientists from many nations of the world participated actively. These Core Projects have been designated by the ICSU Special Committee for the IGBP as established, proposed, or potential, reflecting the current status of endorsement by the world scientific community and the state of readiness for implementing them.

Following two key activities relate to the needs of all Core Projects and for this reason are managed separately:

1. The development of a global Data and Information System that will provide immediate and open access to all researchers, that will provide information needed for Earth system models, and that will define and sustain the long-term observations needed to detect significant global changes.
2. The establishment of a set of Regional Research Centers in developing countries where strong synthesis and modelling projects of relevance to overall IGBP objectives and regional priorities will be developed, in close cooperation with existing research networks. Training and exchange programmes will be one of the mechanisms to involve the scientists from the region in Core Project activities.

Descriptions of the specific objectives of the Core Projects, the IGBP Data and Information System, Regional Research Centres, and the relationships between the Core Projects are given below:

Question 1: How is the chemistry of the global atmosphere regulated and what is the role of biological processes in producing and consuming trace gases?

The International Global Atmospheric Chemistry Project (IGAC) - An Established Core Project

• To develop a fundamental understanding of the processes that determine the chemical composition of the atmosphere.
• To understand the interactions between atmospheric chemical composition and biogeochemical and climatic processes.
• To predict the impact of natural and anthropogenic forcing on the chemical composition of the atmosphere.

Stratosphere-Troposphere Interactions and the Biosphere (STIB) - A Proposed Core Project

• To determine the consequences of changes in stratospheric O3 on penetration of potentially harmful UV radiation.

Proposed Special Commitments for the purpose of developing models of the energy and water fluxes in the soil-vegetation-atmosphere system at temporal and spatial scales ranging from vegetation patches to CCM grid cells.

• To develop appropriate data bases that can be used to describe the interactions between the biosphere and the physical Earth system and to test/collate model simulations of such interactions.

Question 2: How do ocean biogeochemical processes influence and respond to climate change?

Joint Global Ocean Flux Study (JGOFS) - An Established Core Project

• To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries.
• To develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular, those related to climate change.

Global Ocean Euphotic Zone Study (GOEZS) - A Potential Core Project

• To develop a predictive understanding of the basic relationships among the physical, chemical, and biological properties of the oceanic euphotic zone.

Question 3: How changes in land use affect the resources of the coastal zone, and will changes in sea level and climate alter coastal ecosystems?

Land-Ocean Interactions in the Coastal Zone (LOICZ) - A Proposed Core Project

• To develop predictive understanding of the effects of changes in climate change, land use and sea level on the global functioning and sustainability of coastal ecosystems, with emphasis on the interactions between changing conditions on land and sea, and on possible feedback effects physical environment.

Question 4: How does vegetation interact with physical processes of the hydrological cycle?

Biospheric Aspects of the Hydrological Cycle (BAHC) - An Established Core Project

• To determine the biospheric controls of the hydrologic cycle through field measurements for the purpose of developing models of the energy and water fluxes in the soil-vegetation-atmosphere system at temporal and spatial scales ranging from vegetation patches to CCM grid cells.

• To develop appropriate data bases that can be used to describe the interactions between the biosphere and the physical Earth system and to test/collate model simulations of such interactions.

Question 5: How will global changes affect terrestrial ecosystems?

Global Change and Terrestrial Ecosystems (GCCTE) - An Established Core Project

• To develop the capability to predict the effects of changes in climate, atmospheric CO2 and land use on terrestrial ecosystems, and how these effects can lead to feedbacks to the physical climate system.
Question 6: What significant climatic and environmental changes have occurred in the past, and what were their causes?

Past Global Changes (PAGES) - An Established Core Project
- To reconstruct the detailed history of climatic and environmental change for the entire globe for the period since 2,000 B.P., with temporal resolution that is at least decadal and, ideally, annual or seasonal.
- 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 drive global climate changes.

Question 7: How can our knowledge of components of the Earth system be integrated and synthesized in a numerical framework that provides predictive capacity?

Global Analysis, Interpretation and Modelling (GAIM) - A Proposed Core Project
- With the aid of models, synthesize a fundamental quantitative understanding of the global physical, chemical and biological interactions in the Earth system during the last 100,000 years and assess possible effects of future changes.

The science components of the above Core Projects are described in this report. For the established core projects (IGAC, JGOFS, BAHC, GCTE and PAGES), reasonably detailed science plans have been formulated. Implementation of the JGOFS and IGAC Core Projects has already begun. Implementation plans for BAHC, GCTE and PAGES are yet to be developed.

For the proposed Core Projects (STIB, LOICZ and GAIM) science plans have not yet been developed and it is expected that the Scientific Committee for the IGBP (SC-IGBP) will consider their possible establishment within the next year.

The SC-IGBP will consider at a later stage if a science plan should be developed for the potential Core Project (Guebas and GCEC) following full discussions and consideration by the international science community.

Tentative timelines for IGBP Core Projects and complementary activities.

Data and Information Systems

Efficient data and information systems must be developed and supported in order to accommodate the voluminous amounts of data necessary to address the objectives of the IGBP. Provision must be made for the accessibility and worldwide exchange of information and data. Directories of available data must be compiled and disseminated throughout the research community. Data sets for many properties and processes of the Earth system need to be indexed on comparable time and space scales. The IGBP, in collaboration with the World Data Centres, is undertaking a study to determine the needs of a data and information system for the study of global change, and to develop a strategy for implementation. These and other studies will give particular attention to problems relating to the interpretation and distribution of the vast quantities of data that will be generated by satellite-borne observing systems.

A network of about ten regional research centres for global change studies (RRCs) is being proposed for establishment in developing countries. They will facilitate regional collaboration and research on global change issues, with special emphasis on aspects of processes that manifest distinctly in that region. These centres will assimilate, synthesize, and interpret regional data sets for integration into global-scale synthesis and modelling efforts. They will also extract the relevant regional component from global model output. In this way, these centres will provide to resource managers and decision makers information of particular importance to the region. These centres will also ensure that scientists from less developed countries have an equal opportunity to contribute to the research activities of the IGBP. Long-term core funding for the RRCs must be secured from a broad spectrum of sources and should be administered through a central source to guarantee stable and continuous support during the lifetime of the IGBP.

The science components of the Core Projects described in this report clearly have many common links. Particular care has been taken to ensure that the individual descriptions of any Core Project contain explicit reference to links with other Core Projects. The broader linkages between the Core Projects are briefly described below.

Production and consumption of important greenhouse gases occur in the terrestrial ecosystem, oceans and the atmosphere. Production and consumption of trace gases other than CO2 are in principle covered in IGAC (Chapter 2.1), while the role of oceans in regulating the atmospheric CO2 concentration is covered by JGOFS (Chapter 3.1) and the comparison studies of the role of the terrestrial ecosystems is described in GCTE (Chapter 6.1).

Water availability is a crucial regulating factor for primary production in most terrestrial ecosystems, and any climate change affecting water availability will have a profound effect on these terrestrial ecosystems. The effects of such changes may influence ecosystem distribution, and in view of the importance of vegetation for the hydrological cycle (BAHC Chapter 5.1), feedback on water availability. The development of Soil-Vegetation Atmosphere Transfer (SVAT) models is an essential component of both BAHC and GCTE.

The studies of processes on land (BAHC, GCTE) and in the oceans (JGOFS) are linked through a proposed Core Project on land-ocean interactions in the coastal zone (LOICZ, Chapter 4.1). Shelf-break processes studies need to be developed further in a dialogue between JGOFS and LOICZ.

The PAGES project addressing past global changes will have close links with the projects assessing the present functioning of the Earth system and in the science plans, several of the latter outline the needs to understand past and present changes in order to predict the future.

In order to distill the information from the core projects dealing with sub-components of the Earth system and to obtain a comprehensive and predictive understanding of the Earth system, a separate Core Project (GAIM, Chapter 8.1) addresses the integrative aspects of Earth system analysis, interpretation and modelling.

In view of the involvement of many scientific disciplines, the IGBP constitutes the most ambitious scientific programme ever initiated at the international level. Execution of this programme will require unprecedented coordination of field experiments and laboratory studies, powerful computer capability for modeling and data synthesis, Earth-based observations, and multinational ventures in building and operating a comprehensive suite of Earth-observing satellites.
IGBP research will be initiated in the 1990s and will require a decade or more of intensive effort.

The success of the IGBP will depend on the commitment of scientists who are adept at putting disciplinary research into a wider interdisciplinary framework. The IGBP will require the involvement of scientists and national support from all areas of the world in activities such as:
- long-term monitoring and documentation of the Earth system;
- process studies to understand the linkages among the component parts of the Earth system;
- studies to analyze and to synthesize global data sets; and
- development of comprehensive quantitative Earth system models.

Such a bold, urgent, and complex undertaking as that of the IGBP demands that an international infrastructure for planning, coordination, and synthesis be continually and sufficient supported by nations as well as international governmental bodies. There is also an important need for the private sector to participate in this endeavor and to help ensure adequate support for all aspects of the IGBP. The scientific progress of the IGBP will depend on high priority being given to a sustained, long-term commitment of financial resources for manpower and facilities in individual nations, as national research programmes will provide the foundation for implementing the research activities of the IGBP. A firm investment now will help to ensure that the abundant gifts of the Earth will be preserved and passed on to future generations.

The ICSU initiated detailed planning for the IGBP in late 1986 and appointed a Special Committee to guide the planning and implementation of the programme. Detailed development of the initial research priorities into core projects has been conducted by a number of planning groups that draw upon the expertise of the international science community. Many other ICSU bodies are participating in this process.

Collectively, it is the national IGBP programmes that will have the resources required to implement the core projects. Thus, a close partnership between the national and international planning efforts is essential. To facilitate this, a Scientific Advisory Council for the IGBP has been established. This body consists of representatives from national IGBP committees and ICSU's scientific members with interest in global change research. The council advises on the development of the research programme.

In order to provide for joint planning and coordination with bodies of the United Nations, an Interagency Coordinating Committee has been formed with the participation of the United Nations Environment Programme (UNEP), the United Nations Educational, Scientific, and Cultural Organization (Unesco), and the World Meteorological Organization (WMO).

Other groups are laying the groundwork for a social science based counterpart to the IGBP. The SC-IGBP will strive to ensure the complementarity of these two dimensions of the study of global change.

A Secretariat for the IGBP has been established at the Royal Swedish Academy of Sciences to support the planning and implementation process and to provide a focal point for communication and coordination. The Secretariat publishes the findings of planning group deliberations in a series of IGBP reports, as well as the Global Change Newsletter.

The planning phase of the IGBP has been supported by ICSU, the governments of Sweden (especially in support of the Secretariat) and other nations, particularly those with established IGBP National Committees, UNEP, Unesco, the Commission of the European Communities, the Organization of American States, the African Biosciences Network, the Commonwealth Science Council, and the Third World Academy of Sciences. Other groups are laying the groundwork for a social science based counterpart to the IGBP. The SC-IGBP will strive to ensure the complementarity of these two dimensions of the study of global change.

The planning phase of the IGBP has been guided by Special Committee (see Appendix 1). Since its first meeting in July 1987, 50 planning meetings have been organized with the participation of close to 500 scientists (Appendix 6). The dedicated work of all these scientists have been instrumental in the development of the initial IGBP Core Projects.

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How Is the Chemistry of the Global Atmosphere Regulated and What Is the Role of Biological Processes in Producing and Consuming Trace Gases?

Atmospheric concentrations of several trace gases are increasing rapidly, mainly due to human activities. Increases in so-called greenhouse and other trace gases result in changes in the composition of the atmosphere that affect the physical aspects of the climate system. These gases interact in the stratosphere resulting in alteration in the chemical composition, radiation, and dynamics in the stratosphere and potentially affect the lower troposphere and even the biotic system via modulations of the solar UV-B radiation received at the Earth's surface. Many of these gases are produced biologically or affect biological processes. The sources and sinks of important chemical components of the atmosphere and their interactions with living organisms need to be identified and quantified. An understanding of the key processes regulating the composition of the atmosphere and feedback mechanisms that affect the behaviour of the system is necessary.
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The chemical composition of the atmosphere is to a large degree determined by the uptake and release of a large variety of trace gases by the biosphere. In turn, the Earth's climate and the deposition of chemical compounds, containing essential nutrient elements (such as C, N, P, S), are of critical importance for the sustainability of the biosphere. Climate, biospheric conditions and atmospheric chemical composition together thus form a strongly interactive system. The biospheric production of relatively small amounts of trace gases such as CO$_2$, CH$_4$ and N$_2$O are of special interest, as these greenhouse gases trap terrestrial infrared radiation, thus warming the Earth's surface. In addition, CH$_4$, N$_2$O and a large variety of other biogenic trace gases, such as CO, NO, and a wide range of Volatile Organic Compounds (VOC), play a key role in atmospheric chemistry by affecting tropospheric and stratospheric concentrations of ozone, the penetration of photochemically and biologically active solar ultraviolet radiation to the Earth's surface, and the production of hydroxyl (OH) radicals. These are responsible for the removal of almost all trace gases that are emitted by biological or anthropogenic processes into the atmosphere.

Information obtained from the analysis of air bubbles trapped in glacier ice strongly suggests that at least during the present geological period the chemical composition of the atmosphere has tended towards equilibrium conditions that were characteristic of the glacial and interglacial periods. Changes in the atmospheric concentrations of CO$_2$ and CH$_4$ with lower values during the glacial periods, together with lower water vapour concentrations, have been shown to be significant amplifiers of the climate forcing that were driven by variations in the orbital characteristics of the Earth's motion around the sun.

The chemical composition of the atmosphere has for the past few centuries been changing, initially under the influence of agricultural, more recently by industrial activities. As a consequence, the atmospheric volume mixing ratio of CO$_2$ has increased from 280 to 350 ppm and for CH$_4$ from 0.7 ppm to 1.7 ppm over the past two centuries. Currently, the measured annual increases of these gases are equal to 0.4 - 0.5% and 0.7 - 1.1% respectively. In addition the atmospheric
concentrations of several other trace gases are increasing. The most important among these are the industrially produced chlorofluorocarbons CFC-11, CFC-12 and CHF₃, but also N₂O with annual atmospheric growth rates of about 4%, 0.2 - 0.3%, respectively. All these gases have long atmospheric residence times, ranging between about 10 years for CH₄ and about 110 years for N₂O. All these compounds are important greenhouse gases. Although CO₂ is the single most important among them, the combined greenhouse forcing of CH₄, N₂O, CFC-11, CFC-12, N₂F and a few additional gases together is about equal to that of CO₂. In addition, and in contrast to CO₂ which is chemically very stable, CH₄, N₂O, CFC-11, CFC-12 and CF₂Cl₂ are of critical importance for stratospheric and tropospheric chemistry. The observed increases in the above mentioned gases have caused great concern for a rapid climate warming by several degrees in the next century, especially because of the rapid growth of CFC-11 and CF₂Cl₂ major depletions in stratospheric ozone have already occurred.

In the troposphere, the observed increase in CH₄ concentrations is of great significance for the oxidative power of the atmosphere which is largely deter-

By the action of solar ultraviolet radiation on ozone and water vapour. In most of the troposphere, OH radicals react mainly with CH₄ and CO. The atmospheric concentration of CO is increasing, at least in the Northern Hemisphere, by 0.7 - 1% per year. With both CO and CH₄ increasing, the result could be an overall increase in the global average OH concentrations, leading to further accumulation of most trace gases in the atmosphere, including CH₄ and CO themselves, thus opening the possibility of a strong positive feedback mechanism. This development may to some degree be counteracted, however, at the cost of the buildup of tropospheric ozone during the photochemical oxidation of CO, CH₄ and VOC in the presence of anthropogenically produced NO, which serve as catalysts to produce ozone, especially in the middle latitude regions of the northern hemisphere. The latter development has indeed been observed and may imply an increase stress on the mid-latitude biosphere. Presently the input of NO into the troposphere is dominated by anthropogenic activities; fossil fuel burning in the industrialized and biomass burning in tropical developing countries. It is thus important to obtain information on the atmospheric and biospheric sources and sinks of the aforementioned trace gases. This will be one of the main goals of IGAC.

In addition, studies of the sources, sinks and atmospheric chemical trans-

formation reaction of volatile sulphur compounds, especially dimethyl sulphide (DMS) and sulphur dioxide (SO₂) are of eminent importance, as their oxidation leads to the formation of sulphuric acid aerosol. This is the main source for cloud condensation nuclei (CCN) for much of the atmosphere. This has a large influence on cloud formation processes, and thus on the hydrological cycle and the radiative properties of the Earth’s atmosphere through effects on albedo and cloud cover.

The main source of SO₂ is the combustion of sulphur-containing fossil fuels; most DMS is produced by marine phytoplankton. It is of importance to find out whether and how the cloud climatology of the mid-latitude regions of the northern hemisphere may have been affected by the large industrial SO₂ emissions. Regarding the DMS emissions, measurements of its oxidation product methanol sulphonic acid in polar ices cores show the presence of higher concentrations during glacial than interglacial periods, indicating higher sulphate aerosol concentrations during glacial periods and thus suggesting another positive feedback mechanism between the biosphere and climate in addition to those observed for CO₂, CH₄ and N₂O.

Especially in the tropics the rapid rate of land-use changes that accompany human population growth is contributing to the perturbation of biosphere- atmosphere interactions. For example, the emissions of hydrocarbons, carbon monoxide and nitrogen oxides from biomass burning during the dry season result in the photochemical production of large amounts of ozone. Increased rice production most likely contributes significantly to increasing CH₄ concentrations. Enhanced N₂O releases may well result from increased application of N-fertilizers and tropical deforestation activities.

These and other anthropogenic emissions affect the atmosphere over a range of spatial scales. Hydrocarbon and NO emissions from automobiles produce their greatest impact in the form of photochemical smog in the environs of major urban centers, although some other products, such as CO and O₃ may spill over into the background troposphere. Carbon dioxide, emitted from the burning of fossil fuels and deforestation activities, has a global impact on climate, while sulfuric and nitric acid deposition, originating from the sulphur dioxide and nitrogen oxides from the same combustion, has impacts on regional or subcontinental scales due to the shorter atmospheric lifetimes of these gases.

Many of the atmospheric chemical aspects of the issues indicated above still need to be clarified by research efforts, several of them requiring close international participation. In addition, despite the indisputable importance of atmospheric/biosphere exchange, the magnitude of the fluxes of all of the aforementioned important gases with biological sources, the processes that control these fluxes, and possible future changes in flux strengths remain poorly known. This is due to the complexity of processes occurring in the atmosphere and in the biosphere, as well as at their interface. To address especially the atmospheric chemistry part of these important issues the Commission on Atmospheric Chemistry and Global Pollution (CACGP) of the International Association of Meteorology and Atmospheric Physics (IAMP/IGAC) has developed an International Global Atmospheric Chemistry Project (IGAC), as described in Galbally (1989), with the following objectives:

**Objectives**

- To develop a fundamental understanding of the processes that determine the chemical composition of the atmosphere.
- To understand the interactions between atmospheric chemical composition and biotic and climatic processes.
- To predict the impact of natural and anthropogenic forcing on the chemical composition of the atmosphere.

Although IGAC project planners addressed some of the biosphere-atmosphere interaction issues, the need for stronger interdisciplinary approaches to these problems was recognized, requiring collaboration between specialists such as plant physiologists, marine chemists, microbiologists, ecologists, soil scientists, cloud physicists, meteorologists, oceanographers and atmospheric chemists. While there was thus a strong perception that biological interactions would have to be an essential component of the research activities, the biological and ecological community was not well enough represented to formulate the
Science Components

**Focus 1**

**Natural Variability and Anthropogenic Perturbations of the Marine Atmosphere**

The oceans are both major source and sink regions for various atmospheric C, N, S, and halogen containing compounds that influence climate, cloud microphysical properties and atmospheric chemistry. The chemistry of the marine atmosphere can be strongly affected by natural and anthropogenic substances carried through the atmosphere from continental sources. In fact, the marine environment constitutes a suitable environment to study the atmospheric chemical processes in "background air", isolated from the large and patchy features of the continental environment. Furthermore, the marine environment can be substantially altered when substances of continental origin are deposited on the ocean surface. This Activitiy is focused under Focus 1 and will concentrate on these issues. Some of them will be carried out in collaboration with JGOFS (Chapter 3.1).

**Activity 1**

**North Atlantic Regional Study**

The North Atlantic is rimmed by continental industrial regions, which are major sources of compounds that influence the concentration of tropospheric ozone, as well as hydroxyl radicals, and thus the oxidizing efficiency of the atmosphere. In the marine atmosphere, these compounds are being processed chemically, together with the resulting products, deposited on the ocean surface by wet and dry deposition. These processes have not been studied in any large-scale experiments. They are, therefore, proposed to be carried out in this Activity which will develop from a number of existing regional-based projects (AEROCE, WATOX, GACE, and TOR). At measurement sites on Barbados, Tenerife, Brazil, and Ireland, the Activity will be expanded step-wise to include other activities in the North Atlantic region. Among the first activities to be added will be the field campaigns.

The oceans are both major source and sink regions for various atmospheric chemicals. The chemistry of the marine atmosphere can be strongly affected by natural and anthropogenic substances carried through the atmosphere from continental sources. In fact, the marine environment constitutes a suitable environment to study the atmospheric chemical processes in "background air", isolated from the large and patchy features of the continental environment. Furthermore, the marine environment can be substantially altered when substances of continental origin are deposited on the ocean surface. This Activity is focused under Focus 1 and will concentrate on these issues. Some of them will be carried out in collaboration with JGOFS (Chapter 3.1).

**Activity 2**

**Inventory of Chemical Climatology and Meteorology**

A preliminary inventory will be made of the chemical climatology and meteorology obtained by existing programmes in preparation for the choice of locations, seasons and meteorological situations for upcoming field experiments.

**Task 2. Marine atmosphere chemical data base.**

Preliminary investigations will be made of the important chemical mechanisms that operate in the marine atmosphere. This phase will thus involve intensive surface measurements of O$_3$, CO, NO, NO$_x$, PAN, HNO$_3$, NO$_y$, SO$_2$, DMS, particulate nitrate and sulphate, 

**Activity 3. Regional Integration.**

A comprehensive chemical data set of the North Atlantic region will be developed along with the key mechanisms involved in the processing of chemicals contained in air masses of continental origin. Ground-based, ship-based and aircraft studies will be conducted. Chemical transport modelling will form an integral part of the study, both in the planning of the experiments and in the interpretation of the results.

**Marine Aerosol and Gas Exchange: Interaction with Atmospheric Chemistry and Climate**

The oceans are important sources of DMS, NH$_4$, sea salt hydrocarbons, and halogenated organics of biological origin. These trace gases influence the acid-base characteristics of marine aerosols and precipitation in the ocean regions and may play a role in atmospheric oxidant formation. Emissions of DMS and their conversion to sulphate aerosol probably control the formation of cloud condensation nuclei in much of the marine environment and thereby may affect climate by altering the microphysical and radiative properties (especially albedo) of clouds. This Activity will furthermore be measured the deposition of nutrients to the ocean and study their influences on biological productivity. Understanding the exchange between the atmosphere and oceans requires studies of both emissions from the ocean surface and of deposition to it from the atmosphere. Currently such studies are limited by a lack of methods for direct measurement of the most important fluxes.
Objectives

- To understand the chemical, biological, and physical mechanisms that control the exchange of trace gases and particulate materials between the atmosphere and the ocean surface.
- To develop formulations of ocean exchange processes for inclusion in global-scale climate and air chemistry models.
- To extend the experimental knowledge of air-sea exchange to conditions with strong winds, rough seas, and spray.

Task 1. Development of novel measurement techniques.

Improvements in the understanding of marine aerosol properties and gas exchange processes can only be achieved through the development of new measurement technologies. High priority goes to fast-response DMS instrumentation for direct flux measurements. Significant improvements are required in speed and accuracy for airborne aerosol and sulphur gas measurements. Likewise, the development of adequate marine platforms for unprompted micro/meteorological measurements (e.g., buoys and towers) is urgently needed. Measurement methods facilitating studies of the fate of emitted gases will be developed, such as the use of aircraft to repeatedly make measurements in the same air masses, which may be traced by the use of balloons or chemical tracer release. At every possible opportunity, intercomparisons will be made with complementary techniques.

Task 2. Methodology intercomparison tests.

Three field campaigns are planned in which new techniques will be tested against traditional methods. The first, to be conducted on the Equatorial Pacific JGOFS cruises, is to take place in November of 1991. The second will be conducted in the Eastern Atlantic in association with the ASTEX programme planned for June, 1992. The third campaign, which is presently planned in collaboration with Focus 6 in 1995, may involve release of a sulphur gas in the Southern Hemisphere, where it will be composed, and the impact on cloud properties can be studied simultaneously.

Activity 3

East Asian/North Pacific Regional Study

The region of East Asia is characterized by high and rapidly growing anthropogenic emissions of NOx, SO2, hydrocarbons and other air pollutants due to its high and growing population density and, in some regions intensive, industrial development. Evidence has already accumulated that concentrations of lower tropospheric ozone during high pressure episodes are substantially elevated compared to those characteristics of the central Pacific. Long-range transport of continental aerosols from the northwestern Pacific regions to Hawaii has also been reported. No systematic study of atmospheric chemistry in East Asia and the Pacific mid-latitudes has been conducted. Quantifying the emissions and the fate of atmospheric constituents in the East Asian troposphere requires international cooperation among scientists from this part of the world, as well as from other interested nations. Although the scientific objectives are rather similar, a major distinction compared to Focus 1, Activity 1 will be the substantially different meteorological conditions and emission patterns between the study areas. The proposed study will be centred on the oceanic region bounded by the coasts of China and Japan.

Objectives

- To assess transport and chemical transformations of air pollutants over the East-Asian continent and the North-Western Pacific Ocean.
- To determine the depositions of primary and secondary pollutants (sulphate, nitrate, organics) in the East Asian region.

Task 2. Surface measurements of important trace gases.

It is important to conduct surface-based measurements of NOx, HNO3, CO, CH4, VOC, and SO2. Furthermore, a compilation of existing measurements on these compounds and ozone should be developed.

Task 3. The intensive field programme.

Emissions inventories and meteorological data will be incorporated into a numerical model, which includes transport and chemical processes. Aircraft and shipboard measurements will be conducted to verify model predictions. The NASA Pacific Exploratory Mission-West will be the starting point of this task.

Natural Variability and Anthropogenic Perturbations of Tropical Atmospheric Chemistry

Anthropogenic disturbances of the chemistry of the tropical atmosphere are especially important, as the removal of many atmospheric trace gases is a large degree determined by the high concentrations of hydroxyl radicals in the tropics caused by the maximum penetration of solar ultraviolet through the relatively thin stratospheric ozone shield. Large natural emissions of biogenic trace gases occur from tropical forests and savannas, which play a large role in the regional photochemistry of the atmosphere of these ecosystems. These emissions can be rapidly transported to the troposphere by convective cloud systems and subsequently carried to other regions of the world, thus influencing extratropical global chemistry as well.

Tropical regions are experiencing rapid changes in land use due to expanding agricultural activities and, in certain areas, accelerated industrialization. Land use conversions due to expanding agricultural activities are often associated with the burning of large quantities of biomass, leading to the emission of large amounts of aerosol particles and many important atmospheric trace gases, such as CO, CH4, NOx, and hydrocarbons, some of which influence the chemistry of the atmosphere even outside the tropics. Changed change, especially due to population growth will produce changes in the biogeochemical cycles of the affected tropical ecosystems with repercussions for the emissions of trace gases, such as NOx, N2O, CH4 and other VOC. As a consequence, global atmospheric chemistry and associated potential impact on climate cannot be uncritically addressed without much improved understanding of the chemical state of the tropical ecosystem/atmospheric system.

During the last decade some national and bilateral experimental campaigns have been conducted to study the chemistry of the tropical atmosphere. These campaigns, e.g., the NCAR 1979 and 1980 and the ABLE II experiments of 1985 and 1987 in Brazil, and the DECAFE programme in 1988 in Western Africa have proven highly informative. Additional experiments of this kind, including DECAFE II and TRACE, are planned for the next three years. These campaigns involve ground-based and aircraft measurements to assess the respective roles in atmospheric and precipitation chemistry of processes and human activities in equatorial forest and savanna areas, including those caused by biomass burning. Because of the complexity of the biological/atmospheric system, it is essential to develop coordinated activities, pooling the resources of more nations and the expertise of the atmospheric, chemical, and biological disciplines. Coordination will thus also be required with other IGDP Core Projects including BAHC (Chapter 5.1) and GCTE (Chapter 6.1) and the documentation of tropical land cover changes addressed in IGBP-DIS (Chapter 9).
Activity 2

Deposition of Biogeochemically Important Trace Species

The deposition of chemical species is a source not only of essential plant nutrients, but also toxic substances to the biosphere. At the same time it is a sink for atmospheric trace species that influence atmospheric chemistry. Current knowledge of processes and rates of dry and wet deposition for many compounds must be expanded if the impacts of future environmental change are to be properly assessed.

Objectives
- To determine the atmospheric removal rates by dry and wet deposition of biogeochemically important chemical species.
- To identify the factors that regulate these deposition fluxes.

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- To determine the atmospheric removal rates by dry and wet deposition of biogeochemically important chemical species.
- To identify the factors that regulate these deposition fluxes.

Activity 3

Task 1. Composition and acidity of S.E. Asian precipitation.

The composition and acidity of South-East Asian precipitation will be determined on a precipitation chemistry network to be set up in the S.E. Asian region, from India to China, south to Australia and on several Pacific islands as the first task of this Activity. Its goal is to quantify the wet deposition component of the atmospheric cycles of nutrient-containing and reactive species and to assess the current state of rainwater chemical composition across the region.

Task 2. Extension of activities to other regions

Possible future expansions include studies in other tropical regions and consideration of measurements of additional precipitation and gas phase compounds at each operating site. The long-term goal of assessing the importance of dry as well as wet deposition of atmospheric chemistry in all the tropical regions will require substantial extension of the observational network. Emphasis will be placed on cooperation with existing facilities in many countries, in particular those that are already or will become part of the World Meteorological Organization BAPMoN network.

Impact of Biomass Burning on Atmospheric Chemistry and Biogeochemical Cycles

The products of biomass burning represent a large perturbation to global atmospheric chemistry. Satellite observations have revealed vast areas of the tropics over which \( O_3 \) and CO concentrations are strongly elevated. This is due to biomass burning, which represents a major global source for a number of important gases, including CO, NO, CO, and \( CH_4 \) as well as particulate matter.

The gas emissions affect regional ozone concentrations and the oxidative characteristics of the troposphere. The participates affect regional, and possibly global, radiation budgets by their potential influence on tropical cloud microphysical processes. This Activity will seek to quantify the extent of the temporal and spatial distribution, dynamics, species emissions, and atmospheric consequences of biomass burning.

Fire also has both short- and long-term effects on trace-gas emissions from affected ecosystems which, for instance for \( CO_2 \) and \( CH_4 \), may be more significant than their immediate release during the fire. Fire also alters the long-term dynamics of the cycling and storage of elements within terrestrial ecosystems, thereby altering their significance as sources or sinks of various trace gases.

Finally, deposits of compounds produced by biomass burning on pristine tropical ecosystems may affect their composition and dynamics.

Objectives
- To characterize the production of chemically and radiatively important gases and aerosol species from biomass burning to the global atmosphere.
- To assess the consequences of biomass burning on regional and global atmospheric chemistry and climate.
- To determine the short- and long-term effects of fire on post-fire exchanges of trace gases between terrestrial ecosystems and the atmosphere.
- To understand the biogeochemical consequences of atmospheric deposition of products of biomass burning.

Task 1. Global inventories of biomass burning.

An initial survey will be made to construct worldwide regional inventories of biomass burning, both current and past. The amount of biomass in important ecosystems subject to biomass burning will be quantified. Remote sensing supported by ground-based evaluations provide the most promising tool for compiling geographical information on the extent of fires and on the distribution of biomass. At a few selected sites, the emissions of a wide range of gases and particulate matter will be measured.
Task 2. Quantification of gas and aerosol emissions from biomass burning.

Process models describing fire dynamics as a function of biomass type and environmental variables will be developed as well as integrated models coupling fire dynamics and combustion chemistry. The models will be tested with field experiments especially in savanna regions. The chemical reactivity of biomass burning plumes will be documented and modelled.

Task 3. Chemical transformation in fire affected air masses.

The chemical transformations in fire plumes and fire affected air masses, as well as their transport into other regions of the atmosphere will be studied through repeated aircraft-based sampling programmes. Satellite observations providing a global survey of the effect of burning on tropospheric chemistry will become available by the middle to late 1990s and will be an important contribution to this task.

Task 4. Post-fire fluxes of trace gases.

Long-term post-fire sampling of trace gas fluxes will be performed in sites that differ in fire history and will be based on the pattern of nutrient dynamics at particular times post-fire. Field experiments and models will be used to determine, integrate, and extend knowledge of post-fire trace-gas exchanges. In the longer term, a set of experimentally burned plots will be established in tropical savanna and cleared forest regions, and the long-term effects of fire on the dynamics of C, N, and other nutrient elements, as well as vegetation composition and flammability will be studied in collaboration with the studies conducted within GCTE (Chapter 6.1).

Task 5. Oxidant effects

Information from measurements of plume dispersion and regional deposition will be used to establish studies of the effects of burning-derived oxidants on pristine tropical ecosystems and agricultural yields.

Activity 4

**Chemical Transformations in Tropical Atmosphere and Their Interaction with the Biosphere**

Land use changes and industrial developments strongly influence the emissions of several trace gases in tropical regions, thereby substantially affecting the photochemistry of the tropical and global troposphere. Depletion of the tropical forests will reduce VOC emissions, but increase the transport of NO to the free troposphere, possibly leading to much enhanced regional ozone formation. The latter trend is strongly enhanced during the dry season, as biomass burning produces large quantities of fire effluents, especially CO, NO and VOC, which interact photochemically, together with water vapour and high intensities of ultraviolet radiation, to produce O₃. As the air moves from the savanna regions to the convective inter-tropical convergence zone, the fire effluents and their photochemical products are transported at high levels into other regions of the atmosphere. Substantial changes in the overall photochemistry, not only of the continental tropics but also globally, may result.

Many important facets of the atmospheric chemical effects of rapid developments in human activities in the tropics are being and will be more intensively studied regionally by interdisciplinary research groups in Latin America, Africa and South-East Asia, mostly by national and bilateral arrangements. These activities must, however, from time to time, be enhanced by some large-scale experiments to be conducted within IGAC.

**Objective**

- To understand the photochemistry of the tropical atmosphere and its effect on the global atmosphere, including how these are influenced by industrial and agricultural developments and resulting changes in trace-gas emissions.
Activity 1

Polar Atmospheric Chemistry

The current spatial and seasonal distributions, the chemical- meteorological origin and the atmospheric chemical transformations of key atmospheric constituents and precipitation in the polar troposphere will be studied in order to assess the impact of anthropogenic activities on polar habitats and climate.

There are many chemical changes that take place in the atmosphere at polar sunrise, most likely via reactions on ice and snow, the study of which will reveal insight into atmospheric chemistry relevant to global change, including processes that may be related to stratospheric ozone hole generation (see STIB, Chapter 2.2). Also, as airmasses are transported into the Arctic region from mid-latitudes, they undergo chemical reactions that alter their gas and particle composition.

The influx of particulate matter into the Arctic during winter and early spring influences the radiation budget of this region with potential climatic consequences.

Objectives

- To understand local sources of chemical compounds in the polar regions particularly from ice-free ocean surfaces.
- To quantify regional industrial sources and the transport of chemical compounds from mid-latitudes into the Arctic.
- To understand the transformations that determine the chemical composition of the Arctic troposphere.
- To determine the influence of atmospheric chemical composition on the radiative properties of the Arctic atmosphere.

Task 1. Arctic sunrise experiment.

An intensive study of atmospheric chemistry at polar sunrise is planned in the Arctic, utilizing the unique shift from total darkness to total light in a few weeks, without any marked change in large-scale meteorological conditions. It has been noted that under such circumstances ground-level ozone concentrations may be reduced to very low values, concomitant with high concentrations of gaseous and particulate bromine, indicating a possible relationship. Measurements of these phenomena were started in Spring 1986 at Alert, Canada, coordinated by the Canadian Institute for Research in Atmospheric Chemistry (CIRAC) and this work will be expanded in coming years by participation of scientists from other nations (e.g., US, Scandinavia, and Germany) to conduct larger-scale experiments and to extend the measurement network.

Task 2. Long-range transport of air pollution into the Arctic.

The fourth international Arctic Gas and Aerosol Sampling Programme (AGASP IV), with participation from several nations bordering the Arctic, will be undertaken in 1991 using aircraft and ground-based observational platforms, involving both measurements of inert tracers to follow air parcels over long distances while simultaneously studying chemical composition changes during transport. Emphasis will also be placed on the optical and chemical characterization of the Arctic haze aerosol particles.

Activity 2

Polar Air-Snow Experiment

This Activity is aimed at improving quantitative knowledge of the relationship between atmospheric composition and the chemical composition of ice in the central polar areas. It will study in detail the incorporation of constituents into polar snowfalls and the exchange of gases and particles between the atmosphere and snowpack to the point of ice formation. The possible production and destruction of compounds by reactions on snow and in ice will be investigated.

Key constituents to be studied include the greenhouse gases, H2O, H2SO4, HNO3, HCl, black carbon, and pesticides (see also PAGES, Chapter 7.1).

Objective

- To establish the relationship between atmospheric chemical composition and that of glacier ice in the central polar areas.

Task 1. Model development.

Development of a model of the major physical and chemical processes occurring at very low temperatures, using data that have been obtained in past experiments.

Task 2. Chemical analysis of current snow, trace gas and aerosol composition in the Central Antarctic plateau.

An initial one-year experiment on the central Antarctic plateau is planned which will include measurement of atmospheric trace gases and aerosols and the composition of falling snow, firm snow, ice and air in the ice pores. This Activity will be coordinated with PAGES (Chapter 7.1). The central Antarctic plateau is chosen because major ice-core chemistry records have been retrieved there, so that the results will have the greatest relevance to these records. The Amundsen Scott base is selected as the first site to be studied, as it is a good ice core region possessing a long-term baseline air chemistry station and year-round facilities. Other sites will be added in future.

The Role of Boreal Regions in Biosphere-Atmosphere Interactions

The boreal ecosystems of forests, lakes and wetlands, covering vast areas of North America, Scandinavia and the Soviet Union, have significant influences on global climate and atmospheric composition. Climate change modelling scenarios agree that warming will intensify towards the poles providing the potential for strongly enhanced CO2 and CH4 emissions from northern wetlands and permafrost regions. These regions may also make substantial contributions to the emissions of other chemically active compounds and act as significant reservoirs for trace-gas species transported from mid-latitudes. Emissions may increase considerably in response to changes in soil temperature, water table and organic matter storage.

High Latitude Ecosystems as Sources and Sinks of Trace-Gases and their Sensitivity to Environmental Disturbances

This Activity will examine the relations and potential feedbacks between climate change, biogeochemical cycling and trace gas production, especially CO2, CH4, N2O, CO.
and N\textsubscript{2}O in northern wetlands, building up from past and ongoing studies in Alberta and in the Hudson Bay Lowland/Labrador region of Canada.

**Objectives**  
- To estimate trace-gas emissions and uptake in high latitude ecosystems.  
- To determine the principal ecological and environmental characteristics that control ecosystem trace-gas production, consumption, and transport.  
- To estimate the sensitivity of northern ecosystems (in terms of trace-gas emissions) to environmental change.

**Task 1. Development of budgets for trace-gas fluxes in northern wetlands.**  
Standardized ecosystem classifications, based on vegetation, soil types, hydrology and nutrient status, will be developed and data bases established of these northern wetland ecosystems. Existing data bases will be evaluated and new data sets will be obtained, where necessary, for use in modelling studies. Year-round field measurements of fluxes of CH\textsubscript{4}, CO, N\textsubscript{2}O, NO, CO\textsubscript{2}, H\textsubscript{2}S, and VOC will be made using chamber, tower and aircraft techniques covering temporal and spatial variability. Methane and CO\textsubscript{2} flux measurement systems are relatively advanced (including both box and tape-record eddy correlation methods), but appropriate techniques for several of the other gases will have to be developed. The study of the atmospheric chemistry (particularly surface exchange) of the Hudson Bay Lowland and Labrador regions of northern Canada, conducted by CIRAC in collaboration with NASA (ABLE-3B) in 1990, will initiate these kind of experiments. Similar measurements are planned to be made in other major boreal regions in Western Siberia, Scandinavia, and Alaska. Models will be developed for process studies and extrapolation purposes to larger scales to be tested by comparison with aircraft-based large regional flux and concentration distribution surveys. Isotopic analyses of emissions and CH\textsubscript{4} isotope (13C, 14C, 2H) concentration distributions in the atmosphere will add significant information.

**Task 2. Controlling factors and processes of trace-gas exchange in northern wetlands.**  
On an ecosystem and regional basis, trace-gas exchange will be examined for a range of different physical and environmental conditions. These studies must include the below-surface processes responsible for both production and the partial oxidation of CH\textsubscript{4} prior to release into the atmosphere as well as processes related to trace-gas release to the atmosphere, e.g., by vascular transport in plants. Such studies are being initiated in the 1990 CIRAC/ABLE-3B study, but will be extended and also carried out at other sites around the world for extended measurement periods. Models will be developed to relate these process studies to the flux measurements.

**Task 3. Sensitivity of high latitude trace-gas sources and sinks to climate change.**  
This task includes the establishment of long-term atmospheric observatories to measure trace-gas emissions at a range of research sites accompanied by regular aircraft transect surveys. An important part of this task will also be long-term studies of ecological processes and changes affected by anthropogenic factors, including climate changes. These studies of trace-gas emissions will take place at sites along primary and secondary successionary stages to examine the control of vegetation, soil, and micro climate on fluxes. Ecosystem manipulations are planned in order to examine the influences of changing environmental factors to establish trends of trace gas emissions over time. Predictive ecosystem process models will be developed that incorporate relationships between forcing variables and trace-gas exchanges. Landscape models will be developed and estimates of trace-gas fluxes for present and potential future climatic conditions.

**Global Distributions, Transformations, Trends and Modelling**

*Focus 5*

In order to understand the chemistry of the atmosphere and its role in the Earth's overall biogeochemical system, much more needs to be learned about how both short- and long-term variations in the chemical composition of the atmosphere reflect the interaction of the major processes to which atmospheric constituents are subjected: emissions, transport, transformation, and removal. This Focus is aimed at determining the global distribution and temporal variations of important trace gases that are subject to chemical transformation and long-range transport and to quantify their emissions. This will require the establishment of a network of large-scale aircraft surveys, remote sensing, from satellites, and model development, and development of emission inventories.

**Global Tropospheric Ozone Network**

*Activity 1*

Since ozone plays a central role in most of the key chemical processes in the troposphere, far too little knowledge of its global temporal and spatial distribution and long-term trends is available. There is, therefore, an urgent need to enlarge the data base.

**Objective**

- To improve the climatology and trend estimates of ozone in the troposphere.

**Task**

The existing ozone sonde network together with available ozone lidar stations will be optimized for accurate measurements of tropospheric ozone profiles by appropriate inter-calibrations, intercomparisons and agreements on protocols, frequency and timing of measurements.

Doubling the current number of ozone measurement stations would result in a network that will greatly improve our knowledge of the global distribution of tropospheric ozone in space and time and provide the capability to detect regional and global trends of tropospheric ozone with an accuracy of about 1% per year or better. Uniform procedures for data processing, analysis, archival, distribution and publication are necessary. New stations should be established where the scientific need is greatest.

A close interaction between modelling and the development of measurement strategy is essential. The network will be coordinated with the existing Dobson and Brewer total-column network, which is run by individual nations under the auspices of the Ozone Commission of IAMAP, the newly established UNEP-WMO network for the detection of stratospheric change, the European TOR/Eurotrac project, the WMO BAPMoN Network, and existing surface-ozone measurement programmes that are run in several nations.

**Global Atmospheric Chemistry Survey**

*Activity 2*

The global, three-dimensional distributions of solar ultraviolet radiation and the reactive gases O\textsubscript{3}, CO, NO, NO\textsubscript{2}, H\textsubscript{2}O, CH\textsubscript{4}, and VOC determine the concentrations of hydroxyl radicals and thus the oxidative efficiency of the atmosphere, affecting the removal of most chemical constituents in the atmosphere. Current knowledge of the global distributions and annual cycles of the above factors is insufficient in order to understand the fundamental oxidation processes operating over most of the globe and the oxidative efficiency of the atmosphere. Particularly useful will be observations of industrially produced halocarbon gases, such as CH\textsubscript{3}CCl, and the various replacement products that are being introduced in the fully halogenated, now internationally regulated compounds.
Because the former are broken down by reactions with hydroxyl radicals in the troposphere, their removal rates are a measure for average global concentrations of OH radicals. Their long-term, worldwide observations can thus reveal trends in global average OH concentrations.

Objective

- To establish the spatial and temporal distributions of key chemically reactive species and photochemically active solar radiation.

Task 1. Surface-based and aircraft-borne observations.

The most practical way of substantially improving our knowledge of the distribution of the gases mentioned above involves a series of regular coordinated campaigns of both surface-based and aircraft-borne observations over several regions. Other photochemically related, or otherwise important, species (HOCl, PAN, sulphur gases, CHI, organic acids, etc.) should also be included when possible. This work would be multinational: eight nations with suitable research aircraft and a total of about 16 aircraft potentially available for such an undertaking have been identified. There should be opportunities for multinational participation in each flight, to ensure that the more complex measurements with less available instrumentation can be made during as many campaigns as possible.

Intercomparison and intercalibrations between the individual instruments used for all the experiments is of the greatest importance to the success of this task. Also essential is a uniform approach to processing, analysis, archiving, distribution, and publication of the data.

Data from regional air pollution oriented networks projects will be included to strengthen the global database; strong links with those Activities will thus be established. This Activity will also profit greatly from those proposed under Activities (1) and (2). It will be established. This Activity will also profit greatly from those proposed under Activities (1) and (2).

Task 2. Observations by remote sensing.

The development of remote-sensing techniques for tropospheric composition measurements is an important step in support of these Activities and would substantially help in this task. Several proposals for this have been made within NASA, ESA, and national space agencies.

Task 3. Model development.

The development of regional- and global-scale models should be an integral part of this Activity both for the interpretation of the observations, and the extrapolation of knowledge to times and regions where no measurements can be made.

Development of Global-Emission Inventories

Detailed emission inventories, if possible on a 1° x 1° global geographic grid, should be developed for future detailed modeling simulations of the behavior of chemically and radiatively important trace substances. A comprehensive and uniform international Activity needs to be initiated to establish an inventory of the natural and anthropogenic sources of the most important atmospheric constituents, such as NO, CO, CHI, VOC, NH3, CH4, CC1, and other halocarbon gases, especially those that are being introduced as replacement products for CFC-11 and CFC-12. Among the aerosol components, their nutrient element, trace metal and elemental carbon contents, are of special interest.

Objectives

- To establish a framework for the development and evaluation of global emission inventories.
- To conduct a critical survey of emission inventories of compounds of major importance in global atmospheric chemistry and biogeochemical cycles.
- To publish inventories in the open literature and design easily accessible data bases for use by scientists worldwide.

Activity 4

An international working group has been formed to review the inventories presently available both for natural and man-made substances. Based on this review, one or two substances will be chosen for a pilot study. For these an archive will be established. Problems such as consistency and coverage in these inventories will be examined as part of the programme to develop generalized strategies for the construction of accurate emission inventories. Further substance will be added to the inventories depending on the judgement of the working group. Close coordination with ongoing national and regional Activities will be established.

Global Integration and Modelling of Fluxes

While many of the programs for measuring the fluxes of trace gases are regional, IGAC is chiefly concerned with the global integration. This is especially true for the longer-lived species (e.g., CO2, CO, CH4, N2O). Global extrapolations require the ability to generalize flux measurements in space and time. Such work will be designed to rigorously test the models and methodology required to achieve this goal.

Objectives

- To quantify fluxes of gases significant to global atmospheric chemistry.
- To develop and test extrapolation approaches using combined ground-based process studies and mesoscale modeling and measurements.

Task 1. Global synthesis of N2O, CH4, and CO fluxes.

This integration task will require a number of Activities, similar to those proposed within regional studies, but at a larger scale. These are, first, the development of a global geographic data base including a suitable classification of areas by flux potential (i.e., soil, vegetation class) and distribution of driving variables (e.g., climate, N deposition). Second, measured flux rates or models of rates will be used to estimate fluxes of the various combinations of areas and driving variables in the GIS. These estimates will be compared to the model predictions and driving variables. Third, global models must be compared to atmospheric sinks and to the predicted distribution of sources and sinks using inverse evaluation. This final step constitutes the validation of the regional estimates and techniques used in global extrapolation. When these source-based extrapolations fail to match inverse predictions, both calculations must be examined.

Task 2. Flux extrapolation pilot study.

The extrapolation of small-scale field measurements to regional estimates is a crucial methodological problem due to heterogeneity in the land surface. The first step will be to establish a measurement network at a location which consists of a limited number of ecosystems (e.g., a study area consisting of a forest-agricultural land mixture).

The size of the study area should accommodate various observational and measurement scales including satellite observations (c. 30-1000 m), airborne measurements, eddy correlation flux measurements (c. 10-1000 m), and plot studies (c. 1 m). An ideal size is approximately 10 x 10 km.

The study area, a stratified measurement network will be established to determine the environmental variables controlling fluxes from the various ecosystems and the role of landscape characteristics contributing to variability in the emissions.

After one year of process-level measurements, a large boundary layer experiment will be performed. In this experiment, aircraft will be used in order to get estimates of fluxes over the region. These flux estimates will be compared to estimates derived from models capable of depicting fluxes over the same spatial and temporal scales. The results of these comparisons will be used to evaluate both the modeling and aircraft approaches to large area flux estimates. This evaluation is crucial for the development of flux models and better understandings of the processes controlling these fluxes.
standing of the spatial and temporal variability of fluxes, and thus leading to methodology for global evaluation of source/sink relationships in the terrestrial ecosystems.

**Intercalibrations / Intercomparisons**

The use of the data from separate measurement programmes requires an understanding of the relative agreement of the separate standards used in each of them. There is not a well-developed set of international standards for measurements of trace constituents in the atmosphere, and conflicting calibration standards exist for some species. The WMO has tackled the problems of standards for precipitation chemistry analyses and the International Ozone Commission has established recommended absorption coefficients for ozone. For most other species this problem still remains to be solved.

**Activity 1**

**Gas Standards for CO, CH₄ and Chlorinated Hydrocarbons**

The use of the data from separate long-term measurement programmes requires an understanding of the relative agreement of the separate gas standards involved. Gases for which a standard has been made are CO, CH₄, and certain chlorinated compounds. However, these gas standards are not known to a precision that allows differences measured by separate groups to be interpreted as real, rather than as differences among standards.

An inter-laboratory comparison of CH₄ measurements will be undertaken to be followed by the development of an absolute standard for CH₄. Methylchloroform (CH₃CCl₂) and HCFC-22 (CHClF₂) have been identified whose absolute calibration is important in the determination of the average tropospheric hydroxyl radical concentration. A major uncertainty exists for CFC-113 (CCl₂FCF₃), which should be resolved, since this compound is the fastest growing source of stratospheric chlorine.

**Objective**

- To utilize the current inadequacies in the standards for CO, CH₄ and some chlorinated compounds.

Three phases are envisaged, including the following studies: (i) stability experiments on containers; (ii) inter-laboratory comparisons, so that various data sets collected around the world by various groups can be compared; and (iii) supply and dissemination of absolute standards.

**Activity 2**

**Non-Methane Hydrocarbon Intercomparison Experiment**

The non-methane hydrocarbons (terpenes, isoprene, alkanes, alkenes, alkynes and aromatics) are involved in ozone formation and are sources of carbon monoxide and of reactive hydrogen species. To form a global picture of these abundances there is a need to know whether there are any systematic differences between the methods used by various investigators.

**Objective**

- To assess how accurately the non-methane hydrocarbons can be measured.

An intercomparison experiment will be conducted under typical field conditions with simultaneous measurements at the same place.

**Task 1. Standards and cross referencing**

A travelling standard will be made and circulated to groups for intercomparison of individual standards used by the investigators and to determine the absolute accuracy of current and past measurements.

**Task 2. Whole-air surface measurements**

"Blind" whole-air samples will be circulated and this gas concentrations measured. This also will be simultaneous ground-based measurements at a mountain (free troposphere), a remote (low VOC levels) and a heavily forested site (high VOC levels).

**Task 3. Aircraft intercomparison campaigns in background air and polluted areas**

It will include onboard analyses and air sampling in flasks in order to obtain height profiles across the marine and continental boundary layer. The goals are, in this case, to assess inlet problems, storage and shipping.

**Trace Gas Fluxes in Mid-Latitude Ecosystems**

Much of the temperate region of the Northern Hemisphere is densely populated and most of its ecosystems have been subject to strong human disturbances, such as the conversion of large areas of forests to grasslands and agricultural lands. In addition, as a result of industrial activity, since many decades the mid-latitude ecosystems have experienced strongly altered atmospheric chemical conditions such as enhanced ozone concentrations and acid deposition. Strong interactions occur between emissions of industrial and biological origin, such as NO, and VOC, contributing to enhanced ozone concentrations with negative consequences for the biological functioning of affected ecosystems. These processes are partially being studied in some existing programmes in North America and Western Europe, but need to be expanded to other regions and extended to include their impact on overall nutrient cycling of ecosystems and exchange of trace gases, in particular VOC, CH₄, CO, and N₂O. In addition to the direct climate effects of pollutants emitted by industrial activity, the emissions especially of NO and N₂O, as well as soil uptake of CO₂, CO, and CH₄ may be strongly affected by intense agricultural activities and heavy-use of fertilizers.

**Mid-latitude Ecosystems as Sinks for Atmospheric Oxidants and Sources of Oxidant Precursors**

Substantial ranges of the mid-latitude ecosystems are exposed to high oxidant levels due to large anthropogenic emissions of VOC and especially NO, which under the influence of solar radiation, induce reactions leading to photochemical ozone production. VOC emitted by plant canopies are important precursors for photochemical ozonidion production. The magnitude of the production of VOC by vegetation and the uptake of NO, O, and other oxidants by the biosphere, as well as the controlling physical chemical and biological processes remain poorly understood.

Enhanced O₃ concentrations downwind of industrial regions may cause phytotoxic stress on many plant communities. Effects of this stress on physiological processes and on the exchange of heat, water vapour, CO₂ and other trace gases, in particular VOC and NO, have been observed but cannot yet be quantified sufficiently.

**Objectives**

- To quantify source and sink strengths of NOx compounds and volatile hydrocarbons and to determine the plant physiological processes responsible for them.
- To determine the effect of changes in physical and chemical conditions on the sources and sinks of NOx and VOC.

Continuous field measurements will be set up in representative mid-latitude ecosystems, particularly in regions subjected to intensive ozone concentrations.
Activity 2

**Exchanges of N_2O, CH_4, and CO Between Terrestrial Ecosystems and the Atmosphere in Mid-latitudes**

Heavy fertilization of agricultural land and high inputs of nitrogen in precipitation to forests may have increased their capacity to produce N_2O. The regional magnitude of this increase is not well documented, although, at least for agricultural systems, they may be substantial. Drainage of wetlands and increased nitrogen inputs to both agricultural and non-managed ecosystems have an effect on production and consumption of methane. The importance of these factors on the global CH_4 and N_2O budgets has yet to be determined; preliminary experiments indicate that they may be significant. In addition, it is known that CO can be exchanged between the biosphere and atmosphere. However, too few measurements have been made to assess the importance of this exchange process and how it may be influenced by environmental changes.

**Objectives**

- To quantify the role of northern hemisphere mid-latitude ecosystems as sources for N_2O.
- To quantify the role of mid-latitude ecosystems as sources and sinks for CH_4.
- To define the processes and land management practices that control N_2O and CH_4 exchange in mid-latitude systems.
- To understand the biological sources and sinks of CO.

This Activity will be undertaken by the establishment of several sites on different continents to examine the seasonal dependence of N_2O, CH_4 and CO emission and deposition. A range of cropping systems, forest and grassland types will be covered. At each site, time series of fluxes will be determined and related to the controlling factors, some of which (N-inputs, precipitation, etc.) may be manipulated. Fluxes will be measured for at least two years, after which sampling frequency at some sites may be reduced and intensified at others for conditions of particular significance. Models of both CH_4, CO and N_2O exchange processes from soils will assist in the integration of the results over larger spatial scales.

Activity 3

**The Importance of Mid-latitude Ecosystems as Net CO_2 Sinks**

Large portions of the mid-latitudes have undergone substantial land-use changes, including extensive reforestation with increased storage in woody biomass and soil organic matter. With much of the present forest area in the region now in a mid-successional stage, it is possible that they are a significant C-sink. Moreover, increasing, inadvertent N inputs by dry deposition and precipitation due to industrial and agricultural activities and the increasing atmospheric CO_2 content may boost net primary production and carbon storage, implying a potential growing sink of CO_2. On the other hand, this potential may be reduced or reversed if the deposition of acidic compounds and ozone concentrations result in significant forest decline and soil organic matter losses in agricultural ecosystems. Because of the multiple controls over CO_2 exchange and C storage, manipulative experiments will be required to develop quantitative understanding on the importance of these alternative possibilities. This will be done in cooperation with GCTE (Chapter 6.1).

**Objectives**

- To determine the consequences of changing land use (reforestation, succession, deforestation, urbanization) on CO_2 exchange between atmosphere and biosphere.
- To evaluate the effect of changing temperature and moisture on CO_2 exchange.
- To evaluate the effects of N and S species deposition on CO_2 exchange.

Networks will be established in temperate forests around the world to include sites of varying successional age and management practices. Measurements of net primary production, soil respiration, decomposition, and the climatic and biotic variables that drive these processes will be made for at least one year. After this intensive year, measurements will be continued at a lower pace to determine interannual variation and long-term changes in site C-dynamics. Manipulative experiments to improve our understanding of the long-term effects of various climatic drivers on ecosystem functioning (e.g., water and nutrient use efficiency) and trace gas exchange will include elevated CO_2, soil temperatures, soil moisture, and increased N and S, and acid depositions.

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**Cloud Condensation Nuclei as Controllers of Cloud Properties**

Clouds strongly influence global climate by their influence on the Earth's radiative balance. Chemical transformations in clouds also play a major role in the atmospheric chemical transformations of many compounds of global significance, and for the transfer of essential chemical elements and compounds, as well as pollutants to the biosphere. Central to all these influences, and greatly sensitive to human activities, are the chemical and physical characteristics of the nucleation on which all cloud droplets form. Of special importance in this regard are natural DMS emissions from the oceans, reduced sulphur gas emissions from continental areas and SO_2 emissions from fossil fuel burning. These are converted to the troposphere to sulphate particles, which may be the most important sources for the atmosphere's cloud condensation nuclei (CCN). However, other sources for CCN may also be important, such as smoke particles from biomass burning.

Although understanding the chemical and physical evolution of CCN is thus central to cloud and climate modelling, knowledge of the dynamics of this system is virtually non-existent. It is possible that these feedback processes involving, for example, modification of the Earth's surface temperatures via anthropogenic S emissions, leading to CCN-modulated droplet size distributions and cloud reflectivities, modification of rainfall patterns and aerosol particle lifetimes. At present, models are needed to address these issues, and the current lack of knowledge is severely limited by the availability of instrumentation, observational platforms, and scientific personnel. International collaboration could achieve the critical mass for the necessary comprehensive studies.

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**Cloud Condensation Nuclei**

**Objectives**

- To develop a much improved database on the chemical and physical characterization of particles that act as CCN in different climatic and ecological regions.
- To understand the sources and physical and chemical factors that produce CCN and that control their evolution.
- To relate the factors controlling CCN production and distribution to the large-scale factors that are carried in climate model calculations.
- To evaluate means to utilize remote sensing to estimate CCN concentrations.

Simultaneous measurements are required of gase-phase precursor concentrations, especially SO_2, and DMS; primary aerosol production rates and properties, total particle (Aitken) concentrations, sub-cloud aerosol size distribution and size-dependent chemical composition of particles, as well as their morphology, physical state, and surface chemical properties. Also required are CCN concentration, size distribution and chemical composition as a function of supersaturation, as well as size spectra and size-resolved chemical composition of cloud droplets in clouds, their relations to the optical and microphysical properties of clouds, and dependence on meteorological factors, such as updraft velocities and rate of air entrainment.

Because some of these measurements are slightly beyond the current technical capability, there is a need for instrument development, measurement standardization and intercalibration.

Models must be extended to link the chemical composition of various parts of the aerosol population to activation under conditions favourable to cloud
formation and to describe the chemical changes of CCN after they are cycled through clouds.

Both the International Commission on Cloud Physics and the International Radiation Commission (of IAMAP) have parallel projects on aerosols and clouds in the International Aerosol Climatology Project (IACP), and the International Satellite Cloud Climatology Project (ISCCP), respectively. Collaborative opportunities with these projects will be pursued.

Field studies of the evolution of CCN and their interactions with clouds will be conducted in three geographical regions as a part of the IGAC Activities Focus 1. Activity 1, 2, and 3, and Focus 2. Activity 3. An important aspect of the research will be intercomparisons of cloud properties in various atmospheric environments with widely different sulphur sources, such as pristine marine and continental environments, and their more polluted counterparts.

Implementation

The IGAC Core Project, will hold its first open meeting on 8 September 1990 in Chamrousse, France, as part of the Seventh International Symposium of the Commission on Atmospheric Chemistry and Global Pollution (CACP), "Chemistry of the Global Atmosphere". A Core Project Office (CPO) has yet to be identified, however, discussions are in progress for securing the adequate resources to fund the operation of the CPO. An IGBP Scientific Steering Committee (SSC) for IGAC has been formed (see Galbally 1989). Additional members will be selected to represent the biospheric components of the Core Project.

Several of the Activities listed in the IGAC Core Project have begun including:

Focus 1, Activity 1: North Atlantic Regional Study
Activity 2: Marine Aerosol and Gas Exchange: Atmospheric Chemistry and Climate

Focus 2, Activity 1: Biosphere-Aerospace Trace-Gas Exchange in the Tropics: Tropical Land-Use Change and Trace-Gas Emissions
Activity 3: Impact of Biomass Burning on the World Atmosphere

Focus 4, Activity 1: High Latitude Ecosystem

Focus 5, Activity 1: Global Tropospheric Ozone Network

Focus 6, Activity 1: Gas Standards for CO, CH₄, and Chlorinated Hydrocarbons
Activity 2: Non-Methane Hydrocarbon Intercomparison Experiment

Others listed in this Chapter are expected to begin within the next two to three years.

References


Suggested Reading


Global Change and STIB ................................. 2.2-3
Science Components ................................. 2.2-5
Stratospheric Changes and the Penetration of UV Radiation
Stratosphere-Troposphere Exchange
Anthropogenic Trends and Natural Variability
Stratospheric Aerosols and their Climatic Effects
The Impact of Stratospheric Changes on Climate
Plan for Action ............................................ 2.2-14
Field Programmes
Satellite Observation
A Network for Detection of Stratospheric Changes
Modelling
Implementation ........................................... 2.2-17
References ................................................ 2.2-17

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The Stratosphere-Troposphere Interactions and the Biosphere (STIB) project is concerned with the processes through which biogenic and anthropogenic emissions change the composition, radiation and dynamics of the stratosphere and how these changes in turn affect the biosphere. Trace substances in the stratosphere can modulate the intensity of solar UV-B radiation received at the Earth's surface, which has a direct effect on the biosphere and the chemistry of the troposphere. The chemical and dynamical state of the stratosphere can also influence the troposphere by exchange processes at the tropopause. Conversely, some of the gases emitted from the surface determine the concentrations of stratospheric ozone. These gases are relatively inert to oxidation in the troposphere and therefore have sufficiently long lifetimes to be transported into the stratosphere. They include the biogenic gases (N$_2$O and CH$_4$) and several industrial halocarbons. The photochemical breakdown of these gases under the influence of ultraviolet radiation in the stratosphere leads to molecules and atoms, such as NO, NO$_2$, Cl and CIO, which catalytically destroy ozone.

The concept of STIB is derived from earlier proposals by IAMAP/IUGG and IAGA/IUGG (Middle Atmosphere Response to Change - MARC and Role of the Middle Atmosphere in the Climate System - MACS). Unlike those proposals, the STIB project emphasizes the coupling between the stratosphere, the troposphere, and the biosphere. Within IGBP, STIB is complementary to the
IGAC (International Global Atmospheric Chemistry project) which focuses on studying tropospheric processes.

The basic motivation for the STIB project is provided by the critical influences of stratospheric processes on the global biosphere system. The stratosphere is coupled to the surface in a number of important ways (Fig. 1). The most familiar is the stratospheric ozone layer, which determines the amount of biologically harmful solar ultraviolet radiation reaching the surface. Less familiar, perhaps, is the fact that downward transport of stratospheric ozone into the troposphere via the formation of OH radicals plays a large role in determining the oxidative state of the troposphere, being responsible for the removal of many of the gases emitted from the surface, either from biogenic or anthropogenic sources.

Stratospheric composition also has two important climatic consequences. The first is through the attenuation of solar radiation, which affects both tropospheric climate and biological activity at the surface. Again, we should note a two-way coupling. For example, when transported to the stratosphere, a biologically produced gas, such as CO₂, is responsible for the stratospheric aerosol layer. Such aerosols reflect incoming solar radiation and thereby influence the climate of both the stratosphere and the troposphere. Direct emission of sulphur gases into the stratosphere by volcanoes also contribute to the aerosol layer in the stratosphere.

The second, less direct, influence of stratospheric composition is through the coupling of stratospheric and tropospheric climate and dynamics. Nitrous oxide, CH₄ and the halocarbons not only affect ozone concentrations, but are powerful infrared absorbers that contribute significantly to greenhouse warming. For example, methane oxidation is a major contributor to the stratospheric H₂O content, and methane is a strong greenhouse gas implicated in the formation of the Antarctic ozone hole. Increases in emissions of these gases, as well as volatilized lead to greenhouse heating of the troposphere and cooling of the middle and upper stratosphere. Radiative cooling of the stratosphere affects stratospheric circulation and circulation, Dynamic coupling of the stratosphere with the troposphere, in ways which are still not completely understood, may influence the climate of the troposphere.

In addition, changes in the stratospheric temperature distributions resulting from increased emissions of greenhouse gases affect stratospheric ozone concentrations through temperature dependence of the rates of the chemical reactions that produce and destroy ozone. It should also be borne in mind that reactions in the stratosphere are the major sinks for NO₂ and the halocarbons. Major volcanic eruptions are known to put very large quantities of material directly into the stratosphere. The conversion of SO₂ to sulphuric acid leads to the formation of particulate matter which can scatter solar radiation away from the earth. Their long residence time in the stratosphere can influence the global radiation balance. In addition, variations of solar intensity on a number of time scales induce variability in the temperature and chemical composition of the upper atmosphere.

Another issue to be considered is the possibility that hypersonic and other aircraft operations in the stratosphere will substantially increase in the near future, with potential consequences for stratospheric ozone and temperature.

In view of the above, the objectives of the STIB project are to gain predictive understanding of:

(i) the consequences of changes in stratospheric O₃ on penetration of potentially harmful UV radiation - this effort should be based on the comprehensive state-of-the-art review being currently conducted by SCOPE;
(ii) the stratosphere-troposphere exchange processes - this effort should be conducted in close collaboration with the IGAC project;
(iii) the natural variability of the stratosphere and the impact of anthropogenic activities - this effort should be conducted in collaboration with IGBP/SCW-STEP's STEP project.
(iv) the influence of stratospheric aerosols on climate - this effort should be carried out in cooperation with WCRP and IAMAP's International Global Aerosol Programme (IGAP);
(v) the impact of stratospheric changes on climate - this effort should be carried out in close cooperation with WCRP.

Stratospheric Changes and the Penetration of UV Radiation

The spectral distribution of solar radiation reaching the Earth's surface depends on the earth-sun distance, the irradiance emitted by the sun, and the transmission properties of the atmosphere. Changes due to orbital parameters will not be considered here, where it is assumed that the Earth is in a state of the Earth-Sun fixed orbit (Chapter 7). As a result of the changing earth-sun distance, the irradiance received at the top of the atmosphere varies with an annual cycle, being 3.3% above and below the mean in January and July, respectively.

Temporal variations of the total irradiance affect climate directly. Spectral changes in the ultraviolet range on the other hand, influence the ozone density profile and hence stratospheric temperatures. The stratospheric ozone content is perturbed by the release of man-made trace gases such as chlorine containing emissions (CFCs). The transmission of the atmosphere, mainly in the biologically active UV-B part of the spectrum, is strongly affected by changes in ozone abundance. The available UV radiation at the surface is variable due to both natural and anthropogenic causes.

Efforts to monitor the total solar irradiance, or solar "constant", have for many years been attempted from the ground without any conclusive evidence of change. During the past 11-year sunspot cycle, an apparent cyclic variation of about 0.08% was measured from space observations. Such a change, small in comparison with the day-to-day variability, probably will not have any significant direct influence on surface temperatures. As most of the variability is due to changes in the photochemically important ultraviolet region, any climatic effect should be modulated through changes in the stratospheric ozone concentrations and heating rates. Despite considerable observational effort during the last solar cycle, the amplitude of the solar variations associated with the 11-year activity cycle is still uncertain, but the best estimate is 3% between 200 and 300 nm, the spectral range of importance for the stratosphere and troposphere with possible implications for the biosphere.

Knowledge of the amplitude of the solar-cycle irradiance variability is of fundamental importance for ozone-trend studies. Theoretical considerations imply that total ozone should vary in phase with solar activity. The maximum of the current 11-year cycle should be reached in 1990-1991, implying in turn that the solar cycle variation in irradiance over the past few years should have counterbalanced the expected decrease in ozone over this time due to anthropogenic CFCs. After the solar-cycle maximum in 1991, the total ozone column is predicted to decrease due both to increased CFC levels and the decline in the solar variability.

UV Radiation Received by the Biosphere

Global-scale data on UV radiation reaching the surface of the Earth or penetrating to various levels in the ocean are largely lacking. It is theoretically possible to assess the amount of UV radiation reaching the biosphere, assuming that we know the incoming solar flux, atmospheric-ozone abundance, aerosol content and cloud optical depth. But, high variability over time and space in these variables make assessments of the time history of the local or global ultraviolet radiation environment very difficult.

The penetration of solar ultraviolet radiation through the stratosphere is determined primarily by the total amount of the absorbing stratospheric ozone. In the troposphere, UV is attenuated by molecular (Rayleigh) scattering, as well as scattering and absorption by aerosols and clouds. Tropospheric ozone and other absorbing gases may also play an important role in UV attenuation because the path length of photons in the troposphere is markedly enhanced (compared to that in the stratosphere). This is due to multiple scattering; therefore, a small increase in tropospheric O₃ may counteract a larger decrease in stratospheric O₃.
UV Monitoring

A UV-monitoring project in the United States (the Robertson-Berger (RB) meter network) has provided a long-term record of ultraviolet radiation at the Earth's surface. This data set is, however, limited to a single broad band obtained by weighing the spectrum by a response function designed to approximate the erythemal (sunburn) response of Caucasian skin. Analysis of data from this network have yielded inconclusive results regarding the trend in UV-B radiation. However, similar measurements over the Swiss Alps indicate a slight increase of about 1 percent per year in the flux of solar UV-B radiation since 1981 (Blumthaler and Ambach 1990), which can be related to a long-term ozone depletion.

Spectral measurements of solar radiation have been made in the Arctic and in Antarctica using double monochromators calibrated in absolute units. The data from Antarctica show that irradiances at wavelengths shorter than 310 nm measured in mid-to-late October often equal or exceed values measured through summer solstice, and that these enhanced levels of UV radiation are a direct consequence of the depleted ozone abundance during Austral spring.

Model Calculations

Radiative transfer models have been used to study the effect of varying ozone abundance and cloud cover on UV transmission. Such calculations have demonstrated that increased levels of UV-B radiation may be the result not only of an ozone depletion, but also of a decrease in cloud cover. The computed annual effective UV-dose using the action spectrum for erythema (Fig. 2) varies by approximately 4% per degree in latitude in the Northern Hemisphere. Based on the ozone-trend data, the corresponding annual UV-dose varies with latitude as shown in Table 1. The region 53°N to 64°N are calculated to have experienced the smallest increase in UV-dose (only 0.5%) in spite of the annual average reduction in ozone being rather large (2.3%). This is due to the fact that the largest ozone reduction takes place in winter at these latitudes. Hence, wintertime ozone reduction has a relatively minor effect on annual UV-dose.

The annual effective dose at 60°N is shown in Figure 2, as a function of ozone depletion. The amplification factor (rate of change of UV radiation to O₃ depletion) depends on solar zenith angle and therefore is latitude dependent, because with increasing solar zenith angle, radiation in the UV-B range (which is strongly absorbed by ozone) becomes depleted relative to radiation in the UV-A range. Ozone depletions of 10% and 20% yield 12% and 26% increases in annual UV-dose, respectively. Since the DNA action spectrum (Fig. 2) falls off very sharply with wavelengths longer than about 310 nm, this spectrum will yield a larger amplification factor than the erythema action spectrum. An amplification factor near 2 has often been adopted, implying that a 1% decrease in ozone gives rise to a 2% increase in UV dose. However, a value is obtained for the DNA action spectrum for a latitude solar zenith angle and changes in ozone of 10% or less. Hence, the amplification factor will depend on the particular type of biological response considered, as well as on latitude and season.

Effects on the Biosphere

UV radiation has been known to split nucleic acids, causing damage to higher plants, microorganisms, and plants and animals (Caldwell 1981). It is a well-known cause of melanoma in human tissue. Quantitative predictions of the potential direct effects of increased UV-B radiation on the human health and the environment are not possible at present. The principal limitation is lack of information and coordinated synthesis of research results in this area. This is particularly true with regard to the effect on plants. Even within species, different varieties may have different sensitivity to UV-B. Within aquatic ecosystems, increased UV-B irradiance may have a negative influence on a variety of organisms, such as phyto- and zooplankton, which form the base of the marine food web. Under decreased stratospheric O₃, major changes in ecosystem structure and functioning could occur as species sensitive to UV-B radiation are replaced by more resistant species, in both terrestrial and marine ecosystems.

Additional synthesis of existing information is needed to define the needs for additional research. In addition to tropical and sub-tropical regions, emphasis should also be placed on establishing the effects of increases in UV-B radiation in polar regions, where the largest variations in relative UV-B occur. However, the effects on adaptation and sensitivity to UV-B of organisms in these areas is not known with any certainty.

A review of the possible effects of UV-B on the biota will be carried out by SCOPE and on the basis of this review, a possible research activity for STIB will be formulated.

Table 1. Changes in the ozone layer in the period 1969 to 1986 as reported by NASA and the resulting changes in the calculated effective UV-dose. The deviation from zonal average normal values is given in percent. Winter values represent the months December to March and summer values May to August (after Dahlbeck et al. 1989).

<table>
<thead>
<tr>
<th>Period for the Ozone Changes</th>
<th>Region 53 - 64°N (%)</th>
<th>Region 40 - 52°N (%)</th>
<th>Region 30 - 39°N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Average</td>
<td>-2.3 ± 0.7</td>
<td>-3.0 ± 0.8</td>
<td>-1.7 ± 0.7</td>
</tr>
<tr>
<td>Winter Values</td>
<td>-6.2 ± 1.5</td>
<td>-4.7 ± 1.5</td>
<td>-2.3 ± 1.3</td>
</tr>
<tr>
<td>Summer Values</td>
<td>+0.4 ± 0.8</td>
<td>+2.1 ± 0.7</td>
<td>+1.9 ± 0.8</td>
</tr>
<tr>
<td>Annual UV-dose</td>
<td>+0.5%</td>
<td>+3.1%</td>
<td>+2.0%</td>
</tr>
</tbody>
</table>
Research Recommendations

Measurements

In view of the potentially harmful biological effects of increased levels of UV radiation at the earth's surface and into the oceans, a global monitoring activity is urgently needed. Such a measurement activity would provide a direct link, which is currently lacking, between incoming solar flux, biological UV dose, atmospheric ozone abundance and cloud cover. Establishing this link is of crucial importance for progress in this area. The requirements for such a monitoring activity should be: (i) observations of solar spectral irradiance variations (both from space and at the surface) with a precision of 1% over at least a full solar cycle are needed to discriminate between natural changes and anthropogenic perturbations in the stratospheric composition; (ii) the spectral distribution of the UV-radiation, from which appropriate UV-doses can be derived, should be monitored at a surface network of properly chosen stations around the globe. The spectral resolution of the measurements should be sufficient to provide a simultaneous measurement of column ozone abundance and biologically relevant UV-radiation. It should also be capable of quantifying the influence of other environmental parameters on UV radiation levels, such as cloud cover, atmospheric aerosols and gaseous absorbers related to anthropogenic pollution.

Modelling

Accurate assessment of atmospheric heating rates is needed in global models aimed at predicting the impact of greenhouse gases on climate. Photolysis of several atmospheric trace constituents as well as many chemical reactions, important in ozone chemistry, occur at temperature-dependent rates. An accurate model of atmospheric temperature variations and hence heating rates is therefore essential in photochemical models. Since both photolysis and heating rates depend directly upon the radiation field, an accurate description of the radiative field as a function of altitude and solar zenith angle is of paramount importance. As it is unlikely that monitoring of these effects would be feasible on a global scale, reliable and efficient modelling of the solar radiation penetrating to various levels in the atmosphere is important.

Prediction of UV doses received by the biosphere in the oceans requires coupling of the radiation field in the ocean and the atmosphere. This can be done in principle, but efficient numerical algorithms are still lacking. There is also a need to estimate UV penetration through ice and snow to determine the UV dose received by organisms at high latitudes.

Stratosphere-Troposphere Exchange

The troposphere and stratosphere are photochemically and dynamically very different regions. Exchanges of material between them not only determine the flux of H2O, NO, CH4 and the CFCs to the stratosphere, where their photochemical breakdown yields ozone-destroying radicals, but also transport ozone from the stratospheric reservoir to the troposphere, where it plays a large role in defining the oxidative efficiency of the troposphere via the formation of OH radicals.

Transport of air from the troposphere to the stratosphere takes place primarily in the equatorial region. The return flow in mid-latitudes occurs primarily through tropopause-folding events. The location and strength of troposphere-stratosphere exchange are linked to surface temperatures and to the general circulation patterns in the troposphere, both via the control of the convective upwelling in the tropics and by storm-track patterns in middle and subtropical latitudes.

Changes in the temperature structure of the troposphere can also affect the height and structure of the tropopause and the strength of the exchange processes across it. Thus, the flux of gases to the stratosphere may be affected, in particular, by those gases that are involved in ozone destruction and those that are radiatively active, especially water vapour.

Research Recommendations

Observations

Observational data of mid-latitude exchange processes between stratosphere and troposphere are already available from a few ground-based atmospheric radiances and lidar instruments. These need to be enhanced by a wider network to especially quantify the exchange in sub-tropical and equatorial latitudes. There is also a need for high resolution, in situ measurements from aircraft and balloons. The instruments required for aircraft measurements are only partially available. There is a need to develop and deploy state-of-the-art instrumentation to measure the radiative flux divergence in the short-wave and long-wave regions, and thereby measure the local radiative heating and cooling rates. It is particularly important for this to be done above and within cirrus cloud decks and polar stratospheric clouds. Measurements of tracer substances, such as N2O and CFC11, that permit detection of diabetic descent, and CO2, that allows stratospheric air to be dated, are also essential. Further aircraft measurements in regions of complex exchange processes are also required, as a follow-on to the recent NASA Stratosphere Troposphere Exchange Project. In addition, present and future measurements from satellite instruments (e.g., UARS and polar platform will supply data with extended coverage so that the larger scale processes may be examined.

Modelling

Improved (3-dimensional) numerical models are required that (i) include the troposphere and stratosphere with sufficient spatial resolution to allow a well-conducted study of the exchange processes and interactions outlined above; (ii) contain an adequate treatment of the radiative effects of tropospheric clouds and PSCs; and (iii) contain not only the full feedback effects of the stratosphere-troposphere interactions may be represented.

To some extent these separate requirements may be tackled individually. For example, progress in understanding radiative feedbacks of PSCs does not require a GCM with complete treatment of chemical modelling and, similarly, the study of the detailed mechanisms of exchange processes is perhaps best conducted using trajectory analyses and extremely high resolution dynamical models. Ultimately, in order to fully assess the impacts of the interactions described in this section, the development of models that include the full range of radiative-dynamical-chemical interactions between the stratosphere and troposphere and the radiative effects of sea-surface temperature are required. Hence, a hierarchy of models must be developed. These efforts must be carried out in collaboration with the WCRP Working Group on Numerical Experimentation.

Finally, as a test of these models, at all stages comparisons with observations are essential. Towards this end a close cooperation with IGAC field measurements (see Chapter 2.1) is essential so that the field campaigns of mutual interest can be coordinated for maximum benefit of both groups.


**Anthropogenic Trends and Natural Variability**

The stratosphere is the region of the atmosphere which to date has been impacted in a most dramatic and unpredictable manner through the formation of the Antarctic ozone hole. The stratosphere is also the place where the largest changes in both ozone and temperature profiles are expected to occur in the future. In fact, in the Antarctic lower stratosphere, large springtime ozone depletions several tens of percent have been observed over the past decade (Fig. 4).

![Figure 4. Total ozone. Observational data that first indicated the existence of the Antarctic ozone hole. TOMS, total ozone mapping spectrometer (NRC 1989).](image)

Recent reviews of ozone trends (e.g., UNEP-WMO 1989) were limited by the uncertainty regarding the impact of the El Chichon eruption and the role of the 11-year solar cycle on the stratospheric behaviour, despite the use of the highest quality satellite and ground data, which extended over less than 10 years. This time scale is not adequate for volcanic eruptions and solar variability. Major eruptions affect the radiative balance of the Earth and atmospheric temperatures. The main consequence of volcanic eruptions for the stratosphere is the injection of sulphur dioxide into the stratosphere. The response of climate to solar forcing may be due to either changes in orbital parameters or to changes in solar output itself. On decadal time scales the principal effect is that of the 11-year sunspot cycle. The higher frequency modulation imposed by the 27-day sun rotation cycle is too rapid to affect climate significantly. Nevertheless, a better understanding of shorter-term effects on the atmosphere may lead to a better understanding of the role of the cycles of longer periods on the atmosphere as well as on the climate. For these reasons the STEP project should encourage the study of both the influence of the 11-year and 27-

day cycles. Both are associated with changes of about 3% in solar irradiance in the wavelength range of importance for the lower atmosphere and have a measurable and well-recognized impact on the structure of the atmosphere above approximately 40 km. The important question concerns the depth in the atmosphere to which the impacts of solar variability can penetrate and how whether they affect the climate and the biosphere.

Studies of satellite data have yielded significant correlation of both ozone and temperature with the 27-day solar cycle in the middle stratosphere, and major solar disturbances yield clear signatures in the ozone concentration. Recent studies by Van Loon and Labitzke (1990) suggest an association between the 11-year solar cycle and the atmospheric structure at different levels of the atmosphere. In the Northern Hemisphere, they identified a pattern of correlation between the 11-year solar cycle and temperatures and geopotential heights at 100 hPa and 30 hPa (16-25 km).

**Research Recommendations**

Reliable, detection of trends in thermal, chemical and dynamic properties of the middle atmosphere requires an accurate and long-term monitoring effort, using satellites and ground-based stations. Even though the ozone-trend issue has been the subject of intense research in the last two decades, the observational network and the data quality are still inadequate to provide the required accuracy on a global scale. Satellite data of appropriate spatial coverage are of too short a record length (about one 11-year solar cycle) to differentiate between the effect of natural and human-induced effects on ozone. Furthermore, most of the satellite data are not yet calibrated in absolute terms and need to be validated against ground-based measurements.

Thus, a comprehensive, consistent and long-term data collection effort is needed. SCOSTEP’s STEP project seems to be the appropriate organization to lead an effort in this regard.

**Stratospheric Aerosols and Their Climatic Effects**

Stratospheric particles can influence the surface climate of the Earth through their effects on atmospheric radiation. They can also influence the trace composition of the atmosphere and ozone concentrations. In this regard, both natural and anthropogenic influences need to be considered.

It is now fairly well established that the stratospheric sulphate layer is formed by chemical transformation and condensation of sulphur-bearing gases (COS, SO2) transported into the stratosphere from the troposphere or directly injected there by large volcanic eruptions. In addition to the chemical reactions of precursor sulphur gases leading to the production of condensable sulphur compounds, primarily H2SO4, evolution of the particulate layer involves a number of microphysical processes including aerosol nucleation, growth by condensation, evaporation, coagulation and gravitational sedimentation.

Studies indicate that anomalous weather patterns and regional to global-scale cooling are likely to follow major volcanic eruptions. Volcanically-induced sulphate aerosols can affect the global radiation budget. When injected in the stratosphere, volcanic aerosols can rapidly disperse around the Earth, increase the reflectivity of the atmosphere for solar radiation, thus reducing the incoming solar energy at the Earth’s surface. The aerosols also produce a modest infrared trapping effect, which is insufficient to reverse the cooling caused by an increased reflectivity. A number of statistical correlations have been discovered between volcanic eruptions and global cooling in the following years, but the significance of these is not universally accepted. The net effect of major volcanic emissions of sulphur gases into the stratosphere appears to be a global surface cooling of less than 0.5 °C that may persist for 1-3 years. During previous centuries much larger volcanic eruptions, such as Tambora and Krakatao, may have had substantially larger effects. More intense or widespread volcanic activity may re-occur in the future.
Following major volcanic eruption, the stratospheric aerosols fall into the upper troposphere over a period of several years. These sulphate particles are highly soluble and enhance the cloud condensation nuclei (CCN) population of the upper troposphere. It has also been speculated that such soluble aerosols may provide nuclei for cirrus cloud formation. The stratospheric particles, acting as nuclei, could thus modulate the properties of upper tropospheric clouds, and hence have a global impact.

The recent discovery of an ozone hole over Antarctica in late Austral winter and early spring has led to considerable research on the causal processes. Current chemical theories assume that heterogeneous reactions occur on polar stratospheric cloud (PSC) particles composed of HNO₃ and H₂O. Laboratory studies show that the ice-catalysed reaction of HCl with chlorine nitrate (ClONO₂) produces active chlorine. Through known homogeneous photochemical processes, this enhanced activated chlorine can explain most, if not all, of the measured ozone loss.

The role of other stratospheric aerosols in heterogeneous chemical conversion processes that might affect stratospheric composition and ozone depletion needs to be investigated. In this regard, a principal concern for the future is that increasing concentrations of background stratospheric chlorine from chlorofluorocarbons might be extensively activated over the entire globe on sulphate aerosols generated by a major volcanic eruption. Accordingly, a reassessment of the potential importance of heterogeneous stratospheric chemistry is timely.

Human activities can also affect the composition and structure of the stratosphere and stratospheric aerosols in a number of ways. In particular: (i) carbon-dioxide concentration increases lead to a significant cooling of the middle and upper stratosphere thereby altering the dynamics, chemical kinetics and thermodynamics of sulphate particle formation; (ii) tropospheric emissions of sulphur-bearing gases such as COS reach the stratosphere and, upon decomposition, modify the sulphate layer; and (iii) chlorofluorocarbons released at the surface diffuse into the stratosphere and are decomposed into chlorine species that react with stratospheric aerosols.

**Research Recommendations**

To achieve greater certainty of the possible connections between the stratosphere and the troposphere that involve stratospheric aerosols and that have

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**The Impact of Stratospheric Changes on Climate**

The stratosphere affects the troposphere through radiative, dynamical and chemical processes.

**Radiative Processes**

The stratosphere affects the radiative balance of the atmosphere by absorbing a fraction of the incoming solar radiation and by exchanging long-wave radiation with the troposphere and the Earth's surface. The absorption of solar radiation in the stratosphere, principally by ozone, reduces the net solar heating of the surface/troposphere system. The downward emission of long-wave radiation by the stratosphere contributes to tropospheric heating and stratospheric cooling. It is a significant component of the greenhouse effect, maintaining the surface temperature above the black-body temperature required for equilibration with the insolation absorbed by the earth/atmosphere system. Trace gases such as ozone, water vapour, CO₂, and the chlorofluorocarbon gases CFC₁₁ and CFC₁₂, the concentrations of which are changing with time, produce significant downward emission. Changes in stratospheric composition involving trace gases, especially CO₂ and ozone, lead to strong cooling of the upper stratosphere (Rind et al. 1990).

**Dynamical Processes**

Planetary scale (Rossby) waves and gravity waves propagate vertically out of the troposphere into the stratosphere, where they decelerate the mean winds and change the temperature distribution. Strongly modified waves are reflected back in to the troposphere. Simulations with general circulation models (e.g., Rind et al. 1990) have shown that the nature of wave propagation into the stratosphere has a significant impact on the troposphere. A joint effort with WCRP/WGNE is necessary to address this issue.

**Research Recommendations**

A thorough scientific understanding of the chemistry of the middle atmosphere and its effects on the troposphere requires a balanced approach involving laboratory measurements (reaction rates, molecular absorption cross sections), field measurements, long-term monitoring of crucial solar fluxes and atmospheric
circulation, temperature and chemical distributions. Development of a hierarchy of computer models that include the radiative, dynamical and photochemical processes in the atmosphere and their feedbacks is also required. A cooperative effort with the WCRP is required to develop such models.

Plan for Action

The intention is to initiate research activities along several fronts that will address the scientific components and related issues discussed above. Specifically, the activities will involve field campaigns to make specific measurements, analysis of satellite observations, establishment of a complementary ground-based network for monitoring stratospheric variables and numerical modelling.

Field Programmes

In recent years, field programmes have been of immense value in obtaining answers to crucial questions dealing with the middle atmosphere. Several ground-based campaigns, e.g., balloon sounding programmes and aircraft missions directed to study the polar ozone problem, have proved to be essential in addition to the studies using satellite observations. There is a range of exciting experiments within reach, given the necessary investment in platform and instrument development. The most complete synthesis will be achieved by meshing field campaigns with their excellent spatial resolution and flexibility, with satellite observations, which yield global coverage.

The following is a list of initial priority issues which can be addressed in well-conceived field programmes. No attempt is made here at detailed definition, other than some fairly specific instrumental requirements discussed in the next section.

- Improve the understanding of the exchange of gases between the troposphere and the stratosphere. Recent work on the stratospheric water-vapour content suggest that not all air is dried to the lowest values allowed by the minimum temperature experienced upon entering the stratosphere in the tropics. The actual mechanism for drying most stratospheric air is still not known in detail; until it is established it is difficult to be certain how air enters the stratosphere.

- Improve the understanding of the mechanisms for the large extent of diabetic descent in polar and subpolar latitudes in winter and spring. In this regard, measuring, analyzing and understanding the radiative and induced dynamical effects of high cold cirrus clouds may also be of interest.

- Improve the understanding of halogen-induced ozone loss around Antarctica and investigate the likelihood of this effect spreading to middle latitudes.

- Improve the understanding of the effects of aerosols from large volcanic eruptions on stratospheric chemistry.

Some Platform and Instrumental Requirements

Major requirements for aircraft are increased ceiling and range. Both are technologically feasible, at least to a 27 km (20 hPa) ceiling and 6000 nautical-mile range, with a one ton payload. Such an aircraft would probably be unmanned. In addition, long endurance balloons would be a very valuable development, particularly in the Southern Hemisphere.

Few instruments to measure parameters of interest are available. There is a need for state-of-the-art instrumentation to measure the radiative flux divergence in the short and long-wave regions and thereby determine the local radiative heating and cooling rates. Additionally, fast response in situ detectors of a number of reactive and tracer molecules are required to augment the existing capability for NO/NO₂, CO, BrO, O₃, H₂O, and N₂O. For large, lower-flying aircraft, the development of Differential Absorption Radar (DAR) systems for extending the current capability for aerosols and ozone to water vapour and possibly other species should be encouraged.

Satellite Observations

Global, long-term monitoring of a wide range of atmospheric variables is essential if changes in the structure and composition of the stratosphere are to be quantified. Measurements from satellites with their global coverage will, when coupled with a suitable ground-based observation system, be crucially important if this aim is to be achieved.

Operational meteorological satellites make extensive measurements of the stratospheric temperature structure. Stratospheric ozone-profile measurements above the maximum are available from some satellites and some information on water-vapour abundances in the low stratosphere and upper troposphere can be obtained. These are likely to continue to play a central role in detecting stratospheric change.

Because of the long period between conception and execution, satellite platforms and instruments that will be available during the next decade are already largely known. A major data set will come from the Upper Atmosphere Research Satellite (UARS) to be launched in 1991. Global measurements of atmospheric wind and temperature structure and a wide range of molecules, including elements of the NOₓ, HOₓ, and COₓ families are expected to lead to a major improvement in understanding the photochemical, dynamical and radiative processes controlling stratospheric ozone abundances. However, the lifetime of UARS (2-4 years) will limit the usefulness of UARS data for detecting stratospheric trends and there is expected to be a gap of several years before a new generation of instruments can fly on the polar platforms (EOS and the European and Japanese platforms).

Several proposals are being discussed by space agencies for satellite-borne instruments to measure a range of atmospheric variables, with improved height resolution, including stratospheric temperatures, the concentrations of a variety of molecules, stratospheric aerosol distribution and radiative budget parameters as well as the tropospheric concentration of several molecules (CH₄, N₂O, CO, O₃). Development of such satellites should be encouraged as they would be an important contribution to the IGBP in general and the STIB project in particular.

A Network for the Detection of the Stratospheric Changes

Ground-based measurements to complement satellite observations are an essential component of any observation system for global ozone and related stratospheric variables. Such measurements should be developed within a network of stations with appropriate locations and instruments to obtain optimum information possible. They should be performed using recently developed instruments, which will allow appropriate accuracy, precision, and vertical and temporal resolutions. It is essential that the network has an integral research-oriented approach to data analysis, since once any trend has been reliably characterized there will remain the task of interpretation.

Objective

- Temporally (diurnal to seasonal, annual, interannual and perhaps longer term) and spatial variability of stratospheric composition and structure, and to assess with such data the current status of stratospheric chemical and dynamical models.

- To provide the earliest possible detection of large-scale changes in the stratosphere and the means to understand them.

- To provide an independent calibration of satellite sensors.

The scientific rationale for selecting such objectives is based on the following considerations.

- Changes in ozone concentration, leading to increasing surface UV-B radiation, have consequences for human health, and terrestrial and oceanic ecosystems.

- The vertical distribution of ozone controls the temperature structure of the stratosphere, and changes in it can influence the climate of the Earth.

- The temperature profile of the stratosphere influences the rates of chemical reactions, and hence the abundance of ozone. In addition, the temperature structure of the stratosphere itself is controlled by the ozone distribution.

- The CIO radical is the chlorine species responsible for directly catalyzing the
destruction of ozone. Its atmospheric concentration is predicted to be increasing at a rate of at least 5% per year due to the increasing atmospheric concentrations of chlorofluorocarbons.

- NO2 and NO are important for the catalytic control of ozone and play a vital role in coupling the NO2 and ClO families. Consequently, the atmospheric concentration of NO2 may decrease in the future as increased concentrations of ClO will convert a growing fraction of it into ClONO2. Conversely, the observed increase in the concentration of N2O, the stratospheric precursor molecule NO2, would offset some of these decreases.

- HCl is the key temporary reservoir species in the ClO family. It should be monitored in conjunction with ClO in order to see whether the partitioning of species within the chlorine family is changing over time.

- Aerosol particles are now thought to play a major role in the chemistry of the stratosphere, at least under ozone-hole conditions, through heterogeneous processes. Such effects may also be important following major volcanic eruptions. In addition, the presence of high levels of aerosols can influence the interpretation of some optical sensor data.

- Water vapour plays a vital role in controlling the radiative and chemical balance of the stratosphere. It is the dominant source for the hydroxyl radical, which influences the concentrations of NO2, NO, and ClO molecules and in turn affects ozone. Its abundance is an important determinant for the formation of polar stratospheric clouds. The concentration of stratospheric water vapour is expected to increase due to increasing concentrations of atmospheric methane, and may also change if surface temperature in the tropics increase, leading to changes in the intensity of the Hadley circulation and the exchange of water across the tropopause.

- Nitrous oxide has a long lifetime in the stratosphere and quite simple photochemical removal mechanisms due to photolysis. This makes it an ideal tracer for studying changes in atmospheric circulation.

**Modelling**

Numerical models are essential for predicting and understanding the effects of changes in the meteorology and composition of the stratosphere on tropospheric climate. One-dimensional (altitude only) photochemical models have been useful in the initial examination of various photochemical scenarios. For instance, the first models of ozone depletion by the chlorofluorocarbons were made using such models. They have proved useful in initial examination of various trace-gas-climate effects. Some assessment of feedback effects can also be made using one-dimensional climate models.

The next level of complexity in atmospheric modelling is the two-dimensional approach (altitude and latitude). Various approximations can be made in formulating such models. One of the better approximations is that of fixed dynamical heating. In this approximation, the temperature distribution is determined by the sum of the radiative heating and the dynamical heating (driven by the circulation). As the atmospheric composition changes, the radiative heating changes, but in many models currently in use, the dynamical heating (i.e., the circulation) is assumed to remain constant. Given this limitation, predictions using such models remain open to question.

One- and two-dimensional models cannot fully represent the three-dimensional complexity of the atmosphere. Ideally, numerical studies of atmospheric dynamics and chemistry should therefore be based on three-dimensional models. Because fully coupled 3-D models of dynamics and photochemistry are still very complex to run, with present day computers, simplifications must be introduced whereby the photochemical calculations are performed off-line. In this approach, winds and temperatures obtained from integrations with a purely dynamical model are used as input data to three-dimensional models of transport and photochemistry. This approach obviously has the limitation that the dynamics, being fixed, cannot respond to changes in composition.

A better approach is to use models in which the radiative, dynamical, and photochemical processes are fully coupled. This is, however, a very expensive approach and has not so far been used to any great extent. Such models might be used in future to investigate the effects of the stratosphere on tropospheric climate.

Clearly, modelling is a major activity that needs to be further developed in close collaboration with the WCRP and other appropriate international and national efforts.

To realize the objectives of STIB, coordination with several other organizations and development of a strategy to assure long-term international commitment is an obvious necessity. If the project becomes an established Core Project, then a Scientific Steering Committee will be appointed by IAGA, IAMAP, SCOSTEP and IGCP. Other international organizations, such as WCRP and SCOPE will also be invited to participate in the committee work. In addition, the STIB project must establish links with other existing programmes and projects, such as the already existing national or regional O3 projects, IGAP, and STUP, as well as with other Core Projects of IGCP, especially IGAC, CCFI and PAGES.

For the present, the main effort should be directed to ensuring coordinated planning. This can be done in an open meeting that should be organized as early as possible in 1991 to refine the science plan and develop an implementation strategy to assign the responsibilities for the different sub-projects.

**References**


How Do Ocean Biogeochemical Processes Influence and Respond to Climate Change?

Through a combination of physical and biogeochemical processes the oceans function as both source and sink for carbon dioxide. Thus, the oceans play a key role in regulating the climate system, partly through biological processes such as marine primary production. Climate change will alter marine biogeochemical cycles, which in turn will affect the physical aspects of climate to an extent that is as yet unknown. Human-induced changes on land will influence coastal biogeochemical cycles, and expected sea-level rise, as a consequence of climate change, will have profound effects on coastal ecosystems. The specific role of the oceans in shaping the Earth’s environment for life needs to be understood. In particular, a quantitative knowledge of the key interactions linking oceanic process and the climate system must be developed.
3.1 Joint Global Ocean Flux Study (JGOFS)  
An Established Core Project

Scientific Rationale

Of the estimated input of carbon dioxide due to fossil-fuel burning and changing land use, less than 60% is now present in the atmosphere. The ocean is believed to be taking up much of the remainder, at a rate of about 2 Gt/yr; but we do not know how this capacity is regulated. The ocean stores some 50 times more CO₂ than the atmosphere, and a relatively small change in the oceanic carbon cycle (for example, in response to climate change) can have large atmospheric consequences. Moreover, the ocean has a more complicated CO₂ cycle than the atmosphere, involving many inorganic and organic forms. Various sophisticated measurements and models of the atmosphere and ocean give different estimates of how much CO₂ is exchanged and where. Clearly, we must improve the observational and conceptual bases of our estimates and predictions. JGOFS has therefore been designed to increase our understanding of the ocean carbon cycle, its sensitivity to change, and the regulation of the atmosphere-ocean CO₂ balance. More formally, it has two objectives (SCOR 1987).

Objectives

• To determine and understand on a global scale the processes controlling the time varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries.
• To develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular, those related to climate change.

The entry of anthropogenic CO₂ into the ocean is a net result of much larger carbon fluxes between the ocean and atmosphere and within the ocean. Any attempt at prediction has to consider likely changes in fluxes throughout this network. A reasonable target for JGOFS would be to reduce the uncertainties in the fluxes to the level of 2 Gt/yr, the size of the anthropogenic input. Then if, as seems reasonable, the changes in the gross fluxes are a small fraction of the gross fluxes themselves, the precision of our prediction of the net uptake should be a small fraction of the net uptake. For some of the important fluxes this means improving precision by a factor of 10 over current knowledge.

Summary of Present Knowledge

The flow of carbon dioxide between atmosphere and ocean is dominated by ocean upwelling and downwelling. High latitude water cools and dissolves more CO₂ before it sinks; water upwelling at the equator warms and releases CO₂. The rate of carbon entering the oceans at high latitudes and leaving at low by this route is about 40 (±10) Gt/yr (Moore and Bolin 1986). The gas flux across the sea surface at a point is a product of the partial pressure difference and a surface transfer coefficient. The transfer coefficient increases with wind speed in a known way, and global wind speed will be available from satellite measurements in the near future. Surface measurements of pCO₂ (ocean) are sparse, and therefore global estimates of net air-sea exchange must now depend on averages over large areas of ocean and over seasonal or even annual time scales: this is what contributes most of the uncertainty in our estimates of the net CO₂ flux. Much of JGOFS will therefore be devoted to determining how the key processes vary in space and time, to improve the accuracy of interpolations.

Surface transfer is closely related to vertical mixing in the water column, which determines the gradient of CO₂ concentration with depth and hence helps determine the surface pCO₂. The physics of vertical mixing is not an explicit component of JGOFS, but it is an active area of research in its own right, and it
is an explicit component of the potential IGCP/SCOR project COEVS (Chapter 3.2).

Chemical and biological processes determine $pCO_2$ away from the region of direct atmospheric exchange. Dissolved inorganic carbon (DIC) is divided between $CO_2$ and the much larger pool of bicarbonate and carbonate, the balance is determined by the reversible reaction:

$$CO_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3$$

The rates of the reaction in each direction depend on pH, alkalinity, and temperature. Changing the reaction rates in this reversible reaction can change the endpoint concentrations. The half-time for the air-sea exchange and water chemistry equations to approach equilibrium is about 5 months (Broecker and Peng, 1982). Another important process is photosynthesis in the well-lit surface layer, say the top 100 m. At some times of year this reaction is so fast that $CO_2$ is driven far from its physical-chemical equilibrium. The amount of carbon taken up depends on inorganic nutrients like nitrogen (unlike terrestrial ecosystems, marine primary production is never carbon limited), and in low-latitude regions basically all the nutrients are used up in the summer and therefore as much carbon as possible is taken up. At high latitudes, for example in the Southern Ocean, large amounts of nutrient remain in the water all year round. If they were taken up then $pCO_2$ (ocean), and therefore $pCO_2$ (atmos), could be drawn down further. There is evidence that this happened during glacial periods. Ice-core records show that changes as large as (though much slower than) the anthropogenic input occurred between glacial and inter-glacial periods.

Much of the biological production is quickly recycled back to $CO_2$ through respiration, and therefore does not represent a net removal. Total primary production in the ocean is perhaps 40 Gt/yr, of which perhaps half sinks out of surface waters as particles (plant cells, faecal particles, etc). The fraction of recycled primary production is not at all well known. Recent measurements (Sugimura and Suzuki 1988) suggest that a large amount is locked up in high molecular weight, non-volatile organic molecules, which are broken down only very slowly. These measurements imply a downward net DOC flux of 4 (± 2) Gt/yr.

The recycling of production through respiration can be difficult to estimate. There is no way to distinguish "new" or "recycled" $CO_2$ in primary production, and direct the "new" production has any net effect on reducing $pCO_2$. However, nitrogen is taken up as well in an almost constant proportion of 1 nitrogen atom for every 7 carbonate; and we can distinguish "new" nitrogen (primarily ammonia or urea). So new and regenerated production, defined operationally by the kind of nitrogen taken up, are equated to exported and recycled carbon uptake (Eppley 1989). Measurements of the "n-ratio", the ratio of new to total production, have been made in many places and related to many features of the water (e.g., nitrate concentration), but the relations are at best tentative and empirical, and model studies suggest no theoretical basis for them.

The calcium carbonate components of some phytoplankton and zooplankton also contribute to the downward flux of carbon. When organic carbon sinks, it is typically regenerated as $CO_2$, in the top 100 m; when shells sink they are dissolved and $CO_2$ is regenerated at much greater depths. As carbonate is removed from the water, the reaction depicted in equation (1) must move to restore carbonate and therefore increase $CO_2$, leading to a potential reduction in the oceanic drawdown of atmospheric $CO_2$.

Many attempts have been made to describe the processes that produce the distributions of bio-active compounds in the ocean using mathematical models. Simple chemical models, in which the role of the biota was either ignored or parameterized by simple linear models, have proved very useful in trying to understand the role of the ocean in modifying atmospheric $CO_2$ concentrations in the geological past (Sarmiento et al. 1989) and in understanding the controls on $CO_2$ uptake in the present world ocean (Volk and Liu 1988). Biological models have from their earliest development used more detailed nonlinear functions to describe the interactions between organisms, but a global perspective has, until recently, been lacking.

**Summary of JGOFS Structure**

There are three different directions along which we can divide this massive task into more manageable parts: according to what processes JGOFS will study, how, or where they will be studied. In addition, as a basis for prediction, there is the need to survey the present values of key variables, and to establish strategies for detecting long-term changes in ocean cycles above the background of natural variability.

**Carbon Transformations and Transports**

This division centres on what the main carbon fluxes are, and how they respond to physical and chemical forcing on time scales from sub-seasonal events to decades. JGOFS will consider the following questions:

(i) What processes change the phase, or form, of organic and inorganic carbon in the ocean?
(ii) How does carbon move with and through the water, via ocean currents, mixing, diffusion and sinking?
(iii) What exchanges occur at ocean boundaries? These include air-sea exchanges (those most directly related to the rationale for JGOFS), exchanges at the bottom (both benthic communities and buried sediments), and exchanges at continental margins. Processes on continental shelves are considered in the proposed IGEP project LOICZ (Chapter 3.1). JGOFS and LOICZ each represent a crucial boundary condition for the other. At the moment, neither project is in a position to measure transboundary flow over the continental shelf, but this is recognized as an important area for future research.

**Approaches**

JGOFS will combine the strengths of many ways to study the ocean (Fig. 1). The global view will come from satellite measurements of key variables like wind speed, temperature and chlorophyll. A global survey from ships will establish the present distribution of DIC and its seasonal variation. Detailed, long-term variability in time will be studied at a few time-series stations. Both the global survey and the time-series studies will measure more variables than the satellites, and with vertical resolution in the water column, while remotely sensed observations will put the detailed observations in their space-time context.

**Figure 1.** The JGOFS approach
A series of process studies will investigate the factors determining the important rates, and provide the basis for making predictions. They will be much more intensive than the other studies, typically involving hundreds of ship days, many countries, and measurements of more standing stocks and rates. Tracers preserved in the sedimentary record will extend our knowledge to the scale of hundreds to tens of thousands of years, a time over which there have been very large changes in atmospheric CO₂. Models that embody and reflect the knowledge gained in the above studies will be used to fill in the picture of the ocean as it is now, and to predict its response to change.

Regional and Basin-Scale Processes

Time-series stations have been established near Bermuda and Hawaii, and others will be set up in representative ocean regions. The first process study began in early 1989 to study the spring bloom and associated reduction of CO₂ and downward flux of particulate carbon in the North Atlantic Ocean. Data from a five-nation, 400-ship-day study are now being analyzed and combined. Follow-on research will take place in 1990-1991.

Planning for a process study in the Equatorial Pacific is now underway. This is an important upwelling, outgassing region, and also a region where the sedimentary record is particularly well studied. The study will last for at least five years, because interannual variability (e.g., related to the El Niño/Southern Oscillation phenomenon) is important in the region.

Future process studies will take place in the high latitude Southern Ocean, to address questions of downwelling and nutrient use; and the Indian Ocean, where the monsoon circulation of the atmosphere induces large seasonal variation in ocean circulation.

More details of the areas of process studies and the coverage of the global survey are given in the JGOFS Science Plan (SCOR 1990).
JOINT GLOBAL OCEAN FLUX STUDY (JGOFS)

- Physical properties: Specifying the structure of the vertical and horizontal fields in which biogeochemical measurements are made.
- Optical properties: Photosynthetically active solar radiation, profiles of plant pigments and light absorption by particulate matter.
- Biological standing stocks: The organisms regulating the cycling of carbon, nitrogen and other elements. Resolution of taxonomic identity, size and chemical composition will depend on the needs of each study. Current efforts suggest resolving phytoplankton into 2-3 size classes.
- Chemical stocks: The elements and compounds of greatest importance in the carbon cycle and the biogeochemical cycles that drive it, including CO₂, N₂, and total dissolved inorganic carbon, dissolved and particulate organic matter, the plant nutrients nitrate, ammonium, urea, reactive inorganic phosphorus, silicate, and trace metals (particularly iron, which may limit phytoplankton growth). Dissolved oxygen and certain other dissolved gases will be measured primarily to specify important fluxes (photosynthesis, respiration, denitrification). Additional chemical species will be important as tracers of fluxes and other biogeochemical processes; for example, thorium, uranium, lead, polonium, palladium, and organic biomarkers such as individual pigments, lipids, and structural polymers.
- Biological and chemical fluxes: The following processes ideally require several independent measurements: primary production (total and new production), zooplankton grazing, bacterial production, nitrate regeneration. Vertical transport will be measured by moored and floating sediment traps.
- Benthic fluxes: Processes at the seabed are important because the sediments are the largest and slowest changing store of carbon. Some of the organic matter that reaches the benthic boundary layer is converted to CO₂ and released into the water, the rest is permanently buried. One can measure benthic fluxes with benthic chambers, porewater gradients, in situ electrode measurements, sediment composition studies. Biuturbation can be studied with radiochemical measurements, field observations and modelling.

JGOFS will provide a firmer understanding of the biogeochemistry of the deep ocean so that better models of remineralization can be developed. Most recent models have parameterized this process by using a depth-related function empirically derived from sediment-trap data. More definitions of deep-ocean trace-metal distributions will help to resolve this problem.

JGOFS will parameterize the response of chlorophyll to available light. In most empirical regression methods, this parameter is buried in the regression coefficients connecting biomass and production. One advantage of using a more mechanistic formulation is that such coefficients can be interpreted directly in terms of known physiological variables, such as the quantum yield of photosynthesis. Moreover, these physiological processes can be measured at sea during process and time-series studies.

A key aim of process studies is to determine new production and what controls it. At present this requires detailed measurement of primary production. The ultimate hope is that new production, or the f-ratio, can be related to some variable that is accessible to remote sensing. Perhaps in future we will learn how to account for local and transient variations in the f-ratio within biogeoographic provinces. Perhaps some oceanographic property field other than ocean colour (e.g., temperature) could serve as a proxy index of local perturbation in water-column structure leading to local change in productivity and, therefore, in f-ratio. Regional and annual estimates of new production would then be calculated as weighted integrals of the local results. Another possibility is offered by some recent global or basin-scale biogeochemical cycling models. Such models could combine satellite data on the biomass field with model-derived data on nitrogen supply and f-ratio to calculate new production.

Processes that lead to the permanent burial of sediments will be studied. These include the fate of calcite and aragonite and the coupling of organic-inorganic carbon; for example, sedimentary carbonate dissolution by biologically-produced CO₂. Processes studies concerned with formation of permanent sediments will help in the interpretation of the historical sedimentary record. In this regard close collaboration must be maintained with PAGES (Chapter 7).

Large Space/Time Scale Surveys

The Global Survey

JGOFS will need a global survey of the important biogeochemical variables. It should be possible, in cooperation with other international programmes, to achieve a reasonable global survey using the following strategy:

- A suite of biogeochemical core measurements will be made throughout the water column at a regular spacing on all JGOFS transects. Such a suite would include pigments, nutrients, biomass components, gases, dissolved organic species, particulate organic carbon and nitrogen, and radionuclides.
- The same suite will be measured during passage to JGOFS process studies.
- A global array of sediment traps will be deployed near the JGOFS transects, to estimate the vertical particle flux.
- A set of benthic measurements will be made to provide boundary constraints.
- Along-track observations of surface pigments, nutrients, CO₂, and O₂ will be made on all JGOFS cruises.

JGOFS will benefit from the extensive spatial and temporal coverage of the WOCE Hydrographic Programme (WHP), and will make the CO₂ measurements on WHP cruises. The specification for these measurements is to measure full-depth profiles of total CO₂, alkalinity, and pCO₂ to within 1 µmol/kg, 1 µequiv/kg, and 1 µatm, respectively. A fully documented and internally consistent description of the oceanic carbon dioxide system will be produced for the first time. If such a survey is repeated in the late 1990s the anthropogenic increase in oceanic CO₂ could in principle be detected. The existence of the WOCE nutrient data set will also be of great significance for JGOFS. Such data provide a powerful check on modelling the oceans' biogeochemical cycles. When space is available, JGOFS will also undertake a survey of pigments like chlorophyll on WOCE cruises.

Seasonal Survey of pCO₂

There is an urgent requirement to document more accurately the seasonal cycle of pCO₂ in the North Atlantic, North Pacific, and Southern Ocean, in order to constrain more closely the estimate of net annual flux of CO₂. Logistically, seasonal surveys of the North Atlantic would be the easiest to achieve. The minimum requirements would be underway measurements of pCO₂ and total CO₂ along the cruise track, backed up by measurements of chlorophyll. Use of satellite ocean-colour data would then allow the effective integration of pCO₂, in areas and seasons where pCO₂ and chlorophyll are correlated (and most likely show patchy distributions).

In spring and summer it is known that pCO₂ in surface waters is reduced sharply, leading to a flux from the atmosphere to the ocean. Recent results from the JGOFS North Atlantic Bloom Study have shown this very clearly. Ongoing CO₂ analysis methods have revealed a very patchy distribution, and cast doubt on the accuracy of basin-wide integration of pCO₂ based largely on data from bottle samples, particularly when comparable data from other seasons are not available.

Long Time-Series Observations

Much of the data obtained during the JGOFS programme will be collected during cruises lasting a few weeks. Examination of the few long-term data sets we already have shows the importance of understanding the variability of marine ecosystems at time scales ranging from seasonal to interannual periods. Therefore, JGOFS requires a network of Time Series Stations at which regular measurements will be made, and which will provide key properties and processes are made once or twice a month, or continuously for those properties measurable by untended, automated sensors. Perhaps the best known time series is the three years of regular primary production measurements made at Station S near Bermuda (Menzel and Ryther 1969). Station S is also the site of a longer series of observations of hydrography and of a continuous deployment of deep ocean sediment traps. These data
demonstrate strong seasonal variations in primary production and vertical transit fluxes forced by annual episodes of convective mixing and vernal restri-

JOGFS. The US JGOFS Programme has recently established new time-series tification. The US JGOFS Programme has recently established new time-series stations at Bermuda and in the central North Pacific off Hawaii. These initiatives will be located near islands or coastal nations with well-equipped marine laboratories and research vessels capable of performing, high precision measurements of chemical, biological and physical variables. At present, both JGOFS time-series sites are located in tropical, oligotrophic waters. Additional stations are needed in higher latitude, coastal, upwelling and boundary current regimes. Once established, these sites will provide the means to define the time varying behaviour and spectral properties of the physical, ecological and biogeochemical system in each area. These data sets will also provide invaluable material for calibration and validation of biogeochemical models. Furthermore, these sites will attract many other short- and longer-term investigations, which can draw on the resources and historical data base collected at each place. Time-series observatories also provide useful centres for the development and testing of new instruments. Each site requires a dedicated team of ~10 individuals to make measurements, collect and analyze samples and process, tend instruments and interpret and report data.

Remote Sensing

Synoptic observations on global scales over at least several decades, frequent enough to resolve the dominant scales of variation, and with spatial and temporal resolution adequate to make use of such remote observations can the objectives of JGOFS on the global scale be achieved. For the first time, it will be possible to estimate wind speed and direction, the fluxes of heat, momentum and material, including carbon dioxide, at the sea surface, the biological production of organic matter and the variability of the surface currents at the requisite scales. The ready availability of these data on an international basis will permit answers to questions that have hitherto been impossible to address.

Air-Sea Fluxes of Heat, Momentum and Mass

Estimation of these fluxes from remote observation is now within reach in a form and on scales appropriate for JGOFS. Statistics of cloud distributions, from remote observations of visible radiances, can be used to estimate the solar radiation flux at the sea surface with considerable skill. Microwave radiometers can be used to estimate wind speed. Accurate measurement of sea-surface temperature from passive radiometers permits acceptable estimation of latent heat fluxes. The importance of global wind speeds for air-sea gas exchange has already been mentioned.

An area of concern involves the flux of materials from land to ocean via aeolian transport (see JOECC, Chapter 4.1). Dust from the Asian desert can be detected in the marine atmosphere; trace metals in this dust may stimulate primary production. Observation of the marine atmosphere in the visible bands may permit quantification of this flux.

Biological Production of the Ocean

The remote measurement which has caused the greatest interest within JGOFS is the estimation of annual and global-scale variability in the concentration of chlorophyll in the upper ocean. The images of the global distribution of these pigments, derived from the Coastal Zone Color Scanner (CZCS), have revolutionized the oceans. For the first time, the blooming of the ocean basins in the spring has been observed, as has the extent of the enriched areas associated with the coastal ocean.

A number of models, using either empirical transfer functions or more mechanistic physiological models, have been proposed for estimation of total primary production from remotely-sensed data. The signal received by the colour scanner contains information from only the upper one fifth or so of the photic zone. Any bias due to chlorophyll concentrations at the depth of penetration of the colour scanner signal can be removed if independent information is available on the shape of the pigment profile (Fitt and Sathyendranath 1988).

Well-established algorithms exist for estimating the biomass field from the CZCS data, and processed data are now available on a routine basis from NASA. New algorithms are now emerging for estimation of primary production using remotely-sensed data, and there is a need for further testing and improvements to these algorithms. However, the next generation of sensors will have improved capabilities, and there will be a need for development of new biomass algorithms to capitalise on the better-quality data. An important element of the JGOFS field programme will be to provide sea-truth data for verification of algorithms relating to pigment concentration, total primary production and new production.

Aircraft Surveys

Airborne lidars now available offer some advantages over satellite sensors, especially: (i) higher spectral resolution and therefore scope for more rigorous algorithms and for retrieval of more variables; (ii) capability of obtaining depth resolved data; and (iii) operation under dense cloud conditions. In addition, when available concurrently, the fluorescence technique of the lidars can be used to check or validate the ocean-colour algorithms applied to satellite data. The depth-resolved signals from aircraft lidars will be a valuable tool for extending local ship observations, and for parameterizing the biomass profiles of a given biogeographic zone. Major JGOFS field studies would therefore benefit from concurrent lidar overflights. In the JGOFS North Atlantic Bloom Study, for example, aircraft data proved extremely useful in identifying bloom areas and, therefore, in effecting mid-course cruise corrections for the research vessels in the field.

The Future

There is now no satellite ocean colour sensor in orbit. JGOFS crucially needs the new ocean colour sensor planned for 1992/1993, the Sea-viewing Wide Field of View Sensor (SeaWiFS). It will produce images of global distributions of plant pigments and productivity with a resolution of two days and 4 km. In addition, higher spatial resolution will be available for selected regions, for example, the sites of process studies. These data will be a cornerstone of the JGOFS effort and will drive new modelling efforts as well as serve as a base upon which the success of models can be evaluated.

The Sedimentary Record

JGOFS proposes to use the Quaternary palaeoceanographic record to determine
the relation of ocean circulation, productivity and CO₂ content of the atmosphere, to aid in the prediction of CO₂-related climatic change. Variations on time scales within the Quaternary represent a period when large shifts in atmospheric CO₂ concentrations have occurred and are associated with periods of major climatic change. Ice-core studies have established that atmospheric CO₂ is about 80 parts per million by volume lower during cold glacial climates than it is during warm interglacial times. The past variations in atmospheric CO₂ are recorded in sediment cores and examined in the terms of their rate of accumulation in the sedimentary record. The other is to use proxy indicators (O and C isotopes, Cd/Ca and other palaeochemical tracers, organic biomarkers, etc.) to reconstruct the temporal variations in chemical composition and circulation of past oceans and atmospheric composition. Central to both approaches is the requirement for precise chronology and for this there is a need to supplement classical oxygen isotope stratigraphy and conventional radiocarbon dating with radiocarbon dating of foraminiferal species by accelerator mass spectrometry.

Benthic studies address the processes by which the sedimentary record is formed. As new palaeochemical tracers are explored and old ones are used more extensively their calibration will be firmly established, comparing water column properties with their record in foraminiferal calcite, opal, and sediment geochemistry.

It will be important to document changes in the fluxes of the relevant JGOFS variables for comparison of contemporary benthic fluxes with the historical record. It will be necessary to evaluate glacial-interglacial differences in carbon fluxes and their regional variability and to decide whether they reflect productivity changes or changes in carbon preservation, possibility through the development of low-oxygen bottom waters. Property distributions for critical variables (CO₂, nutrients, hydrography) must be obtained for crucial oceanic sectors. The time variability of carbon fluxes should be determined at sites within different oceanographic provinces. Other approaches include high-resolution studies of the transition from the last glacial maximum to the present; a history of low- and mid-latitude upwelling as related to the accumulation of organic matter in sediments in order to deduce relationships between atmospheric CO₂, variations and productivity changes. The North Atlantic Ocean has experienced the largest climatic change of any ocean during the last 20,000 years. It is therefore an excellent place to study the effects of migration of the polar front on productivity, particulate-matter fluxes and atmospheric carbon dioxide concentrations. The activities of JGOFS on this topic will be coordinated with PAGES (Chapter 7.1).

Modelling

The ultimate aim of modelling in JGOFS is to embody, reflect, test and advance our understanding of, and ability to predict, the evolution of carbon and other biologically important elements throughout the world oceans decades to centuries ahead. JGOFS observations will help to provide a firm conceptual understanding of many key processes in the ocean biogeochemical system, and also data with which to test the models. Sufficient computing power will become available during the decade. The time is therefore ripe to embark on an ambitious modelling programme, both for interpreting the process studies and for making global extrapolations and predictions.

JGOFS process studies must be designed specifically to obtain the information required by the global models discussed below. Furthermore, the local hydrography of each area will present specific sampling problems. Each process study should be preceded by a modelling exercise in which the present level of understanding of the biogeochemical and physical processes are incorporated in models which can provide a theoretical underpinning for designing and interpreting the observational programme. Sensitivity analysis techniques should be used to identify the critical variables and parameters. For example, in temperate latitudes, the winter values of primary production and zooplankton biomass have a critical effect on the development of the spring phytoplankton bloom, and winter sampling is needed. Also modelling has highlighted the potentially important role of being played by dissolved organic matter in the ocean and, therefore, the importance of obtaining accurate estimates of this quantity.

The process studies will also feed back into the JGOFS modelling programme. They can provide estimates of parameters required for process sub-models, such as photosynthesis, zooplankton grazing, or particle settling; they will provide data with which to test the validity of these sub-model parameterizations; and will provide time series of biological stocks, chemical concentrations, and biogeochemical fluxes with which to test both local and global models.

A longer-term aim is to develop process-oriented equation models that can predict the time evolution of biogeochemical fluxes from given starting conditions. Such models will utilize the state-of-the-art General Circulation Models (GCMs) driven by observed surface boundary conditions to predict the fields of advection, convection, and mixing in the ocean. When supplemented with equations representing nutrients, dissolved inorganic carbon, and some depiction of the biogeochemical transformations near the ocean's surface and in the interior, these models will predict full three-dimensional concentrations fields for comparison with JGOFS observations. As such, these models focus on oceanic processes with longer time scales. Preliminary models of this type are currently operational at Princeton University and at the Max-Planck Institute in Hamburg, where they have been used with some success to predict the observed distribution of bomb-produced tritium and ³⁵Cl distributions. Initially, such models will be used in a hindcasting role to predict the evolution of, say, the satellite-derived surface chlorophyll distribution over a given time period. Success with this sort of prediction is an essential precursor to the next stage of the modelling enterprise, which is the prediction of the future evolution of ocean variables, such as the CO₂ concentration, that are implicated in scenarios of climate change.

Until recently, global biogeochemical models have not explicitly modelled the surface-water biological production, or this production has been rather parameterized by restricting the surface nutrient concentrations to observed values. Sarmiento et al. (1989) have made a first attempt at explicitly modelling the biological nitrogen cycle in the euphotic zone of the North Atlantic. Preliminary results show rough agreement with satellite-derived maps of the spatial and seasonal pattern of surface phytoplankton; areas of disagreement indicate where more theoretical or observational work is needed. For example, the present generation of GCMs do not adequately model some of the key physical processes such as equatorial upwelling. We are therefore dependent on progress being made on the next generation of GCMs. Furthermore, if upwelling associated with mesoscale eddies is a key process in providing nutrients to the euphotic zone, then it will be necessary to use eddy-resolving models with their attendant computational demands.

Recent research has demonstrated the potential importance of small organisms, such as bacteria and protozoa, in the recycling of dissolved and particulate organic material, and a number of recent models have incorporated these ideas. We must compromise between the need for a parsimonious model for incorporation in a GCM, and the requirement to capture the complexity of the actual biological interactions that is valid in all geographical regions. We are not yet know how well the biological size distribution needs to be resolved in order to attain the predictive goals of JGOFS. Research into the effect of different levels of physical and taxonomic detail will be an important component of JGOFS modelling efforts.

In the past most oceanographic biological models have been constructed using equations describing the flow of a particular element between the various compartments, and carbon and nitrogen have been the most commonly used "currencies". However, elements other than nitrogen may limit primary production. Moreover, the formation of calcium carbonate hard parts by, for example, coccolithophorids, has a direct effect on alkalinity and thereby the partial pressure of carbon dioxide. Such considerations lead to a requirement for multi-element models that can predict the concentrations of these specific components of the phytoplankton. 
The interaction of the biological and chemical processes at the ocean margins with processes in the open ocean looms as one of the most difficult issues in JGOFS. Direct measurements of offshore and onshore fluxes are extremely difficult, if not impossible, to make. GCMs run with current levels of resolution do not resolve the shallow water regimes near the margins. The best hope for progress in this field lies with nested high-resolution models of particular ocean margins within basin-scale GCMs. The two models would use the same physics and algorithms for transformation at much different levels of resolution. Key predictions of coupled margin-basin models involve the onshore and offshore transport of nutrients, dissolved organic matter, and particulate organic matter. The ground truth provided by JGOFS data includes the margin-basin contrast and seasonal changes in phytoplankton biomass and nutrient fields.

Because these models are likely to be used to make predictions for the coming decades and centuries, it is important that they be constructed using rules that we believe will continue to be true in a different climate. Modelling tricks, such as restoring the surface temperature, salinity, or nutrient fields to observed values, or introducing empirically determined geographical variations in biological rate parameters, may be valuable during the learning process, but are not suitable for long-term prediction.

Data Management

To date, biogeochemical observations have not been readily catalogued or exchanged, because of the labour-intensive nature of the analysis process, differences in analysis protocols, lack of confidence in the data product, etc. The JGOFS observational and analysis framework is based on a distributed international approach to the observing system, and requires rapid, easy sharing of data, models, analyses, and observation systems.

We foresee international data exchange occurring through interactions between national oceanographic data centres. In each national centre, a JGOFS data coordinator will be responsible for acquiring national data sets, analyses, etc., for extra-national use; acquiring extra-national data sets, etc., for national use; ensuring conformity with agreed international exchange models and formats; maintaining inventories of national holdings; and interacting with the JGOFS Data Management Working Group as needed. Individual scientists will interact with their national JGOFS data coordinator.

The JGOFS Data Management Working Group has proposed a common self-describing data format for data archiving and exchange and use of modern object-oriented data-management approaches for retrieval, merging and analysis. Development of portable access software and network-based distributed data-accession models should provide scientists with direct paths to data-accession models should provide scientists with direct paths to

As a trial of the proposed data-exchange formats, the Data Management Working Group focused on the needs of the 1989 JGOFS North Atlantic Bloom Study. A set of twenty core measurements, to be conducted on all cruises in the Bloom Study, was defined early in the planning stages for the study. For each of these measurements, a protocol was reached on a standard measurement protocol and accuracy to be attained. The success of the proposed formats was tested at the JGOFS Bloom Study Data Analysis Workshop in Kiel in March 1990. Cruise participants from all nations involved brought their data to Kiel for a week-long "hands on" session at which the various data sets were merged and preliminary scientific findings discussed. Some problems were identified in the way the data were collected — it was difficult for all parties to adhere to agreed protocols — but there were no serious incompatibilities in the way data were handled subsequent to collection.

The JGOFS Committee considers that free exchange of information is essential for the success of JGOFS and at its 1989 meeting in Hawaii the following policy regarding data access and submission was adopted.

- Recognizing that science is best served by free and open communication of findings, including data in raw form; and,
The role of the oceans in climate change is understood only very generally, and it is anticipated that contemporary global-scale research projects, such as the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS) will significantly improve this understanding. WOCE, under the auspices of the WCRP, focuses on the physical processes responsible for the transport of energy and momentum within the oceans and between the oceans and atmosphere. JGOFS, a Core Project of the IGBP initiated and organized by SCOR, focuses on the biogeochemical processes responsible for the fluxes of carbon and associated biogenic elements within the oceans and between the oceans and their boundaries.

Thus, it is timely to anticipate the new level of understanding that will evolve as WOCE and JGOFS are completed, and to formulate the next generation project that will build upon the data and understanding obtained and that will also address fundamental questions regarding global change in atmosphere-ocean interactions.

Whereas the fundamental scope of both WOCE and JGOFS includes (with WOCE in particular paying little attention to the time varying properties of the mixed layer), investigations that consider the full depth range of the oceans, this new project will focus primarily on approximately the upper hundred meters of the ocean (the euphotic zone), in the context of the decade-to-century time-scale priority of the IGBP. This is the region where physical mixing processes are most intense and where the penetration of sunlight is sufficient to support primary production. It is here that the small time constants for atmosphere-ocean exchange allow for highly significant effects of atmospheric change on ocean biological processes with a correspondingly large potential for biogeochemical feedback to the climate.

Because of its focus on the upper ocean zones, where biological processes are most intense, this new project is termed the Global Ocean Euphotic Zone Study (GOEZS). It will require balanced and highly interactive efforts in observation (both in situ and from space), in process studies, and in modelling. It will also require new efforts to synthesize the physical, conceptual, and disciplinary interfaces. Its time frame for implementation will be the late 1990s, i.e., when the field phases of WOCE and JGOFS are completed. This project will require the deployment of next-generation technology for remote and automated sensing of ocean properties.

One rationale underlying the conceptual development of GOEZS is the...
growing evidence that biological equations that describe the dynamics of phytoplankton and zooplankton processes can be used to characterize the regional biological response to physically driven ocean processes. It can be anticipated that further refinements of this approach, using the existing and the evolving (WOCE and JGOFS) data sets, will permit extrapolation to different climate conditions, thereby allowing the addition of these equations to coupled ocean-atmosphere circulation models that are designed to predict climate change.

Specific goals of GOEZS include:
- developing models that accurately simulate biological conditions in the euphotic zone as a prerequisite for predicting how these conditions will adjust with changing climate, and how in changing they will modify climate through their action on production or consumption of radiatively active gases and atmospheric aerosols;
- assembling a global data set suitable for use in establishing the necessary biological equations and their associated parameter sets for use in computer models of climate change; and
- developing large-scale experiments to improve basic understanding of the interactions between the physical, chemical, and biological properties of the euphotic zone.

The GOEZS data set, which will build upon the WOCE, JGOFS, and other existing and evolving data sets, has yet to be specified in detail. In order to be used in predicting biogeochemical responses to climate change the implementation of GOEZS will, however, require new physical, chemical, and biological data for the euphotic zone of all oceans and for all seasons. The requisite synopticity for certain physical, chemical, and biological observations will be made available by new analytical methods capable of higher sampling and data processing speeds than those currently available. Some of these methods are now being developed, and will probably be deployed in WOCE and JGOFS for the first time. Although a detailed science plan for GOEZS has yet to be developed, the need for additional developments in upper ocean sampling can be envisioned in the following areas:

(i) remote sensing from aircraft and polar-orbiting satellites;
(ii) optical and acoustic remote sensing within the ocean;
(iii) autonomous unmanned vehicles for more efficient ocean sampling; and
(iv) novel methods of sampling and analyzing chemicals and plankton, including molecular genetic probes.

The development of GOEZS will be guided by an IGBP Scientific Steering Committee appointed in consultation with SCOR. A science plan should be developed in the 1990-1992 time frame, with the modelling component to be initiated soon after. Field campaigns will be timed post WOCE and JGOFS, when the Earth Observing System Polar Platforms are operational, and will continue for 5-10 years. The development of the GOEZS project will be facilitated by an International Planning Office to be located at the U.K. Institute of Oceanographic Sciences, Deacon Laboratory, Wormley and supported by NERC.

How Changes in Land Use Affect the Resources of the Coastal Zone, and How Changes in Sea Level and Climate Alter Coastal Ecosystems?

In many parts of the world human activities, including fishing, mariculture, agriculture, forest clearance, urban development and freshwater management, are altering the properties of coastal seas. Any rise in sea level and modification of climate will further influence directly the sustainability of marine living resources, the stability of coastal habitats, and the biogeochemical cycling of carbon, sulphur and other important elements. The overall, long-term impacts of these changes in the coastal zone are largely unknown on both regional and global scales. Severe environmental problems are already being experienced in major delta systems, and along the coasts of certain tropical countries.
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4.1 Land-Ocean Interactions in the Coastal Zone (LOICZ)

A Proposed Core Project

Properties of Coastal Zones and Interactions Between Land and Sea

The coastal zone, where land, air and sea meet, is a region of high physical energy and biological diversity that is heavily exploited by man. It is also a zone particularly vulnerable to global change. For these reasons, the IGBP proposes a core project on the coastal zone with special emphasis on the interactions between land and sea under changing global conditions.

Definition of Coastal Zone

The coastal zone includes the area extending from the landward margin affected by salt water to the outer edge of the continental shelf (Fig. 1). It is "that space in which terrestrial environments influence marine (or lacustrine) environments and vice versa" (Carter 1989).

Figure 1. Distribution of continental shelves (<150 m; from Postma and Zijlstra 1988).

This definition covers a wide range of terrestrial, intertidal and subtidal ecosystems. It includes at least parts of coastal plains where they exist; sea cliffs, beaches, lagoons, estuaries, salt marshes, and mangrove swamps, that are under the influence of tides and storm surges. It also includes aquifers overlying salt wedges. The definition of the landward boundary varies for different phenomena. For example, the extent of coastal terrain affected by salt-spray aerosols will be much greater than that influenced by storm-driven erosional processes. The seaward boundary is set by the shelf break and continental slope.
thereby including submarine features varying in depth, currents, turbulence, and sediment type.

An important political/legal definition of the coastal zone has been set by international agreement as the Exclusive Economic Zone (EEZ), the 200 nautical mile limit from land (or agreed coastal reference line in the case of archipelagic states) over which coastal nations exert certain rights with respect to resources. As a legal boundary it is important in terms of rights of access for scientific research as well as economic exploitation.

**General Properties of Coastal Zones**

Important factors determining the nature of the coastal zone in a particular region are geomorphology and climate. Shoreward margins, associated with river mouths or subsiding coastlines of divergent land margins, may have little elevation gradient thus featuring extensive intertidal areas. On tectonically convergent land margins where crustal uplift dominates, there may be high relief above and below the shoreline so that intertidal areas and the continental shelf are more limited in extent and different in kind. Classifications of coastlines and their geological and geomorphological causes are discussed in Inman and Nordstrom (1971) and Kennett (1987).

At smaller scales, well-defined boundaries are usually observed within the coastal ocean related to horizontal gradients in density (temperature, salinity). Water tends to move along rather than across these frontal boundaries, inhibiting exchanges of energy and matter between inner and outer coastal regions. Fronts often mark transitions between distinct hydrological and sedimentological regimes, characterized by different communities of pelagic and benthic organisms. Intertidal and terrestrial environments are also clearly demarcated by the effects of tidal amplitude, wave action, sea-spray deposition or soil conditions.

The high physical energetic states of coastal zones are caused by the combined effects of ocean currents, tides, wind and freshwater buoyancy. Ocean tides and shelf flushing frequencies, related to river inputs and shelf edge exchange, determine relatively high and low energy shelf systems which, in turn, define the spatial extent and boundary dynamics of associated ecosystems. These physical characteristics underlie many of the biological properties of these zones.

Favourable conditions of light and nutrient availability, controlled by the turbidity and surface mixing depth and by inputs of nutrients from ocean and land, maintain relatively high rates of primary production in coastal seas. Inputs of dissolved and particulate organic material from land provide additional organic energy for consumer organisms (Berger et al. 1989). Consequently, coastal zones are typically areas with living resources (fish, crustaceans, molluscs) of great commercial value.

Cycles of biogenic materials in the coastal zone oscillate rapidly between organic immobilization and heterotrophic mobilization (or mineralization). In addition, the accumulation of organic carbon in muds of marshes, lagoons or bays creates low redox conditions promoting the biological formation of nitrogen oxides, sulphides, and molecular nitrogen (Keil and Sørensen 1988), as well as soluble reduced forms of transition metals, such as iron and manganese. These reactions can also alter the availability of other biologically important substances such as phosphorus and accumulated pollutants. Interfaces of high and low redox sites are often loci of intense nitrogen fixation as well (Capone 1988).

In other parts of the coastal zone, high redox conditions dominate so that reduced substances are reoxidized (Henriksen and Kemp 1988), providing a chemosynthetic energy base for other organisms. Such reactions are not unique to coastal zones, but the variety of physical environments and abundant supply of organic energy maintain high rates of many types of biogeochemical transformations. Collectively, these reactions lead to the rapid cycling of the elements involved so that coastal zones are important zones of biogeochemical activity, especially for the carbon cycle and production of some trace gases.

The land boundary largely determines the particular physical properties of a given stretch of coast and, for inshore waters, provides many of the chemical resources through ground- water and river water that drive the biological and biogeochemical processes described above. Furthermore, all land surfaces are
Questions and Issues about Global Change and Impacts on the Coastal Zone

A wide range of general questions is being raised within the scientific community regarding the response of coastal zones to global change. These are discussed below as a means of evaluating issues upon which the design of this proposed core project is based. From the coastal zone perspective, the major issues of global change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affected by human actions are: (i) climate change; (ii) sea-level change (itself a derivative of climate change); and (iii) change affects climate change. This variability in relation to changes in climate, land use, hydrology, etc., will be critical to the prediction of nutrient budgets for coastal zones.

How will changes in climate and land use affect delivery of materials from land to rivers and the coastal zone?

Issue 1: Erosion and basin geomorphology

Fluvial erosion rate is a function of rainfall, slope length, vegetation cover and a soil erodibility factor (Mulkey 1980). Aeolian erosion operates similarly but with different values placed on these parameters together with the dominant influence of wind (Oye 1987). Each is a function, to some degree, of other aspects of climate, geological substrate, weathering rate, regional geomorphology, fire frequency and land use. Clearly, all these conditions are susceptible to alteration in the coming decades so that changes in the amount and distribution of fluvial erosion on land, in surface water flows and soil erosion, in other geomorphological processes and in land forms can be anticipated. The delivery of sediments to coastal zones as well as maintenance of agricultural lands, river transport and urban protection structures in these basins will be affected.

Issue 2: Basin hydrology

The distribution of incoming precipitation into evapotranspiration, ground-water and surface water flows is a function of climate, topography, soils, geology and vegetation (Baumgartner and Reiche, 1975). Both ground-water and surface runoff vary with changes in climate, soil conditions and vegetation cover. While ground water is considered to be much less important than surface water in terms of total water flux, it may be relatively important in geochemical terms due to its dissolved constituents (UNESCO 1978, Zektser et al. 1983). Any change in flows will affect erosion and the delivery of sediments, nutrients and organic carbon to drainage basins and coastal zones.

Issue 3: Fluvial transport

Rivers are a major means of transporting material including suspended sediment, organic matter and nutrients, to the coastal zone. The rate of delivery of sediment, showing great variations worldwide (Fig. 2), together with erosional agents at the coastal zone, largely controls levels of deltas, distributions and sizes of depositional features such as mudflats, beaches and bars, and the derivative ecosystem properties such as wildlife habitat and fishery nurseries (Carter 1989). Delivery of dissolved materials, including inorganic nutrients and contaminants, depends on riverine geochemical and hydrological processes. River geochemistry varies considerably with the types of lithology, topography, hydrology, agricultural development, and vegetation cover of the river system. Understanding this variability in relation to changes in climate, land use, hydrology, etc., will be critical to the prediction of nutrient budgets for coastal zones.

A key question involving the global carbon cycle is how much terrestrial-derived organic carbon is buried in coastal oceans (Degens et al. 1984), particularly in deltas and estuaries (Litvak and Hake 1986). Rivers are possibly the most important source of carbon buried in recent marine sediments. More...
Detailed budgets for changes in the riverine delivery of particulate and dissolved organic carbon (POC, DOC) and for its fate in coastal waters are needed to evaluate this part of the global carbon cycle (Degens et al. 1990), especially if significant increases in the rate of delivery of organic matter to the sea are thought to have occurred already as a result of changes in land use (Berner 1989).

Issue 4: Aeolian transport from land to sea
Removal of soil from land surfaces by wind and atmospheric transport to sea is another important aspect of land-sea interactions. As with fluvial erosion, wind erosion processes are likely to be altered in spatial distribution and intensity by other factors of global change. The dust is mostly lithogenic (Pye 1987) and the degree of atmospheric loading significantly affects the input of solar radiation globally, thus altering photosynthetically available light and even surface temperatures. When deposited, dust enhances the sinking and consequent burial of organic matter (Ittekkot and Haake 1990, Buat-Menard et al. 1989), and may stimulate photosynthesis by providing iron and other limiting trace nutrients to phytoplankton (Dupe 1986, Martin and Fitzwater 1988).

How will changes in riverine discharge, sea-level rise and episodic storms influence geomorphological processes in the coastal zone?

Issue 5: Coastal geomorphology
The complex geomorphology of highly dynamic nearshore features, such as sea cliffs, beaches, barrier bars, submerged bars, marshes and mangroves and their associated channels, lagoons, etc., will be affected by changes in sediment delivery, sea level and climate, particularly the incidence of storms (Bird 1992, Bardach 1989). While these geomorphological features are evanescent in geological terms, they are regarded as permanent on the time scale of human occupation of the coastal region, leading to huge efforts to maintain them.

Sea level rise will have a very large influence on erosion since, for every linear unit of sea level rise, geomorphological zones will tend to move shoreward on average 100 units (Bruun 1983). The impact will be critical in the short term to the maintenance of human structures and activities and of existing ecological systems. In the long term, human activities will either have to be defended at great cost or relocated as the distributions of natural coastal features are altered.

Sediment supplied by rivers is a crucial to many geomorphological processes in the coastal zone. The causes and possible effects of alterations in sediment supply are discussed above. As coastal geomorphological features are modified, the spatial distribution of biologically productive and regenerative zones will undergo extensive changes that may alter the overall energy flow and biogeochemical interactions within coastal ecosystems (Constanza et al. 1990). Some zones could be lost permanently if their maintenance is restricted by geomorphological barriers such as sea cliffs or by engineering structures. It is conceivable that some changes could be of such magnitude as to have very high regional importance. For example, rises in sea level could result in the loss of barrier islands that produce and protect extensive lagoons important to wildlife, fish and the air-sea exchange of trace gases.

Issue 6: Structure and function of deltas
Deltas include diverse range of topography including distributary channels, river-mouth bars, open and closed interdistributary bays, tidal flats, tidal ridges, beaches, beach ridges, dunes and dune fields, and swamps and marshes. They are extremely important in terms of human habitation so that the influences of environmental change on delta systems deserves special attention (Bardach 1989, Day and Templet 1989, Milliman et al. 1989).

Deltas are constantly changing as the balance between tectonic forces, eustatic changes in sea level, and the rates of deposition of sediments and of subsidence through consolidation and dewatering varies. Fluctuations in sediment supply through climate and land use change, through channel diversion, variations in sea level, change in deltaic vegetation management, or groundwater or hydrocarbon extraction determine the altitude and thus, composite structure and functioning of deltas. The serious threats to vitally productive agricultural and aquatic ecosystems that may be suffered through on deltas through global change are vividly described by Milliman et al. 1989).

Issue 7: Coral reefs and low-lying islands
Low relief islands and barrier reefs in tropical areas are particularly vulnerable to global change. Because coral reefs are constructed and maintained by living organisms, they are sensitive to changes in temperature freshwater surges, sediment deposition (Rogers 1990), eutrophication and pollution (Bardach 1989). In some cases, ecological structure and human welfare may be altered by diminution in freshwater lenses underlying these islands. In other cases, major parts of countries may be lost or rendered inhabitable through these changes.

Issue 8: Arctic coastlines
Climatic warming as well as sea level rise will seriously affect arctic coastal systems. Loss of permafrost in coastal zones could bring about large-scale disruption of the structure and stability of soils and of bottom sediments offshore. On land, loss of permafrost typically leads to surface collapse and accelerated erosion, and even widespread subsidence where the terrain is flat. These effects, in turn, can cause reorganization of hydrological, geomorphological and ecological features for entire stretches of coastline.

Issue 9: Coastal zone habitats
The high productivity and unique qualities of the coastal zones provide a range of critical habitats for many organisms, that are vulnerable to severe change or loss. Changing conditions in coastal zones could threaten the survival of certain species and communities of plants and animals.

How will changes in climate, land use and sea level influence saltwater intrusion to freshwater aquifers?

Issue 10: Aquifer volume
Freshwater meets saltwater below ground as well as in estuaries on top of saltwater wedges. Relative volumes of salt and freshwater vary with variations in the flow of groundwater to these marginal aquifers as a result of changes in precipitation and/or land use (Williams 1989), of loss of recharge area, of rise in sea level (Vellinga and Leathern 1989), and of loss of the aquifers themselves through erosion as discussed above or through groundwater pumping (Carter 1989). It is important to note that increased retention of fresh water on land through the creation of reservoirs, irrigation and other schemes has significantly slowed down the rate of sea-level rise over the last few decades (Newman and Fairbridge 1986).

Issue 11: Aquifer contamination
Shallow coastal aquifers that produce and protect extensive lagoons important to wildlife, fish and the air-sea exchange of trace gases.

How will changes in climate, and sea level alter transport of materials from sea to land?

Issue 12: Sea-spray aerosols
The sea produces between 1,000 and 10,000 Tg/yr of atmospheric sea salt particles with radii less than ca. 20 μm (Dupe 1983). The chemical constituents of these aerosols was reviewed in Buat-Menard (1986). The dominant ions of sea water, as well as trace quantities of organic compounds, are transferred to land in this form, sometimes with important ecological and agricultural implications. Sodium chloride is generally deleterious to land plants but in some regions...
Land-ocean interactions in the coastal zone (LOICZ)

Issue 13: DMS aerosols

Dimethyl sulphide (DMS) is a breakdown product of cellular solutes of many species of macroalgae and phytoplankton (Andrée 1986). DMS is volatile and lost at least in part to the atmosphere where it is oxidized to sulphate. This non-eutrophic sulphate is thought to be the major source of cloud condensation nuclei in the marine atmosphere and to play an important role in cloud formation (Charlson et al. 1987). If the abundance of DMS-producing algae changes with nutrient conditions, water temperature, sunlight or other factors related to global change, then variations in DMS production may act as a feedback effect to climate change. The release of DMS is not a special phenomenon of coastal zones, but in as much as the coastal zones are biologically active regions vulnerable to global change, then the potential for significant variations in emissions of DMS must be considered (see also IGAC, Chapter 2.1). Also the lifetime of biogenic sulphur compounds in the atmosphere is relatively short so that climate effects and acid deposition (see Turner et al. 1988) over the land margin will be most influenced by coastal sources of DMS.

How will climate change affect physical dynamics of coastal oceans?

Issue 14: Ocean boundary conditions

Important processes at the shelf edge that influence shelf-ocean exchange include interactions due to ocean and slope currents, mesoscale eddies and internal waves all of which are affected at least indirectly by climate (Casady 1982). The direct effects of climate include variations in wind-induced upwelling (Bakun, 1992) and off-shelf cascading following strong winter-time cooling. All these processes contribute to large-scale exchanges of energy, momentum and matter between the oceans and shelf seas.

Issue 15: Land boundary conditions

Close to land, variations in the inputs of freshwater and suspended material largely determine the nature of the physical environment, affecting buoyancy-driven circulation patterns and the properties of the bottom fluid-sediment boundary layer. Interactions with tide and wind are complex. Estuaries may be well ventilated with a consistent throughput of materials from land to sea, or act as efficient traps (Nichols 1986) for both terrestrial and marine particulate matter. The dynamics of coastal jets constrained by offshore density gradients (fronts) are important for the transport of dissolved and suspended material from rivers and estuaries (Skreslet 1986, Jansson 1988). The formation and melting of winter ice at high latitudes also strongly affects the physical properties of freshwaters, as well as erosion/deposition processes at the land interface. The implications of sea-level rise in terms of mixing and circulation on shelves are not well known, although tidal models suggest that significant changes are possible especially in large, elongated estuaries.

Issue 16: Shelf processes

Rates of tidal energy dissipation are extremely variable from one shelf to another and within any particular shelf area, so that mixing and advection processes may be dominated by tide or wind. Much progress has been made recently with models to predict the positions of tidal fronts (e.g., Pingree and Griffiths 1978), but the interactive effects of wind, buoyancy, air-sea heat exchange and coastal topography remain poorly understood. At higher latitudes, especially climatic changes are likely to affect the timing and rate of development of seasonal stratification and, therefore, primary production.

Issue 17: Episodic events

Climate change will influence extreme as well as mean climate conditions.
types of noxious blooms, but the partitioning of food between pelagic and benthic herbivores is strongly affected by hydrographic conditions (Townsend and Cannen 1988) and, in turn, influences the feeding and growth of pelagic and demersal fish.

Schematic representation of the dominant fluxes of nutrient elements through the first topic levels of the food web of a coastal ecosystem (DOM = dissolved organic matter; Lancelot et al. 1987).

Fluctuations in the abundance and yields of fish are associated with overfishing (Pauly and Thia-Eng 1988) and also with changes in climate (Southward et al. 1988), including the effects of prevailing winds on upwelling and shelf circulation (e.g., Dickson et al. 1988; also see Bakun 1990). Other impacts on fisheries include the direct influence of climatic temperature shifts (see Franks et al. 1990) and indirect effects related to various forms of habitat modification such as the destruction of marginal ecosystems (mangroves, saltmarsh, seagrasses, etc.) the manipulation of river discharges (e.g., Milliman et al. 1989).

Issue 22: Mariculture
Increased demand for aquaculture products, increased competition for space, and changes in climate and sea level are expected to affect mariculture (Bardach 1989). By comparison to natural fisheries, additional factors such as site exposure, variations in freshwater outflows, winter temperature minima, and the impact of derived waste products must be taken into consideration.

How will changes in climate, land use and sea level alter biogeochemical processes in the coastal zone?

Issue 23: Estimates of global fluxes
Considerable advances have been made over the last two decades in elucidating the nature of important biogeochemical transformations in coastal oceans, including aerobic and anaerobic degradation of organic matter, denitrification and the production of sulphur gases all of which directly affect the composition of the atmosphere. However, from a global perspective, the particular environmental conditions that determine total fluxes between the ocean and atmosphere are not well known. Changes in external inputs (for example, of organic matter or particular nutrients from land) can alter biogeochemical balances in the coastal ocean. Thus, an important priority for any new research programme on the coastal zone must be the development of observational methods and of a biogeochemical classification system for the construction of accurate regional budgets for biological consumption and production of atmospheric trace gases.

Issue 24: Carbon cycle
Most of the attention on the marine portion of the carbon cycle by JGOFS has focused on the open ocean. The crucial role of the coastal seas as the interface to land and as a zone of relatively high biological activity is well recognized, however, through studies on the input of organic matter from land (e.g., Mantoura and Woodward 1983, Ittekott 1988), and by studies on sedimentation processes (see Berner 1982). A consistent picture has emerged of a net consumption of organic matter in the oceans (i.e., land + atmospheric inputs exceed sedimentary outputs), making the marine system effectively heterotrophic (Smith and Mackenzie 1987), and therefore a source for CO₂ and a sink for O₂ in terms of the cycling of organic matter. This conclusion has important implications for the control of the cycles of other important elements such as N and P (Smith and Mackenzie 1987).

With the present conditions of flooded continental shelves, most of the terrestrial organic matter is trapped within deltas and estuarine systems except where large rivers such as the Amazon discharge material directly to the ocean (Muller-Karger et al. 1988). Changes in the total flux of organic matter from land to sea and the relatively efficiency with which it is degraded or buried (Mann 1986) in the marine environment are important variables in the ocean-atmosphere exchange of CO₂. Whether anaerobic processes in coastal marine sediments are a significant global source of methane is not certain (Heinrichs and Resburgh 1987).

Another controversial aspect of the role of the coastal ocean in the global C cycle is the hypothesis that biological activity on the shelf is a significant source of organic matter buried on the continental slopes (Walsh 1989). Opposing this view are geochemical arguments (Peng and Broecker 1984), and ecological data for efficient utilization of organic matter in shelf ecosystems (Rowe et al. 1986), suggesting that there is little net export of organic carbon to the slope. It is important to resolve this problem as well as the important ancillary question of whether primary productivity on the shelf might be enhanced by anthropogenic sources of nutrients (Wollast and Mackenzie, 1989).

Issue 25: Nitrogen cycle
Several aspects of the marine nitrogen cycle are important within the context of global change effects on coastal zone ecosystems (Blackburn and Serensen 1988). First, the problem of distinguishing between N and P limitation is fundamental to our understanding of what determines primary productivity. Recent observa-
Current assumptions suggest that the geochemical conclusion that P is limiting in the global ocean (Smith and Hollibaugh 1989) must be modified due to significant losses of inputs of N by denitrification (Seitzinger 1988). This latter process is considered the main marine source of nitrous oxide, a greenhouse gas (Christensen et al. 1987). Total marine emissions of N₂O are uncertain, especially with respect to the contribution of the coastal seas.
Plan Development

This focus is too complex in nature and immature in development to permit any detailed description of methods. Generally, it requires interdisciplinary teams to understand, measure, experiment and develop models for:

- erosion rates on land (e.g., Ahnert 1987, Eybergen and Imeson 1989, Kirkby 1989, Bork et al. 1989);
- hydrological fluxes across land and through river channels (BAHC, Chapter 5.1);
- material transport down rivers, through reservoirs and into the coastal zone with consideration of changing geomorphological alterations in the riverways (e.g., Richey 1983, LICC 1989);
- physical oceanography, in particular changes in oceanic currents and tides related to modification of climate and sea level;
- material discharge, distribution, transformation and deposition in the coastal zone (e.g., Costanza et al. 1990, Dyer 1989) in conjunction with;
- changing configurations of the land margin and physical movements of waters, including storms (e.g., Carter 1989);
- the relationships of organisms and coupled biogeochemical and energetic processes in the full complex of coastal zone ecosystems from swamp forests to deep shelf waters (e.g., Wollast 1983).

These tasks should be undertaken for each of the catchment-coastal zone complexes, but should be cross-linked between the study units to share new discoveries or innovative methods, and to ensure common measurements of comparable resolution.

To obtain broadest interpretative predictive power for other catchment-coastal zone complexes the selected study complexes must be as contrasting as possible. Possibilities are temperate zone, industrialized river-delta complexes like that of the Rhine; agricultural, temperate zone rivers like the Mississippi or Yellow River; tropical shelf zones like the Indonesian shelf; and Arctic river-shelf complexes like the Lena or McKenzie.

Focus 2

Organic Carbon Dynamics in the Coastal Zone

Objective

To evaluate the role of the coastal environment in the global carbon cycle and to develop predictive capacity for change in net organic carbon storage for different scenarios of change in climate, land use, and sea level rise.

Whereas Focus 1 is site-specific and intensive in nature, this Focus would be extensive, in fact, global in nature.

While the focus is on carbon, behaviour of other elements such as P, N and Si must become involved because of the intimate interactions between the cycles of these elements (e.g., Wollast 1983). Thus, this would be a biogeochemically-centred activity with specific questions focused on carbon. The project must rest on the best predictive capacity for changes in physical oceanography. Fundamentally, these questions are whether, when, where and how much organic carbon is being deposited in the coastal zone, and how would these variables be affected by global change?

Physical, chemical and biological dynamics at the continental shelf break, are certainly of global significance in relation to land-ocean interactions. Moreover, this domain is recognized to play an important role in the ocean carbon cycle which is the focus of JGOFS (Chapter 3.1). It is suggested that the topic of exchange processes and biogeochemical process at the shelf break, including deposition of organic carbon on the slope, be considered as soon as possible by a joint JGOFS/LOICZ panel. Such mutual effort should provide guidance for developing a specific research proposal on this topic.

Plan Development

As with Focus 1, a detailed plan needs to be developed. Perhaps with both extensive and intensive components. The extensive component might be the accumulation of data from the literature and from short-term campaign-style sampling efforts over a wide range of coastal situations. The intensive component could include process studies and field measurements of carbon fluxes in selected field sites. These extensive and intensive components must be coupled with other core activities, the best possible physical oceanographic modelling, and proper data-base management to achieve the general objective.

Impacts of Global Change on the Land Margin-Sea Boundary

Focus 3

Objective

- To develop a predictive capacity for predicting the effects of global change on the geomorphological and hydrological relations between land and sea, with an ecosystem focus, and including studies of habitat stability and the ecological and genetic viability of communities.

This Focus will take into account climate, sediment transport by rivers, storm patterns, and changes in tides and currents as well as sea level rise.

Ecosystem focus denote all marginal systems, excluding those controlled by human structures (harbours, marinas, etc.). It also entails attention to the influence of global change on the structure and function of coastal ecosystems such as barrier island vegetation or coral reefs. Sea margin systems would include subtidal and supratidal terrains that might be geomorphologically altered by rising sea and storm surges, and would include salt penetration across broad fronts into freshwater aquifers and through estuarine surges. This Focus would be highly interactive with other Foci as shown in Figure 3, and would require strong coastal zone physical oceanography linked with larger-scale circulation models as will be developed by WOCE. This activity would be extensive in its goals, to make predictions for all kinds of land margins, but not geographically bound as in Focus 2.

Figure 3. Relationships between major global change issues, other IGBP Core Projects, LOICZ, Foci, and Core Project products. D/M = data base development/modelling. Arrows represent the main directions of physical influence in phenomenological terms, and/or information flow in Core Project operational terms.
Plan Development

In general terms, this focus might take the same kind of extensive and intensive divisions described for Focus 2. One activity might be to gather data the on geographical conditions for the coastal zones of the world and seek a classification that would break these down into model systems for more direct analysis. It would require a strong, data base support system (see below). A second activity could be to make appropriate observations on test case systems defined by the first activity, which would run concurrently with incorporating and further development of existing geographical and hydrological models. To the degree, the geomorphology and hydrology (aquifer invasion) may be treated as separate tasks in this activity but at some level they should be tightly linked because of their interdependency.

Ultimately, these predictive models will be coupled with hydrodynamic and geomorphological models developed in the integrated catchment-coastal zone activity for concerted simulation (Fig. 3).

Special Project Needs

Common Modelling Support

Modelling will be an explicit function in each of the foci but some common modelling capacity will be needed to address different issues common to all. These include: (i) modelling across scales; (ii) scaling-up; (iii) modelling for episodic events; (iv) modelling feedbacks between subject areas of this core project and with other core projects; (v) developing and coordinating scenarios for model testing, and (vi) providing linkages between models.

Appropriate models or modelling techniques do not now exist for some of these problems areas and will require development. Examples of models are illustrated in Krysanova et al. (1989), Constantz et al. (1995), and Wronkiewicz and Hofmann (1989). In addition to these common areas of need, coordinated modelling will play a leading role in bringing about integration between the predictive models developed by the individual Core Activities to provide a predictive capacity.

This is a research area requiring planning by teams of modellers and process-centered scientists in each of the core activity areas. An organizational device must be developed to ensure satisfactory cross-activity modelling capacity.

Data Acquisition and Management

An imperative need of any coastal zone core project is a comprehensive and responsive system for data acquisition and management. Such a system must include a geographic, specifically geographically specific, data base for several kinds of coastal zone variables used by this project, other marine scientists, governments, policy makers, etc. These variables include the following, some of which would be available as global coverage, others for intensive research areas in the core activities: (i) topography from upper edge of coastal plain to shelf break world wide; (ii) hydrography currents, tides, freshwater inputs, temperature, salinity, nutrients/trace elements (in situ measurements in their several forms), inorganic particulates in terms of size class distributions and total bulk, locations of frontal boundaries; (iii) meteorology-solar radiation, air temperature, humidity, wind, precipitation, and (iv) biology-chlorophyll, plant biomass, animal biomass.

This data base will be essential for identifying further information needs including localized data collection, providing the GIS base for extensive activities and for applying the results of and model predictions to parts of the world outside of specific study areas. In addition, general questions of global relevance might be addressed immediately by the use of such a data base. Examples are: (i) How much new shelf area would be added world wide if a 0.1 m sea level rise result from global change? (ii) How much land might be lost to subsidence due to permafrost melting and sea-level rise along the Arctic Ocean? (iii) How would length of global shoreline be changed by inundation due to sea level rise combined with changes in storm activity? (iv) How would the area of lagoonal habitat worldwide be changed by alteration of sea level and storm frequency? (v) How would barrier island freshwater aquifers be influenced by prescribed changes in sea level and climate?

This is a research area requiring planning by teams of modellers and process-centered scientists in each of the core activity areas. An organizational device must be developed to ensure satisfactory cross-activity modelling capacity.


Suggested Reading


Suggested Reading
CLIMATE and land-surface systems are dynamically coupled through the physical processes of energy and water fluxes. Vegetation plays a major role in regulating water transport to the atmosphere. Changes in land use, such as conversion of forests to agricultural land, affect physical aspects of the climate system, for example, through changes in patterns of transpiration and runoff. Interactions of terrestrial ecosystems with the hydrological cycle at continental scales need to be coupled to global climate models. The processes governing the role of vegetation in the hydrological cycle must be identified and a quantitative understanding of the interaction between vegetation, the hydrological cycle, and climate, needs to be developed.
5.1 Biospheric Aspects of the Hydrological Cycle (BAHC)

An Established Core Project

The terrestrial hydrological cycle is an integral component of the climate system and is strongly modulated by the atmosphere and the biogeophysical characteristics of the landscape. It supplies the necessary water resource for sustaining life on Earth and also is a major medium for the biogeochemical cycles.

Associated with the terrestrial water cycle there is a continuous exchange of energy, water and other substances through the atmosphere, the landscape, and inland aquatic systems. Vegetation cover is influenced by the climate. Conversely, vegetation plays an important role in determining the partitioning of the energy and water inputs at the lower boundary of the land-atmosphere system thus influencing the surface hydrological processes and, consequently, the climate. The dynamics of the hydrological processes and linkages between soils, vegetation and atmosphere along with their integrated global effects are only poorly understood. A thorough understanding of key biological-hydrological interactions of the soil-vegetation-atmosphere system is a prerequisite to predicting impacts of climate change on unmanaged and managed vegetation.

During the last two decades there has been a growing awareness of the importance of land-surface processes in global climate models. Model simulations are very sensitive to changes in surface albedo, moisture availability and surface roughness. In particular, the importance of evapotranspiration over land as a moisture source for the atmosphere and subsequent precipitation has been clearly demonstrated in several GCM experiments. Nevertheless, the representation of hydrological processes is one of the weakest and most challenging aspects of the present climate models.

The WCRP has responded to this challenge by establishing the Global Energy and Water Cycle Experiment (GEWEX) Programme, which is dedicated to understanding the role of physical-hydrological processes in the climate system. The IGBP Core Project on Biospheric Aspects of the Hydrological Cycle (BAHC) will deal with the complementary problem of resolving the role of the biosphere and land surface processes in this context. The BAHC project addresses the following question: how do plant communities and ecosystems function in combination with the topographic structure of the land-surface affect the cycle of water on Earth? These investigations must resolve not only the "scaling-up" problem of extending vegetation patch-scale information to larger meso- and GCM grid-scales, but also the basic question of how the impact of the biosphere on the water cycle will change as vegetation itself responds to changes in the physical climate system or is modified through human activities. The elucidation of these phenomena will provide a fundamental input to the IGBP core project dealing with ecosystems response to a changing environment (GCTE; Chapter 6.1).

The BAHC project will also complement the WCRP's GEWEX programme by gaining an understanding of the interactions between vegetation, land cover and the hydrological cycle. The strategy for achieving this includes field studies from small scale (patch, small catchment, landscape) up to the mesoscale and river-basin scale using in situ and remote observations to develop Soil-Vegetation-Atmosphere Transfer (SVAT) models that can be incorporated into complex GCMs and GHMs (Global Hydrological Models).

To achieve these goals, it will be necessary to work together with GEWEX programme to:
- determine the biospheric controls of the hydrologic cycle through field measurements for the purpose of developing models of the energy and water fluxes in the soil-vegetation-atmosphere system at temporal and spatial scales ranging from vegetation patches to GCM grid cells;
- develop appropriate data bases that can be used to describe the interactions...
between the biosphere and the physical Earth system and to test/validate model simulations of such interactions.

Vegetation influences the hydrological regime in several important ways (Fig. 1). First, vegetation canopy and litter surfaces are partitioning points for the physical inputs (energy and water) into the system. Here, the relevant processes are surface reflection, absorption and emission for radiation, sensible and latent heat fluxes, interception, through-flow and water-holding capacity. The canopy also determines aerodynamic roughness. Second, stomata-controlled leaf transpiration regulates the water flux from the soil to the atmosphere in response to the balance between water availability and evapotranspiration demand. Third, root systems (i) increase soil porosity and vertical hydraulic conductivity; (ii) enhance infiltration and percolation; (iii) augment the soil water-holding capacity; and most importantly, (iv) provide transport of water back to the canopy. Fourth, the biomass and its root system enhance lateral hydraulic resistance to surface runoff and subsurface flows, protecting the soil against erosion.

In contrast, the effect of the ambient hydrological regime on the vegetation cover depends upon the time scales under consideration. For the IGBP time scale (decades-to-centuries), the main issues are changes in leaf area index (LAI), primary productivity, and species adaptation or replacement. However, in order to understand these long-term effects, it is necessary to consider the shorter-term effects of component processes amenable to observation. Specifically, on intermediate time scales (months-to-few years), phenology, rooting density and distribution, possible stomatal adjustment, etc., and at short time scales, changes in stomatal control in response to water availability are of importance. Additionally, extreme events, such as fire, storms and floods, and their frequencies, often determine vegetative cover.

The role of seasonal snowcover and snowpack dynamics in temperature and boreal systems is profound. The partitioning of precipitation into snow versus rain often determines whether that precipitation is stored in the system for many months, or leaves the system within hours to days as evaporation or transpiration or streamflow. During snowmelt, watershed hydrograph peaks are dampened substantially because of the moderating pace of snowmelt compared to the instantaneous peaks of rainfall runoff. Hence, the initial time constant of the entire hydrologic cycle is controlled by snowpack processes. Meteorologically, snowcover produces an instantaneous shift in surface albedo and influences latent energy exchange, radically changing energy budgets. Ecologically, snow cover stores seasonal precipitation in arid areas, and snowmelt then may produce only the time of the growing season that soil profiles are water saturated. In these areas, there is a high correlation between spring snowpack water equivalence and ecosystem primary production. Protection of vegetation during harsh winters by snow influences timberline vegetation survival. In mesic climates, heavy snowpack may impede vegetation development. The snowmelt period is the trigger for a short, intense period of annual nutrient mobilization and transport in snow dominated ecosystems. This nutrient flush and warming spring temperatures can be the most active time of the entire year for ecosystem trace gas fluxes and photosynthetic activity. Finally, changes in the areal coverage and seasonal timing of continental snowpack may be an early and important signal of progressive climatic warming.

For study of the above biological processes, a thorough understanding of certain physical processes is required, which necessitates cooperation between BAHC and GEWEX. The physical processes that will be addressed in GEWEX, especially at the spatial scales of GCMs, are: (i) exchange of latent energy at the canopy level, as it determines the partitioning of net radiation between latent and sensible heat fluxes; and (ii) soil processes, especially the partitioning of water into surface runoff, infiltration and percolation below the root zone, and direct evaporation associated with upward capillary movement of water. In contrast, the processes that will be addressed in the BAHC project are: (i) evaporation of intercepted precipitation by the major functional vegetation type; and (ii) transport of interception depending upon the atmospheric demand, availability of water in the soil, LAI and phenology, root-system state and functional vegetation type. In addition, groundwater transfer under humid and arid conditions, long distance transport through preferred pathways and storage for continental scales associated with climate and land-cover changes, will be an associated topic to be jointly
Interactions, Variables and Data

Quantitative knowledge of the volume and dynamics of the major terrestrial water reservoirs and of the main processes of the local, regional and global hydrological cycle is incomplete. Precipitation, evaporation and water transport are very poorly documented on the global scale. Information from a variety of sources needs to be integrated into a common data base. The data vary in type from continuous temporal measurements of a few selected locations to geographically referenced maps of various surface properties and other information.

For BAHC, a Geographic Information System (GIS) is needed which includes the following attributes of the surface and subsurface: (i) climate data such as precipitation, humidity, radiation, temperature, wind speed, soil moisture, snow cover, etc.; (ii) river discharge and runoff data; (iii) functional vegetation and soil-types data; (iv) topographic, catchment boundary and land-use data; and (v) regolith, bedrock, and groundwater system data.

The issues related to climate, river discharge and runoff data both by conventional and remote-sensing methods are described in detail in WMO/ICSIU (1989a, 1989b). In addition, issues relating to palaeohydrological data needs are discussed in Chapter 7.1 on PAGES.

Vegetation and Soil Attributes

Vegetation cover

Vegetation or land cover is a fundamental property of the land surface with respect to hydrological processes. In this regard, the most important attributes of plant cover are: (i) extension, density, height and permanence (portion of time the land remains covered) and phenology of vegetation; (ii) the structure of the canopy, especially leaf area and leaf distribution profile; and (iii) mean stomatal response of functional vegetation types.

Currently available global land-surface data, such as vegetative cover (Matthees 1983, 1984), land-use and soils (Wilson and Henderson-Sellers 1985) as well as remotely-sensed information, such as the normalized vegetation greenness index (NDVI), do not cover all the parameters mentioned above. Therefore, the determination of these parameters should be given a high priority. In particular, a more complete understanding of the cycling of water requires information on the interactive effects of climate-induced feedbacks within and between the biosphere and the atmosphere, and reliable global estimates of land cover and land-cover change. For this purpose, IGBP has initiated a Land-Cover Change Pilot Study (see Chapter 9) that has as a core objective to develop, validate and demonstrate a methodology capable of monitoring global land cover and its changes. GCTE (Chapter 6.1) has proposed a complementary activity that focuses on gaining predictive capacity for future land-cover change.

Soil attributes

The partitioning of water at the land surface, between surface runoff and infiltration, is determined by the state of the vegetation and soil as well as by the nature of precipitation events. The overall water-holding capacity of the soil is determined by soil texture, fabric and structure, which determine total pore space, and by the presence of roots and organic material. The global storage of water in the land surface layer (soil moisture) is not well defined over large scales. Soil infiltration rates during a given precipitation event are determined by precipitation intensity, hydraulic conductivity and water-holding capacity. The rates are also influenced by the slope of the terrain and antecedent climatic conditions, which determine the amount of water still within the soil, and by the physical characteristics of the surface, such as the degree of crusting or compaction which, in turn, is influenced by litter and root systems. Water movement within the soil may be hampered by compacted layers (e.g., iron or carbonate pans, clay-enriched horizons).

The following soil processes are important to understanding the biophysical aspects of hydrology: (i) infiltration into the soil layer, particularly in relation to soil horizon and permeability; (ii) water retention, especially in the rooting zone, which limits plant function at high or low water content; (iii) percolation below the root zone; (iv) subsurface runoff within the soil (interflow), along surfaces of less permeable horizons and lithic contacts; and (v) upward capillary movement due to withdrawal of water by roots or direct evaporation from the soil surface.

These aspects of soil attributes are also important to GCTE (Chapter 6.1).

Landscape and Subsurface Attributes

Changes in landscape properties, as a result of either climate changes or Mau’s activities, affect the hydrological cycle. Changes due to climate proceed at relatively slow rates. Human activities, however, may cause rapid modification of the characteristics of the landscape. Changes of land use (e.g., agriculture, urbanization, deforestation and drainage of swamps), changes of topography and drainage systems (e.g., construction of hydraulic structures, terraces and contour ploughing) all influence the hydrological cycle locally. The following attributes are of importance to the present project.

Surface topography

The realistic estimation of surface-water transfers and storages requires information on surface topography. This is of fundamental importance in determining plant communities, species location, growth and phenological behaviour. Topographic data exist as digital elevation grids at a global scale (e.g., U.S. Navy topographic data base). The spatial resolution varies from continent to continent, from 1.5' by 1.5' at best (for Australia) to 10' for most other continents. Further details on existing topographic data archiving efforts are discussed in the Chapter on IGBP-DIS (Chapter 9).

Aquatic system topology

An accurate description of the physiography of river drainage basins and lakes, such as length, width, slope gradients, floodplains, geomorphology of the bottom and meandering, is important for global change studies at the local to continental scales. Rivers, such as the Amazon or the Mississippi, that have a very gentle gradient, may be altered significantly by, for example, sea-level rise. The physiography of a river will determine certain characteristics of the riverine vegetation (LOICZ, Chapter 4.1).

The present state-of-the-art in river network topology documentation for South America is characterized by manually determined data (Vorosmarty et al. 1989) from a series of 1:1 M Operational Navigation Charts. For some countries more detail exists, for instance, for the UK at the Institute of Hydrology, with the 1:250,000 scale digitized river pattern already supplemented with a 1,500,000 scale grid for most of the country.

Slope and aspect

Slope and aspect are important for runoff and for computing radiation input, snowmelt and evapotranspiration. A high resolution (10 m or less) digital elevation grid is required to generate realistic values of slope and aspect. For many regions of the world, such resolution is unattainable continentally in the foreseeable future, unless there are new developments in remote-sensing radar and major international survey programmes. The distribution of different slopes and aspects within a grid must therefore be generated statistically.
In view of this, a global topographic data base that includes local base-level information and river network topology should be developed. A standard global data set being developed under the World Digital Database for Environmental Sciences (WDDIES) is of great importance for BAHC (Bickmore 1988).

Attributes of the subsurface systems

Subsurface water movement is governed by fundamental properties such as porosity, permeability, transmissivity, strata-depth and structure. These properties are not systematically between subsurface strata. Data on these properties are available at local scales in some continents but not on continental to global scales. Only some fundamental hydrological properties (e.g., porosity, transmissivity, erodibility) can be estimated from sources such as geological and soil maps, but a substantial part of the regolith remains undescribed because it falls outside traditional classifications of the subsurface. From the biospheric standpoint, the following classification of subsurface regions is of importance: (i) groundwater recharge areas, where the groundwater recharge rate is controlled by vegetation and soil, but the groundwater does not exert control on vegetation; (ii) groundwater discharge areas, where vegetation controls the groundwater table via transpiration and, in turn, the water table controls vegetation in a closed loop (for example, in arid zones, groundwater discharge areas can be located by presence of vegetation); and (iii) wetlands, where probably the most complex interactions of groundwater with vegetation exist. Unfortunately, this information cannot be derived from simple landscape attributes, as it is also influenced by the subsurface properties.

The source data of the soil at global scales are maps at 1:5 million (FAO-UNESCO World Soil Map), a scale vastly inferior to that at which topographic data are available. A global terrain and soils data base is currently being developed by ISRIC (SOTER) at a scale of 1:1 million. Delineating groundwater basins is a difficult task. Hydrogeological maps and groundwater observation series with sufficient detail are not available for a number of regions. Information on the storage capacity and the time (storage) constants can be obtained from long-term analyses of historical hydrographs, using conceptual hydrological models combined with water-balance calculations.

For a hydrological model, the horizontal stratification of the component of the hydrological system below surface must be based on functional properties. The need for a total regolith survey is critical and is without active leadership from an appropriate international organization. The UNEP GRID system, or a similar organization, should be encouraged to initiate such a study.

Field Experiments

Recently land-surface experiments to provide data at proper spatial and temporal scales for validating soil-vegetation-atmosphere transfer (SVAT) schemes have been proposed for: (i) implementation within atmospheric general circulation and climate models; and (ii) interpretation of land-surface characteristics derived from space-based radiation measurements (WMO/ISRU 1990).

The concept of Hydrologic-Airshaphetic Pilot Experiments (HAPEX) was introduced by the WCRP to provide the basis for improving and validating the parameterization of land-surface processes in climate models (Andre et al. 1987), where both atmospheric water demand and the moisture availability are simultaneously measured over at least one year, with intensive study periods of a few months. The representative regimes proposed for this purpose were: (i) temperate climate conditions with variable vegetative and agricultural cover; (ii) semi-arid zone with rapid soil water depletion following rainy periods; (iii) high-latitude forest with an extensive period of snow cover; and (iv) tropical rain forest. The major land-surface field experiments either undertaken during the recent decade or planned for the future are summarized in Table 1 and a schematic representation of some of the field measurements obtained during one field experiment (FIFE) is shown in Figure 2.
The first generation of experiments such as HAPEX, FIFE, etc., (WMO/ICSU 1990) were targeted to improve the representation and accuracy of parameterization schemes implemented within climate models, which characterize the two components of the coupled system. While the atmospheric part typically has a characteristic length scale of the order of 100 km, the biological part has to represent processes that go down to much finer scale. The scaling-up problem is a major modelling issue for the IGBP core projects involving land-surface processes (i.e., BAHC and GC3E). Typically, the scaling problem is resolved through use of soil-vegetation-atmosphere (SVAT) models. A conceptual description of scales of surface and atmospheric models as well as a schematic diagram of the hierarchy of models from patch-to-mesoscales to be developed under BAHC are shown in Figures 3 and 4, respectively.

The recent decade has seen a significant advance in the formulation of SVAT models for use in GCMs. Some of the more advanced models are the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson 1986) and the Simple Biosphere scheme (SiB; Sellers et al. 1996). These numerical schemes vary widely in their complexity and realism and require calibration. All SVAT models attempt to improve vegetation-dependent description of the energy, water and momentum interaction over land surfaces. The number of land-cover types considered is typically limited to between 10 and 20. Some models assume uniform coverage of a single vegetation type in distinct regions (biomes), while others allow fractional cover selected from the land-cover subset and seek to define average parameters at each grid point for the assigned vegetation mix.

The minimum requirement all SVAT models attempt to meet is to introduce land-cover dependency into key parameters such as albedo, aerodynamic roughness, the ‘surface resistance’ exerted by vegetation on transpiration in dry conditions, the amount of rain or snow held in an interception storage following precipitation, and the size of the accessible moisture store in the rooting zone. The latter parameter is influenced not only by rooting depth, but also by infiltration rate and deep drainage. The range of complexity for models meeting these requirements is currently very large, and model sensitivity studies to define the minimum complexity required are a high priority.

All the biosphere models currently used in GCMs are, in essence, one-dimensional SVAT models, as that is the format most compatible with the GCM.
Ongoing research of the type currently being carried out under ISLSCP and proposed for the Earth Observation System (EOS) is required to facilitate this. Another essential requirement for biospheric and ecological studies related to global change is the GCM-based simulation of precipitation in terms of frequency and intensity of events, typical rainfall-event totals, and distribution patterns. The crude representation of the essential physics due to necessities of parameterization for large spatial scales and our lack of full understanding of the processes make it difficult, if not impossible, to provide such information for the present day climate simulations. Clearly, close collaboration between the IGBP core projects dealing with land-surface processes (BAHC and GCTE) and the WCRP's GEWEX project is needed to fulfill this requirement.

Further discussion of IGBP-related land-surface modelling needs and recommendations for global change studies is given in the IGBP Report No. 10 (IGBP 1990).

The non-linearities of the biospheric interactions with the hydrological cycle and the specific needs of numerical modelling and predictions require the integration of state variables from point and patch scales, where data are collected, up to model grid sizes (the scaling problem). Interacting processes and ecosystem attributes at a wide range of spatial and temporal scales need to be understood and modelled. Most of the biological processes related to hydrology respond slowly to changes in the environment. Changes in structure and function occur at time scales of weeks to decades. In contrast, the atmosphere has a much faster response time, with dynamic processes spanning from seconds to years. Considering that the time-scale of processes to be studied covers a broad range in both components of the system, with an intrinsic phase lag between the responses, the recommended core activities are divided into categories selected according to an appropriate space scale.

**Objective**

- How do plant communities and ecosystems in combination with the topographic structure of the land surface affect the cycle of water on Earth.

Two sub-objectives are:

- To determine the biospheric control of the hydrologic cycle through field measurements for the purpose of developing models of the energy and water fluxes in the soil-vegetation-atmosphere system at temporal and spatial scales ranging from vegetation patches to GCM grid cells.
- To develop and implement a long-term commitment to observations designed to test the results of global change modeling of the interactions between the biosphere and the physical Earth system in relation to the hydrological cycle.

Specific core activities to achieve the goals of the core project are described below. These follow the spatial-scale categories defined in Table 3.

There is a need for development within WCRP of a "climate simulator/weather generator" that provides information on precipitation in terms of frequency and intensity of events, typical rainfall event totals and distribution patterns. Within the IGBP (BAHC and GCTE) and in close cooperation with WCRP's GEWEX project, the need to develop soil vegetation-atmosphere transfer models from patch to large river basin and continental scales is emphasized. To achieve these goals, the Core Project has to improve the knowledge of the soil-plant-atmosphere processes through field studies from site to GCM grid-size scales. The project has to develop a data baseline which includes long time series of hydroclimatological variables, in situ and remote-sensed data sets of special field experiments (FIFE, HAPEX-MOBILHY) and surface-attribute data, such as vegetation cover, soil and landscape type.

Considering the large diversity of temporal and spatial scales involved, the core activities are arranged in hierarchical spatial setting to highlight the following different conditions: (i) on the local patch scale of SWATs for single vegetation patches, vegetation, soil, geology and topography are considered to be homogeneous in the study area; (ii) on the scale of a really integrated SWAT or small-catchment and landscape scale, vegetation and soil are "patchy" but
Activity 1: Local (Patch) Scale Process Studies and Development of SVAT Models

Objective
- To explain and model the partitioning of evapotranspiration into plant- and non-plant processes in key vegetation types and its role in the energy and moisture exchange at the land surface, particularly the significance of canopy structure for exchange processes with the atmosphere.

<table>
<thead>
<tr>
<th>Scale km²</th>
<th>Modelling</th>
<th>Field Experiments</th>
<th>Research Thrusts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x 1</td>
<td>1D SVAT Models for homogeneous units (patch), including vertical water movement in the soil, sub-basin scale</td>
<td>Single or few parameter studies, ISLSCP type, e.g., La Crau, France</td>
<td>Validation and calibration of single parameter satellite data (albedo, temperature, NDVI)</td>
</tr>
<tr>
<td>10 x 10</td>
<td>Integrated SVAT model arrays in non-homogeneous areas (landscape) including hydrological models of small drainage systems</td>
<td>Complex experiments at pixel array scale, ISLSCP type, e.g., FIFE</td>
<td>Validation of algorithms to derive complex parameters from satellite data (fluxes)</td>
</tr>
<tr>
<td>100 x 100</td>
<td>Mesoscale models for complex terrains, including soil hydrology models with lateral exchanges and ecosystems models</td>
<td>HAPEX and ISLSCP type experiments, e.g., HAPEX MOBILHY</td>
<td>Algorithm validation at grid scale by intercomparison with experimental results; application to ecosystem interactions</td>
</tr>
<tr>
<td>Continental</td>
<td>Coupled 3D Hydrological, Ecosystem and General Circulation Models</td>
<td>Production of global data sets over decadal time scales</td>
<td></td>
</tr>
<tr>
<td>Global</td>
<td>Coupling of Atmosphere, Ocean and Complex Land-Surface Models (including Biosphere and Continental Hydrology Models)</td>
<td>Interactive global data analysis and 4D Assimilation Models of Global</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Integrative process studies from patch to global scales

The typical scale of these studies is 1 x 1 km; this is the size of ISLSCP scale la and of the pixel size for certain satellite data (e.g., AVHRR). It can also be determined by the height-to-fetch requirements for measuring certain atmospheric variables, i.e., at a ratio 1:100, measurements at a height of 10 m require a horizontal fetch of 1 km. The physical and biospheric aspects of the main processes necessary for construction of SVAT models are discussed above. This scale is also of relevance to GCSE (see Chapter 6.1).

During its initial phase 1990-1997, the Core Project will develop, test and validate SVAT models using data collected in the patch-scale field experiments. At this scale, numerous plot experiments, mainly agricultural fields, are conducted by various research institutions around the world. It is necessary that such plot experiments are fully interpreted, their outcomes be made available to the scientific community and that as much as possible, they be nested in larger field studies recommended by the Joint IGES/ECGRC Working Group on Land Surface Experiments (WMO, 1990). In order to obtain maximum benefit from these experiments, a unified methodology for field experiments has been recommended (WMO, 1990). The status of such field experiments, over different functional vegetation types is summarized in Tables 1 and 2. In such experiments, the specific biospheric aspects that must be measured or evaluated are: (i) partitioning of net radiation into latent and sensible heat (fluxes and precipitation into interception and throughfall); (ii) canopy and litter water-holding capacities (stresses) and evaporation of intercepted precipitation; (i) plant control of evapotranspiration: its dependence upon leaf-area index and phenology, state of the root system, water supply and meteorological variables; (iv) surface, canopy and aerodynamic resistances to evapotranspiration; resistance of water paths through vegetation; and (v) overall water-holding capacity of soils, infiltration, percolation below the root zone and upward capillary movement. In addition, effects of climate change on plant response, especially on stomatal behaviour; changes in photosynthetically active radiation (PAR), photon flux density, leaf temperature, water vapour saturation deficit of the air, CO₂ concentration and water supply should also be determined.

At this spatial scale, modelling activity essentially consists of developing soil-vegetation-atmosphere transfer schemes ranging from simple algorithms to parameterized functional relations. The specific tasks in this regard are: (i) intercomparison of appropriate SVAT models with respect to the corresponding model at higher generality by means of numerical simulation experiments; (ii) development of appropriate SVAT models to fit available data sets of small-scale experiments such as listed in Table 1; and (iii) sensitivity tests of SVAT models with respect to water stress and inhomogeneities in vegetation cover nutrient supply and against CO₂ fertilization effects, with special emphasis on a corresponding shift in water-use efficiency (see also Chapter 6.1).

For natural vegetation, the following important modelling hypotheses with respect to the auto-regulation of vegetation density, structure, and diversity should be investigated.
- A water-limited vegetation functional-type controls the canopy density in a way that controls the moisture stress at the roots to biologically tolerable limits with respect to the local climate and soil conditions.
- An energy-limited vegetation functional-type would maximize leaf area and/or photosynthetic efficiency. The response would be affected by nutrient availability.

Areal Integrated SVAT Studies

Objective
- To quantify and model areal evapotranspiration (ET) over heterogeneously vegetated and topographically uniform areas, e.g., small catchments with mixtures of two or more vegetation classes that can be integrated in a manner analogous to that in Activity 1.

The atmospheric variables that force ET, such as net radiation, water vapour saturation deficit of the air, and wind speed, are spatially integrated results of the direct and feedback interactions between the atmosphere and the underlying heterogeneous surface.
Activity 3

To accomplish the main goal at this scale, point or site measurements have to be translated into areally integrated properties and the simple mechanistic SVAT models are inadequate and complex, but still one-dimensional models. For example, mixing ratios appropriate to heterogeneous vegetation types may be used as parameters to describe the state of overall vegetation in the whole space as basis for an areally integrated SVAT model.

There are two main approaches to the scaling-up procedure. One is the statistical treatment of the heterogeneities that formulates the probability density functions of measurements and surface attributes made at different sampling points within the scale. Another approach is to use remote sensing, aircraft and spaceborne, since the pixel is already an integrating entity in itself. Care must be taken, because averaged spectral radiances are different for sensors with different aperture angle and spatial resolution. Thus, the averaging procedures have to be standardized to give comparable results. These techniques are described in more detail by Becker et al. (1988). The scale selected for these studies is in the order of 10 x 10 km. This corresponds to the ISLSCP scale 1b, and is useful for representing averages of several pixels for most existing satellite sensors. Whenever possible, it is recommended that the study area be a small watershed because this allows the closure of the water balance, and thus the cross-checking of the areal ET resulting from the energy and water balance schemes. The specific tasks at this scale are: (i) development of formulae that can represent average stomatal conductance, interception, throughfall, and other water relations; (ii) studies of interception of throughfall, infiltration and other soil-water relations; (iii) studies of the effects of spatial variability of soil hydraulic properties and of changes in root density profile and effect on evapotranspiration; (iv) development of estimates of areal precipitation interception as a function of remotely-sensed vegetation indices; (v) development of relationship of canopy phenology to remotely-sensed vegetation indices; and (vi) monitoring of the seasonal and interannual changes that occur in vegetation cover, using remotely-sensed vegetation indices.

For the period 1990-1997, the BAHC activities will focus on the field experiments shown in Table 2, with special emphasis on those vegetation types which have not yet been studied, i.e., tropical forests, boreal forest and tundra/taiga. Following the recommendation of the IGBP/WCRP Working Group on Land Surface Experiments, an IGBP field project in Amazonia should be given high priority.

Mesoscale Studies

Objective

- To develop relationships of vegetation-atmosphere interactions from smaller scales to GCM scales via field studies and development of an advanced tethered atmosphere model.

Previous research under various programmes has shown that such mesoscale atmospheric and hydrological models are powerful tools to achieve the required spatial integration of land-surface processes. For this purpose, field studies and modelling of the role of the heterogeneities of land-surface attributes and their influence on the hydrological mesoscale processes, with associated feedbacks, have to be carried out. The land-surface attributes are taken from existing databases. The typical scale for these studies is 100 x 100 km, i.e., the size of WCRP's HAPEX studies and current typical climate model resolution. The important characteristics of this scale are horizontal transport and flux divergence of water and heat. The study area should be a hydrological basin whose surface and subsurface basin divides are as close to identical as possible so that full accounting of the water budget can be assured. At this scale, the lower atmosphere is modulated both by large and mesoscale atmospheric forcing and by surface aerodynamic roughness and topography.

During the period 1990-1997, BAHC activities should include field experiments of the HAPEX type, especially for the Amazon Basin. These field experi-ments should be used for the comparison of different approaches to large-scale ET modelling (e.g., resistance models, complementary relationship ET model, coupling satellite data with ecosystem simulation), and the development of a coupled vegetation-atmosphere mesoscale boundary-layer model. This model should be used as a "translator" for the continental-scale hydrological model. The requirement that the study unit area be a hydrological basin should be stressed. Land-surface attribute data necessary to perform these tasks will require remote sensing, by both aircraft and satellite. For details, see WMO (1990)

Continental-Scale Studies

Objective

- In cooperation with GEWEX, to improve upon the inadequate representation of land surface hydrology and mesoscale atmospheric phenomena (weaknesses in present GCMs), mainly by improvements in the treatment of topographic representation, evapotranspiration, and to distinguish between the natural and man-induced changes in the hydrological cycle for selected continental basins.

Initial priority must be to participate in the GEWEX Continental Scale Project on the Mississippi River Basin. However, in view of the convergent interest of several IGBP Core Projects (ICAC, LOICZ, BAHC and GCTE) in the coupling between hydrology, vegetative cover and biogeochemical cycles in the Amazon River Basin and its influences on the global earth system, BAHC should endeavour to develop a long-term strategy for studying the biophysical aspects of the hydrological cycle over Amazonia. Thus, BAHC activities at the continental scale should develop in not only concert with the GEWEX continental study of the Mississippi River Basin, but in addition, a study of the Amazon Basin should be initiated in collaboration with other IGBP projects (LOICZ, GCTE), engaging appropriate IGBP Regional Research Centres.

In this regard, an essential requirement is the development of vegetation-atmosphere process models for inclusion in global or continental-scale climate models. For this activity, a high resolution coupled vegetation-atmosphere model is necessary. A fine mesh of 0.5° x 0.5° (55 x 55 km at the equator) grid size, or even smaller, should be nested into an existing GCM. In addition, SVAT models for different functional vegetation types of the basin should be used as "translators" of surface variables and attributes. While current land-surface parameterization in GCM models can crudely resolve changes that occur in the regional climate and hydrological cycle due to modifications in surface properties, ecosystem dynamics models are required which represent vegetation behaviour in response to climate changes (see Chapter 6.1).

Critical data for this effort will be produced by the IGBP-Dis. Specifically, the land cover study initiated by IGBP-Dis (see Chapter 9) will provide monthly or more frequent, or global maps of LAI and other vegetation parameters based on remote sensing products and complementary in situ information.

An IGBP Steering Committee (SSC) on Biospheric Aspects of the Hydrological Cycle (BAHC) will be established during 1990. In addition, establishment of an IGBP-BAHC Core Project Office (CPO) is planned for the later part of 1990. Under the supervision of the Chairperson of the BAHC Scientific Steering Committee, the CPO will serve as the central office for coordination, communication, etc., between the core project activities, interested research institutions and groups. Ongoing tasks of the CPO will include developing implementation plans for core activities under the direction of the BAHC-SSC, holding necessary meetings, workshops, etc., maintaining an information bulletin on the project activities and research results, data, etc.

An offer to host the IGBP-BAHC CPO at the Potsdam University Berlin under the joint sponsorship of the Federal Republic of Germany and the German Democratic Republic is currently being finalized.

In the implementation of the BAHC, close cooperation with the WCRP's GEWEX project is a must. Additionally, it should be noted that the International Association of Hydrological Sciences (IAHS) has set up three Working Groups in support of BAHC activities. Thus, close cooperation with IAHs should also be
During the period 1991-1997, the following Core Activities discussed above will be carried out in cooperation with the WCRP/GEWEX project:

- observational studies and field experiments in the priority regions as recommended by the Joint IGBP/WCRP Working Group on Land Surface Experiments to better understand the direct and feedback processes within the soil-vegetation-atmosphere system in relation to the hydrological cycle;
- validation and calibration of existing SVAT models, with available data sets (FIFE, HAPEX, Amazonas) and in close cooperation with the IHP of Unesco, WCRP/GEWEX, IAHJS activities and various national groups;
- development of simple and annexed integrated SVAT models for different plant functional types;
- development of a coupled SVAT model for studying the hydrological cycle of large river basins as a first step toward a global hydrological model;
- development and practical investigation of algorithms to solve the scaling problems;
- participation in the construction of a complete hydroclimatological data base, and GIS for surface and subsurface attributes, including remote-sensing data.

Around 1998, new orbiting sensors will be launched and provide better data of the land-surface characteristics and measurements of the atmosphere variables. New generation computers and climate models with higher resolution, improved data assimilation schemes, biogeophysical and hydrological processes and boundary conditions, will permit the testing of more complicated hypotheses relating to future climate scenarios.

In order to develop detailed research implementation plans and coordinate the research effort discussed above, the following meetings and workshops are proposed for the 1990-1994 time frame:

(i) an Open Meeting of scientists from the IGBP National Committees, ICSU bodies, and other international organizations to agree on the detailed science plan and to develop an outline of the implementation strategy (early 1991);
(ii) a focused topical workshop for each core activity organized and run by the core activity leaders (i.e., three workshops during 1991-1993);
(iii) a workshop on intercomparison of modelling results from the various scales (1994).

References

How Will Global Change Affect Terrestrial Ecosystems?

Climate change and increased nutrient deposition from the atmosphere will affect soils, plant productivity, biogeochemical cycles, vegetation structure, and species composition. Temporal and spatial patterns for temperature, precipitation, and the occurrence of extreme weather events influence not only natural ecosystems, but also impose regional constraints on agriculture and forestry. Major changes in ecosystem extents will have important feedback effects on physical aspects of the climate system through associated changes in roughness and reflectivity of the Earth’s surface and altered fluxes of \( \text{H}_2\text{O}, \text{CO}_2 \), and trace gases. Global change may also affect ecological complexity with possible important feedbacks to ecosystem functioning.
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6.1 Global Change and Terrestrial Ecosystems (GCTE)
An Established Core Project

The Response of Terrestrial Ecosystems to Global Change

The elements of global change included in this project concern changes in climate, atmospheric carbon dioxide and land use. The potential increase in UV-B and its effects on biological processes are not included at this stage. They may develop as part of STIB (Chapter 2.2) in a later phase, following the present SCOPE analysis of the topic. Air pollution effects are also excluded, but they may be taken into account in a later phase of the proposed work on the impacts on agriculture and forestry.

Global climate and land-use changes will have direct effects on terrestrial ecosystems, such as alteration of water-use efficiency by plants, increased carbon (C) storage caused by elevated CO$_2$, or the net release of soil C caused by elevated temperatures. These direct effects will induce changes in structure and function of ecosystems that are expected to feedback to the atmosphere, soils, and the geosphere. For example, changes in energy partitioning in deforested regions may reduce evapotranspiration, and this in turn may have a positive feedback on the greenhouse effect through reduction of cloudiness.

Developing the means to predict and monitor changes in terrestrial ecosystems is needed to provide the necessary inputs to global models of climate and biogeochemistry. In addition, these investigations will lead to the capability of predicting changes for regional and local situations. The development of a capability to predict responses by terrestrial ecosystems will involve combinations of efforts including synthesis of literature, experiments and observations at a number of scales, and modelling. The goals of this Core Project involve development of a predictive capacity by all useful means. Models are one of the means to that end, and the project is intended to lead to the development of a range of models, using a generic model structure.

Definitions

Throughout this document the term ecosystem is used as a general term for any interactive, ecological unit, generally involving a set of functionally different biological entities and a dynamic abiotic component. This term by itself does not connote any specific dimensions. The term patch indicates a land unit treated as internally homogeneous for the purpose at hand, and integrated for the ecological property in question.

The term landscape indicates a unit of terrain consisting of more than one contiguous patch. The dimensions of patches and landscapes are also non-specific, in general becoming specified by the property addressed. Patches and landscapes, and indeed the world, can all be viewed as ecosystems.

There is a need for a single term to cover the non-demographic, functional attributes of ecosystems; the processes involving exchanges of energy and matter with the atmosphere, nutrient cycling and storage, biomass accumulation, etc. Following much debate about ambiguity in use of the words "function", and "metabolism", the term ecosystem physiology was adopted.

Objective

- To develop the capability to predict the effects of changes in climate, atmospheric CO$_2$ and land use on terrestrial ecosystems, and how these effects can lead to feedbacks to the physical climate system.
This capability is required for two reasons. The primary reason is to predict the consequences of global change for ecosystem structure and physiology, since these ecosystem attributes have direct effects on issues important to humans including productivity, future land use, and biotic diversity. The second reason is to estimate the potential feedbacks of the changes on further atmospheric and climate change.

Figure 1 represents the structure of this Core Project in terms of issues of global change; the linkages between activities of this and other Core Projects of IGBP, and the general products of these activities.

**Science Components**

This project has three main Foci:

1. The physiology of ecosystems that relates to the ways in which ecosystems exchange energy and materials and the processes through which they change biomass and storage of elements.
2. The dynamics of ecosystems as a function of changes in the composition, and the physiognomic structure of ecosystems and their spatial distributions.
3. The impacts on agriculture and forestry concerned with effects on the major crop, forest and livestock species in terms of the yield of harvestable products.

In regard to the first two Foci, the interactions of structure and function are at the heart of understanding how ecosystems will respond to global change (Fig. 2). The interactions are specifically addressed in two of the core activities (Focus 1, Activity 3, Changes in Water and Energy Fluxes and Focus 2, Activity 1, Changes in Biological composition and Ecosystem Structure at the Patch Scale), which link Focus 1 and 2. These six activities of Foci 1 and 2 constitute a progression leading to the capability to predict the distributions, composition and physiology of ecosystems on a regional scale. Focus 3 on agriculture and forestry represents the first phase of what is intended to be developed into a separate Core Project. Additional issues which should be studied include mixed farming systems and socio-economic interactions and controls on managed systems, and a wide variety of disturbance regimes specifically important in agroecosystems. Ultimately, GCTE must make continental scale predictions for several properties, such as albedo, evapotranspiration, carbon storage, etc. This means that some research tasks must be directed toward the continental-scale issues. These include development of necessary geographic data bases for application of smaller scale predictions, and coarse resolution, land cover predictive modelling.

**General Design of the Core Project**

The central problem is developing an understanding of regional and global systems. The general strategy for achieving this is essentially one of stratified sampling (Table 1). The world can be viewed as composed of biomes, the largest class of ecosystem type. These biomes may change character in a changed world, but also, the borders or transitions between these biomes are likely to be highly sensitive to the rates of global change. In particular, the tundra-boreal forest, the temperate grassland-shrubland-forest, the subtropical-tropical woodland-savanna, and the wet tropical-seasonal forest transition zones have been identified as sensitive transition zones of global relevance (IGBP, 1990b). A model-based predictive capacity developed for the range of such sensitive areas over time will be most useful in extrapolation to the continental scale. In addition, studies conducted in sites of representative conditions of a biome-type are also needed.

Four kinds of activities are envisaged (Table 1). One is the execution of field experiments within representative ecosystems and associated transition zones. Another is the development of land-cover change models, themselves entailing...
Table 1. Table of area of study, relevant operations and corresponding GCATE activity (Focus number, followed by Activity number)

<table>
<thead>
<tr>
<th>Scale</th>
<th>Operations</th>
<th>Activity No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch-scale experiments</td>
<td>CO2 and climate experiments. Biogeochemical experiments. Soil experiments. Landscape manipulation. Soil-vegetation-atmosphere analyses of water and energy fluxes. Agricultural species experiments and models.</td>
<td>F1-1, F1-4, F1-2, F3-1</td>
</tr>
<tr>
<td>Controlled experimental facilities</td>
<td>CO2 and detailed laboratory experiments.</td>
<td>F1-1, F1-2, F3-1</td>
</tr>
</tbody>
</table>

identification of functional biotic groups, etc. A third is landscape analysis for C02, from large scale to and methodological techniques, including data-base extrapolation and a fourth is development of an adequate geographic data base for a region so that is needed primarily to estimate feedback to the climate system, with the regional information being of particular importance for analyzing transition zones likely to show greatest change. The landscape and patch predictions are needed to provide greater realism at the local level, both for incorporation into the larger-scale estimates, and because of their importance to humans.

The Problems of Space and Time Scales and Variability

The proposed research strategy involves the parallel development of measurements and computer-based, mechanistic models. For example, we propose well-focused physiological measurements of the effects of CO2 and climatic variables on selected plant functional types at the scale of individual plants, and also large-scale field experiments on the effects of altered CO2 on ecosystems. The results of the large-scale experiments will likely not be obviously predictable from the results of the small-scale experiments, because of the complex interactions among plants and between plants and soils. These large-scale experiments are expensive and only a limited number can be done. In order to develop a general predictive capability from these experiments, we need to build and test models that start from a simple representation of the plant-level effects and also include representations of our current understanding of interactions among plants. The great value of the large-scale experiments is in providing data on parameters for models and in validating the models. They will provide data that the models must be shown to reproduce, at least approximately.

The integration of experiments and modelling also provides a way to address the time-scale problems. Owing to the decadal to century focus of IGBP, mechanistic models are a necessary tool for looking forward and extrapolating beyond present conditions. The problems of variability, including changes in the nature and frequencies of extreme events, and possible unrecognized feedbacks, may lead to "surprises" (Holling 1978) that our models cannot predict. In this sense, models developed in the IGBP must be regarded as benchmarks reflecting the current state of knowledge, and they must be designed to allow incorporation of new insights that arise when monitoring of global systems produces qualitatively unexpected results.

A final problem concerns the large numbers of species that occur in ecosystems. Species differ greatly in their physiology and responses to changing environment, but we cannot expect to characterize them all. How, then, do we choose the basic taxonomic entities in our models? We propose the use of "functional types" (IGBP 1989, 1990a; Smith and Huston 1983, Prentice et al. 1989). For each specific research problem and modelling effort, the task is to identify the smallest appropriate number of distinct, functionally different types of organisms and to focus experimental study on examples of each. The functional types will be the basic biological entities in experiments and the models, making the modelling problems tractable.

Thus, although we refer for example to predicting the dynamics of species composition as an important goal, we do not, however, expect to be able to work at the species level everywhere. Studies must be clearly directed towards the project's overall objective to develop a predictive capacity for ecosystem dynamics over a significant portion of the Earth's surface.

Project Organization

The Core Activities are highly interlinked with each other and with other IGBP effort and, to a certain extent, in the controlled environment of information flow between them and to products of the Core Activity. These relationships are illustrated in Figure 1.

Eight of the Core Activities must be administered as an integrated set of activities within this Core Project and two should preferably be administered by, or at least shared with, other IGBP Core Projects and Activities. All ten are required to achieve the Core Project objective.

Typically, the Core Activities combine monitoring, experiments, modelling at various scales, and inputs from other sources. Some of the larger field experiments will contribute to several Core Activities and will jointly serve other Core Projects, e.g., BAHIC (Chapter 5.1) and IGAC (Chapter 2.1). Because of their cost and complexity, they will be located in a limited number of regions and the proposed IGBP Regional Research Centres (Chapter 11) may play a role in their implementation.

Ecosystem Physiology

Of the many functional attributes of ecosystems that may be influenced by global changes, those which are of primary interest to IGBP can be grouped into four main areas of research activity.
Activity 1: Effects of Elevated CO₂

Two major questions underlie the need for this activity:

1. How will increases in atmospheric CO₂ influence plant physiology?

Carbon dioxide is a limiting substrate for photosynthesis in C₃ species, but less so in C₄ species, which are CO₂ saturated. Photosynthetic rates of C₃ species are therefore expected to rise with CO₂, when other resources for photosynthesis, such as nitrogen and phosphorus, are not limiting (Ainsworth and Long 1990). Increased photosynthetic capacity or decreased respiration at elevated CO₂ leads to an increase in carbon compounds relative to tissue protein (Lincoln et al. 1986, Gifford et al. 1985). This change can cause increased fungal decomposition (Muller et al. 1984). The increased supply of carbohydrates increases the capacity of plants to support mycorrhizae and nitrogen fixing associations, enhancing the capacity of these species to grow on nutrient-poor soil (Norby 1987, O'Neill et al. 1987). The occurrence of sinks for photosynthetized assimilates, such as mycorrhizae and fruits, enhances the CO₂ stimulation of photosynthesis (Coughlin et al. 1981).

Increased CO₂ causes stomatal conductance to decrease and as a consequence water use efficiency increases (Warrick et al. 1986a), enhancing the capacity of plants to grow in water-limited environments (Morison and Gifford 1984).

2. How will the known plant physiological response to CO₂ influence ecosystem processes and vegetation function at the patch scale?

Species differ in their photosynthetic and stomatal responses to CO₂. These physiological differences may lead to changes in patch structure by changing competitive interactions (Drake et al. 1989, Reckie and Bazzaz 1989). Enhanced water-use efficiency at elevated CO₂ will allow increased leaf area index (LAI) in water-limited environments (Woodward 1987). An increase in LAI will change light levels within a patch, influencing the capacity of light-limited species to survive. Other changes will be induced by differential responses to herbivore (Lincoln et al. 1986, Fager 1989) and by influencing soil processes. Soil processes may be influenced by changes in C/element ratios, which will alter nutrient availability, through stimulation of nitrogen fixation (Masterson and Sherwood 1987, Norby 1987) and through increased carbon sequestration in the soil (Overdieck and Reining 1986).

Objective

• To determine and predict the effects of elevated CO₂ on ecosystems, at the patch scale.

Activity 2: Changes in the Biogeochemistry of Carbon, Nitrogen, Phosphorus and Sulphur

In the past decade, substantial progress has been made in understanding the biogeochemical cycles of carbon, nitrogen, phosphorus, and sulphur, in describing their interactions, and in determining the direct effects of climate and land-use change in regulating these cycles. Research is not yet far advanced on the effects of an altered atmospheric composition in controlling terrestrial biogeochemistry (see IGBP Activity 1 above) and a number of ongoing studies are beginning to address that deficiency (see IGAC Chapter 2.1). On the other hand, we have very little information on the interactive effects of an altered atmosphere (especially elevated CO₂) on plant competition, on herbivore and phosphorus, and water-use efficiency, carbon allocation and decomposition); and the responses of overlapping phenologies (IGBP 1990b).

There will be few large-scale experiments because of their expense and the heavy requirement for trained personnel. As a consequence, there should be an agreement on the ecosystems most suitable for study. These will be communities expected to differ in their sensitivity to CO₂ increase, such as those in which temperature and water are stressed in different combinations. Experiments should be given high priority in the following areas: currently cold and wet and where significant changes in temperature are expected (e.g., tundra), cold (or cool) temperate, or sub-arctic (temperate, semi-arid grasslands or shrublands), hot and dry (southern tropical arid savannas), and hot and wet (tropical rain forest).

As stated earlier, achieving the objectives of this activity will require an integrated set of experiments, across a range of scales. The fine scale (i.e., leaf, plant and hours to a season) experiments are most likely to be run in a controlled environment at the plant level, and need to focus on the interactions between changes in CO₂ concentration and temperature, humidity, water supply and soil nutrients. In addition, controlled environment experiments are also required for investigating the effects of CO₂ on plant competition, on herbivore and pathogen effects, on plant phenology, and on carbon and nitrogen cycles in soil.

Medium-scale experiments (in the order of a growing season in duration and small patch size) should be attempted in the field to complement the controlled environment. The focus of these experiments will be on plant-plant and plant-soil interactions, and they will facilitate scaling-up predictions from the controlled environment to the large-scale patch experiments.

The experimental and modelling aspects of the CO₂ studies must develop in parallel. Model development needs to focus on transient changes in CO₂ concentration and the corresponding impact on ecosystem processes. Path models of vegetation dynamics (Activity 5) are needed to incorporate the direct effects of CO₂ on path processes. In addition, atmospheric measurements of CO₂ concentration in certain regions will be needed to better quantify the influence of the patch scale CO₂ fluxes on the atmosphere. These measurements could be made through an expansion of the on-going CO₂ monitoring network as described in Focus 1, Activity 2.
likely to change substantially as a consequence of global climate change; (ii) interactions among the driving variables are likely; and (iii) feedbacks from ecosystem-level alterations to regional and global changes are plausible. We suggest three ecological regions for initial focus: tropical regions that are undergoing intensive agricultural or pastoral development; semi-arid regions on ecotones between woody and grassland vegetation; and high latitude regions with substantial soil carbon storage. (iv) Ongoing syntheses of information on the global biogeochemical cycles, their interactions, and their controls. (See Chapter 8.1, I, GAIM).

These three regions, described above in point (iii), define the locations for initial tasks of this activity. For each task, field measurements and experimentation is emphasized. However, we recognize that for the experimental designs to be meaningful and the measurements to be broadly used, they need to be based on ecosystem models, and that the results of measurements and experiments will be synthesized with the aid of models. Extension of the results to unstudied or newly developed land-use practices will similarly require a substantial modelling effort. Finally, extrapolation of results in space and time will require a substantial investment in remote sensing as well as modelling—particularly in models that can be driven by remotely-sensed inputs.

Four tasks are outlined for this activity. The first task is designed to reduce the uncertainty in the carbon fluxes and the magnitude of storage pools of terrestrial ecosystems. The next three tasks outline regional priorities for focused studies on a suite of biogeochemical elements (C, N, P, and S) and their interactive behaviour.

Objectives

- To develop the capacity to predict how fluxes and pools of carbon, nitrogen, phosphorus and sulphur change in ecosystems in response to changes in CO₂, climate and land use (including fire regimes).
- To estimate the distribution of terrestrial carbon pools within continents and, to predict how they might change under given scenarios of global change.


One of the major uncertainties regarding the global C cycle relates to the importance of terrestrial ecosystems as sources and sinks (Bolin 1986, Tans et al. 1990). After a number of years in which calculations of the global carbon budget appeared to be converging on a small net flux from terrestrial ecosystems to the atmosphere, a recent paper by Tans et al. (1990) made a strong case that terrestrial ecosystems, in particular northern temperate systems, are significant net sinks of CO₂. If this atmospherically-based analysis is correct, previous analyses must have erred in their treatment of land-use change and its consequences (Bolin 1986), the effect of elevated CO₂ on carbon storage, or other processes subject to human modification (such as the effects of enhanced nitrogen deposition on carbon storage).

The objective of this task is to establish quantitatively the terrestrial ecosystems as sources and sinks for atmospheric CO₂. This objective will be addressed in several ways. First, the CO₂ enrichment experiments (Focus 1, Activity 1) will determine the overall effect of elevated CO₂ on carbon storage. Second, the precision of atmospherically-based analyses (such as Tans et al. 1990) can be increased substantially if a more detailed spatial and temporal monitoring network for CO₂ concentrations over continental areas can be established. Current measurements of the atmospheric CO₂ are made in remote areas and are highly associated with maritime regions so that continental measurements are relatively sparse. The established Background Air Pollution Monitoring Network (WMO-BAPMN) and the NOAA Geophysical Monitoring for Climate Change (GMCC) network partially meets the needs, but an expansion of the flask sampling network would greatly assist in resolving the issue of identifying the source and sink regions of the terrestrial biosphere. At the same time, an effort should be made to improve our knowledge of sources and sinks of carbon associated with land clearing. The approximate storage and net turnover of C from various ecosystem types are generally known (although these studies are relatively few in number; see Bolin 1986). However, the areal extent of the major ecosystem types and the distribution and dynamics of their successional stages are poorly known relative to the global carbon storage. This study should be conducted jointly with the IGBP-DIS, as part of the Land Cover Study (Chapter 9).

Task 2. Tropical areas undergoing human development.

Land-use change is currently most rapid, and its consequences most evident, in tropical regions, in part because of the disproportionate share of human population growth that is taking place in the tropics. Land clearing and conversion causes substantial losses of carbon and nitrogen, lesser losses of sulphur and of phosphorus from cleared sites in most regions, but the rate at which this is lost is much faster in the tropics. Accordingly, a number of the IGBP Core Projects, including IGAC (Chapter 2.1), LOICZ (Chapter 4.1) and BAHC (Chapter 5.1), emphasize these tropical systems.

To evaluate the consequences of environmental change in tropical regions that are under development, we need to:

1. Determine the fate of the carbon, nitrogen, phosphorus, and sulphur lost during, and in the few years following, land clearing. How much is volatilized in fires or afterwards in cleared sites, and in what forms (e.g., carbon dioxide or methane, nitrogen gas, ammonia, nitric oxide, nitrous oxide)? Leached to streamwater and groundwater? Eroded?
2. Determine the regional consequences of land-use change through watershed studies, a gas-flux measurement studies, and regional climate measurements in relatively large cleared areas (several to tens of kilometers).
3. Determine interactions of land-use change with increasing carbon dioxide concentrations and other atmospheric changes such as elevated oxidant concentrations (many of the latter themselves driven by land-use change) in a few experimental sites. Temperature change is likely to be less significant in the tropics than in higher latitude systems.

The rapid rate of change in element pools following land clearing in tropical areas is likely to be an advantage in these studies; massive amounts of material are moving in a short period of time, and hence fluxes are more readily detectable than in other regions.

To meet these goals, a coordinated regional watershed study of the effects of land conversion should be undertaken on large watersheds in tropical forest and savanna regions nested within large river basin measurement programmes like those now underway in the Amazon and Orinoco Basins, and proposed in BAHC (Chapter 5.1) and LOICZ (Chapter 4.1). Losses of elements in solution, erosion, and gaseous emissions should be carried out. The experimental programme should interact with the "tropical land-use change" activity of IGAC (Chapter 2.1) which is proposing ground- and aircraft-based measurements of trace-gas fluxes over tropical forest and savanna areas. In addition to these intensive sites, plot-level measurements of the fate of elements in different land use systems should be undertaken on a number of sites, and interactions of land use change with atmospheric change should be pursued in a few well-equipped sites. Close coordination of among other IGBP Core Projects (i.e., IGAC, LOICZ, and BAHC) and with other ongoing studies must be maintained during the development and implementation of the study.


Semi-arid areas as a transition zone (ecotone) between woody and grassland vegetation are widespread globally. They are also particularly interesting due to the proximity of ecosystems dominated by contrasting life forms (e.g., forests compared to grasslands or shrublands) and often contrasting photosynthetic pathways (C₃ versus C₄). There is therefore a substantial likelihood that changes in atmospheric chemistry, climate or land use will result in radical alteration of biogeochemical dynamics due to physiognomic shifts in this region, which will feedback, positively or negatively, to future climate and atmospheric
composition conditions. For example, increasing CO₂ concentrations should favour woody C₃ vegetation over C₄ grasses, thereby increasing carbon storage. However, increasing temperatures should favour C₄ grasses. Human activity can also have opposing effects. Increases in fire frequency may favour grasses; intensified grazing may increase the patchy distribution of certain soil and set in motion a positive feedback towards shrub invasion. Land cleared in dry-forest areas is often converted to self-maintaining grassland, with potential climatological and biogeochemical consequences. All of these are likely to be strong effects, and the net effects of all of them together are not clear and not likely to be clarified without experimentation. Accordingly, a detailed study of the interactive effects of atmospheric chemistry, climatic, and land-use change in semi-arid areas is proposed. Such a study should include demographic measurements of the major woody and grassland species as well as carbon, nitrogen, sulphur, and phosphorus dynamics. There is evidence that limitations to plant or animal mobility or establishment govern the rate of response of woody vegetation to land changes, and the same could be true of responses to global change. Moreover, demographic processes are unusually amenable to systematic study at grassland/woody vegetation transition zones.

It would be most logical to establish an intensive site in the tropics (savanna-forest boundary) and in the temperate zone (prairie-shrubland or forest boundary) in which a full range of measurements would be undertaken. Many of the issues in Tasks 2 and 3 would be best addressed in a study which cuts across a rainfall gradient in the tropics, which ranged from humid tropical forests to semi-arid savannas. Such studies have already been proposed in West Africa and northern Australia, and comparable studies in other tropical and sub-tropical regions are required.

**Task 4. High-latitude ecosystems**

Predicted temperature increases are greatest in high-latitude areas, and direct effects of elevated CO₂ on terrestrial ecosystems are also likely, because high-latitude ecosystems are already relatively carbon-rich and nutrient-poor. All else being equal, increases in temperature alone are expected to lead to increases in decomposition greater than any increases in net primary production, and therefore to increases in CO₂ flux from soils. Depending on changes in precipitation, which cannot yet be predicted with confidence, methane fluxes might increase as well. These effects do not occur independently, but interact intimately with other ecosystem processes, so that an increase in decomposition will lead to increased mineralization of nitrogen and to a lesser extent sulphur and phosphorus. These could cause an increase in productivity that could temporarily (decades to centuries) override any increase in decomposition and cause increased carbon storage on land (Pastor and Post 1988). Elevated CO₂ could also cause increased carbon fixation, but that in turn might widen carbon-nutrient ratios to the point that immobilization by microorganisms was substantially increased. That in turn would decrease nutrient availability, increasing plant carbon-nutrient ratios still further, and hence decreasing productivity. The net results of these interactive effects are fundamental and very poorly known.

An intensive effort to determine the effects of atmospheric chemistry and climate change should be carried out in high-latitude ecosystems. Some experimental work along these lines has been carried out. This should be extended to other sites, and with a strong emphasis on interactions among the biogeochemical cycles. An intensive experimental site should be established in the tropics (savanna-forest boundary) and in the temperate zone (prairie-shrubland or forest boundary) in which a full range of measurements would be undertaken. Many of the issues in Tasks 2 and 3 would be best addressed in a study which cuts across a rainfall gradient in the tropics, which ranged from humid tropical forests to semi-arid savannas. Such studies have already been proposed in West Africa and northern Australia, and comparable studies in other tropical and sub-tropical regions are required.
A generalized SVAT model will provide this linkage (see BAHC, Chapter 5.1). The following two tasks are to be jointly developed and implemented with BAHC. Details of these tasks are presented in BAHC (Chapter 5.1).

Task 1. Vertical partitioning of water and energy by the biota.
Task 2. Three-dimensional movement and storage of water in terrestrial ecosystems.

Focus 2
Change in Ecosystem Structure

The three activities in this section constitute the progressive development of a model for predicting the dynamics of composition and structure at the patch, landscape and, finally, regional levels. The relationships between the various models at each scale are illustrated in Figure 3. Emphasis is given eventually to predicting change at the scale of a GCM grid cell. The landscape level fits between the patch and this grid-cell scale (which is equivalent to the regional scale).

Figure 3. Relationship between models of ecosystem change at different scales. Grid-cell size is approximately 100 by 100 km. The patch scale is considered less than 10 km and is usually much less than 100 m. Development of models to translate between these scales will be a major consideration in GCTE in collaboration with IGAC, LOICZ, BAHC, and IGBP-DEA (IGBP 1990b).

Changes in Biological Composition of Species Functional Types and Ecosystem Structure at the Patch Scale.

Changes in climate and atmospheric CO₂ will influence the interactions among functional types of organisms, and hence lead to changes in the biological composition of ecosystems. The manner in which these changes take place is the main research focus of this activity.

Because temperature change will alter global atmospheric circulation patterns, many climatic variables other than temperature will be influenced. From the perspective of ecosystems, changes in temperature seasonality and the seasonal distribution of precipitation, December to February variability, annual total and the sequences of "year types" may be more important than average annual changes in temperature or rainfall. Changes in the extreme values of temperature, or any other environmental factor, are likely to have major effects on ecosystem components and their functioning. Climatic changes will force plant and animal species to respond by genetic adaptation, migration, or extinction (Prentice 1986, Woodward 1987). Changes in the distribution of different functional groups of plant and animal species will confer changes in ecosystem structure (or physiognomy), in the habitat for animal species, and in aspects of ecosystem physiology such as evapotranspiration and nutrient cycling, that are partly determined by vegetation physiognomy and composition. The species (or more practically, functional groups) interact in complex ways to determine the relative abundances of taxa and the consequent structure and function of an ecosystem. Many interactions occur at a fine spatial scale, including resource competition between individual plants on a patch, and succession and gap-phase dynamics (Shugart 1984). Other interactions occur at a somewhat larger scale, through secondary effects of climate-induced changes in herbivores and pathogens on changes in fire or hurricane frequency (Prentice et al. 1989). Changes in episodic events of all types are likely consequences of climate change, both as a direct effect of changes in temperature and humidity, and indirectly through changes in primary productivity, plant physiognomy or tissue chemistry. Any such changes in disturbance will have significant effects on species composition and structure.

Objectives

- To predict the transient dynamics of change in biological composition, in terms of the relative importance of different functional types of organisms, in response to environmental changes at the patch scale including what is commonly known as community dynamics.
- To determine the effects of changes in occurrence and abundance of functional types on ecosystem physiology and possible feedbacks.

This dual focus will be on broad functional types of species identifiable within evolutionarily distinct biotas, and on limited number of species that are particularly important in their own right, e.g., dominant species in species-poor communities, or economically important pests (IGBP 1990b).

Task 1. Classification of functional type
Species functional type classifications will be developed, with the help of guild analyses for major groups of organisms, leading to selection of species for intensive study. Sets of properties must be defined that can indicate functional-type responses to changes in key climate variables, e.g., growing-season temperature, winter minimum temperature, growing-season drought, ET, rooting depth, etc., and indicate the functional-type characteristics (IGBP 1989, 1990a).

Task 2. Characterization of functional type responses to key climate variables and CO₂
Laboratory and field measurements of growth, mortality and reproductive potential of functional types under altered climate and CO₂ conditions need to be conducted in conjunction with experiments in Activity 1. The intra-patch
dynamics of individuals belonging to the major species functional types need to be characterized within a model framework. The sensitivity of these functional types to changes in meteorological, chemical, and pedological parameters will be tested with the model and field observations.

Task 3. Linkages between community dynamics and ecosystem processes

The interactions between ecosystem structure and ecosystem physiology must be determined to achieve the ability to predict ecosystem response to global change. This determination will involve developing the capacity to predict interactions among individuals of similar and different functional types and, consequently, the dynamics of community composition. In turn, this will require field observations and experiments to quantify the effects of organisms on their local environment and on each other (IGBP 1994b); controlled environment and field experiments to quantify the effects of depletion of specific resources on the growth of different types of organisms, and parallel with these experimental efforts, the development of mechanistic models. These will be generalized patch-scale models for vegetation dynamics (IGBP 1990b, Prentice et al. 1989) that can predict such interactions from basic physiological and life-history attributes and physical representations of resource competition. They may involve detailed simulation models based on individual organisms as well as state-and-transition models.

Task 4. Climate-induced changes by fire (in particular) and other disturbance regimes that affect community composition and ecosystem physiology.

Changes in the frequency and intensity of pest outbreaks, herbivore, storms, droughts and fire resulting from climate change can dramatically alter the community composition under certain conditions. Change in fire regimes is a prime example of the climate-induced impacts and ecologically significant phenomena.

Fire is of such importance in determining ecosystem structure and function in many regions that it requires particular attention. The aim here is to develop a generic model of fire effects, with specific attention being paid to changes in fire regimes (i.e., frequency, seasonality, intensity). An associated requirement will be to define and collect appropriate data. Much will come from synthesis of existing information, but new observations and some experiments will also be required. These should be developed jointly with the requirements for Activities of Focus 1, Activity 1 and Focus 2, Activity 2.

Activity 2

Ecosystem Dynamics at the Landscape Level

A landscape is composed of an interacting set of contiguous patches. At this level, structural and functional elements of biotic and abiotic systems combine to create the landscape pattern of interactions. The nature of these interactions at the landscape level includes soil and water movement, biological dispersion/invasions, gaseous transfers, and disturbances (e.g., fire or wind-storms). These processes are typically a function of topography, land cover, the prevailing climatic regime and land use.

Objectives

- **To identify and quantify the landscape-level processes that will change in response to changes in CO₂ climate and land-use.**
- **To incorporate these into a generic model of landscape dynamics.**

Task 1. Development of a generic model of landscape dynamics

This task will combine experimental results and model products from activities on CO₂ effects, biogeochemistry, soil movement, ecosystem structure, and water and energy fluxes. Model output from individual activities will be linked as a series of modules into a model of the system. Ecosystem physiology (Focus 1, Activities 1-3) needs to be linked across patch boundaries via simulation models, which take spatial interactions into account. Disturbance is a critical landscape level phenomenon (IGBP 1989, 1990b), and the effects of fires, droughts, frosts, wind storms, and particular combinations of such events need to be explicitly included (Focus 2, Activity 1, Task 4). The outcome for the landscape model will be dynamically changing spatial patterns driven by combinations of smaller scale functional and structural attributes that specifically are susceptible to global change phenomena.

Task 2. Monitoring and observation

Landscape-level changes in patch relationships will be identified, and quantified as a function of their determinants, by a combination of ground-based measurements and fine-grain spatial and spectral resolution remote sensing by either aircraft or satellite. Landscape attributes should be monitored to include areal extent of ecosystem patches, demographic development of specific patch types, and disturbance incidents in the landscape. This monitoring effort will best be accomplished by using the same representative landscapes from around the globe that are to be used for the experimental areas of the preceding Core Activities (see Focus 1, Activities 1 and 2).

Change in the Distribution of Biota and Regional and Continental Land Cover and Land Use

The main issue to be studied at the regional and continental scale is the consideration of transient dynamics. It cannot be assumed that propagules of adapted species will be available, and that the biota will be able to move (migrate) as dictated by changes in climate. Given the anticipated rates of climate change, it is highly likely that for many species the rate of climate change will exceed their
maximum rates of dispersal. At this level predictions about change in ecosystem composition must take into account the interactive effects of changes in climate and \( \text{CO}_2 \), changes in the nature, frequency and sequences of extreme and rare events, and the rates of change in climatic variables relative to the potential rates of species dispersal. Models will play a fundamental role in studying these transient phenomena relative to changes in community composition. In addition, these effects will be modified by the effects due to past and current land-use patterns and management.

Objectives
- To develop predictive models of change in the distribution of biota, and of land-cover types.
- To monitor the changes in land cover, based on a classification of land-use categories and vegetation functional types.
- To develop scenarios of future changes in land-use, based on integrating the effects of future climate change scenarios and scenarios of changes in human demography, economics and technology.

The first objective will be specifically addressed in this Core Project. The second will be addressed by the IGBP-DIS study on Land-Cover Change (Chapter 9). The third lies outside the expertise of the IGBP, and it is hoped that this requirement will be taken up by IGBP’s counterpart programme on Human Dimensions of Global Change, in close collaboration with IGBP scientists. In Focus 3 of this Core Project, the agricultural issues are dealt with, and special attention is given to the global effects on yield and management practices of agroecosystems. The additional technological developments and commodity/supply issues go beyond the scope of this Core Project. Therefore, scientific programmes or studies underlying these models will be treated in the later development of the Core Project proposed for agroecosystem research.

Task 1. Develop a functional classification of global vegetation types
This task must be developed in conjunction with the IGBP-DIS study on Land-Cover Change (Chapter 9). The prime need is to define the vegetation attributes (e.g., albedo, evapotranspiration, surface roughness, biomass/primary productivity, seasonal \( \text{CO}_2 \) uptake and decomposition) that indicate functional change in vegetation in terms of global change objectives. A classification scheme needs to be developed on the basis of these attributes. An early requirement will be to decide on the degree of difference that is considered significant. Development of this classification scheme will be developed in concert with IGAC (Chapter 2.1) and BAHC (Chapter 5.1).

Task 2. Predicting changes in functional type distributions at the regional or continental scale
Since this task addresses issues related to understanding the causes of the distributions of animals and plants on regional or even continental scales, the first step is to develop correlations between the distributions of species and various limiting environmental factors. Fundamental to understanding the current and future distribution of the biota is the assessment of the dispersal abilities of species (or functional types of species) of interest. These analyses are profitably done on the edges of a species’ range or in transition zones. Once correlations are established, experimental studies to determine the cause-effect nature of the correlations should be undertaken. The variety of experiments that are necessary is extensive and cannot be discussed here. However, the simplest studies are likely to involve elucidation of abiotic relations to key processes of the organism’s life cycle such as mortality or reproductive capacity. Determining the limiting effects of species such as pollination, parasitism, or predator-prey relations is more difficult but no less important.

Development of predictive, correlative models will be an important component of this activity. Modelling work should aim towards a scaling-up from the mechanistic landscape-scale models developed under Focus 2, Activity 1 to the scale of regions and continents. Just as the scaling up from patch-scale models (Focus 2, Activity 1) to the landscape (Focus 2, Activity 2) involves incorporating new processes (spatial interactions between patches), so scaling up to regions includes other processes (e.g., long-distance dispersal of organisms between distant phenomena relative to changes in dispersal capacity of organisms must be reduced to the basic minimum in this level of models (IGBP 1990b, Prentice 1986), but the representation of dispersal is crucial. It seems likely that rare, long-distance events are important in the climatically induced migration of taxa (Prentice 1986), so these must be considered in the model design.

There are three basic approaches to achieving the modelling of this task:
(1) Correlative models. The approaches of Box (1981), Emanuel et al. (1985), and others need to be developed further and used to obtain rapid, first-cut, continental-scale predictions of change. For vegetation, many models exist that purport to predict the distribution of vegetation types by using simple climatic variables as model inputs. These extant models need to be assessed to determine whether or not the vegetation types that are predicted are useful for inferring a variety of ecological processes, such as net annual primary production, or presence or absence of an animal species. The major disadvantages (e.g., lack of transients) are dealt with in detail in IGBP (1989, 1990b) but the models will be of value in indicating areas of likely major change.

(2) Mechanistic, plant-by-plant replacement models, of the FORET type (Shugart 1984) expanded to be spatially explicit and to include spatial dynamics. These are powerful models and could meet the objectives of the project. Their major disadvantage is the amount of information required to run them. It will take a long time before they can be applied to all regions of the world to produce underlyng vegetation coverages at a level of resolution at which they are needed.

A variation of this approach is the use of matrix transition models, such as the FATE (Functional Attributes in Terrestrial Ecosystems) model of Moore and Noble (1990), which is an extension of Noble and Slatyer’s (1980) attributes model of change, involving many spatial units (see IGBP 1990b).

3) State-and-transition models. These are essentially rule-based models, using existing knowledge and understanding of vegetation dynamics. For the purposes of this project, they would require a classification of the present land cover into a number of essentially different vegetation types, or vegetation mosaics, each of which is then further defined in terms of a limited number of possible states in which they can exist. These states are defined in terms of the project objectives, on the basis of what is currently known about vegetation dynamics. The conditions which give rise to a change from one state to another are then cast in the form of rules, in a state-and-transition model.

The disadvantage of this approach is that it is imprecise and non-quantitative. However, it will allow for a rapid assessment of regional vegetation change, based on mechanisms that are known to be important in regard to global change phenomena. In addition, ecosystem attributes that can be remotely sensed will be especially useful for addressing this activity. Without remotely sensed data the regional and continental scales of resolution cannot be adequately addressed. While remote sensing is by far the most time and cost effective way to obtain data relative to this activity, there is considerable need to develop new ways to analyze images and to produce different kinds of images so that relevant ecosystem data can be obtained. The current “state of the art” in remote sensing leaves much to be desired from the perspective of estimating ecosystem structure and functioning and determination of species’ distributions. Investigations are underway to overcome these deficiencies through the IGBP Land-Cover Study (Chapter 9).

Task 3. Testing models against historical data
The palaeoecological record provides a means to test models that predict vegetation cover or taxon distributions at a broad spatial scale. Global changes during the Holocene (c. 20,000 years) have included the appearance and disap-
pearance of large-scale assemblages of plants and animals that have no modern
counterpart (e.g., open forests with certain boreal trees and steppe elements in
the eastern USA, Webb 1987, "disharmonious assemblages" of animals in North
America), which can be explained by prevalence of climatic conditions with no
equivalent in the present. "No-analogue" biotic assemblages are thus just as likely
to occur in the "greenhouse" world. Models should be able to predict their
occurrence, palaeoecological data provide a best test of whether they can.

Simulations of climates during the Holocene can be compared with the
distribution of terrestrial communities (e.g., COHMAP Members 1988) and,
unlike the future case, these scenarios can be checked and improved against
independent palaeoenvironmental evidence. Past climate scenarios can then be
used as input to the models, the predictions of which can be compared with the
continental record of past vegetation that can be pieced together from pollen and
macrofossil analysis (COHMAP Members 1988). The Core Project on Past Global
Changes (PAGES, Chapter 7.1) builds on the work of COHMAP by providing
improved palaeoclimatic scenarios and continental-scale syntheses of data on
vegetation and plant and animal taxon distributions at key times during the
Holocene, for use in testing and improving large-scale models.

The palaeoecological record will also be crucial in developing large-scale,
mechanical models incorporating dispersal. Past migration rates can be inferred
(e.g., Davis 1981). These rarely represent maximum rates (Prentice 1986), because
climate has rarely changed as fast as it is expected to during the next 200 years,
but nevertheless any model must be able to produce migration rates at least as
fast as those seen in the past. Further, when supplied with scenarios of past
climate change, models should be able to simulate the actually observed migrati-
on patterns of taxa across continents.

Global Change Impact on Agriculture and Forestry

The world's ecosystems constitute a continuum from virtually pristine to inten-
sively managed and highly modified systems devoted to some form of produc-
tion. Agroecosystems represent the latter end of this continuum. The risk
imposed by human-induced global change presents us with both the most urgent
requirement for understanding and evaluation. Such scientific knowledge is
essential in any attempt to develop proper management schemes and a socio-
economic evaluation of the consequences. Although many ecosystem processes
operate over the entire continuum, the IGBP needs to focus on the study of
agroecosystems. The research priorities identified in this focus concentrate
on yield of the major crop, forest and livestock species, and key factors which
affect harvestable products.

Agroecosystems around the world share a number of common characteris-
tics, which make practical an integrated research focus to study the impact of
environmental change on agroecosystems. It is recognized that the intensity of envi-
ronmental change is contingent on the way climate and land use affect various
ecosystem and landscape characteristics. Thus, some of the tasks outlined for
each activity may have to be adapted to specific agroecosystems, while maintai-
ning the ability to integrate information across systems. Other national and
international organizations are addressing similar questions (IBSNAT, CGIAR,
FAO, and others). This focus must complement these programmes while attaining specific IGBP research goals for agroecosystems.

It is necessary to identify those key elements of agroecosystems for which
understanding is paramount. The Core Activities required involve monitoring,
experimental research, and modelling. Monitoring is required for direct assess-
ment of change, in order to test hypotheses about change and to obtain informa-
tion in order to generate new hypotheses. Modelling will allow prediction of
the net effect of several concurrent changes, and allow understanding to be integra-
ted across systems. The model structure should offer the means for integrating the various impacts of climate change and will be an
important guide in the development of research and data needs. Models
developed for this focus will differ from those in the other Foci, because of the
inclusion of management and the importance of production and yield of harve-
stable products.

Each of the Core Activities addresses some aspect of developing the
capacity to predict the outcome of global changes on agroecosystems in terms of
production of food and fibre, quality of the land resource, or the distribution of
species. Many of the issues important for agroecosystems are addressed by the
other Foci. Soil-related activities are important in all three Foci, but because of
their overriding importance to agroecosystems, they are most fully developed in
this focus.

In this initial phase of research, the focus is on monoculture agricultural
crops, livestock and forests. As the IGBP develops this focus, further planning
will be carried out to specify research needs for additional aspects of pastoral
systems and for mixed crop/forest/livestock systems and the possible advantages
of a separate Core Project on "Global Change Impacts on Agriculture and
Forestry" will be evaluated.

Effects of Climate and Atmospheric Change

on Key Agromonic Species

The primary question is what will be the direct and interactive effects of changes
in climate and atmospheric composition on selected agromonic plants and
animals, and on the yield of harvested products.

Changes in climate and atmospheric concentration of CO2 and pollutants
acting singly or interactively can influence production of crop, forest and
livestock species (IGBP 1998b). It is necessary to identify the impact of changes
in temperature, humidity and rainfall and atmospheric composition on growth
and yield of crop and forest species and on the growth, fitness and reproductive
capacity of livestock.

Given this information, base-management options, such as selection of
adapted species, may be implemented. Implementation must incorporate
understanding of the interactions across the plant-soil-atmosphere contin-
num. For instance, selection of plant species is based on above-ground yield,
which in turn is related to water-use efficiency. Change in the concentration of
CO2 and climate may change root/shoot and carbon/nitrogen ratios, which will
affect yield and has implications for decomposition processes and the long-term
quality of the land resource.

The key issue is the effect on yield and sustainability rather than on biomass
or primary productivity of plants. A slowing in the rate of flower development
in sorghum with CO2 enrichment (Marc and Gifford 1985) may impact yield if
combined with a changing abiotic environment. Understanding temperature
effects on crop plants is also critical. Corn yield for instance, may be impaired by
high temperatures during the brief period of pollination (Walker et al. 1989).
It has been shown that climate and atmospheric changes each separately will have
an effect on species (Warrick et al. 1986b), but we know little about their potential
interactive effects. Experimental research consistently demonstrates that eleva-
ted CO2 may, with optimal abiotic conditions, act as a fertilizer for crop and forest
species (Shugart et al. 1986). However, changed climatic conditions will modify
the effects of enhanced CO2 on plants (Warrick et al. 1986b). Increasing tempera-
ture, for example, will generally increase respiration more than photosynthe-
sis and may counteract higher CO2 uptake due to CO2 increase. Furthermore, an
increase in atmospheric CO2 interacting with climate will have an effect on
areal yield of crop plants, which may be different to the overall effect on primary
production. In the case of forests, it is the effect on timber yield which is of prime
concern. Interactive effects of water and temperature are primary determinants of
regrowth processes of trees, and of production in commercial forestry.

With regard to livestock, temperature change may have the greatest direct
effect on animal net production, mortality, fecundity and milk production.
Higher temperatures could reduce fertility in sheep in some areas while an
increase in summer rainfall could promote the incidence of footrot and fleece rot
in other areas (Walker et al. 1989).
Objective

- To understand the effects of climatic and atmospheric changes, singly and interactively, on major crop, forest and livestock species.

There are three main tasks related to species which have been or will be targeted as critical agroecosystem species (IGBP 1990b).

Task 1. Develop an understanding of the effects of climate change on crop and livestock species.

The effects of climate change will include single and combined effects of changes in temperature, precipitation, soil moisture regimes, and solar radiation. This task involves identification of those species which are critical and which may be seriously impacted by the direct effects of climate change. The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) has identified eleven such species or groups of crop plants (aroids, barley, cassava, dry bean, maize, peanut, potato, rice, sorghum, soybean and wheat). Additional crops have been identified as important and are suggested for inclusion within this activity (IGBP 1990b). These include: bananas/plantains, sugar cane, grain legumes, oil seeds, root crops, vegetable and fruit crops, fibre crops, and industrial crops. An equivalent list of tree species needs to be developed for the major, commercially important forest production regions in the world. The list of livestock species that will be influenced by climate change is quite long. Priority attention should be focused on the major breeds of cattle and sheep. A survey of species production at their biological limits for each of these abiotic parameters must be conducted to provide information about changes which might be expected.

Modelling of plant and animal species at the climate imposed physiological limits of spatial distribution will be required to integrate information, develop a classification of the types of responses which might be expected for extension to species not yet investigated, and to link information to the full agroecosystem. IBSNAT models of key species provide the basic format for crop plant species. Appropriate models for tree and animal species must be developed. Such models should be linked to GIS systems to evaluate their future potential distributions in relation to climate and soil.

While the direct effects of climate change on livestock may be significant, the greatest changes in livestock production from the extensive pastoral regions of the world will more likely be a result of changes in rangeland production and composition. Much of the basic understanding required for predicting these changes will come from the research in Focus 1 and 2. However, there is an additional need, to meet the requirements of this task, to specifically address the changes in productivity or grazed rangelands, and the dynamics of the functional composition of rangelands. This work needs to be closely integrated with that proposed under Focus 2. It should be focused on sites representative of selected, major rangeland types (see IGBP 1990b).

Task 2. Determine the impact of climate change on the physiology of plant development

With regard to agricultural plants this task requires a basic understanding of the environmental and genetic control of plant development. The primary impact of climate change on a crop will depend on the stage of plant development and the rate of change from one life stage to the next. The environmental and genetic control of development is not understood for most grain and fruit crops (IGBP 1990b). This understanding of the relationship between the genetic control of development and environment is necessary to determine the flexibility of species to accommodate production under changed conditions, and to determine the modified conditions or areas which are required for continued production.

The main requirement is for controlled experiments under field conditions. Selection of plant species for inclusion in the experiments should be drawn from those grain and fruit crops identified as critical for world food production. (IGBP 1990b).
pest or disease vector. These functional characters should be applied to other less-studied organisms in each category to determine which organisms should receive the highest priority for research.

Activity 3 
Change in in situ Properties, Redistribution and Net Loss of Soil

In common with other ecosystem components, soils have variables that operate at slow, intermediate and fast rates. It is important to recognize this, and the fact that these variables may not always move soil properties or development in the same direction. Many soil properties are highly dynamic, whereas others are relatively static. Soluble salts are examples of highly dynamic variables, changing over a season and capable of approaching equilibrium in a few years. Organic matter levels have a time dimension of decades to centuries, while carbonate and (particularly) clay weathering have a scale of millennia in semiarid climates (Anderson 1977). Despite a medium time-scale for organic matter build-up in soils, at another level of detail one can differentiate fast (mainly microbial processes), intermediate (where turnover is dampened by physical sorption to clay), and slow (or chemically-stabilized) changes in humus components in soils (Anderson 1979, Jenkinson and Rayner 1977). Episodic events that initiate a threshold response in soils result in considerable change in properties over short time spans. In this respect, soils must be considered as being highly dynamic, and land use and climatic changes may significantly modify the rates of these processes.

Consequences of changes in climate and land use on soil processes and properties include:

- Carbon accumulation and distribution in the soil. Most of the changes associated with a change in atmospheric CO₂ concentration and climate will impact on soils through the amount, distribution, concentration of plant biomass above- and below-ground. These changes will alter the rates of plant decomposition and in combination with any observed moisture effects will alter the distribution of organic C, N, P, and S in soils. It also can alter the availability of organically held nutrients that are normally released over a season by nutrient cycling processes.
- Soil water supply and the ability of the soil to sustain the growth of crops. These will involve changes organic matter content, water holding capacity, and changes in soil surface characteristics as compaction, which will affect permeability and water infiltration.
- The distribution of salts, other soluble components and nutrients. These will result mainly from changes in the hydrological cycle (e.g., accumulation of salts, leaching of nutrients, leaching of soluble organic components, clay migration and other pedogenic processes). The consequences of changes in these highly dynamic processes can become evident in a few years.
- Soil erosion, which includes accelerated wind and water erosion of croplands. Managed areas are particularly susceptible because changes in land use, such as changes in canopy cover and surface soil protection, and in carbon inputs and distribution. In general, these changes make soils more vulnerable to erosion.

Objective

To develop the capacity to predict the effects of changes in climate and atmospheric composition on the quality of land through changes in situ soil processes and in soil erosion.

Task 1. Changes in soil processes resulting from climate and land-management changes.

Soil modifications resulting from climatic and land-use changes in non-agricultural as well as agricultural and forestry systems will require: (i) comparative analyses of soils along existing temperature and rainfall gradients (longer term effects); and (ii) manipulative experiments in which chemical, physical and biological processes are measured under different temperature (if possible) and water regimes. These studies should complement those outlined in the previous POCI.

The soil changes which need to be examined (as based on the UNEP/ISSS workshop, February 1990) include: (i) amount and quality of organic C, N, P, and S; (ii) structural stability and moisture characteristics; (iii) nutrient status, availability and redox regime; (iv) salinity and nutrient availability; and (v) iron and aluminum amorphous minerals.

Task 2. Soil erosion and redistribution of soil in response to changes in climate and land management.

The work required for this task involves specific attention to the interactive effects of changes in rainfall regime and land-cover characteristics, including changes in vegetation cover resulting from climatic changes or agricultural management activities. Erosion rates are far higher where the original vegetation cover has been removed or where the soil surface has been disturbed.

This task requires the development of a geomorphological, mechanistic model based, in turn, on a GIS for intensive study areas and, in coarser detail, continents. Information required includes: (i) climate-change scenarios and local climate/weather simulations from WCRP and others; (ii) land-cover change predictions from Focus 2, Activities 1-3; (iii) land-use change predictions from Focus 2, Activity 3; and (iv) hydrologic change predictions from BAFIC and Focus 1, Activity 3 (Fig. 1). Remote-sensing will be necessary in this task, firstly to provide information to develop and test erosion models (e.g., Pickup and Chewings 1986), and secondly to initiate a monitoring system designed to detect trends in the selected regions.

The information produced in Tasks 1 and 2 can be integrated by means of generalized agroecosystem models, which include information on driving variables, processes and properties (e.g., Parson et al. 1987, 1989). Processes already studied and integrated into models include above- and below-ground primary production, decomposition and nutrient cycling. Major driving variables include climate (temperature and water), parent material (soil texture), base status, total S and P, topography and management. The effects of these controlling factors can be expressed over a broad spatial scale from the global to the regional, landscape or field plot levels.

Two main approaches are available for this purpose: (i) analogue studies using soil chronosequences or using situations where (e.g., due to deforestation, mine reclamation studies, volcanic areas, etc.), local soil climate has changed, and (ii) manipulation studies (e.g., elevated CO₂) in the field (small chamber, small water body), greenhouse or laboratory.

Other approaches are given in. "Methods of Soil Analysis", American Society of Agric., v. 1 & 2, Tropical Soil Biology and Fertility Programme of IUBS (Ingram and Swift 1989). Processes which are important in elemental interactions and which are important for soil quality have recently been reviewed (Anderson 1988, Stewart and Cole 1989).

The work on processes needs to be developed in conjunction with soil process models. Models have been developed to understand the functioning of agroecosystems in relatively young unvegetated soils. These models can be used to simulate the effects of a range of climatic conditions on productivity and soil quality. Extrapolation of this approach to more weathered soils will depend on a better understanding of several major processes, including the effect of soil inorganic constituents and selected minerals on abiotic and biotic formation and stabilization of organic matter.

General

Implementation

The implementation of the Core Activities will be phased according to the logical sequence of information transfers between tasks and activities, and (pragmatically) on gaining support from the scientific community, national and regional support for the specific tasks and the establishment of cross-activity linkages. Monitoring progress of the Core Project must be explicitly built into the implementation plans of each task.
The Scientific Steering Committee (SSC) will facilitate coordination of tasks among the activity or focus of responsibility (e.g., ensuring that variables being measured, time intervals, levels of accuracy, etc., are compatible between tasks and allow for the activity as a whole to come together). Occasionally, a task working group may be formed to work on a specific topic or methodology for the Core Project. These task working groups will have defined life times and will be disbanded once the objective is achieved.

### Core Project Office

The CPO will serve as the base of communication between activities and other projects, where this is needed. Activity offices will also be identified, and much of the coordination of the research would be conducted at this level. The core activities are the operational units of the project, and as such are the most important.

### Meetings and Initiating Workshops

The initiation of the Core Project depends on its acceptance by the scientific community and the ICGBP member nations. An Open Meeting of scientists from the member nations, ICOS bodies, and other associated organizations will be arranged in March 1991 to formulate an implementation plan.

In addition to the Open Meeting, a series of regional and national presentations of the Core Projects and Activities will be conducted at pertinent scientific society meetings. These presentations, based on a package of visual aids, are necessary to ensure acceptance by the community of ecological scientists.

Following the Core Project Open Meeting, it is planned to hold an initiating workshop for each Core Activity, to which all National Committees of ICGBP will be again invited. The workshops will be organized and run by the Core Activity leaders, in association with the Core Project Office, and will be aimed at refining priorities, setting targets, selecting areas, identifying research groups and agreeing on broad methodological approaches and research products.

### Progress Assessment

A mid-term check of progress of this Core Project is proposed for April 1994. A workshop to make an intercomparison of modelling results from all scales of the project will be held. The workshop will enable participants from various research groups to compare field and model results through model validation and verification comparisons. Progress assessment and identification of gaps in the operational aspect of the Core Project will be made. Means for assessing progress of specific tasks will be developed at the initiating workshops, planned for each task.

### Other Workshops

A number of developments will require specific workshops. One example is the need to bring together social scientists and ICGBP scientists to plan and initiate a project on predicting changes in land-use.

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6.2 Global Change and Ecological Complexity (GCEC)
A Potential Core Project

Objective

- To develop a capability to predict the relation between global change and ecological complexity. In this context, global change is defined as changes in land use, atmospheric chemistry, and climate. Ecological complexity is understood to be a function of genetic, alpha, beta, and patch diversity ranging from genetic variation at the individual population level through diversity of functional types of species to regional community complexity.

There are two as yet untested hypotheses relating to the effects of global change on ecological complexity that are potentially very important.

- Changes in species diversity lead to changes in ecosystem function, such as, productivity, nutrient cycling, and response to disturbance.
- Genetic variation is necessary for species survival in a variable environment; if variability drops below a certain threshold, species survival is endangered.

The question of the level of species redundancy in ecosystem species composition is at the core of the first hypothesis. However, some key species and habitats may regulate ecosystem function and dynamics, and already some such have been identified. If genetic variability does influence species vigour, a change in diversity involving such species and communities will have a significant effect on ecological complexity.

A significant change of biological/ecological diversity may have already occurred because of the fragmentation of habitats. This existing pressure in combination with the anticipated rapid climate changes constitute a potentially serious threat to ecosystems. For some systems, e.g., stranded mountain-top relics, the probable effects are obvious. However, for other systems the effects that may occur as a result of climatic changes are not so obvious.

There are two important questions that need to be answered before the IGBP can proceed with an active research project.

- What kinds of diversity (genetic, populational, community) in which kinds of ecosystems are ecologically important?
- What will the likely effects be of global change, land-use and climate, on the diversity of those ecosystems (genes, species, communities) if diversity is of vital importance?

An analysis of the existing data is needed to examine these questions in detail and to better define the research problem. It is proposed that SCOPE and IUBS undertake an initial analysis as a first phase of this potential IGBP project. Based on the outcome of this analysis, a science plan may be developed.
What Significant Climatic and Environmental Changes Have Occurred in the Past, and What Were Their Causes?

Changes in the past global environment are recorded in natural archives of many kinds: ice cores, ocean and lake sediments, tree rings, pollen and coral deposits. Analyses of such records have provided much of what we know of past climatic change and its effects. For example, pollen records have allowed us to deduce the effect of climate change on the distribution and composition of terrestrial ecosystems during a glacial cycle. Variations in concentration of gases trapped within polar ice cores provide evidence for change in atmospheric conditions through the last ice-age cycle of 160,000 years. This record indicates that variations in the atmospheric carbon dioxide content and average global temperature are linked, but in its present form cannot be used to infer cause and effect. It does, however, demonstrate the bounds for the extent and rate of such natural changes, and, importantly, it provides a context against which the measured record of carbon dioxide abundance over the last three decades can be interpreted. A continued and focused effort in examining the information available in natural archives will provide us with a unique data base for the periods in the Earth's history when human influences were absent and will also highlight past periods when humans started to perturb the global system.
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In foretelling global changes of the future we are faced with questions which can be answered only through a better knowledge of the past. For this purpose we need to know not only the history of climate per se, but also the related changes, be they causes or effects, in the entire Earth system. These include the chemistry of the air and the water and the soils, the state and distribution of vegetation and marine biota, and the level of the oceans and their mode of circulation, to mention but a few.

In seeking and interpreting these data we must be aware that the Earth system is never in a state of absolute equilibrium. As an example, the last stages of transition from a glacial to the present interglacial state occurred only about 10,000 yr ago, a reach of time which is of the same order of magnitude as the mean residence time of ice in the Greenland and Antarctic ice sheets (even though the deepest ice is an order of magnitude older). The polar ice sheets may thus be yet approaching their interglacial state, such that rates of accumulation and ablation are not in balance, with resultant changes in world sea level.

Secondly, the Earth system is continually changing, due to natural processes. Global surface temperature, for example, varies considerably from year to year and from decade to decade, in reaction to external forcing or through internal oscillations of the atmosphere-ocean system. These natural changes are of both short- and long-term. Thus, the instrumental global temperature record of the last 100 yr must be interpreted in the perspective of the natural variations of a much longer span, which include, in the last 1000 yr, the probably global Little Ice Age (ca. AD 1500-1850) and the preceding Medieval Warm Interval (AD 1000-1200). It thus becomes a matter of some urgency to improve our knowledge of these past events, and to identify their causes. Similar natural variations may well be superposed on any current global warming trend; knowledge of these forcing mechanisms and their effects are necessary to quantify anticipated warming due to the enhanced greenhouse effect.

There are many lessons to be learned from the remarkably steady rise in \( \text{CO}_2 \) found in atmospheric samples taken from around the world. Each year about 1/3 of the \( \text{CO}_2 \) in the atmosphere is exchanged with the biosphere and with the oceans. A yearly imbalance of but 1/3 between the flux of \( \text{CO}_2 \) into and out of the atmosphere would fully account for the observed upward trend. Measurements of air drawn from polar ice cores show: (i) a relatively constant concentration of atmospheric \( \text{CO}_2 \) through the millennium that preceded the Industrial Age; (ii) an increase in the 19th century; and (iii) a steeper increase in the current century. Measurements of \( \text{CO}_2 \) taken from polar ice yield abundances for the period 1960-1970 that overlap with those from air samples taken during the same period. Hence, there can be little doubt that the ongoing increase in atmospheric \( \text{CO}_2 \) is due to anthropogenic emissions. The ice core studies also show that during certain periods the \( \text{CO}_2 \) exchange fluxes were not in balance, leading to changes in atmospheric concentration. The ice-core drawn from the Antarctic Vostok station, covering the period of the last 160,000 yr, demonstrated that both \( \text{CO}_2 \) and \( \text{CH}_4 \) varied in step with temperatures derived from isotopic ratios in the ice itself. This finding is important in several respects. It implies that changes in greenhouse forcing, associated with \( \text{CO}_2 \) and \( \text{CH}_4 \) fluctuations, played a critical role in the climate change of the last two glacial-interglacial cycles. It also raises fundamental questions as to how the atmospheric concentrations of these gases are controlled. The observed fluctuations in \( \text{CO}_2 \) are most likely due to changes in the vigor of the biological pump in parts of the surface ocean. The changes in
Figure 1. The record of global changes during the past 150 years. Curves a-b, reconstructions of atmospheric CO₂ and CH₄ concentrations based on the analysis of gas trapped in ice collected at Byrd Station, West Antarctica (from Stauffer 1988). Present concentrations are 345 ppmv (CO₂) and 1.7 ppmv (CH₄). Curves c-d, records of global mean annual temperature (from Hanson 1989) and sea-level changes (from Barnett 1988). In both curves, the average value for the period 1951-1970 is set equal to zero, with data reported as deviations from zero; the dashed lines are annual mean values and the solid line, a 5-year running mean.

CH₄ are fundamentally different; they are probably the result of changes in source terms, as for example, from a change in the amount of wetlands, although changes in the oxidizing capacity of the atmosphere, which controls the natural destruction of CH₄, cannot be excluded. Furthermore, it reveals that with anticipated global warming, we can expect feedback effects involving processes similar to those which took place in the course of past climatic changes.

An unexpected finding from polar ice cores was that between 70,000 and 30,000 B.P., the climate of Greenland and probably of the entire North Atlantic region oscillated, back and forth, about a dozen times between colder and milder climate states. Not only CO₂, but all the parameters measured thus far, including airborne dust, appear to follow the same natural oscillation between two distinct climatic states. The last of these events occurred during the last glacial-interglacial transition and coincides with the Bolling-Allerød warm phase, determined by pollen studies in peat bogs. What followed was a rapid cooling, found in continental records, that is known as the Younger Dryas cold period. At about 10,000 B.P. the Younger Dryas drew to a sudden end, marking the final transition to the contemporary, warmer Holocene Period.

These climatic changes of the glacial-postglacial transition are related to changes in the extension of the cold region of the North Atlantic ocean, as derived from ocean sediment studies. This observation reveals the sensitivity of the North Atlantic region to ocean circulation changes. It has been speculated that the abrupt climatic changes during the glaciation and at its end are due to a switching on and off of deep water formation in the North Atlantic ocean (Broecker and Denton 1990). Regional and global responses of vegetation to these climatic changes can be readily identified in, for example, pollen information in peat bogs and in laminated lake sediments.

**Rationale**

Data concerning previous environmental conditions are available from instrumental records and documentary histories, as well as from the information preserved in natural archives of many types, including ice cores, marine, lacustrine and terrestrial sediments (loess deposits, in particular); tree rings; corals; and palaeosols. Studies of the physical, chemical and biological parameters recorded in such archives have provided a wealth of information on both the "natural" behaviour of the Earth system and on more recent human impacts. Quantitative information on global changes of the past can be used to document forcing factors and to understand the large-scale responses to such forcing mechanisms; to place observed trends in contemporary data into a broader context; to identify unknown and potentially important processes that link biological, physical and chemical components of the Earth system; to test hypotheses regarding these linkages; and to evaluate the validity of analytical Earth system models through sensitivity studies and detailed comparisons of simulated behaviour with changes reconstructed from palaeodata.

Insights from global changes of the past have already enhanced our understanding of changes in atmospheric composition, albedo, landscapes and land-use, global biomass and biogeochemical cycles, the mixing rate of the ocean, solar modulation of cosmic radiation, and the magnitudes and rates of environmental changes associated with glacial-interglacial climatic cycles (Bradley 1980). Much of the evidence for human-induced change and all of the evidence for past changes resulting from natural forcing are drawn from records of the past. Natural archives of past environmental conditions provide important clues about Earth system processes, and help focus research activity on key questions concerning forcing functions and system responses. Parameters such as albedo, atmospheric greenhouse gas and aerosol concentrations, and the distribution of types of vegetation derived from palaeodata are needed to fix the primary boundary conditions used in model simulations of climate and to perform model validation tests.

The recovery and interpretation of historical and proxy data, including the development of tools and techniques, have been traditionally done through individual or single-laboratory efforts, employing an often specialized technique to examine typically regional or continental records that cover an often
limited temporal domain. The emergence of an integrated Earth system science calls for a much fuller knowledge of the past, in both space and time, and for data sets that are drawn as composites from different efforts and disparate techniques. Concerns of impending climate change impose a sense of urgency in this endeavour.

The PAGES Core Project has been developed to respond to these needs through a set of coordinated activities that address key scientific questions through specific research tasks. It will enlist the intellectual efforts of scientists and technicians of many nations, employing the full spectrum of techniques to recover and interpret the past record of global changes. It will also require a significant increase in the level of human resources that are now being applied to the problem.

**Organization**

Focused research will be carried out in four general activities. The first three address fundamental Earth system processes for which palaeodata are of particular value. The fourth is an all-pervasive effort in coordinated data collection that supports the other three. These activities are: (i) Solar and Orbital Forcing and Response, (ii) Fundamental Earth System Processes, (iii) Rapid and Abrupt Global Changes, and (iv) Multi-Proxy Mapping.

As described below, specific research tasks within each activity are further divided into one of two streams of temporal emphasis: Stream I tasks will focus on the last 2000 yr of Earth history; Stream II tasks will address the general period encompassing the glacial-interglacial cycles of the late Quaternary.

Three cross-project needs are also identified which are common to each of the research activities. These are: (i) The development of analytical models of the palaeoenvironment, including climate, ocean circulation, ice flow, vegetation, hydrology, biogeochemical cycles, and of the coupled Earth system. (ii) The improvement and modernization of the technology that is employed in recovering and interpreting data from natural archives. (iii) The management and dissemination of palaeodata, including both existing information and the new data that will be obtained through activities of PAGES and other relevant efforts.

The organization of PAGES into four research activities, further divided into two streams of temporal emphasis, is shown in Figure 2. A fuller description of the specific research tasks that are included in the matrix, and more specific information on each of the cross-project needs, is given in the sections describing the Core Activities. Additional background regarding the needs and rationale of the PAGES project may be found in Eddy and Oeschger (1989).

**The Two-Stream Approach**

The two temporal streams of PAGES define periods of special importance in understanding anticipated global climatic changes of the next 50-100 yr. The first will concentrate on shedding new light on the fixed period of most recent and most relevant change; the second will focus on the processes that have driven the glacial-interglacial cycles that have dominated Earth system history in the last several hundred thousand years. Although the two streams concentrate on periods of Earth history that are very recent in geologic terms, data and insights from the more remote past are also needed to define the background on which more recent changes are imposed, and to illuminate the more fundamental processes that link elements of the Earth system. Research elements of the project will specifically include the study of earlier Earth system history, as an additional source of information relevant to the study of more recent and more rapid changes.

**Earth History During the Past 2000 Years (Stream I)**

Stream I will endeavour to improve, significantly, our understanding of the history of the Earth system over the past 2000 yr, through the documentation of changes in the physical climate system, air and ocean chemistry, and conditions in the biosphere. The chosen period is that of man’s greatest impacts on the planet and the era of significant overlap between written records and the environmental information stored in natural archives. A better understanding of the climatic fluctuations that occurred during this period (such as the Little Ice Age and the preceding, Medieval Warm Interval) can be expected to 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; 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
will provide a Rosetta stone which can be used to validate and interpret data
obtained from natural archives of the much more distant past.

**Objective**

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

Individual tasks will concentrate initially on critical time periods, specific
regions of interest, or parts of the globe for which multi-proxy data are particu­
larly needed and presently inadequate. Results of Stream I research will provide
the data necessary to establish a detailed baseline of natural change, to measure
human impact, to calibrate and quantify environmental signals from the more
distant past, to elucidate the connections and phase relationships between
biogeochemical and climatic changes, and to validate numerical models of the
Earth system and explain the primary forcing mechanisms for the various
responses that are documented, using models to test hypotheses.

**Key scientific questions**

Research in the Stream I time domain will focus on a set of pressing unsolved
questions, which include the following:

- What were the causes of decadal and interannual climatic variations of the
  past?
- Were the Medieval Warm Interval and Little Ice Age global events? Were the
  responses synchronous and the amplitudes comparable in the Northern and
  Southern Hemispheres? What were the relevant forcing mechanisms? Were
  these events accompanied by changes in atmospheric \( CO_2 \) and \( CH_4 \)? If so, what
  were the causes of such trace gas changes? What were the phase relationships
  between those changes and surface temperature?
- How have landscapes changed during the past 2000 yr? What are the causes
  of such changes?
- How can responses to anthropogenic impacts on the Earth system be distin-
  guished from those induced by natural forcing mechanisms? How can forced
  responses be distinguished from natural system variability or internal insta­
  bility?
- How can we improve the record of human-induced vs. natural changes in
  atmospheric \( CO_2 \), \( CH_4 \) and other trace gases?
- What quantitative palaeoenvironmental information is recorded in the va­
  rious natural proxy records?

**Glacial-Interglacial Cycles in the Late Quaternary (Stream II)**

The Stream II focus is on understanding the dynamics that cause glacial­
interglacial variations, as well as the interactive feedbacks among various
components of the Earth system that control the response of the system to
climatic forcing.

**Objective**

- 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 purposes are to understand both the causes of change and the way the
Earth system functions during times of glacial maximum and minimum condi-
tions; to document the onset and nature of the transitions from warm to cold and

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**Figure 3.** Examples of Stream I data records. Curve a, raw values (thick curves) and
standardized indices (thin curves) of maximum wood density for spruce and fir trees from
the Alps (top) and for pine trees from northern Scandinavia (bottom). Annual data have
been smoothed with a low-pass filter; dotted and hatched portions have been corrected
(from Schweingruber et al. 1988). Curve b, corresponding time-distance diagrams of
glacier margin fluctuations based on historical and geological data for glaciers in the
Swiss Alps (Lower Grindelwald Zumbuhl et al. 1981; Rhone and Rosenlaui, Zumbuhl
and Holzhauser 1988) and in southwestern Norway (Nigards breen and Austerdals­
breen; Grove 1988). The termination of the Little Ice Age around 1860 A.D. is evident
(from Broecker and Denton 1989).
Heimuguon loess section, Loess of modern analogue for fossil pollen assemblages (from Guiot et al. 1989). Changes (expressed as deviations from modern values) for La Grande Curve (from An et al. 1990). Curve a, July insolation at 65°N (the Milankovitch forcing parameter) expressed as the percent deviation from the present value (from Berger 1978). Curves b–d, records of temperature deviations from present in °C, based on oxygen isotope data (Buscal et al. 1987; atmospheric CO₂, Barnola et al. 1987; and atmospheric CH₄, Barnola et al. 1987) determined on gas trapped in the Vostok (Antarctic) ice core (from IPCC Working Group I Summary). Curve e, SPECMAP O-isotopic record (Imbrie 1984), indicating major isotopic stages (from An et al. 1990). Curve f, magnetic susceptibility profile from Hemaguan loess section, Lourz plateau, central China (from An et al. 1990). Curve g, palaeoecological operator (PBO, or best possible climate profile of fossil vegetation changes) time-series reconstructed from the Grande Pile pollen records (from Guéret et al. 1989). Curves h–i, annual total precipitation and mean temperature reconstructions (expressed as deviations from modern values) for the Grande Pile, based on determination of modern analogue for fossil pollen assemblages (from Guéret et al. 1989).

Key scientific questions

- How did the chemical composition of the atmosphere change through the last glacial cycle?
- What are the causes of atmospheric CO₂ and CH₄ variations?
- What are the phase relationships between atmospheric CO₂, CH₄ and other radiatively active gases and climate change? Do CO₂ and CH₄ play a significant role in coupling the climate of the Northern and Southern Hemispheres?
- What processes in the geosphere-biosphere system have responded to the variations in insolation that have presumably triggered the onset and demise of the major ice ages?
- What feedbacks operated within the Earth system in connection with past changes in ocean and atmospheric circulation, atmospheric turbidity, the hydrological cycle, surface albedo, ice volume, and sea level?
- Are high-frequency δ¹⁸O, CH₄, and, perhaps, CO₂ oscillations that have been observed in Greenland ice cores the result of internal forcing? Are those oscillations indicative of temperature fluctuations of global scale?
- How did vegetation and ocean productivity respond to climate changes of the past? How did vegetation and ocean productivity changes affect the abundance of atmospheric CO₂, CH₄ and other radiatively active trace gases?
- How can data from land and ocean records be integrated?

Activity Descriptions

Solar and Orbital Forcing and Response

Solar luminosity and Earth orbital parameters are the primary external controls on the amount of solar energy received by the Earth system; the state of the atmosphere (e.g., trace-gas composition, turbidity, cloudiness), which is addressed by Activity 2, modifies the insulation received through processes internal to the Earth system. Here we consider the external forcing mechanisms.

Task 1. Intrinsic solar changes

What is known about intrinsic changes in solar behaviour in the past is now limited to the reconstruction of an index of solar activity for the past 7000 yr, which is based on the analysis of tree-rings ¹³C (Stuiver and Braziunas, 1989). The index can be related to the more relevant parameter of insolation through modern, spaceborne measurements that have documented changes in solar energy flux, and related them to concurrent changes in solar activity. These relationships and the history of solar activity through both the recent and more remote past each need further clarification. The analysis of ¹⁰Be in ice cores should provide the data to extend the proxy record of solar energy flux as much as several hundred thousand years into the past (Beer et al. 1988), despite complexities introduced in these data by variations in local precipitation and by changes in the Earth's magnetic moment. Developing a reliable means for deducing quantitative changes in solar luminosity from changes in the more easily recovered parameter of solar activity, which modulates the photospheric production of the radioisotopes that are sampled in tree-rings and ice cores, is at present our only hope for recovering a long-term record of past variations in solar output.

Task 2. Earth orbit changes

Parameters describing the Earth's orbit and axis of rotation determine the latitudinal and seasonal distribution of solar irradiation that is received at the top of the Earth's atmosphere. The Milankovitch or astronomical theory of periodic

Science Components

Activity 1
glaciation holds that long-term changes in these parameters are sufficient to explain the glacial-interglacial cycles of the last 200,000 yr, given the present proportion of land mass at high latitudes and assuming a roughly constant solar luminosity. Prominent periodicities of this forcing are (i) 41,000 yr (obliquity) and 23,000 yr and 19,000 yr (precession of the equinoxes) (Berger 1977). The response of past climate to these slowly changing orbital parameters has been identified in deep-sea sediments, coral deposits and a variety of continental archives, including ice cores. It was the interpretation of δ18O data obtained from deep-sea cores that demonstrated, for the first time, that a frequency spectrum similar to that derived mathematically for the orbital parameters is also evident in the natural spectrum of palaeoclimatic change throughout the late Quaternary (Hays et al. 1976).

Objective
- To determine the role of external forcing mechanisms in fixing the climate of the late Quaternary, including that of the last 2000 yr, and identify the feedbacks in the Earth system that respond to these forcing mechanisms to bring about major climatic changes.

These feedbacks are now thought to include, among others, changes in the partitioning of carbon or distribution of biota, changes in atmospheric composition, turbidity and cloud cover, and ice-sheet growth and decay.

Initial planning for this Core Activity should establish the minimum critical data that must be obtained from each of the different natural archives in order to evaluate the role of external forcing mechanisms in driving both decade to century-scale climatic changes and those of longer term.

Stream I Tasks
- Reconstruct an improved history of solar activity using annually-resolved data that must be obtained from each of the different natural archives in order to evaluate the role of external forcing mechanisms driving both decade to century-scale climatic changes and those of longer term.

Stream II Tasks
- Obtain sequences of lacustrine, palaeosol and aeolian (loess and marine) deposits that extend through the last full glacial cycle. Continental records are needed to compare responses to external insulation forcings over land and ocean regions in both hemispheres and to provide data comparable with the relatively high-resolution atmospheric records of ice cores.

- Deconvolve the responses of the Earth system to external (orbital and solar) and internal forcing mechanisms. The frequency spectrum of reconstructed ice-sheet volume changes must be compared with variations in the external insulation forcings that have been determined independently, particularly the mathematically-derived model of orbital forcing, and, if possible, with reconstructions of changes in the cosmogenic production of 10Be and 14C and 18O (Berger 1977). The interpretation of δ18O data obtained from space borne measurements of changes in solar output to reconstruct a 2000-yr history of insulation changes, describing both total and spectral irradiance.

Activity 2

Fundamental Earth System Processes
The major components of the geosphere are the atmosphere, oceans, and solid Earth, which are linked by complex and interactive physical, chemical and biological processes. Presently, our clearest insights into the fundamental biogeochemistry of the globe concern the more distant past: namely, the findings from polar ice cores that associate glacial-interglacial changes in surface temperature with concurrent changes in CO2, CH4, and aerosols (Raynaud et al. 1988, Stauffer et al. 1988). The nature of these records now precludes an unambiguous distinction between human-induced changes in atmospheric composition and global surface temperature: that is, which came first, and by what interval of time.

The discovery of pronounced variations in the atmospheric concentration of CO2, CH4 and aerosols in ice cores implicate the existence of a strong interaction between the physical climate and the chemical and biological components of the total Earth system. Understanding the origin of the changes now documented in trace gases, ions and aerosols, and the processes of interaction that are involved, can provide insights regarding tree-rings and palaeoclimatic records that almost certainly pertain to modern concerns regarding enhanced greenhouse warming. Moreover, these records of past changes in atmospheric composition will be of continued use in separating natural changes from those due to human activities, which is one of the major challenges of the IGBP.

Stream I Task
- Reconstruct comparable records of climate and of the abundance of atmospheric CO2, CH4, and other trace gases throughout the last 2000 yr, with a temporal resolution of at least 10 yr and with emphasis on periods of known or suspected changes in mean global surface temperature, such as the Medieval Warm Interval, the Little Ice Age, and the period of subsequent global warming. A detailed reconstruction of these more accessible periods of Earth history may give new information on the phasing of changes in temperature and in atmospheric composition and help differentiate between human-induced and natural changes in atmospheric composition. Both will require GCM and time-dependent modelling. The record of atmospheric chemistry may be obtained through the collection of short, annually resolvable cores from polar ice, supplemented by low-latitude ice cores which give information on regional climate, air quality and other parameters. Lacustrine and other sediments, tree-rings and historical data will yield additional information regarding local climate conditions in this period.

Stream II Tasks
- Improve the temporal resolution of climatic and trace-gas data through the collection of short, annually-resolvable ice cores and the expanded collection of longer ice cores with optimum attainable resolution to give additional information on climate and air composition and quality; collect additional high-resolution marine and terrestrial sediment cores; compile these and other records time-series data on atmospheric composition and climate varia-
Task 2. Global impacts of volcanic activity

Documentary evidence from large volcanic eruptions, such as the eruption of Tambora in 1815, suggests that injections of volcanic matter into the atmosphere have exerted significant short-term impacts on mean global surface temperature and circulation, presumably the result of the injection of volcanic ash and subsequent changes in the turbidity and composition of the atmosphere that have the potential to affect the Earth's heat budget. The global climate is influenced by the injection of volcanic matter into the atmosphere, which can produce changes in the radiative balance of the Earth-Sun system. The injection of volcanic matter into the atmosphere can lead to changes in the Earth's albedo, which can affect the Earth's heat budget and climate. The injection of volcanic matter into the atmosphere can also lead to changes in the Earth's radiation balance, which can affect the Earth's climate. The injection of volcanic matter into the atmosphere can lead to changes in the Earth's radiation balance, which can affect the Earth's climate. The injection of volcanic matter into the atmosphere can lead to changes in the Earth's radiation balance, which can affect the Earth's climate. The injection of volcanic matter into the atmosphere can lead to changes in the Earth's radiation balance, which can affect the Earth's climate. The injection of volcanic matter into the atmosphere can lead to changes in the Earth's radiation balance, which can affect the Earth's climate. The injection of volcanic matter into the atmosphere can lead to changes in the Earth's radiation balance, which can affect the Earth's climate.
Greenland, the North Atlantic, and western Europe. Palaeoclimatic reconstructions from pollen diagrams and lake sediments from North America and Europe have been shown to be linked with changes in North Atlantic deep-water production (Boyle and Keigwin, 1987). Broecker (1987, Broecker and Denton 1989) hypothesized that the reason for the onset of this episode was a major diversion of meltwater into the northern Atlantic and that its abrupt end corresponded to the cessation of this modified flow. By this hypothesis, during the period of meltwater input the salinity of surface waters was too low to permit deep water to form and the heat supply by warm waters moving northward was interrupted. There is evidence that at about 11,000 B.P. meltwater was diverted from the Mississippi to the St. Lawrence River and at 10,000 B.P. back to the Mississippi (Broecker, 1987; Broecker and Denton 1989). Greenland ice cores and North Atlantic sediments are now being used to further study this rapid, short-lived cooling event and its impact on other regions of the globe. Needed are analyses of high temporal-resolution sediment sequences from all over the world, as well as new high-resolution ice cores from the Antarctic.

A search for abrupt changes in the ensuing Holocene Period is of particular importance, in that this period of about 15,000 yr is representative of the present interglacial state of the Earth system. Climate predictions for the next 50-100 yr must rely on careful analyses of climatic changes during the Holocene Period, including their causes and possible cyclic nature. It will be necessary to determine the internal or external causes of each event and to distinguish natural forcing (i.e., variation of solar radiation, solar flux, volcanic dust loading of the atmosphere and stratosphere) from possible human influence (such as changes in albedo, hydrology, the evapotranspiration balance, aerosol loading, and at-

**Objective**

- To identify abrupt environmental changes in the record of the past, and establish their characteristics, including duration and global extent, and their causes and effects, including impacts on the biosphere.

**Research Tasks (Streams I and II)**

- Identify short-term, high-amplitude changes in chemical, biological or physical indicators of climatic variability; identify patterns of recurrence of these anomalies through time at a variety of locations. Through the efforts of this task, a record of extreme events and short-term fluctuations in the Late Quaternary will be established as they are imposed on the baseline of environmental changes of longer term.

- Determine the external and/or internal forcing mechanisms that are responsible for specific abrupt global changes.

- Design tests to determine the possible role of preparatory or compounding events, preconditions, or initiating factors other than external forcing mechanisms in bringing about abrupt environmental changes.

**Multi-Proxy Mapping**

An underlying activity of PAGES will be the collection and intercomparison of a variety of data from the spectrum of historical and natural proxy sources that are available. The ability to integrate information extracted from natural archives of many different kinds is a prerequisite for constructing a composite picture of climatic anomalies and trends in all of the preceding activities. It defines the needed contribution of PAGES to modelling activities of the IGBP and WCRP. The composite records that will be compiled will transcend the immediate goals of the IGBP, in making available for future generations of Earth scientists a fuller and more organized record of the recent history of the Earth system.

The accomplishment of this task will require a critical review of each of the available types of proxy records, including the environmental information they contain, their present spatial and temporal coverage, temporal resolution, and inherent temporal and spatial integration, and links in the incorporation of environmental information into the various proxies. It will also require a determination of the feasibility of precise dating of abrupt or short-term responses to environmental change and of our ability to develop palaeoclimatic transfer functions. The potential for establishing a readily accessible data base adequate to address critical scientific questions will also be considered.

Modelling is an integral part of the IGBP effort to understand past and future global change, and it is imperative that modelling experts and modelling groups be included in the planning of mapping activities. Direct input from modellers and a close interaction between palaeodata and modelling groups will ensure that the models are properly validated; that the best available data are used in the definition of model boundary conditions; and that modelling experiments are designed with the goal of improving our understanding of the forcing factors that drive the climate system. Modelling will provide information on the sensitivity of each proxy to changes in the major climatic variables produced as output from GCM simulations and will also help to identify the critical periods and most sensitive regions for study.

The selection of appropriate time slices and sites for mapping emphasis within this activity will be dictated by the scientific questions that are posed in the other three Core Activities of PAGES, taking into consideration the data requirements of both the mapping and modelling tasks that are planned. Data currently available are particularly lacking for the Southern Hemisphere and for
the Tropical and Intertropical Zones; additional data are also needed from North America for the period between the last interglacial and the maximum cooling of the last glaciation. Some studies of past and present global changes will require that data be obtained over a region encompassing a critical climatic system, such as the Northern Hemisphere monsoon belt through Africa, Asia and North America, or the key sites for the study of ENSO events (i.e., Indonesia, the equatorial Pacific, Peru, and Ecuador). In addition, an attempt should be made to obtain records from the polar regions of the Earth, which are more responsive to short-term climate changes, particularly in surface temperature.

The Stream I mapping effort will focus on the recovery, calibration, correlation, and interpretation of high-resolution (seasonal, annual, decadal) historical and natural proxy records. The emphasis of this activity in Stream II will be placed on the integration of long records (including reliable land/sea correlations), which will provide the data necessary to complete the studies of global changes over the last glacial cycle. The mapping activity will integrate other activities of the PAGES project, and provide the raw data from which parameters necessary for the validation of general circulation models can be quantitatively derived. It will also allow an assessment of the extent to which the past represents a useful analogue for future global changes.

**Objective**
- Establish an authoritative record of global climatic changes of the past 2000 yr with a temporal resolution of at least 10 yr, and multi-proxy record that describes significant global changes through a full glacial cycle.

**Stream I Task**
- Determine and refine the transfer functions used to convert the information recorded in the various proxies into a form that can be interpreted quantitatively in terms of physical, chemical or biological parameters. This task is a prerequisite to efforts aimed at comparing the climatic signals archived in the various types of proxy records and at assessing the relative merits of each proxy in large-scale climatic reconstructions.
- Combine and integrate annual-resolution environmental proxy data from representative geographic locations to reconstruct maps of the spatial patterns of global climatic anomalies, with particular attention to seasonal/annual surface temperature and precipitation. The goal is to map the geographical extent of significant climatic events and to determine whether or not they are global.
- Collect annual time-series data on climatic fluctuations in regions that are representative of major sub-systems of the global climate system (e.g., ENSO, North Atlantic Oscillation, Monsoonal System of East Africa, South and Southeast Asia).
- Acquire historical and high resolution proxy records (e.g., cores from ice caps with summer melting, cores of laminated lacustrine sediments from lakes at various altitudes that are characterized by a long history of undisturbed fine-grained sedimentation, tree-ring samples, and coral reefs) from the Tropical and Intertropical Zones, where data are now severely lacking.
- Evaluate the response of the climate system at times in the past for which specific forcing factors have been implicated, such as the Medieval/Millennium/Little Ice Age and the Mt. Tambora eruption, which was contemporaneous with the globally cooler temperatures of the early 19th century.

**Cross-Project Needs**

**Palaeoclimatic and Palaeoenvironmental Modelling**

The goals of PAGES demand a strong interaction between data acquisition and interpretation and the modelling of palaeoclimatic and palaeoenvironmental changes at various time scales. Involved as subsystems in a more general model are elements involving the atmosphere, ocean, cryosphere, hydrosphere, biota, soils, and the biogeochemistry of the Earth system. The inclusion of modelling in other activities of PAGES is necessary for several reasons:
- Testing climate models. Palaeodata are used both in defining boundary conditions (e.g., sea-surface temperature, sea-ice extent, ice-sheet topography, land albedo) and in identifying the climatic forcing factors (e.g., insolation, atmospheric concentration of greenhouse gases, dust and aerosol loading) that are used in atmospheric general circulation models (GCMs) and future coupled geosphere-biosphere models. The key variables for assessing GCM simulations are temperature, precipitation, other parameters linked to the hydrological cycle, and, to a lesser degree, wind intensity and direction.
- Providing insight into how the climatic system functions. In addition to GCMs, which produce steady-state simulations, there is a particular need for the development of models that are time-dependent (such as ice-sheet mass balance models). Such models need to include both internal and external forcing mechanisms, as well as human-induced effects. A hierarchy of such time-dependent models, based on time scales extending over the full range of Earth system changes of the past, can provide valuable insights into the operation of the Earth as a system.
- Estimating the sensitivity of the climate system to various forcing mechanisms. Knowledge of climate sensitivity is one of the key parameters needed for predicting anticipated changes in the next 50-100 yr. Climate simulations may also be useful in identifying appropriate regions for palaeoclimatic reconstructions (i.e., those that are particularly sensitive to fluctuations in climate parameters).
- Understanding long-term variations and rapid changes in the concentration of environmental and climatic characteristics that are necessary for model validation.
- Recover high-quality proxy records from a variety of natural archives (such as tree-ring data, the chemical composition of ice and gas inclusions in ice cores, palaeosol stratigraphies, and terrestrial and ocean sediments) on a global basis, spanning the last glacial cycle.
- Establish precise correlations between land and ocean archives throughout the last full glacial cycle. This research is needed for the study of phasing and time lags among the different system responses as recorded in different archives around the globe; it will also require new or improved dating approaches, particularly for pre-Holocene ice cores. Key sites for land/sea correlation are Europe/North Atlantic Ocean, Antarctica/Southern Ocean and Asian less polar central North Pacific Ocean. Reconstructions of surface water 2H values may help in interpreting complimentary lake marl data.
- Construct palaeoenvironmental maps for time intervals encompassing key climatic events that represent various degrees and absolute rates of change (as established by detailed time-series studies at key locations). These include the climatic optimum of the previous interglacial age (O-isotope substage 5a); the climatic optimum of the Holocene Period (7000-6000 B.P.); the Younger Dryas/Bolling-Allerod complex (13,000-10,000 B.P.); and the last glacial maximum (18,000-20,000 B.P.).
- Produce palaeoenvironmental maps to investigate transitions between major vegetation regimes throughout the late Quaternary and to enable the estimation of plant biomass at various times in the past, in order to quantify carbon storage in vegetation and to improve our understanding of the CO2 and CH4 cycles.
of atmospheric CO₂ and CH₄ as well as the interaction of these gases with the climatic system. Such studies require the use of a hierarchy of models with the ultimate goal of coupling biogeochemical models with models of the physical climate system (see also Chapter 8). To achieve the ultimate goal of reliable simulations of climate and environmental changes on a global scale, nested, hierarchical models must be based on transfer functions that accurately describe the storage of climate data in each of the various archives.

Types of models that are particularly needed in paleo-studies include:
- Models of ice-sheet dynamics, which correctly simulate both the growth and decay of ice sheets (for Stream II tasks) and of shorter-term glacier and ice-sheet mass balance (for Stream I research).
- Tracer models that rely on GCMS to track specific aerosols (e.g., desert dust) on a global scale, or to pinpoint the source region of precipitation. Such models are also useful in establishing the link between climatic parameters and proxy data.
- Vegetation models that establish the linkages between climate and the response of biota.
- Coupled ocean-atmosphere-cryosphere models at various levels of complexity.
- Nested models for regional simulation studies.

Advances in Technology

Sampling

Many palaeoclimatic records are derived by coring into sedimentary deposits. Limitations on the length and the quality of these records are often imposed by limitations in the equipment currently available for recovering long, undisturbed sediments. In the case of polar ice-core drilling, where technology is relatively advanced, it is not yet possible to drill through the deepest part of the Antarctic ice sheet, yet such a long core should yield a unique record of atmospheric composition spanning many glacial-interglacial cycles. Similarly, many deep lakes which are known to contain long sedimentary records and lakes that contain finely laminated sediments with the potential of providing detailed, high-resolution palaeoenvironmental information have not been adequately studied, because of the technological problems of core recovery.

Efforts will need to be made to develop advanced coring equipment for the purpose of recovering long, high-quality ice core and terrestrial (primarily lacustrine) and marine sedimentary records. International cooperation and the sharing of experience and technology will be required to design and construct equipment capable of operating in a wide range of often remote environments.

Analytical methods

Techniques of accelerator mass spectrometry (AMS) have led to significant improvements in the dating and quantitative analysis of palaeomaterials. They have also proved important in studying the cycling of tracers in the Earth system. Adapting other analytical techniques developed for classical physics and chemistry may also lead to significant advances in the study of records of the past. The application of new exploratory and analytical methods should prove particularly valuable in lacustrine sediment research, including the use of acoustic profiling systems, digital X-ray systems, micro-sampling and analytical procedures, and high-resolution microscopic techniques. Particularly promising is the establishment of analytical centres that may help speed technical advances for specific applications, in this and other areas.

Needed, in many areas, are efforts to streamline and automate analytical facilities and to maximize the rate of sample processing. Few laboratories can handle the very large number of samples necessary for the reconstruction of climatic fluctuations at the high frequencies required for many of the tasks proposed for implementation in PAGES.

Management of Palesedata

Data management is a key requirement in the development of a research programme of the scale of the IGBP to insure maximum data accessibility (Chapter 9).

As global-scale reconstructions of past climate are made, the need for the integration of diverse proxy records will increase. This will require the establishment of well-organized data bases that can be interrogated electronically, and which can respond to diverse enquiries. A European Palynological Data Base system is currently being developed along these lines, particularly for use in IGBP-related research. Careful consideration has been given to issues of data acquisition and accessibility, ensuring data quality, ease of interrogating the data set, the future integration of regional palynological data bases with data bases that may be developed for other types of proxy data, and the management structure, facilities and resources required for successful implementation. In the U.S. the National Geophysical Data Center and the National Oceanic and Atmospheric Administration's National Data Center are establishing palaeoclimate databases to bring together computer-based, interactive archive of palaeoclimatic information for purposes of research in global change. It will include data from tree and ice cores, marine sediments, pollen, and eventually documentary records. A design requisite, as with the European Palynological Data Base, has been that of ready access on a world-wide basis.
Calibration of proxy data

In addition to data base development, the management of paleo-datasets also involves their calibration and careful attention to the quality of the data that are made available. All proxy records must be calibrated with modern observation-al data from the same or similar sites if meaningful, quantitative paleoclimatic reconstructions are to be made. It is often the case that the observations necessary to accomplish this task are not available and the researcher is forced to rely on less-appropriate data, or data from a site far from where the proxy was recovered. This may result in a poorly understood climatic signal in the natural archive, and a less than optimum paleoclimatic reconstruction.

Absolute dating of records less than about 50,000 yr old can be done on small samples using the AMS-14C method on a variety of materials (e.g., CaCO₃ in testate and 14 C age determinations of corals; annually-banded materials such as amino-acid racemization. Stream II studies include isotopic disequilibrium studies of uranium series fission track spin-resonance (ESR) methods; and methods performed on biological materials are found.

Methods applicable to the type of high-resolution dating required for the study of changes during the past 2000 yr (Stream I) include historical records and the precise identification of annual layers in archives such as tree-rings, ice cores and laminated sediments. In some cases, fossil corals or floating tree-ring chronologies are useful sources of annual-resolution data. When laminated sediments are not available, and disturbed sediment sequences with high accumulation rates that allow fine-resolution radiocarbon dating (e.g., 14C, U-series methods) are also useful. The combination of lake, mire and bog data with annual resolution rates that allow fine-resolution radioisotopic dating (e.g., 14C, U-series measurements) is important. It is important to PAGES to take advantage of the data obtained through monitoring programmes of the IGBP and WCRP in the development of quantitative transfer functions. This may involve ocean buoys to record ocean temperature and other parameters, or operational platforms designed to monitor continuous trace-gas and aerosol sampling and meteorological measurements in remote polar or tropical environments. For example, the IGAC Polar Air-Snow Experiment (Chapter 2.1) will provide data on the relationship between atmospheric composition and the chemical composition of ice in central polar areas.

**Methodology**

**Dating and Correlation**

A common requirement in almost any aspect of environmental research is the accurate specification of the time of observation, or in the case of palaeodata, an accurate specification of the age or date of deposition of sampled materials. In order to detect or identify synchronous global changes, to fix the time of long- or short-term events in the past, or to specify the timing of the different environmental parameters that are invoked, records from different parts of the ocean-atmosphere system need to be correlated. The development of precise age determinations and reliable estimates of errors associated with them. In correlating parameters obtained by different techniques from a variety of natural archives, often differing in precision and accuracy, effects of uncertainty in the dating of any of them are compounded. A thorough understanding of the inherent limitations of each method is a prerequisite for a proper evaluation of the time scale. This task of fixing dates and their error bars, often slighted, is one that deserves as much attention as the analysis and interpretation of the data themselves.

Methods applicable to the type of high-resolution dating required for the study of changes during the past 2000 yr (Stream I) include historical records and the precise identification of annual layers in archives such as tree-rings, ice cores and laminated sediments. In some cases, fossil corals or floating tree-ring chronologies are useful sources of annual-resolution data. When laminated sediments are not available, and disturbed sediment sequences with high accumulation rates that allow fine-resolution radiocarbon dating (e.g., 14C, U-series methods) are also useful. The combination of lake, mire and bog data and with annual data from tree rings offers another useful tool. Reference horizons, particularly volcanic ashes, can often be used as stratigraphic markers for dating young deposits. These can sometimes be calibrated with records in historical archives such as those of volcanic eruptions or modern thermonuclear tests, or their ages determined by counting annual layers in ice cores where the tephas are found.

Methods that may aid in establishing dating control in the longer span of Stream II studies include isotopic disequilibrium studies of uranium series isotopes and conventional 14C measurements; radiogenic trend analyses (e.g., fission track 238U-series and K-Ar measurements); detection of ionization radiation due to radioactive decay by either thermoluminescence (TL) or electron spin resonance (ESR) methods; and methods performed on biological materials such as amino-acid racemization. It has been demonstrated that spikes in the ice borne 10Be record, though few and far between, can serve as useful reference horizons in correlating samples of polar ice; since these are of presumed extraterrestrial origin, they seem of particular promise in correlating records from the two poles of the Earth.

**Data Sources**

The most powerful tools available to PAGES are: (i) the potential to collect and synthesize information from many sources to provide clearer global pictures of the past; and (ii) the power to focus effort on selected time slices or regions for particular emphasis through coordinated campaigns. Both involve combining data derived from different techniques.

Five of these techniques, or data sources, are described briefly below with recommendations for advancement; other sources, equally important, will also contribute to the project.

**Historical records**

**Parameters Recorded:** Proxy information (e.g., vine harvest dates and yields, snow and ice records) and direct descriptive information (e.g., daily weather observations, sea level and coastline data, reports of volcanic eruptions and other extreme events).

**Spatial and Temporal Coverage:** New World: < 100 yr; Europe and Eurasia: < 900 yr (the earlier part as a more subjective record); ancient China, Korea and Japan: continuous record to 2200 B.P. Oriental accounts are generally most the extensive, continuous, detailed, and useful. The presence of natural archives for
the same region (Tibetan ice caps, Chinese Loess Plateau) identifies the Asian continent as an area of particular promise for reconstructing natural and anthropogenic changes in the environment.

Recommendations: The tools for building a large, international data bank on climate history have been developed; however, a much greater effort to extract relevant climatic/environmental information from historical records, particularly in China and southeastern Asia, is necessary and should be encouraged through regional workshops.


Tree-rings

Parameters Measured: Tree-ring width, wood density, tissue structure, stable isotopes, and trace-element chemistry.

Resolution and Dating: Annual resolution by counting tree-rings (many tropical species have no clear annual layer); seasonal resolution is possible for certain studies, based on distinction between early and late wood. 14C analysis of cellulose in dated rings is the primary source of information on the variation of 14C production in the past, and hence on 14C calendar-year conversion.

Spatial and Temporal Distribution: Most extensive data are for temperate latitudes, most valuable in higher or drier regions were tree-growth is a more sensitive indicator of environmental conditions; data are concentrated in North America, the Arctic, Europe, and the USSR; greatest potential for new information is in Siberia, India, China, and parts of the Southern Hemisphere (Argentina, Chile, Tasmania, New Zealand); data from the Tropics would be of great value, although technical difficulties must be overcome.

Continuous chronologies extend to A.D. 1700 for most temperate Northern Hemisphere land masses; coverage to 2000 B.P. is sparse (samples of living trees must generally be combined with archaeological and geological timbers); only ten chronologies exist that are longer than 2000 B.P., with potential to obtain perhaps ten more; potential for only one central European and one western U.S. chronology longer than 10,000 B.P. A few chronologies of 200-3000 B.P. length are available from sub-fossil wood older than 10,000 B.P. In many places (several areas have trees in 20,000-30,000 yr age range), but there is little chance of these being joined in continuous sequences.

Recommendations: There is an urgent need to collect samples from tropical regions before the old-growth trees (e.g., teak) are exploited. More fundamental research is needed to assess the possibility of obtaining annual records from arid zones and the Tropics. Some species without clear annual rings, for example, Hucn pine in Tasmania, Kauri wood in New Zealand) before the archive is lost.

Terrestrial deposits: lacustrine sediments, loess and palaeosols

Parameters Measured: Lacustrine sediments (lake, bog, mire, and peat deposits); pollen analysis, fossil assemblages, stable isotopes, organic and inorganic chemical composition, mineralogy, palaeomagnetism. Loess: accumulation rates, sedimentology (e.g., grain size distribution, shape), sediment geochemistry and mineralogy, palaeomagnetism. Palaeosols: presence or absence of specific vegetation types.

Resolution and Dating: Lacustrine sediments: annual to seasonal resolution (if undisturbed); dating by annual layers, 14C, TL, U-series, etc. Loess: variable resolution, depending upon local conditions and availability of stratigraphic layers; sometimes tied to historical accounts of dust storms. Palaeosols: dating generally based on stratigraphy.

Spatial and Temporal Distribution: Lacustrine sediments: presently available data are mostly from Europe, North America, and the Arctic potential for broad, global coverage (South America, Africa, Asia); longest continuous records > 300,000 yr. Loess beds: generally located down-wind of continental areas subject to erosion (although dust is transported at heights up to 10 km); longest records are found in China, followed by the U.S., and Central Europe. Palaeosols: associated with continental sediments, particularly loess deposits.

Recommendations: Multi-disciplinary case studies of carefully-selected sites that can provide long records of annually- or seasonally-resolved lacustrine sediments should be undertaken, with the goal of extracting palaeoenvironmental time-series of biotic and abiotic responses to change climates.


Marine sediments and coral deposits

Parameters Measured: Sediments: organic and inorganic chemical composition; stable isotopes; age (14C, U-series radiochemistry); number/distribution of foraminifera. Corals: 3H0 (surface water temperature); 18O, C4 and B4 (nutrient content of water); 13C (combined effect of nutrient supply and light intensity); annual layer thickness and density.

Resolution and Dating: Anoxic ocean margin varved sediments: annual or greater; open-ocean sediments: variable resolution, variety of dating techniques. Corals: coastal zones, annual resolution (O-ray densitometry detects effects of seasonal changes in surface salinity/temperature on coral growth); gyres regions, U-Th dating.
Implementation

Core Project Office

A Core Project Office will be opened in Bern in 1991, as an international activity jointly sponsored by Switzerland and the U.S. Its purpose will be to coordinate the scientific activities and tasks that comprise the PAGES project and to provide information on plans and progress to the international community. The first goal is to organize and initiate the research activities that will move the PAGES project into an operational stage. Specific functions are:

1. Initiating and organizing international workshops and planning meetings to support the project.
2. Publishing and distributing a quarterly newsletter.
3. Compiling and distributing scientific reports of plans and progress to programme participants as well as to governments and to national and international funding agencies.
4. Apprising national funding agencies on request in connection with individual proposals that may relate to the goals of the PAGES project.
5. Disseminating information that reports on aims and opportunities in the project to aid in recruiting needed efforts from scientists and technicians from all countries.
6. Raising funds for project activities from non-governmental sources, and for the staffing and operation of the Core Project Office.
7. Establishing and coordinating data centres for various types of palaeodata that can be accessed internationally.
8. Establishing and maintaining an active directory of scientists and technicians who are involved in the PAGES project.

Scientific Workshops

A number of planning meetings and workshops will be needed to refine the general research strategy of the PAGES project and to design specific tasks within each of the four activities that are described above.

The following workshops and planning conferences are proposed to refine the definitions of the Core Activities described above, and to lay plans for specific activities within each of them:

Activity 1: Solar and Orbital Forcing and Response

1. An interdisciplinary workshop should be convened to refine research needs, to define a multi-year programme and to coordinate the funding required to mount the field programmes necessary to obtain long records. Preliminary discussions on these topics should be organized in conjunction with existing bodies such as the International Ice Core Forum, IUGS and STIB (Chapter 2.2).

Activity 2: Earth System Processes

2. The Carbon Cycle and Climate Change. A workshop is needed to formulate a coordinated strategy to address problems related to the partitioning of carbon among the atmosphere, ocean (including bottom sediments) and biosphere and the phasing of CO₂, CH₄, and climate changes. This should be coordinated with the IGAC (Chapter 2.1), JGOFS (Chapter 3.1) and GAAM (Chapter 9.1).

3. Global Impacts of Volcanism. A workshop should be convened to develop a strategy for correlating the various types of records that are now available and to plan the mining of field programmes and laboratory investigations that will be needed to improve and extend this record. The workshop should be coordinated with INQUA and with activities of INQUA.

Activity 3: Rapid and Abrupt Global Changes

5. Understanding the Younger Dryas and Other Abrupt Climatic Events. A scientific workshop should be organized to assess the present state of understanding of the Younger Dryas cooling that interrupted the last glacial-interglacial transition. Attention should also be given to the development of methods to identify abrupt climatic changes recorded in proxy records, and to the identification of pilot projects that can be used to test the utility of these methods. The workshop should be coordinated with BAHC (Chapter 5.1) and with activities of SCAR.

Activity 4: Multi-Proxy Mapping

6. PAGES Mapping Strategy. A workshop that brings together scientists with expertise in various proxy methods and from all regions of the globe is needed to establish an overall mapping strategy for PAGES. Needed is a general agreement regarding which time slices will be mapped, and their relative priorities; where time series should be collected initially; which proxies can best provide the key data required to carry out the project activities; and general standards for how the data will be obtained, interpreted, mapped, and managed. The meeting should also assess the need for additional resources to carry out the project; develop plans for implementing the mapping programme; take necessary steps to enlist the aid of scientists in regions where data are particularly inadequate, including the developing nations; lay plans for the involvement of IGBP Regional Research Centres (Chapter 11); and foster the initiation of collaborative research projects between local scientists and established world experts. The meeting should involve representatives from the IGBP Standing Committee on Regional Research Centres and be coordinated with activities of INQUA and IUGS.

7. Workshop on Past Records. A study workshop should be convened to address practical methods of correlating and comparing the information on climatic variability and system responses obtained from diverse types of proxy data, at required levels of spatial and temporal resolution. The workshop should address the goal of assembling comprehensive data bases that describe selected global changes that have occurred in the past; a prerequisite to the eventual global-scale reconstructions envisaged as one

References:


Spatial and Temporal Distribution Sediments: up to 20x10⁶ yr long record in some locations (limited by thickness of soft sedimentary material, coring methods); varied records, < 10,000 yr (deep, anoxic marginal basins); most cores sampled from open ocean at water depths of 2500-4000 m. Corals: Tropical and intertropical waters; some occurrences to 30°, if warm surface currents are present; maximum temporal range to several millennia.

Recommendation: To accomplish the high-resolution studies planned for PAGES, it will be necessary to exploit rapidly-deposited deep-sea sediment (e.g., drift deposits, abyssal fans, ice-rafted debris) and continental shelf/slope rise sediments. Although there are inherent difficulties in the study of such records, they have the potential to improve our ability to correlate land and ocean records and will provide information on the continental flux of dissolved and particulate weathering products and pollen, the nature of bottom circulation and the biological productivity of surface waters.

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5. Understanding the Younger Dryas and Other Abrupt Climatic Events. A scientific workshop should be organized to assess the present state of understanding of the Younger Dryas cooling that interrupted the last glacial-interglacial transition. Attention should also be given to the development of methods to identify abrupt climatic changes recorded in proxy records, and to the identification of pilot projects that can be used to test the utility of these methods. The workshop should be coordinated with BAHC (Chapter 5.1) and with activities of SCAR.

Multi-Proxy Mapping

6. PAGES Mapping Strategy. A workshop that brings together scientists with expertise in various proxy methods and from all regions of the globe is needed to establish an overall mapping strategy for PAGES. Needed is general agreement regarding which time slices will be mapped, and their relative priorities; where time series should be collected initially; which proxies can best provide the key data required to carry out the project activities; and general standards for how the data will be obtained, interpreted, mapped, and managed. The meeting should also assess the need for additional resources to carry out the project; develop plans for implementing the mapping programme; take necessary steps to enlist the aid of scientists in regions where data are particularly inadequate, including the developing nations; lay plans for the involvement of IGBP Regional Research Centres (Chapter 11); and foster the initiation of collaborative research projects between local scientists and established world experts. The meeting should involve representatives from the IGBP Standing Committee on Regional Research Centres and be coordinated with activities of INQUA and IUGS.

Activity 3

5. Understanding the Younger Dryas and Other Abrupt Climatic Events. A scientific workshop should be organized to assess the present state of understanding of the Younger Dryas cooling that interrupted the last glacial-interglacial transition. Attention should also be given to the development of methods to identify abrupt climatic changes recorded in proxy records, and to the identification of pilot projects that can be used to test the utility of these methods. The workshop should be coordinated with BAHC (Chapter 5.1) and with activities of SCAR.

Activity 4

6. PAGES Mapping Strategy. A workshop that brings together scientists with expertise in various proxy methods and from all regions of the globe is needed to establish an overall mapping strategy for PAGES. Needed is general agreement regarding which time slices will be mapped, and their relative priorities; where time series should be collected initially; which proxies can best provide the key data required to carry out the project activities; and general standards for how the data will be obtained, interpreted, mapped, and managed. The meeting should also assess the need for additional resources to carry out the project; develop plans for implementing the mapping programme; take necessary steps to enlist the aid of scientists in regions where data are particularly inadequate, including the developing nations; lay plans for the involvement of IGBP Regional Research Centres (Chapter 11); and foster the initiation of collaborative research projects between local scientists and established world experts. The meeting should involve representatives from the IGBP Standing Committee on Regional Research Centres and be coordinated with activities of INQUA and IUGS.

Activity 7

Workshop on Past Records. A study workshop should be convened to address practical methods of correlating and comparing the information on climatic variability and system responses obtained from diverse types of proxy data, at required levels of spatial and temporal resolution. The workshop should address the goal of assembling comprehensive data bases that describe selected global changes that have occurred in the past; a prerequisite to the eventual global-scale reconstructions envisaged as one
of the primary tasks of the Multi-Parameter Mapping Activity. One task of such a workshop would be to frame the regional boundaries that define the major climate sub-systems (such as the East African monsoon region). Other tasks that will need to be addressed include establishing an overall mapping strategy (including decisions about which time-slices will be mapped; determining where time-series data should be collected initially; determining which proxies can best provide the key data required to carry out the project activities; establishing general standards for how palaeo-data for PAGES will be obtained, interpreted, mapped, and managed; and developing plans for implementing the mapping programme.

**Analytical Centres**

Advances in the technology of recovering and interpreting environmental records of the past that are called for in PAGES Project will require ready international access to its activities, even though funding for such centres will of necessity come from the host country.

**Participation in the PAGES Project**

Participation in the research activities of the PAGES Project will be addressed in a Project Implementation Plan (to be developed in early 1991). The Science Plan described here, after review by the IGBP Scientific Advisory Council and subsequently revised as needed by the Scientific Steering Committee, will be distributed to the international scientific community. The Plan will be encouraged through a semi-annual newsletter issued by the PAGES Project Office.

Participation in the PAGES Project is open to all scientists and technicians who deal with past records of any kind that relate to the project objectives. The intent is to encourage collaborative, multi- and inter-disciplinary research at a time when a fuller knowledge of past changes seems a particularly urgent need.

**References**


Lett, A. F. and Zbinden, H. 1989. Late-Glacial pollen analysis, oxygen-isotope record, and radiocarbon stratigraphy from Rotsee (Lucerne), Central Swis
How Can Our Understanding of Components of the Earth System be Integrated and Synthesized in a Numerical Framework That Provides Predictive Capability?

“The development of advanced geosphere-biosphere models will be an important task for the IGBP. Such models are needed to introduce, as dynamic variables, the biogeochemical source and sink terms into descriptions of the way in which greenhouse gases vary with climate change. That will become feasible with super computers available early in the 21st century. Such models will simulate detailed events with sufficient and temporal resolution to permit explicit treatment of the strong non-linear interactions between physics, chemistry, and biology that occur on small scales.”

IPCC (1990)
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8.1 Global Analysis, Interpretation and Modelling (GAIM)
A Proposed Core Project

The various IGBP Core Projects aim to achieve predictive understanding of the processes and interactions within and among rather distinct components of the global Earth system (Chapters 2 through 7). The collection, analysis and interpretation of new data obtained in these projects, as well as development of new instruments, exploitation of satellite and other remote-sensing information will enable models of the interactions for the various components of the Earth system to be developed. A consistent effort is required to ensure that the knowledge gained about the components of the Earth system fits into a globally consistent and internally compatible description that can be used not only to understand the important biogeochemical cycles and processes, but also the feedback and interactions between the various sub-components that regulate the Earth system. Only in that way will a predictive capability for the global Earth system become a reality. Obviously, a major effort is required to ensure that this will be achieved.

To advance our knowledge of the structure and behaviour of the global geosphere-biosphere system in an orderly manner, a numerical model based on integrating/synthesizing activity that coalesces the knowledge gained from other IGBP Core Projects is essential. Such global models are of course simplified representations of reality. Still, they are useful for internally consistent analyses of the plausibility and compatibility of hypotheses concerning the interaction of key processes in the system. They are indispensable in serving an integrative function in the analysis and interpretation of the data that are being assembled. The development and employment of models is therefore a central activity within a comprehensive Earth system science programme such as the IGBP.

As a starting point it is useful to construct a reasonably detailed qualitative picture of basic interactions. To do so, available data for the various subsystems are combined into a complete description as possible of the internal structures of these subsystems and particularly their interactions. In such an analysis the over-all requirement of energy balance and other dynamical constraints for the system as a whole, such as mass continuity in the biogeochemical cycling of all significant elements, is imposed. Such model developments for the various subsystems also provide a series of physical, chemical and biological constraints that must be considered in the construction of a plausible picture of the overall structure and pattern of interactions.

It is important in the development of such a conceptual picture of the dynamics and changes in the Earth system to specify the characteristic time scales with which we are concerned. Focusing on changes over decades and centuries, as given in the programme definition of the IGBP, should, however, not exclude the consideration of processes operating on longer time scales. The changes that have occurred during Holocene and late Pleistocene, associated with the variations between glacial and interglacial conditions, are particularly important (PAGES, Chapter 7.1). When testing models that are being developed for the study of present, more rapid changes, we can learn from studies of changes that have occurred on such longer time scales.

The following discussion of global change modelling is based on the conceptual diagram of the Earth system that has been developed by the United States Global Change Committee (Fig. 1). The upper part of the diagram shows the physical characteristics of the system, which determine the climate of the Earth. Modelling the climate system has progressed rapidly during the last few decades and its present characteristic features can be reasonably well understood by considering the physical interactions of the atmospheric, oceanic and terrestrial subsystems and prescribing the chemical and biological features as given but not changing. The promotion and co-ordination of climate modelling is a responsibility of the World Climate Research Programme (WCRP).
Models as Simplifications of the Real World

Any attempt to understand or explain observed phenomena in our environment is based on a model of one kind or another. They always represent a simplification of the real world. Even complex models still describe reality only very approximately.

It is useful to distinguish between diagnostic and prognostic models. A diagnostic model is empirical and may well describe processes that are of importance only for some particular space and time scales. In general, the analysis is based on the further assumption of a quasi-steady state, so the diagnostic model defines a relationship between those processes that have been included in the model. This often represents a very useful first approximate description of the system that is being considered. The use of a diagnostic model to analyze a transient change of the system might, however, be misleading. The response characteristics of the model must be carefully analyzed in order to ascertain that changes are within the range of validity of the model. Validation of both steady state and transient characteristics is necessary. If all important processes are included, then the model be used for prognostic purposes with the hope for some success.

There are in principle three different reasons for the uncertainty in the results obtained with the aid of models: (i) only a limited number of physical, chemical and biological processes can be included in the model formulation; (ii) the processes that are included are treated inadequately and may not be representative across scales; and (iii) the spatial and/or temporal resolution is inadequate.

Even in the most complex models of the Earth system that are available today, the so-called General Circulation Models (GCMs), the processes included are rather few and their theoretical formulation crude. The incompleteness of models in this regard also makes it difficult to assess the uncertainties of their results. We simply do not know how different a model would be if another process was included until such an inclusion has been attempted. In some cases we are even ignorant of what are the key processes. This may be the case when small amounts of a compound play a significant (catalytic) role, such as micronutrients in both the terrestrial and marine environment.

Scaling and Parameterization

In any model there is always a minimum scale below which the real features of the system cannot be resolved. This is usually due to limited computer capability, but may also depend on inadequate knowledge of how to formulate a more appropriate model. The basic problem becomes: How to properly consider the collective importance of processes on scales less than those being resolved by the model when we wish to describe the large scale interactions that are of prime concern in the global context? We need to express the role of the small scale processes in a simplified manner, i.e., parameterize them in order to develop an adequate model. Examples of parameterization schemes in climate models are: (i) The role of convective clouds for the vertical transfer of energy, momentum and water in the atmosphere; (ii) The role of small scale motion fields for transfer processes in the oceans; and (iii) Determination of radiative transfer through the atmosphere whereby the integration over the relevant spectral ranges is marked by chemical reaction in the gas and/ or water phases; (iv) How do we describe stomatal resistance in the leaves of tree canopy as a regulator of transpiration, if the minimum scale that is resolved by the model is, much larger, say 100 km?; and (v) How do we compute net primary production in the euphotic zone of the sea without explicitly considering the small scale patterns of upwelling and downwelling?

The problem of parameterization is a central one and is so far only dealt with crudely. Effort is required to provide more systematic procedures in order to make further progress. Thus, a central theme for the global modelling project should be the systematic development of parameterization schemes for subgrid-scale processes to be included in global biosphere models.
Hierarchy of Models

The model formulation leads to a set of equations that describe the steady state or time dependant characteristics of the system. The results of numerical integrations are compared with observations of the variables that define the model. Models of the Earth system must be developed stepwise. In the first instance, when considering the most important processes, simple global models with a limited number of equations often formulated as changes between different reservoirs, i.e., box-models, need to be developed in order to explore the basic modes of interaction between major components of the system. One- or two-dimensional models permit spatial resolution, usually vertically and in a meridional plane, respectively. They are useful in highlighting specific aspects of the full three-dimensional problem and can serve as preparations for more thorough analyses. Models spatially resolved in three dimensions are usually based on General Circulation Models (GCMs) developed for the atmosphere and/or the oceans. General Circulation Models (GCMs) are used to represent quantitatively specific processes that are the building blocks of the global models. Such process models also define additional observational requirements. An example is studies of land surface processes begun by the WCRP with the aim of improving our understanding of the physical boundary conditions between land and the atmosphere as employed in global climate models. Another approach is to make use of inverse methodology, where by information about processes are deduced by determination of key parameters by requiring a best possible fit to data, i.e., inverse models are diagnostic rather than prognostic. Here one can derive a direct measure of how well the processes included into a model are compatible with available data. Such an approach complements the efforts to develop models for direct integration. It should be recognized, however, that an inverse methodology can lead to mathematically ill-conditioned problems and care must be exercised when employing inverse methods. They become cumbersome and require large computers capacity when applied to large systems.

Simple Box-Models

Numerous attempts have been made to describe global interactions in the Earth system by defining simple models having merely a few interacting components and comparatively few variables. The major questions that can be resolved by such an approach are:
- What constraints on the prime interacting variables are imposed by a strict application of the requirement of mass continuity and a steady state? (In some cases a few additional constraints are imposed when such can be easily formulated.)
- Which linear eigen-modes characterize the system and in which way is the linear model modified, if non-linear interactions are included?

In the former case an overview of the system is obtained that is useful, both with regard to the formulation of more complex models and setting priorities on data acquisition programs, and in the latter case, the internal oscillatory characteristics of the system and its response to forcing can be determined.

Simple conceptual models have been used to estimate anthropogenic CO₂ uptake and transient temperature change as atmospheric concentration of trace gases increases. Such simple models are usually too crude to provide credible predictions of future changes. However, their results can be valuable in formulating specific questions to be studied more in detail using models with better resolution.

Geosphere-Biosphere Models (GBMs)

The first step in development of such models is the formulation of a computational scheme for the time integration of the hydrodynamical equations as applied to the large scale motions of the atmosphere, where key features of the ocean systems, the synoptic weather patterns, can be dealt with reasonably well at modest spatial resolution of 100-200 km, although higher resolution seems to improve the realism of the model. Inclusion of the oceans in a corresponding manner pose more difficulties, because the energy carrying modes of the motions are of much smaller scale and the observational base is much more fragmentary. Still, there are ocean models that are able to describe the overall features of the general circulation of the oceans. It is likely that with the advent of more powerful computers, much higher resolution for ocean models can be attained in the future.

A second step is to deal with other physical processes which influence the large scale motions of the system. In the atmosphere we are particularly concerned with a proper treatment of the energy transfer by radiative processes, energy conversion and transfer due to cloud processes, and turbulent exchange processes between the atmosphere and the surface of land and oceans. In the oceans we need similarly to develop means to include the exchange processes with the atmosphere and also with the bottom of the sea, particularly in coastal zones. Formation and melting of sea ice require careful treatment in view of the fact that the exchange processes with the deep sea are decisively dependant on winter conditions in polar regions. All these considerations are central themes in the development of climate models and the WCRP carries a prime responsibility for the international coordinations of the efforts in this direction.

A modelling project for the IGBP should primarily consider chemical and biological processes and their interplay with physical processes. This kind of model development constitutes the core of the IGBP. The problems of devising models of the component subsystems of the Earth system have partially been addressed by the other IGBP core projects. Development of a global model of the Earth system based on general circulation models of the atmosphere and the oceans and including the mutual interplay of physical, chemical and biological processes, i.e., Geosphere-Biosphere Models (GBMs), will be the focus of the GAIM project.

Problems of Predictability

The Earth system, as defined above, is a very complex one. The question arises to what extent is it predictable? Three decades of research and development in the field of numerical weather forecasting has conclusively shown that there is a very definite scale dependent limit to deterministic weather forecasting. Weather patterns cannot be predicted with any skill beyond two weeks (theoretical limit of the deterministic predictability), and present models are able to predict weather for about one week in advance with reasonable success. The limit for predictability for the smaller scale features of the weather patterns is much less, even less than a day for predicting cloud distributions and convective precipitation. The large-scale and slowly varying features of the atmospheric circulation can be predicted on longer time-scales. Clearly, the interactions of the atmosphere, the oceans and the terrestrial biosphere may have to be considered in this context.

The predictability of a system depends on how chaotic its behaviour is and indeed the Earth system has many chaotic features. It is also well known that non-linear systems may have multiple states, the transitions between which become of fundamental importance when assessing the predictability of the system. It is important to establish the criteria that determine if major changes in the system, e.g., from one preferred quasi-steady state to another, will occur or not. There has been a rapidly growing interest in the theoretical studies of chaotic behaviour of non-linear systems. Such research is of importance for improving our understanding of fundamental characteristics of the global models for the Earth system that are being developed.

The preceding sections have summarized the complexities we encounter in the development of the geosphere-biosphere models. It is also clear that there are close similarities between the developments of global climate models and geosphere-biosphere models. For the development of GBMs, it is desirable that formal links between the WCRP and IGBP be established. Appropriate joint working arrangements need to be agreed between WCRP and IGBP in order to ascertain

Science Components
Focus 1

Modelling the Global Biogeochemical Cycles and Their Interactions

It is proposed that the development of Geosphere-Biosphere Models, GBSMs be focused on description and better understanding of the global biogeochemical cycles. Although there are close links between all these cycles, it is considered appropriate that efforts focus on the global carbon and nutrient cycles.

Global Carbon Cycle Modelling

For the past 30 years, CO₂ concentrations in the atmosphere have been measured directly at a few marine sites around the world. More recently, CO₂ concentrations for the past 160,000 years have been extracted from air bubbles trapped in glacial ice. These observations show a dynamic carbon cycle that undergoes large natural fluctuations and rapid anthropogenic modification.

Atmospheric and oceanic models of varying degrees of complexity, ranging from box-models to global three-dimensional GCMs, have been used to deduce the strengths, timing and geographic distributions of terrestrial and oceanic sources and sinks of CO₂. Despite all these efforts, understanding of global carbon exchanges among atmosphere-land-ocean reservoirs is still rudimentary and reliable projections of future CO₂ levels in the atmosphere remain elusive.

Simple models of net photosynthesis and decomposition of the terrestrial biota with regard to their seasonal and geographic variations have yielded atmospheric CO₂ variations comparable with the observations. Air-sea transfer of CO₂ is not very well known, but experiments with ocean circulation models yield preliminary results about the sources and sinks for CO₂ in the world ocean. Inconsistency in our understanding of the global carbon cycle were revealed when atmospheric, terrestrial and oceanic exchanges were included in an atmospheric GCM. It is clear that the simultaneous consideration of all three carbon isotopes ¹²C, ¹³C and ¹⁴C as well as the use of other tracers both in the atmosphere and in the oceans will permit more stringent tests of the models.

The development of more advanced global carbon cycle models requires an expansion of the present network of observations of CO₂ primary productivity, etc., in order to permit adequate testing. The following highlights both key problems that should be addressed and the need for enhancement of the global data base.

Atmospheric carbon dioxide and the importance of isotopic studies

There are no direct means to distinguish biogenic and oceanic exchanges of CO₂ by interpretation of atmospheric but isotopic C measurements provide an indirect method to do so. This is because this rare isotope of carbon is fractionated relative to the abundant isotope, ¹²C, when plants withdraw CO₂ from the air during photosynthesis, but is passed back to the air with little or no further fractionation, during decomposition. In contrast, when CO₂ passes between the air and the oceans little kinetic fractionation occurs.

The combined atmospheric and ¹³C/¹²C ratio of atmospheric CO₂ yield information on the distribution and strength of sources and sinks and allow distinction between biogenic and oceanic CO₂ sources and sinks. The isotopic measurements must be of a high overall precision available at only a few laboratories in the world today. For an expansion of present studies of the isotopic composition of atmospheric CO₂ to be fruitful, close collaboration between laboratories and the establishment of reference standards specific to the study is required.

Additional insight into the carbon cycle may be afforded by studies of the ¹³C/¹²C ratio of atmospheric CO₂, but too little is known at present about the patterns and causes of variations in this ratio.

Interpretation of CO₂ measurements may require the use of mesoscale models nested (embedded) into GCMs. Nested models are crucial for linking ecosystem dynamics models and GCMs. In addition to having higher spatial and temporal resolution, nested mesoscale models have a more physically realistic treatment of atmospheric processes (e.g., cloud formation, flow over terrain) than GCMs. Embedded models can potentially bridge the scale disparities in the Earth system.
to predict how it might respond to future climate change. Finally, satellite
measurements of ocean color provide a measure of ocean pigment for a
relatively thin layer of the ocean surface (approximately 20 m). This informa-
tion needs to be translated into information on the role of biological processes in
the entire ocean mass. The way to do this is by the use of models.
A successful long term research effort on ocean carbon cycle modelling
requires a further development of ongoing observational programmes such as
the JGOFS (Chapter 3.1). It is essential that a more precise formulation of an
observational programme to follow after the realization of the present JGOFS
plans be pursued in parallel with the development of models (Chapter 3.2).
The World Ocean Circulation Programme (WOCE) and JGOFS will provide
a global survey over the next 5 to 10 years which represent a follow-up of the
Geochemical Ocean Sections Programme of 15 years ago, and the Trasient
Tracers in the Oceans programme, which recently completed a survey of the
Atlantic Ocean. The strategy of periodic global surveys needs to be continued on
a time scale of every 10-15 years.

Terrestrial processes
The land surfaces serve as sources and sinks for atmospheric CO₂, and must be
modelled carefully in any attempt to analyze the global carbon cycle accurately.
The key processes, such as photosynthesis and decomposition of organic mate-
rials, are highly dependent on climate. Present rates of emission and absorption
of CO₂ varies around the Earth depending on the prevailing ecosystem, the
development of which in turn are dependent on the geological substrate and
climatic conditions. The former, i.e., soil conditions, conversely have been
modified by the succession of vegetation and climate types during the Holocene.
While short term analyses of the role of the land surfaces in the carbon
cycle can be assessed on the basis of present distribution of ecosystems and their charac-
teristics, the analysis of changes over time periods of centuries or longer requires
the formulation of models that describe the mutual interplay between the carbon
cycle and the climactic system.

Earlier international programmes devoted to studies of specific ecosystems of
the world and their possible modification due to anthropogenic activities, e.g.,
the International Biological Programme (IBP) and Man and the Biosphere
(MAB), have contributed significantly to our present understanding of these
issues. The IGBP must now strive for an extension of those previous studies by
attemping to model quantitatively the complex global patterns of interplay
between physical, chemical and biological processes that characterize the functioning
of the biosphere today as well last century and the Holocene. This necessarily requires the recognition of the interaction of the global
carbon cycle with the global cycles of other key elements, particularly nitrogen,
phosphorus, sulfur and some crucial micro-nutrients.

Biogeochemical Cycles and Their Interactions
The carbon cycle is but one of the many biogeochemical cycles that play a role in the
Earth system. A prescriptive analysis of the carbon cycles necessarily involves a
treatment of the major nutrient cycles and their interactions with the carbon
cycle. Few such attempts have been made so far. During the last few years general
modeling models for the atmosphere have been used for studies of the chemical
interactions in the atmosphere. Similarly ocean circulation models have been
employed in order to grasp in a more precise and internally consistent manner
the biological and chemical interactions in the oceans. Still, truly global models
including a more precise treatment of the mutual interactions between the atmosphere, the oceans and the terrestrial system are as yet available only in the form of crude box models.

In view of the central importance of the carbon cycle for biogeochemical
interactions it is rational that the modelling of the more complex interactions of
the Earth system grows out of the present attempts to model the carbon cycle. Much
will depend upon the knowledge about the key processes gained from the
other IGBP Core Projects and the possibilities to generalize, i.e., parameterize,
those results into globally applicable numerical algorithms.
Data and Information Systems for the IGBP

"In spite of the enormous volumes of data currently being collected annually, it is questionable that specific data have, in fact, been acquired and are in a form required by a particular user. For this reason, in establishing the new international endeavour on global change, the scientific needs must be discussed and reviewed by scientists on a multidisciplinary basis. Once the problem has been clearly stated and agreed to, the data needs (especially in terms of precision and accuracy) have been established, then data systems and computer experts specializing in spatially distributed data may provide advice on how best to proceed. The final decision, however, should rest with the scientists, who are also responsible for deciding what priority is to be given to data acquisition and storage".

(Hutchinson and Bie 1985)
9. Data and Information Systems for the IGBP (IGBP-DIS)

The foundation of IGBP lies in the coupling of observations over a range of spatial and temporal scales with process studies and models in order to understand and eventually predict global change. But currently, global change research is data limited and it is important to begin developing the mechanisms to ensure that global change research can be properly supported by the necessary measurements and data sets.

The crucial role of information systems and the importance of data-management methodologies in support of global change research have been identified during the IGBP planning phase. Two important themes run through these discussions. First, an essential prerequisite for improving our understanding of Earth system processes is the development of geographically referenced models and data sets. Such models typically exploit a wide variety of data and this requires organized and systematic procedures to permit the integrated use of data sets of many different types and formats over a wide range of scales (Fig. 1). Second, methods and protocols for handling the large volume of data inherent in geographically-referenced models need to be developed. Coupled with this, methods need to be developed to enable interpretation of remotely sensed data, and their translation into parametric information that can be used in models and analyses.

Figure 1. The role of IGBP-DIS in relation to the IGBP research components.
There are two kinds of data requirements considered in this chapter. The first is data sets that document global change. These include data precisely calibrated to show subtle changes in ambient conditions such as land and sea surface temperature, global precipitation patterns and amounts (i.e., spatial and temporal distribution), changes in global land-cover characteristics and ecosystem dynamics. The second kind of requirement related to the provisions of data sets for support and parameterization of global process studies. Such studies include:

- Studies of water and energy balance and dynamics, which require data on latent heat flux, surface temperature, soil moisture, cloud evaporation/precipitation, and other dynamic parameters, many of which are derived from land cover.
- Modelling of global biogeochemical cycles, which require data on trace-gas emissions, ocean circulation and gas exchange, and ecosystem element cycle dynamics.
- Studies of ecosystem dynamics for different climatic regimes, which require data on land-surface characteristics including vegetation and soil changes, geomorphographic and data on climate change.
- Marine studies to understand exchange processes of atmospheric trace gases with the marine biophere. These will certainly involve global-scale data sets on, for example, ocean chlorophyll, seawater temperature, and temporal resolution, CO₂ concentration in the upper oceans, and surface winds.

Some of the most basic data sets either do not exist at a global scale or are inadequate to support these purposes. A prime example is that of land cover. Although probably the single most important and universally needed terrestrial data set, it does not exist on a coherent long-term basis, yet observations recorded over the past eight years from satellites are available from which the needed global time series can be derived. Land-cover data are needed for three of the four areas of research listed above. Another example is land-surface temperature. This data set is critical for documenting global climate change; yet, this does not exist with sufficient precision or accuracy, coverage and representativeness for the task. This chapter will discuss mechanisms by which these two issues on exchanging and developing a data and information system and developing global data sets will be resolved.

Plan for Action

Focus 1

Management of Data

Structure of IGBP Data and Information System (IGBP-DIS)

Rationale for a mechanism

The large variety of types and sources of global data needed for IGBP studies makes it important that a structure be in place at the earliest possible date to document what exists, assess its quality, check on accessibility of the data available and finally to foster the exchange of data sets. A number of impediments exist to the free exchange and distribution of data in an international programme. Some of the more important impediments are:

- the lack of a comprehensive inventory of major existing data banks;
- even where data sets exist, there are often major uncertainties about their quality and accuracy;
- there are no consistent international policies and protocols for data exchange, which leaves uncertainties on issues such as charging and licensing (which constrains data sharing) copyright restrictions, import/export restrictions, and technology transfer issues;
- there is no long-term (10-20 years) commitment from any national or international organization to develop the policies and programmes to facilitate data exchange, in the new areas of research of the IGBP;
- the bit stream of data is large, but our ability to analyze the data, or produce information from data, is slow due to the lack of trained interdisciplinary scientists and due to the paucity of experience and methodologies for utilizing large amounts of data.

IGBP is to succeed, each of these impediments must be removed, and this requires the recognition that data management is a fundamental, if not primary, component of a research programme. As such it transcends engineering. It must be an integral component of an overall research strategy and be embedded within the implementation plans for each established Core Project. Thus, the implementation of a data-management scheme for the IGBP must be a visionary one, but must also be realistic. In particular, it must capitalize on existing structures and national-level efforts. A phased approach is needed and the highest priority in the early period of IGBP implementation (1990-1992) must be on managerial and policy aspects. During this period, IGBP would make no effort to develop centralized facilities for data processing and product generation, but would instead focus on three major activities: (i) developing a programmatic infrastructure; (ii) performing studies to develop methodologies for producing globally consistent data sets; and (iii) attempting to install data directories around the world in order to make data more accessible to the global community of scientists.

Later, in the next phase, as specific data needs are articulated by the Core Projects and as critical data gaps are found, the IGBP will begin to utilize data facilities, which meet the research needs or to propose new developments to ensure that these needs are met. This phase would focus on installing an IGBP-DIS facility, which would be co-located at some existing data centre, and which would conduct preliminary tasks such as data reformatting or algorithm development for the IGBP scientific community.

As the IGBP develops, it may be necessary to expand the role of the data-management facility. This could be done in two ways: (i) by expanding the operations, to the development of an IGBP data archive; and (ii) by expanding the number of facilities around the world, linking them together physically through data communications networks.

In accordance with established ICSU policies on open and unrestricted data and information exchange, and the principles governing the ICSU-WDC System, the following policies are proposed:

1. The IGBP places high priority on the establishment, maintenance, validation, description, accessibility and distribution of high-quality, long-term global data sets, including the synthesis, or generation of new global data sets.
2. Full and open sharing of the full suite of global data sets, and other data sets needed for global change studies, is the primary objective of IGBP-DIS.
3. Consequently, IGBP-DIS should have the following characteristics:

   - suitable preservation of all data needed for long-term, global change research must be ensured;
   - data archives must include readily accessible and comprehensive information describing data sets (metadata about the data holdings, including quality assessments, supporting ancillary information, and guidance and aids for locating and obtaining the data);
   - national and international agencies with responsibilities for archiving and distributing global change data should, to the greatest extent possible, use media and processing and communication systems which are consistent with internationally accepted standards and protocols;
   - in those cases in which individual scientists have initial periods of exclusive data use, data should be made openly available as soon as they become widely useful;
   - data should be provided at the lowest possible cost which, as a first principle, should be no more than the cost of reproduction and distribution.

Management structure

The near-term data management role of IGBP will be one of support and coordination. This will be implemented through a small coordinating office, guided by a Standing Committee, with support from a technical staff.

The IGBP Office of Data and Information Systems should serve the following functions:

- ...
- Facilitate and coordinate access to, and exchange of, IGBP data sets by encouraging the development of standards and protocols for data exchange.
- Assist in locating important IGBP data sets, which are currently stored elsewhere. There is also a need to coordinate the development of new data sets, which would otherwise not come online because they fall outside the domain of interest of a specific Core Project.
- Provide the initial data processing and management experience by coordinating and monitoring a series of prototype projects, the first two of which have been identified as the Land Cover Pilot Study and the Surface Temperature Pilot Project. These pilot studies will also perform the role of developing two much-needed new data sets.
- Provide for outreach and training at an international level through the dissemination of sample diskette data sets and instructional material including software through workshops and other related activities.
- Encourage and organize a system for data set and data product review to ensure the development of the best possible data and to provide an environment, which encourages the development and dissemination of data sets by investigators.
- Implement and maintain an international system of data directories which would provide scientists with information on the location of various IGBP and non-IGBP data sets.

The professional staff of the IGBP-DIS Office will have both the scientific background relevant to the Core Projects and some detailed understanding of information systems, remote sensing, and GIS. The IGBP will encourage scientists to be actively involved in data management of the Core Projects.

One key function of the IGBP-DIS Standing Committee and staff would be assisting in acquisition of essential data sets which are needed by the Core Projects, but which do not exist in current holding, at the various national and international data centres, and will not be produced by the Core Projects themselves. The IGBP-DIS Office will coordinate the generation of these data products. The two pilot studies, land cover and surface temperature, are examples of this kind of effort and are now under way by the working group as demonstrations.

The relationship between participants in the research process, various data centres, the Core Projects, and the Regional Research Centres, is clearly defined by the need to exchange information (Fig. 2). The establishment of a directory system managed by the IGBP-DIS Office with cooperation from participating national centres/ agencies (e.g., NASA), will provide information to the various participating IGBP scientists around the world on the location of data sets. As shown in this diagram, the IGBP-DIS Office provides the critical link between data centres and Core Projects, as well as facilitating the management of data.

The IGBP-DIS Office must participate actively with the various IGBP Core Projects to deal with their data needs. Personnel could be provided to the Core Projects by the IGBP-DIS Office to act as a liaison with the IGBP-DIS Office, thereby providing assistance to the Core Projects in the way of data management and to the IGBP-DIS Standing Committee in the way of articulating technical needs.

One tangible function of the IGBP-DIS Office during this phase will be to install a system of data directories, the IGBP Global Environmental Data Directory (IGBP-GEDD, Fig. 3). The directory system will be organized around the NASA Master Directory and would be installed in GRID/Geneva as a central location in Europe. The purpose of the directory system will be to tell scientists where they could find out data sets and to provide online information about their characteristics. It would not be the purpose of this effort to actually archive the data sets.
Data management beyond 1992

A number of facility-based needs are expected to arise during the early implementation phase as the Core Projects begin collecting and assembling their own data sets and begin to exchange data with other groups. A mechanism will have to be developed to facilitate data retrieval, processing, data conversion, and archiving. A facility to conduct these activities must be identified or developed for the IGBP. In addition, the land cover and surface temperature data sets, being produced in collaboration with the IGBP-DIS Office, will be ready for archiving and distribution and will need the appropriate outlet to the scientific community.

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Data Access and Directory of Directories

Introduction

The IGBP-DIS, because of its multi-disciplinary and multi-user characteristics, must be an open and flexible system of data and information exchange. The diverse types of data, which will populate the IGBP data system and be needed by the IGBP research community, demand the development of a system capable of cataloging and accessing data directories or Directory of Directories for the IGBP. This will be necessary in order to facilitate accessibility to the needed information.

The IGBP-DIS should be a distributed system to provide more convenient access to scientists in all countries and provide a tool for preservation of IGBP data sets. The IGBP-DIS should have an interface with and collaborate as appropriate, the various data systems operated under the auspices of ICSU (e.g., the WDC system, WDDDS, IUG), UN bodies (e.g., GRID/UNEP, the MOI, UNESCO data systems and SOTER) and important national data systems (such as those being developed for space-based operations).

Scientists who, in the course of their research, produce new global data or information products should be encouraged to contribute these to the IGBP-DIS, so that they may be readily accessible to others. There should be mechanisms to ensure that both scientists and professional credit is given to scientists, who publish or otherwise contribute data sets for public distribution.

Global environmental data directory

A priority goal of the IGBP-DIS is a management system, which describes data sets and in a format useful for Global Change Studies. The IGBP Global Environmental Data Directory (GEDD) will be developed as a computer tool to satisfy this requirement. The model for the GEDD is the NASA Master Directory (MD), which has been operational since 1988. The MD is the core of an evolving international system of data directories, which includes the European Space Agency in Italy, the NOAA Earth Systems Data Directory, and copies of these directories will be installed in Japan, Geneva, and USA. A copy of the MD will be installed by NASA at the UNEP/GRID computer. The GEDD will use the NASA Directory Exchange Format (DIF) for describing data sets. The DIF is the standard format used in the data directory system. A data set will be formed to develop a standardized protocol for use in the IGBP. It is intended that the GEDD will be a user friendly system, with access via a computer terminal. Information will be displayed on the computer screen. The user will be prompted to input interactive data, such as Discipline, Location, Parameters, Keywords, and Data Center. Titles of data sets which satisfy the search criteria will then be displayed. The user can then display the description of a selected data set. Information will be given about the data set, with the key field being the Data Centre where the data set is available.

Data management functions for the GEDD will be performed by a coordinator responsible for the control of data descriptions in the Directory. This function provides a central point for monitoring the input and update of data descriptions in the GEDD. The IGBP-DIS Standing Committee will provide a forum for locating data sets which should be included in the GEDD, for reviewing data descriptions and for deciding which descriptions should be included in the IGBP-GEDD.

It is believed that the initial processing facility should be co-located with a land processing facility for the IGBP-DIS and Information System, and a facility in the World Data Centre network. The chief responsibilities of this facility will be very circumscribed and restricted during the early development period. In time, it would serve as a distribution centre, a reprocessing and data conversion centre, and, to a limited degree, an archiving centre.

Data Sets for Training and Education

A pilot project consisting of a library of data sets useful for global change studies has been initiated (ICP 1989). A global vegetation index (VI) derived from satellite observations has been compiled from NOAA-AVHRR data. The data sets were made available on computer floppy diskettes to facilitate its use by scientists in developing countries.

A demonstration project for Africa has been completed with four years of data, compiled monthly. Africa was chosen as the first demonstration area, since UNIP-GRID and the UN Institute for Training and Research (UNITAR) indicated interest in using the data sets as hands-on training modules for workshops scheduled for Africa in 1989-1991. In addition, suitable ancillary data sets have been included so that the annual and seasonal vegetation-index could be studied in the context of other land-surface and climatic variables. The data sets are expanded to include South America and Asia. The data set and software package was successfully used at a GRID/UNITAR workshop in Accra, Ghana, November 1989. The participants seemed eager to participate and the idea of collaborative efforts, between research groups and scientists in developing countries to provide improved information to the project, was accepted.

Significant long-term national and international support is needed to assure that the project will be able to continue workshops with GRID/UNITAR beyond 1990 in other regions. A number of groups in both developed and developing countries have offered to use the data sets in global change case studies, and to provide an evaluation of the data set for tutorial in training workshops. These groups have been asked to share any relevant tutorials they develop in using the data sets. Such tutorials or case study exercises are needed to develop a library of training exercises for the GRID/UNITAR workshops.

The Global Change Diskette Project now needs a national-level commitment to provide development efforts that will continue beyond the pilot phase to assure stability of the project, to assist GRID/UNITAR in developing the necessary training materials and tutorials, to provide a focus of feedback of improved data into the project, and to be responsible for updating the database sets and distributing the updated versions. Some relationships might also be possible with the IST Encyclopedia of the Earth project.

The ISU WDG panel should also remain as an active partner in the project, to assist with international aspects, provide assistance in obtaining new equipment such as CD-ROM readers, and, through the WDC System, ensure the
The need for a comprehensive global data base on land-cover change has been identified as having critical importance for a number of IGBP Core Projects. These include International Global Atmospheric Chemistry Programme (IGAC), Biospheric Aspects of the Hydrological Cycle (BAHC), Global Change and Terrestrial Ecosystems (GCTE), and Global Analysis, Interpretation and Modeling (GAIM).

It is clear that the requirements for local land-cover information vary considerably for the different projects. The first project, for example, requires only broadly defined land-cover types, whereas others will require much more detailed information. Existing data sets on land-cover characteristics are derived almost entirely from the compilation of local data sources (FAO 1988; Mathews 1983, 1985), relying mostly on conventional ground-based methods. As a result, the information varies considerably in reliability and in the consistency with which major categories are defined. In recognition of this major omission in environmental data bases for global investigations, a Land-Cover Pilot Study has been initiated.

Objective

- To develop, validate and demonstrate a methodology capable of monitoring land-cover characteristics and its changes in a range of environments which subsequently can be used globally.

In order to achieve this objective a number of tasks have either been carried out or are in the process of being executed within the next two years.

The encoding, processing, and utilization of large volumes of variously formatted data require adoptions of new methodologies, procedures, and approaches to data acquisition, processing, management, and interpretation. Clearly, new global change research initiatives will need to be coupled to efforts to develop special geo-based information systems. This has been a consistent priority in the global change studies, highlighted in several national and international studies and publications (National Research Council 1986; Earth Systems Science Committee 1988; NASA Earth Observing System 1988; International Geosphere Biosphere Programme 1998, 1999; and Space Agency Forums for International Space Year (SAFISY) 1988, 1990). The IGBP Working Group on Data and Information Systems was established to explore ways in which this could be achieved. Because remote sensing holds the greatest promise for obtaining geographically referenced data over large areas of the Earth's surface, it has become an important focus of efforts by the IGBP and is dealt specifically in Chapter 10.

The integrated global land-cover data base

The original concept of the global land-cover product centred around the production of a global map (IGBP 1989). It is now proposed that this concept should be substantially modified, in large part because the varied requirements of the working Group can be satisfied by a single map of one set of attributes. Instead, it is proposed to develop a comprehensive global land-cover data base, which will contain the following sets of data planes: (i) basic calibrated remote sensing data planes; (ii) pre-processed remote sensing data set; (iii) key ancillary data planes; (iv) attribute data sets (base-line and change); and (v) parametric data sets (base-line and change).

Data sets used in the IGBP will largely be derived from the latter two of these data layers. The attribute data sets will contain spatial products including conventional class maps. Ultimately, it is anticipated that several different types of products will need to be generated. For the parametric data sets, quantitative derived characteristics of the land surface will be derived, through statistical approaches, and through full-scale inversions of remotely-sensed data assisted by techniques such as scene modelling. It is anticipated that these latter data sets will eventually be the most significant for the IGBP, because of the requirement to develop quantitative environmental models.

Definition of land-cover classification

During the planning discussions, a classification scheme has been developed, which is hierarchical in character. Initial discussions have focused on the broad, general classes of cover types, and include: evergreen forest, deciduous forest, shrub, grassland, desert, snow, ice, tundra, cropland, and urban land cover (see IGBP 1989). These can be derived from existing satellite data, with satisfactory accuracy for a wide range of applications. Further work is now being carried out to quantitatively define the boundaries between the categories and to define other levels of the classification hierarchy suitable for research studies conducted in other IGBP Core Projects.

Choice of remotely-sensed data and pre-processing procedures

Data from the Advanced Very High Resolution Radiometer (AVHRR) of the NOAA series of satellites have been selected as the prime source of data for the land-cover data base. This choice is based on the appropriate pixel size of the data in relation to the global coverage requirements, the ability of the data to generate land-cover classes of the type required, the past and future continuity of this data source and its frequent global coverage. For several of the pilot areas, AVHRR data have already been collected, composed and processed, notably those for the US, Canada and West Africa. Pre-processing of these data are necessary before use and a considerable number of options are available under pre-processing procedures. These include: (i) compositing methods; (ii) time period for composing; (iii) atmospheric correction procedures; (iv) geo-referencing coordinate systems; and (v) resampling procedures. Standardization of these procedures is necessary for precise intercomparison of cross-site study evaluation as well for infra-site temporal coherency.

Despite the pre-processing of AVHRR data, a resolution has largely depended on the use of ground receiving stations, due to limitations of storage on the sensor's tape recorders. Agreement on re-processing procedures of these data are essential for the creation of internally consistent global data sets. In order to gain international agreement on pre-processing standards, an international meeting of ground-station organizations collecting AVHRR 1-km data has been organized by the IGBP Working Group on Data and Information Systems to evaluate the various techniques currently being used. Presently, even coverage information on the availability of 1-km data from the AVHRR sensors is difficult to obtain. The task of establishing the availability of AVHRR data in order to obtain a global picture of gaps in AVHRR coverage has been initiated. This exercise will be used to make recommendations for the future use of on-board tape recorders, so that a more complete global coverage can be obtained.

Selection of pilot studies

In the original formulation of the pilot studies (IGBP 1989), it was envisaged that a number of separate areas of comparable size would be selected covering a representative sample of vegetation and land-cover types. Subsequent activities of the Working Group in consultation with other IGBP Coordinating Panels and other organizations (e.g., SOTER, ISRIC, UNEP, etc.) have broadened this concept to include pilot areas varying in both geographic extent and in objectives. In both the approach appears most desirable. One class of studies will address the methodology to document and monitor changes in various classes of vegetation types over large areas (approx. 1,000 x 1,000 km) with a surface...
resolution of 1 km. The second class of studies will involve producing a number of complementary data sets over a small region (approx. 100x100 km) to be used for deriving fluxes of energy, water and trace gases. The following pilot sites have been identified and in some cases work has already been initiated in early 1990 for first results to be available in 1992. Figure 4 shows the selected sites for both classes of studies.

Figure 4. Location of IGBP study sites for pilot project on land use change.

West African Pilot Study. This project introduced remotely-sensed energy measurements into models of energy and matter fluxes at the atmosphere and interface in an area which extends from the semi-arid areas of the Sahel to the humid areas of the Sudanian. Direct measurements of land surface parameters will allow the quantitative description of vegetation relevant to global climate and will provide new ways to characterize ecosystems and their interface with the atmosphere.

The work will contribute to methodology through an assessment of the temporal and spatial scale needs for the land-cover information database relevant to process studies and modelling efforts relevant to IGBP Core Projects (i.e., IGAC, BAHC, CCTE). It will also lead to a better choice of data and pre-processing options to make the data more suited to the requirements of the models being developed in these core projects.

South East Asian Pilot Study. The general objectives of this study are to develop, validate and demonstrate a methodology capable of monitoring land cover and its changes in a range of environments, which can then contribute to global investigations. Specifically a study is being undertaken in representative areas of Thailand and Sumatra, including tropical wetlands (natural and artificial), and a tropical mountain zone. In the methodological studies, emphasis will be placed on the integrated use of multiple sets of remotely-sensed data including AVHRR data, and higher resolution SPOT and Landsat data. This will be accompanied by the use of aerial photographs and ground-data collection, focusing on those changes in land-cover and land use that contribute to, or are induced by, global climatic and sea-level changes.

East Africa-South Turkean Ecosystem Project. It is intended to integrate several types of remotely-sensed vegetation index data with a GIS-based vegetation and land-cover maps of Ngocoyoka, Turkana to analyze patterns of vegetation response to precipitation. The analysis will be used to: (i) distinguish the production and phenological patterns among vegetation types and land-cover patterns in Turkana; (ii) characterize the degree to which other different East African ecosystems display the pulsed pattern of production observed in Turkana; and (iii) test the hypothesis that the total amount of rainfall is less important for ecosystem stability than the period over which it is delivered.

Semi-Desert Rainforest. The semi-desert rainforest, especially that occurring in the transition zones between grassland, croplands and deserts is being investigated in the region of Guangzhou, China. Specifically, a climatological investigation is focusing on sustainable development. In this area the hydrological cycle is closely controlled by glacier and snow-pack development in the Tibetan Plateau. Changes in climate could well lead to dramatic changes in land-surface characteristics, involving increased soil erosion and desertification. This area of mixed land use will be used to assess the extent to which current methods of information extraction can be used to classify land cover in a semi-arid region.

Ubsu-Nur Pilot Project. The Ubsu-Nur basin lies across the border of the USSR and Mongolia. It forms a valuable natural laboratory containing an extremely wide range of natural zones within a relatively small area. These zones include deserts, steppes, forests, tundra, and ice fields. Both lowland and mountainous areas are found in the pilot-study area. It will be used therefore for investigations into the quantitative characterization of vegetation types, for hydrological modelling, and quantitative extraction of information from an integrated use of remotely-sensed data and ground investigations.

Amazonian Land Use Project (AMVUSE). The study area of Amazonia represents a very significant portion of the Earth's forest cover. In the context of the present project, the specific objectives will be to investigate an area of tropical rain forest undergoing both rapid and drastic changes in land cover and areas undergoing regeneration through time. It is anticipated that the results of the land-cover characterization of the area will input directly into investigations of biogeochemistry under human influences, especially in relation to the carbon cycle. Methodologically, the project will contribute to the assessment of the deforestation "signal" with low resolution data, and sub-sample finer resolution data from Landsat and SPOT for validation purposes. As part of this project, a prototype fine-scale mapping procedure will also be developed for use in a GIS.

Australian Pilot Project. The Australian pilot project forms an integrated part of a larger multi-disciplinary study on biospheric inputs to Global Climate Models. The objective of the study is to dramatically improve the representation of terrestrial surfaces currently being used in models parameterized for Australia. Studies will be carried out within carefully selected sample areas occupying less than 1% of the continent. However, these areas will be sufficiently representative to allow the development of a methodology to extend the analysis through the use of thematic mapper data and AVHRR to structurally analogous habitats at global scales. It is further intended to parameterize a number of landscapes into surface roughness, albedo and conductance. Methodologically, the study will contribute to development of mixture models for estimating landscape component contributions at the pixel scale.

Canadian Land Cover Pilot Study. The Canadian pilot area has now been extended to include the whole of the country. It will contribute to the objectives of IGBP through a study of land-cover change on seasonal and inter-annual time scales at an initial resolution of 1-km. It is intended to parameterize vegetation development and dynamics through measures such as length of growing season. Phytonass distribution and annual changes will be estimated to provide input to the modelling of carbon and nutrient cycling. Models and predictions will be...
derived from long-term vegetation changes based on observed or postulated climate trends. Methodologically, the project will contribute through the setting up of a Canada-wide data base of ancillary data. A multi-year consistent data base will be created for AVHRR cloud-free composites. Improved pre-processing procedures will be developed. Algorithms will be developed and validated for land-surface parameterization. Procedures will be developed for integrating remotely-sensed data at various resolutions.

**United States Data Set Development.** Methodologies will be developed for land-cover characterization that can be applied to the quantification of land-cover processes. The work will lead to the development of procedures suitable for use at very broad continental scales. Specifically, data sets will be prepared that incorporate time-dependent calibration, justifiable atmospheric corrections, automated correction for image registration, and data quality control. Methods will also be derived for change detection and land-cover monitoring as well as for the production of land-cover maps.

**South American Continental Scale Mapping Using 4-16 km Data.** For South America a land-cover data set which is well suited for biogeochemistry and water-balance models will be developed. The land-cover map will be developed from coarse resolution AVHRR data, first at the 16-km level of resolution and later at 4-km. Finer resolution AVHRR data (i.e., 1-km) will be used to define boundaries and provide sub-pixel information. The goal of the project will be two fold: (i) it will develop a functional classification of land-cover which can readily be parameterized with parameteric information, such as biomass; (ii) it will examine the utility of this data set by linking to its potential for biogeochemical models (carbon cycle and trace gases) and water and energy-balance models.

This project will interface with the pilot studies on Amazon Land Use and in Africa.

**African Continental Scale Mapping Using 4-6 km Data.** For the African continent, so-called Global Area Coverage (GAC) data from the AVHRR with a resolution of 4-km will be used for land-cover characterization. Currently, 1-km data do not exist for the globe with sufficient cloud-free frequency. However, recent GAC data have been processed and are available for the whole of Africa, and these will be used to up-date existing land-cover maps, to provide a template of information upon which to base change-detection studies and to provide test for investigating existing AVHRR data for global land-cover mapping. It is intended to develop sampling procedures for the spectral classification of areas using all five available spectral bands, which will then be used to supplement the classifications based on the temporal profiles of the vegetation in indices. Also, procedures will be investigated to integrate the 1-km with the 4-km data sets and with the 8-km global data set discussed below.

**Global Classification Using 8-16 km Data.** A global data set, suitable for land-cover characterization now exists, which has been registered, atmospherically corrected, and cloud-screened, and it is proposed to use this data set as the prime source for a global mapping exercise, relying primarily on the temporal variations of a spectral vegetation index to carry out the classification. The data have been derived from the 4-km GAC data and have been composited and screened using thermal data to reduce cloud effects by NASA/GSFC. The results of this work should lead to a product processing more than one order of magnitude more detailed information than is currently available from global digital data sets of land cover. Validation and testing of this product will be carried out through cooperative activities with the various other pilot projects described above.

**Data Validation and Quality Control Pilot Studies.** In order to be usable for quantitative analysis and scientific research, data sets must be validated and quality controlled. Furthermore, the users are generally not concerned with the raw-data of radiances measured by satellite, but in the secondary geophysical data which can be extracted from these radiances. Therefore, a protocol for data validation and quality assurance must be developed. A pilot study using Earth surface temperature measured from space has been initiated.

The main reasons for this study are: (i) surface temperature is a good indicator of the energy balance of the planet; (ii) the evolution with time of surface temperature is therefore a good indicator of the greenhouse effect; and (iii) surface temperature is one of the key variables controlling fundamental biogeochemical and geophysical processes between the Earth's surface and its atmosphere.

From a consideration of the physics of thermal infrared radiation, it is necessary to treat sea-surface temperature and land-surface temperature separately. The main reasons being:

- the spectral emissivity of sea-surface temperature in the 10-12m domain is almost the same in the two channels of AVHRR and is very close to unity, but it is more variable over land and may take very small values in the desert area (0.85);
- the emissivity and skin temperature are homogeneous over large areas of sea surface, but quite variable but in the case of land surface temperature the data set will provide a template for the parameterization of surface temperature for sea (SST) and for land (LST) should therefore be different and use different approaches.

Two approaches will be reviewed for integrating remotely-sensed data sets in two intercomparison workshops. The same scientists will participate in both pilot studies to insure coherence between the two aspects. In both pilot studies, the calibration of the various sensors and validation procedures will be addressed.

A first workshop is being organized (i) to analyze the characteristics of the existing algorithms used to determine land-surface temperature, namely the four main steps of such algorithms: cloud filtering, atmospheric correction, emissivity correction, and scaling to a standard reference; (ii) to identify the best data sets and the best sensors suitable for intercomparison of algorithms; and (iii) to determine the processes and criteria for intercomparing the algorithms and the sensors used. The meeting will then be followed by an intercomparison workshop.

As described above, implementation will occur in three phases. Throughout the term of implementation, 1990-1997, there must be a ramped up commitment of resources. The largest share of resources will be needed in the last phase. But we must begin now with the following activities if we are to be successful in the later phase:

- Training of students at the post-graduate level in interdisciplinary science with experience in the fields of remote sensing and geographic information systems;
- Providing Global Change related data sets on diskettes to scientists in developing countries. Assure continuity for at least three years to evaluate results;
- Developing a global network of functional data centres, which would be mature in terms of infrastructure, facilities and programme direction to take on the increased data management after 1997;
- Developing a user-friendly and complete directory of data sets suitable for IGBP science, and developing the technologies to make the directory function for science (e.g., geographical browse capabilities and on-line quick looks);
- Developing the experience and methodologies for integrating many sources and formats of data, including remote sensing, in situ data, and GIS data, into a commonsystem for use at a research site.

The immediate course of action required to implement the IGBP-DIS described above includes: (i) establish an IGBP-DIS Office and provide a professional staff of a few scientists; (ii) implement the NASA Master Directory at GRID in Geneva and establish the IGBP CEDD; (iii) link GRID Geneva to other IGBP "centres" (e.g., RBCs) around the world; (iv) define a set of IGBP data sets within the current holdings, define a list of data sets needed based on a scientific review of IGBP Core Project demands, then establish a plan for developing the designated data sets; (v) complete the development of the Land Cover Data Sets and the Surface Temperature Data Sets; and (vi) identify a primary data facility for the Mid-Term phase activities.
References


Suggested Reading


Needs For Remote Sensing Data In the 1990s and Beyond

"The global change programme will call for coordinated measurements on a global scale of those interactive physical and biological processes that regulate the Earth system. The programme will rely heavily on the emerging technology of remote sensing from airborne vehicles, particularly satellites. Satellites offer the potential of continuously viewing large segments of the Earth's surface, thus documenting the changes that are occurring. The task, however, is not only to document global change, which will be an enormous job, but also to understand the significance of these changes to the biosphere... The possibility of measuring biosphere function remotely and continuously from satellite imagery must be explored quickly and thoroughly in order to meet the challenge of understanding the consequences of global change."

(Mooney and Hobbs 1989).
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10. Needs for Remote Sensing Data in the 1990s and Beyond

Introduction

As the IGBP Core Projects begin to be defined and the research becomes formulated, we must focus our attention on specific needs of the IGBP for global observation from space. A first study carried out by COSPAR (Rasool 1987) described in some detail the existing space capabilities, the upcoming programmes of various agencies and how a number of key data sets, acquired from space satellites, can be useful in Global Change studies.

Now, in early 1990, we are at a critical point not only in the definition of a focused research projects for the IGBP but also in the formulation of plans of space agencies of the world for consolidating their activities for space for the decade of the 1990's through the International Space Year (1992) and beyond.

Elements of Global Change Observing System

IGBP has now established five Core Projects and a number of other are in definition phase. Four of the established Core Projects involve process studies on continental and global scales that can make substantial use of remote sensing: IGAC (Chapter 2.1), JOOPS (Chapter 3.1), BAHC (Chapter 5.1) and GCTE (Chapter 6.1).

Although a measurement strategy for these projects is only beginning to be formulated, it is clear that the measurement needs are going to be global with varying temporal and spatial scales. Also, high quality measurements will be needed over the long-term (decades) for a large number of variables related to the: (i) physical state of the atmosphere, land and oceans; (ii) chemical changes in the atmosphere, oceans and land; and (iii) biological state of the land cover and of the upper layer of the oceans.

The measurement programme will be derived from a variety of observation systems. These include satellite systems for long-term, global coverage and large-scale field experiments for process studies using satellites, aircraft, balloons, and surface stations. It is essential to maintain high quality surface observing networks and that these be appropriately linked to remotely sensed data. These data sets will be instrumental to the development of Earth system models to improve our predictive capability, because such data can be used both as an input to the models and as a test to the model predictions. An integral component of the data measurement activities is a data and information system. The IGBP Data Information System (IGBP-DIS) is proposed to facilitate data collation and dissemination of the various types and sources of data and users. Information flow between various research projects and scientific groups is essential to the success of the IGBP.

The IGBP needs space-derived data for three overriding reasons. These are: (i) document precisely global-scale changes in key variables to assess the way the planet as a whole is evolving with time; (ii) measure the long-term trends in the forcing functions of the global change; and (iii) simultaneous measurements of several parameters to study the interactive processes which regulate the earth system. These are the measurements which are needed for the IGBP Core Projects and will be discussed in the following section.

Despite current availability of remote-sensing data, many of the measurements are only loosely coordinated in time and space. The international collaboration to maintain and coordinate the collection of pertinent Earth system data
for global change studies will need an evolutionary Earth observing system to fulfill the IGBP needs.

In the near-term (1990-1995) the programme will be based on:

- Continuing operational meteorological, geostationary and polar orbiting satellites (Goes, Meteosat, IRS, SMS, NOAA Landsat, Spot).
- Already planned research missions (ERS 1, UARS, Topex/poseidon, SeaWIFS, Nasa-scatterometer, JeRs, Radarsat, Adeos spot 4).
- Instrument development for space use by the mid-1990’s (multichannel imaging spectrometers, SAR, Lidar, Laser altimeter, high resolution images).
- Ground validation and field experiment programme.

In the longer term (1996 and beyond), we will have a new generation of space observing systems based on polar orbiting platforms, which will become available in 1998 and later. Observational requirements for the IGBP are being identified now, so that they can be incorporated in the design of the Earth Observing System. The following is a preliminary attempt to outline the need from remote sensing from space for the established Core Projects IGBP, JGOFS, BAHC, and GCTE.

**IGAC Needs**

A major challenge for IGAC will be to acquire information on a number of trace gases in the troposphere. Data on the concentration and vertical distribution, with appropriate time and space resolution of these trace gases, are needed. It will be important to be able to measure the magnitudes of the terrestrial and oceanic sources and sinks for radiatively and chemically important tropospheric trace gases, in particular CO, CO, CH, O, N, NO, NO, NH, CH, HS, H, OC, and SO. We will need to know their stratospheric survival, altitude, and latitudinal variations, and regional trends, over timescales of 100 years. Because H plays such a key role in tropospheric chemistry, time variation measurements of global water-vapour distribution are an important requirement as well. In order to quantify the fluxes of these trace gases at the land and ocean surfaces, we will need to make simultaneously a variety of measurement from ground, aircraft and space to assess the rate of change of land cover and the ocean biosphere. The measurements needs will include characterization of land cover types, canopy height and density, biomass burning and net primary productivity on land and oceans together with measurements of temperature, albedo and moisture.

So far, most satellite experiments to detect and measure trace gases in the atmosphere have been confined to the stratosphere. Cross estimates of tropospheric water vapour are obtained from current meteorological satellites. The only trace gas in the troposphere with a relatively low mixing ratio, detected up to now, is CO. This has been measured with the MAPS (Measurement of Air Pollution from Satellites) experiment during OSTA-A Space Shuttle mission in November 1981 and October 1984 from a one-month period only. The results showed differences between Northern and Southern Hemispheres and higher concentrations were noticed in the area of South America, which may be caused by tropical fires. Such measurements were, however, never repeated.

Efforts of several space agencies to develop new instrumentation for measuring and monitoring tropospheric trace gases from satellites and to provide better characterization of the biogeochemical functions are noteworthy.

- Vegetation Mapping Instrument (VMI) on Spot 4 for global daily coverage at 1.1 km resolution in 1994.
- Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) and ESA polar platform for trace gas measurements in the troposphere in 1997.
- Moderate Resolution Imaging Spectrometer (MODIS) for high temporal detail, tabulated inventory of biosphere for NASA (EOS-A and High) and Russian Infrared Spectrometer for high spectral and spatial detail of biogeochemical conditions.
- Measurements of Pollution in the Troposphere (MOPITT), Tropospheric

Radiometric for Atmospheric Chemistry (TRACER) on NASA/EOS-A in 1997

Because the existing satellite system is adequate for surface imaging, but severely limited for measuring most of the tropospheric trace gases accurately, a satisfactory observational system for the next decade might evolve as follows:

1. Ground-based measurement network of high accuracy for tropospheric gases or complementary data.
2. Balloon and aircraft measurements for field studies, for complementary measurements, or for instrument technique testing along with overlapping observations from space for surface imaging and radiances.
3. Experimental instrumentation on polar platform and/or on special research free flyers for testing new techniques for measuring trace gases in the lower troposphere.
4. "Permanent" baseline instrumentation on orbit polar platform to measure gases in the stratosphere and troposphere, simultaneously with the detailed characterization of the land and ocean biosphere.

**JGOFS Needs**

The feedbacks between climate, ocean primary production and ocean CO2 storage depend on global as well as regional characteristics of the biogeochemical cycles of carbon, nutrients and key trace elements and on the climate control of the physical environment in the euphotic zone. A much better knowledge of the basic processes that couple physical, chemical and biological processes in the sea, based on in situ and remote-sensing methods of observation, is needed to make it possible to understand and to model the coupled marine-climate system. It is important to know the consequences of these climate-induced changes on the structure and function of the oceanic ecosystem. To this end, JGOFS aims to develop observational methods and models for ocean colour, to better understand the basic processes that couple physical, chemical and biological processes in the ocean. JGOFS aims to develop observational methods and models for ocean colour, to better understand the basic processes that couple physical, chemical and biological processes in the ocean.

Important oceanographic data are already being acquired by NOA, Japanese MOS-Iand by the Defense Meteorological Satellite Programme (DMSF). Ocean and ice measurements will also be provided from the ERS-1 of ESA, scheduled for launch in 1990, and the US/French Ocean Topography Experiment (TOPEX/poseidon) in 1992. Together, these satellites will provide the necessary global coverage of ocean and ice surface properties needed for understanding global change. The properties to be measured or inferred include surface wind stress (scatterometer); sea-surface temperature (infrared-microwave images); ocean currents, fronts, and eddies (altimeter); ice extent, surface temperature, ice and snow cover, and in the future, wind stress from roughness, winds over the ocean, sea-level height, and ocean colour. Long-term monitoring of these marine characteristics is essential in the development of our understanding of how the ocean system interacts with other components of the global system.
the SeaViewing, Wide Field-of-view Sensor (SeaWIFS), Ocean Colour and Temperature Scanner (OCTS) and Polarization and Directionality of Earth Reflectances (POLDER).

However, in the early 1990s, none of these satellite missions are presently on a firm schedule, particularly SeaWIFS which was initially planned for launch in 1992 and now may slip beyond 1994. This will be a major setback to the IGBP/JGOFS ocean colour and IGBP/JGOFS process cruises.

Satellite coverage for ocean colour and IGBP/JGOFS process cruises.

Figure 1. Satellite coverage for ocean colour and IGBP/JGOFS process cruises.

The most hydrologically important surface variables measurable by satellite are land and vegetation characteristics, topography (best done currently with stereo SPOT data or Landsat TM), and snow cover. High spatial detail in a static condition can be achieved with SPOT or TM data. However, temporal dynamics at 1 km resolution are best done with the AVHRR or the new MODIS sensor.

Dynamic properties of different biome types (e.g., forest vs. grassland). Initial efforts to obtain land-cover and vegetation characteristics are now being conducted in the IGBP Land-Cover study (IGBP 1989).

Current research need is the incorporation of these variables directly measurable by satellite into hydrological models. Snowmelt models could incorporate repetitive snow-cover data with surface temperature and radiation conditions. Vegetative canopy partitioning into interception (and evaporation) or throughfall and soil storage could be modelled using satellite vegetation indices to estimate leaf-area index, and precipitation periodicity from Doppler radar. Evapotranspiration (ET) could be modelled using the satellite vegetation indices with the appropriate surface meteorological conditions (incident solar radiation, vapour pressure deficit) to drive an evapotranspiration equation (e.g., Penman-Monteith equation).

New studies suggest that a satellite derived surface resistance factor may also be entered into the equation of evapotranspiration. These simple satellite driven models must be validated with "point" measurement and mechanistic soil-plant-atmosphere models. If precipitation and ET can be calculated adequately at GCM cell scales, reasonable estimates of runoff, or hydrological discharge, would be possible if the basin storage could be assessed. At some future time, efficient testing and operation of these capabilities will demand a computerized global GIS to organize available surface meteorology, topography, vegetation cover, soils and other data, at least to GCM grid spatial detail.

Several needs for future advancement in satellite measurements have been classified in terms of the feasibilities of meeting the needs with existing or firmly planned remote-sensing data from satellites. Using the joint criteria importance and likelihood of achieving useful goals in the foreseeable future for satellite application in hydrology the following priority items are proposed: vegetation and land-surface characterization; rainfall monitoring, surface-water monitoring and inventory (e.g., of rivers, lakes, marshes, reservoirs); measurements and monitoring of snowcover; soil moisture measure, mainly for non- and sparsely-vegetated areas; estimation and monitoring of evapotranspiration. The remote-sensing satellite needs for these parameters are summarized in conjunction with the requirements for GCTE.

**GCTE Needs**

The overall objective of GCTE is to develop the capacity to interpret and predict effects of global change phenomena on terrestrial ecosystems. Global change phenomena include changes in climate, atmospheric composition and land use. This capacity is required for two reasons. The first reason is to forecast the consequences of global change for ecosystem structure and function, since these ecosystem attributes have direct effects on human welfare including primary productivity, future land use and biotic diversity. The second reason is to be able to predict the potential feedbacks of the terrestrial changes on further atmospheric climate and land use change.

One of the most important means of measuring terrestrial ecosystem change will be through remote sensing, and data derived from remote sensing...
Digital elevation data are
needed to model changes in landscape structure. A high resolution sensor, such as SPOT, can provide this data. However, it is essential that at least the present data base be maintained through the years before EOS instruments come on line to develop the capabilities for these remote sensing systems. Remote sensing will be even more central to the process of observing Earth system changes over extensive areas and over time.

Ecosystem properties to be addressed will be both structural and functional in nature. Examples of structural properties are leaf area and the distribution of leaf area in the canopy profile. Functional examples include standing biomass, live-dead ratio of plant material, canopy chemical concentrations (e.g., leaf N, chlorophyll a, and lignin), net primary production, evapotranspiration and trace-gas efflux. Remote sensing is most directly adaptive for measuring structural properties, but some functional attributes will be estimated across extensive areas by coupling remotely sensed data to ecosystem models (e.g., remotely sensed surface temperature and soil moisture are inputs for simulation models to estimate evapotranspiration). Different kinds of remotely sensed data will be vital to meeting this Core Project and the previous Core Project objectives. These are:

(1) A moderate resolution capability for measuring gross structural attributes of vegetation and soils with high temporal frequency but medium spatial resolution. This role is currently filled by the AVHRR for areas with complete canopy cover, but with development of EOS instruments, this role will be filled even better by MODIS. For areas with incomplete canopy cover, that have mixed pixel problems of rock, soil, and plant signals, other low resolution methods need to be improved. It is possible that passive microwave methods for semiarid and arid lands will be the method of choice. This is being tested with SMMR data at present and it seems promising, will be fulfilled by AMSR in the EOS suite.

(2) A high resolution sensor with low temporal frequency for detailed analysis at the landscape level and for chemical assessment of canopy and soil properties is required. The Advanced Very High Resolution Radiometer (AVHRR) on LANDSAT 4 and 5 but there is no routine sensor for chemical analysis. At present AVHRR is being used as a test system for very detailed spectrometry that may measure chemical properties. High resolution infrared spectrometry (HIRIS) may provide reliable estimates of canopy nitrogen and lignin concentrations. These estimates are extremely useful for assessing the metabolic condition of foliage, which together with leaf area measurements provide a good estimate of primary production. In addition, canopy chemistry may be useful to estimate the chemistry of below-ground parts and litterfall and provide a means for calculating biogeochemical properties of ecosystems such as decomposition and nutrient turnover. If there is a suite of sensors, HIRIS will fill this role. In addition, high resolution data on canopy structure may be provided by SAR.

(3) Digital elevation data are fundamental to the GIS data set required for global modeling of terrestrial ecosystem structure and function. The present digital elevation data are inadequate and new models based on better altimetry are essential. In an Earth Probe mission, sensor availability could be increased. Even though the EOS is required to obtain the needed data, in the meantime stereo imaging by SPOT can begin to provide source information for this parameter.

(4) Principle driving variables for terrestrial ecosystems are air temperature, canopy surface temperature, soil temperature and soil moisture. Air temperature is not presently measured by any remote-sensing device below the planetary boundary layer. It must be calculated from models driven by surface temperature (see below).

(5) Remote sensing will be extremely useful for assessing structural ecosystem properties and of lesser value for estimating driving variables as described above. Many of the driving variables necessary for predicting changes in terrestrial ecosystems will have to be calculated indirectly from simulation models or algorithmic routines, or by direct ground measurement. This last process will be vastly facilitated by robotic samplers that can measure a variety of environmental variables at one point and relay them to geostationary satellites such as GOES for retransmission to ground stations. This will give researchers nearly "real time" direct measures that can be extrapolated across landscapes to estimate functional processes. Robotic sensor systems and satellite relay systems might play a large role in achieving the objectives of this GCTE.

In summary, remote sensing will be vital to developing models for predicting changes in terrestrial ecosystems and for observing the changes over long time periods and across the vast areas of the globe. Further development of remote sensing technology and ground validation of the information for interpretation of biosphere function and changes in the coming years must be continued. It is also important to point out that an efficient data access system and a long-term record are necessary for our success. The hiatus in remote sensing data now facing the scientific community represents a serious detriment to our ability to predict or observe global change on land systems. It is essential that at least the present data base be maintained through the years before EOS instruments come on line to develop the capabilities for these remote sensing systems. Remote sensing will be even more central to the process of observing Earth system changes over extensive areas and over time.

Discussions amongst the IGEP scientists have made it clear that international satellite observing capabilities currently existing and those likely to develop over the coming decade will be critical for the success of the IGEP. However, several impediments are currently limiting us from the most effective use of the satellite data.

**Existing Data: 1980-1990**

There are about half a dozen operational geostationary satellites which provide global data on cloud cover and temperatures on a near continuous basis. In the near-polar orbit, there are a number of operational remote sensing satellites including LANDSAT, NOAA, and SPOT which collect a variety of remote sensing data in the visible and IR spectral regions providing more or less continuity of data already available over the last ten years or so including close to six years of global vegetation index. In addition, there are a number of research satellites like SMMR, ERBE, and Nimbus which provide data on many other parameters such as solar flux, sea surface temperature, atmospheric moisture, ocean chlorophyll, snow cover, sea ice extent, Earth radiation budget, and atmospheric ozone and stratospheric dust.

Together these data sets are of unique value for the WCRF and the IGEP provided they are quality controlled and are continuous over at least a decade. Only a few of the above mentioned parameters pass this test. These are the measurement of solar irradiance, stratospheric ozone, stratospheric dust and sea surface temperature. Efforts are now underway to reprocess the data and reassess the algorithms and consistent global data sets for ocean chlorophyll, vegetation index, radiation budget and snow and ice cover for the entire decade of the 1980's may become available. Even the availability of these data will be of substantial benefit to the IGEP community and were given the highest priority in our deliberations. In order to achieve this we will have to give serious attention to current impediments and strategies for the future.
Future Data 1990-1995

As we enter the decade of the 1990s, a number of new satellites with new sensors relevant to IGBP studies are planned by about a dozen countries. These are shown in Figure 2a-c. The challenge for the space agencies and for the IGBP community will be to assume that the data acquired in the 1990s and those acquired, on the same parameter but by different satellites, in the 1990s, are consistent with each other and can be used to derive an uninterrupted time series to document accurately long-term changes in the state of atmosphere, ocean, and land. Some pitfalls loom on the horizon such as a 'data hole' of at least five years on ocean colour between the CZCS on Nimbus 7 (which stopped functioning in 1987) and SeaWiFS which still has an uncertain launch date.

For Global Change Studies, the challenge will be to combine data from several of these satellites to provide the global context for process studies. For example, ocean colour data from SeaWiFS combined with data on surface winds (from either ERS-1 or NASA Scatterometer and sea surface temperature from ERS-1 or NOAA type satellites) will be of essential for the large scale study of marine biosphere-atmosphere exchange.

An ocean colour monitoring instrument less sophisticated that SeaWiFS is planned for ADEOS mission in 1995. The international field campaigns of IGOFS, which began in 1989 and are scheduled through 1996, were planned to be coincident with the deployment of SeaWiFS. Unfortunately, it now appears as though ocean colour data may not be available until late in the field campaigns of IGOFS (Fig. 1). A concentrated effort by the space agencies to narrow the data gap in ocean colour measurements should receive the highest priority.

Beyond 1995

Simultaneity, accuracy, long-term consistency and continuity are the key requirements for IGBP for space observation of several parameters. These conditions are proposed to be met by the launch of polar platforms starting in 1997. While the payload combinations of these platforms are being defined, we would like to re-emphasize the IGBP requirements for data from the Earth Observing System. For the projects shown in Figures 1 and 2a-c, data on tropospheric chemistry, land, biospheric functions, ocean colour, temperature and wind stress, land topography and soil moisture are of critical importance.

One of the principal impediments in the use of space data by the international science community has been its non-availability in a usable format. It is therefore encouraging to note the plans for initiating an Earth Observing System Data Information System. For the IGBP scientists to benefit from the information and data archived in EOS-DIS, plans for establishing an IGBP-DIS are in progress (Chapter 9). The sooner the two systems are put in place and become functional, the more the global change scientific community will be able to investigate the Earth system in its totality.

References


to the problems related to spacecraft sensor calibration. A drift in sensor response and changing algorithm for atmospheric correction can easily be interpreted as an indication of global change on the surface of the Earth. Without a thorough evaluation of such discrepancies, satellite data is of practically no use to a student of global change.
The IGBP Global Change Regional Research Centres (RRCs)
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IGBP research must be carried out in all regions of the world in order to obtain the necessary understanding of global change processes. Likewise, scenarios of global change originating from modelling activities need to be interpreted in a regional context to guide both further research and policy decisions. Global change research to decrease present uncertainty is primarily the responsibility of the IGBP and WCRP, as acknowledged in a UN General Assembly resolution (December 1989). The need for the IGBP and WCRP to narrow uncertainties relating to climate change through research has also been recognized by the Intergovernmental Panel on Climate Change (IPCC).

The scientific understanding concerning global change processes and impacts is generally not well advanced in less-developed countries, where available scientific manpower and financial resources are especially limited. There is an urgent need for the IGBP to stimulate global change research in these regions and to ensure that their scientists are involved in all aspects of data collection, synthesis and global change predictions. In addition, outputs from climate and global Earth system models must be made available to the science community in less developed countries and interpreted in a national and regional context.

IGBP research requires an interdisciplinary approach and few, if any, academic institutions have the full suite of scientific expertise needed to address the synergetic aspects of the IGBP Core Projects. This is especially true for developing countries, where IGBP research needs to be enhanced and facilitated in an academically stimulating environment.

In order to achieve this, a number of IGBP Global Change Regional Research Centres (RRCs) should be established in developing countries. This will permit scientists from these countries to become intimately involved in all aspects of research related to global change. Unless RRCs are established, it is likely that developing country scientists will be solely involved in data collection and will be outside the mainstream of global change research including participation in data analysis, interpretation and modelling. It is important that these centres are established early in the implementation phase of the IGBP, so that the scientific competence in the less-developed countries is harnessed to the fullest extent.

The purpose of an RRC is to facilitate regional interdisciplinary research within IGBP Core Projects, and to promote strong synthesis and modelling activities relating to regional priorities. The RRCs will be established in developing countries, but similar centres may also be set up in developed countries and will in such cases be affiliated to the IGBP-RRCs. The centres will establish networks to link existing scientific institutions in the regions that contribute to the IGBP Core Projects. They will be situated in a research environment involved in all facets of Core Project research including monitoring, field experimentation, integration, synthesis and modelling. The RRCs will play a major role as centres for regional data analysis and synthesis and analyses of global change scenarios in a regional setting. The network activities are important in this regard, since most of the Core Project research in the region will be conducted in affiliated laboratories and not at the centre itself.

The RRCs will:
- Promote cooperation among scientists of the region for the purposes of: (i) facilitating coordination of Core Project research; and (ii) defining regional research priorities and identifying regional questions that have global significance.
- Provide facilities for data management of regional and global data sets.
- Develop synthesis and modelling activities.
- Distribute research results to scientists within the region and establish mechanisms for sharing the results with scientists from other centers.
- Establish training and exchange programmes, especially in the use of new technologies and in the area of data analysis synthesis and modelling.

Regional workshops will evaluate regional priorities in relation to the IGBP Core Projects and discuss the establishment of networks of collaborating laboratories for the IGBP Core Projects. The first meeting was in South America (March 1990, Brazil), a second will be held in Asia (India, February 1991), and a third in Africa (Niger, January 1991). In addition, Southern Hemisphere collaboration is being supported through a series of meetings (Gwaziland, December 1989; Chile, March 1991). Once established, the RRCs should take over responsibility for the regional meetings on a regular basis.

The management of regional and global data sets is a major responsibility of the RRCs in collaboration with the IGBP DIS (Chapter 9). This responsibility has many dimensions including: (i) banking of critical subsets of data from the region; (ii) quality assurance of those data sets; (iii) incorporation of appropriate data in regional geographic information systems that are in place at the RRCs; and (iv) providing scientists with access to global data sets needed to interpret regional research results or to conduct data analysis and synthesis. Help should also be available from the RRCs to various research groups within the region concerning their data-management problems. Close links must be established with GRID (UNEP/GEMS) nodes.

The contents of the regional data bases must be available to all scientists as well as to decision makers. The RRCs will encourage the sharing of research results by establishing easy-to-use communications networks within and among the regions. Electronic networks, newsletters, and scientific meetings will be among the tools used to achieve this goal of data exchange.

One of the major purposes of the RRCs is to foster synthesis and modelling activities that will ultimately lead to predictions of the effects of global change.

Each RRC will have computer hardware and software needed for data management and processing. Links will be established with appropriate centres to ensure that LDC participants are fully involved in global modelling activities.

Site selection criteria:

An Existing Nucleus

Siting RRCs in existing institutions will save set-up costs and minimize the administrative infrastructure that each will require. In addition, ongoing research should be built upon the development of a strong input to IGBP Core Projects. For these reasons, RRCs should primarily be established in active research institutions which are interdisciplinary in nature or that have the potential of becoming interdisciplinary. These centres will serve as nuclei for further growth and for the establishment of networks of collaborating laboratories in the region.

Interest and Involvement of Scientists and of National and Regional Governments.

The proposal of potential sites for an RRC should originate within the region, on the basis of scientific and governmental interest. Governmental recognition is needed to assure stability and continuity in the host country.
Regional Research Centres (RRCs)

Availability of Logistic Support

Certain logistic support is required for a proposed site. This should ideally include, for example, proximity to an international airport, convenient regional and international communications, adequate office space and housing for visiting scientists and technicians. Additional resources include: (i) a number of resident research scientists to provide an "initial critical mass" of talent; (ii) support personnel, including research assistants, clerical and maintenance staff; (iii) a scientific library adequate for initial research activities; (iv) computational facilities; (v) access to Geographical Information System (GIS) and (vi) the availability of a suitable conference facility in the area, for example for the regional research conferences that will be an outreach activity of each RRC.

It is recognized that some of these desired facilities might not be available in a proposed site, and they will need to be provided through additional funding.

Access to RRCs by Visiting Scientists and Technicians

RRCs are defined regionally and are of necessity international. Access to the RRC by scientists and technicians from the region, who are not nationals of the host country, is a requirement of any ICUS activity.

Relationships of RRCs to Other Networks

The RRCs should foster the establishment of regional collaborative mechanisms specifically for the IGBP Core Projects. In doing so, the RRCs will need to build on regional networks, some of which are part of established national and international research networks, (e.g., the Unesco/MAB Biosphere Reserves). It is envisaged that the RRCs will play an important role in facilitating a wider use of data obtained from such networks for IGBP purposes.

Monitoring is an important component of global change research and there are many such existing programmes, both governmental and non-governmental. Monitoring networks should be an integral part of the regional RRC structure and hence the centres should help in ensuring long-term financial commitments to monitoring, both to detect global change and to ensure that the needs of the Core Projects are met. The IGBP-DIS Core Office should act as the coordination node for regional data directories. Special attention should be given to the development of appropriate links with programmes such as the GEOMS/GRID of UNEP. Indeed, in some cases, the RRCs might be formally linked to regional GRID nodes.

Prior to the establishment of an RRC, an inventory of activities within the specific region should be commissioned. A first survey is presently being conducted for Africa with the help of the Commonwealth Science Council and the Association of African Universities.

Funding Strategy

A comprehensive funding strategy for the RRCs would be premature until their number, location, and specific facility needs are known. It is, however, important to proceed with the identification of potential RRC funding sources and to identify procedures necessary to mobilize those funds. A number of general objectives for funding approaches should be highlighted: (i) funding should be directed towards institutionalizing the functions of the RRCs within the regional setting; (ii) funding must be long-term and stable; (iii) funding should be IGBP directed rather than Core Project driven; (iv) funding should include both research and administration; and (v) the RRC activities should be directed by global change scientific concerns and IGBP Core Project needs as opposed to individual interests of funding bodies.

A critical responsibility of the RRC Standing Committee (see Chapter 12) will be to ensure that the scientific goals of the centre are focused on the IGBP objective even in the presence of changing funding-body interests, and specific demands of individual projects or institutions. Rigorous review procedures within funding cycles will be essential for both internal health of the RRC and external perception of the centre's activities. Mechanisms must be developed between the centre and funding agencies to fulfill these two needs, but not be made so complex and frequent that they interfere with RRC activities.

The context in the developing countries is such that the choices of government and government-related funding for RRCs is generally absent. Many governments in the developing world may not have the resources to fund substantial global change related research, but it is necessary that governmental bodies specify global change research to be a national priority in order to attract major outside donors.

To ensure the future development of the IGBP as a whole and to develop an implementation plan for the establishment of the RRCs, including appropriate fund raising activities, a first consultative meeting will be held in December 1990, with the support of the Rockefeller Foundation. The SC-IGBP will then appoint an RRC Advisory Committee to guide the further developments. An RRC Project Office should also be established to coordinate the early phases of RRC establishment.

At present, three initiatives to create RRCs in the developing world are being considered in consultation with governments and international agencies. The Regional IGBP Meeting for South America proposed that an RRC be set up in the Amazon region. The French proposal to create a Sahara-Sahel Observatory offers promise for collaboration and support for an RRC. In addition, a proposal to create an international centre in Indonesia for Equatorial Atmospheric Research with funds from Japan can be built-on to form an RRC.

Given the mission of these centres and the need for global participation in the IGBP, it is essential that the Regional Research Centres are in place as rapidly as possible. As the IGBP has profound implications for sustainable management of natural resources, the RRCs will play a major role in providing the necessary scientific base for evaluating global change scenarios for planning purposes in the developing regions of the world.
CHAPTER 12

GLOBAL CHANGE

Implementation and Funding Strategy
IGBP: A STUDY OF GLOBAL CHANGE

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12. IGBP Implementation and Funding Strategy

The organizational and implementation plans for the IGBP have been based in part on the experiences of other international collaborative research efforts such as the IGY, IBP and WCRP/GARP. The following have been the general tenets:

- Programme development is guided by a strong committee consisting of scientists from relevant disciplines.
- A minimum of new organizational machinery should be created, building where possible, on capabilities and infrastructures that already exist within and outside ICSU.
- The implementation of the programme will require full-time coordination at the level of individual Core Projects. The development of detailed science and implementation plans must be in the hands of active scientists.
- The national programmes of research, which make up the IGBP, will differ in emphasis among themselves and may be less comprehensive, in general, than the composite international programme.
- Since national participants in the IGBP will benefit from the international aspects of the programme, including the provision of data and shared facilities, they must equitably share in the costs of administering the programme internationally.

Based on these considerations, the overall structure illustrated in Figure 1 has been proposed.

![Figure 1. Structure of IGBP implementation phase.](image)
Core Projects, Scientific Steering Committees and Standing Committees

The research efforts of the IGBP will be implemented through a set of Core Projects, which are defined by the SC-IGBP on the basis of the programme objective, the four underlying themes of the IGBP, key scientific questions that are identified in the course of the definition and evolution of the programme, project feasibility, and readiness (see Chapter 1). For purposes of management and support, a maximum of about ten Core Projects will be ongoing at any one time (Fig. 2).

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Figure 2: Tentative timelines for IGBP Core Projects and complementary activities.

Core Projects are considered by the SC-IGBP in three categories of planning and readiness:

1. Established Core Projects, for which a detailed science plan has been developed and approved. The following projects have now been approved and have begun developing implementation plans:
   - IGAC (International Global Atmospheric Chemistry Project), jointly coordinated with IUGG-IAMAP-CACGP
   - JGOPS (Joint Global Ocean Flux Study), coordinated by SCOR
   - PAGES (Past Global Changes)
   - BAHIC (Biological Aspects of the Hydrological Cycle), jointly coordinated with WCRP/GEWEX
   - GCCT (Global Change and Terrestrial Ecosystems)

2. Proposed Core Projects, identified by the SC-IGBP as key to the objective and underlying themes of the IGBP, for which a detailed science plan is not yet developed or approved. The SC-IGBP will appoint ad hoc Planning Committees for proposed Core Projects to accomplish this task. The following are under consideration:
   - STIB (Stratosphere-Troposphere Interactions and the Biosphere) jointly proposed with IAMAP/IAGA/SCOSTEP
   - LOICZ (Land-Ocean Interactions in the Coastal Zone)
   - GAIM (Global Analysis, Interpretation and Modelling)

3. Potential Core Projects, which have direct relevance to the goal and underlying themes, but for which the SC-IGBP has not yet proceeded to develop a science plan. These are, at present:
   - COZES (Climatic Oceanic Evolutionary Study), jointly discussed with SCOR
   - GCEC (Global Change and Ecological Complexity), evaluation being prepared by SCOPE/IUBS

For each established Core Project, the SC-IGBP appoints a Scientific Steering Committee (SSC). In the case of Core Projects established jointly with other organizations, the SSC is appointed by the SC-IGBP jointly with the co-sponsoring body. The Chairpersons of the SSC will be appointed by the SC-IGBP based on recommendations from the SSC. The Chairpersons are full members of the SC-IGBP and participate fully in all deliberations and decisions regarding the IGBP.

Each SSC will organize an annual Open Meeting to which representatives from participating nations, ICSU scientific organizations, other relevant programmes and other IGBP Core Projects will be invited. These Open Meetings of IGBP Core Projects are intended to promote strong interactions between the organized international programme and contributing national efforts, and to ensure necessary interaction among the Core Projects of the programme as well as with other relevant international programmes.

The process of selection, organization, development of science plan and implementation of IGBP Core Projects will, in principle, follow the sequence of steps listed below:

- Designation as a potential Core Project by the SC-IGBP through recognition of relevance to the IGBP objectives and priorities.
- Designation as a proposed Core Project, when project feasibility and community readiness have been ascertained, and appointment of an ad hoc Planning Committee by the SC-IGBP.
- Presentation of a draft science plan by the ad hoc Planning Committee.
- Consultation with national committees, ICSU liaison persons, and other IGBP partners.
- Decision of the SC-IGBP to establish a Core Project and appointment of a Scientific Steering Committee by the SC-IGBP.
- Preparation of a detailed science plan by the SSC.
- Core Project Open Meeting to discuss and refine the science plan.
- Approval of the science plan by the SC-IGBP.
- Approval of an implementation plan by the SC-IGBP.
- Invitation to participating nations to host and/or co-sponsor a Core Project office and establishment of a Core Project office.
- Core Project Open Meeting to discuss implementation plan.
- Project implementation begins.
- Annual Open Meetings to review progress, with subsequent reports to SC-IGBP and SAC.

IGBP Core Projects nominally will operate for about a decade and appropriate mechanisms will be developed to monitor their progress. Standing Committees will be established by the SC-IGBP to guide activities that cut across the Core Projects. Initially, two Standing Committees have been appointed for:

- IGBP Data and Information System (IGBP-DIS);
- IGBP Global Change Regional Research Centres (RRC)

The Chairpersons of these committees will also be members of the SC-IGBP.

Core Project Offices

IGBP Core Projects will be administered through a Core Project Office (CPO), established within the home institution of the chairperson of the SSC or at another suitable location. Funding for the operation of individual CPOs, including necessary salaries, will be sought from funding sources within the nation in which the office is sited, or jointly supported by two or more countries. The responsibility for securing support for establishing and operating a Core Project Office rests with the chairperson(s) of the SSC. Once a Core Project Office is established, support for the project through funds administered by the IGBP
Secretariat will probably be limited to the support of one meeting a year of the SSC. The Secretariat will, however, continue to support especially cross-project initiatives that will promote the overall IGBP objective and other initiatives, depending on availability of funds. The functions of a Core Project Office include: (i) administering the project on a day-to-day basis, under the long-term guidance of the SSC; (ii) coordinating research efforts, and planning and coordinating research campaigns and field programmes; (iii) providing project advocacy and promotion, and enlisting wide international participation in the project; (iv) maintaining needed connections with relevant national projects; (v) ensuring effective coordination with other Core Projects of the IGBP; (vi) disseminating information and research results; and (vii) securing support for the operation of the office.

Table 1. List of established Core Projects, SSC and Standing Committee chairpersons, Core Project sites, and proposed Core Project national sponsors. The GOEZS project development will be facilitated by an International Planning Office.

<table>
<thead>
<tr>
<th>Core Project</th>
<th>Chairperson(s)</th>
<th>CPO Site</th>
<th>Natl.Sponsor(s)</th>
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<tr>
<td>IGAC</td>
<td>R. Primus (USA)</td>
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<td>IGBP</td>
<td>B. Zeitschel (FRG)</td>
<td>Kiel</td>
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<tr>
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<td>H. Oeschger (Switzerland)</td>
<td>Bern</td>
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<td>J. Eddy (USA)</td>
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Scientific Advisory Council

The Scientific Advisory Council (SAC-IGBP) is an advisory body composed of representatives of IGBP National Committees, ICSU national and scientific members, appropriate UN organizations and other international bodies. It is the highest policy discussion forum of the IGBP and it will be convened every two years to provide advice to the SC-IGBP and to allow full discussions on all aspects of IGBP plans and projects. Meetings of the SAC-IGBP will be chaired by the President of ICSU.

National participants in the SAC meetings should include representatives from each national IGBP committee as well as an appropriate national funding body. This dual national representation is necessary to ensure that both the scientific and funding communities are involved in the discussions regarding implementation of the IGBP Core Projects.

To allow these two types of national representatives ample opportunity to meet as a group, the SAC meeting programme will provide for parallel sessions: one for the representatives of national IGBP committees and the other for the representatives of national funding bodies (see below). Regional and international bodies funding IGBP research should also be invited to take part in the IRC meeting. Observers from national ICSU members, which have not yet established IGBP committees, will also be invited to the meetings of national committees.

ICSU scientific members are invited to SAC meetings. All ICSU scientific members have been invited to appoint liaison persons to the IGBP. These persons provide essential links between the IGBP and other ICSU projects. Representatives of ICSU scientific members at SAC meetings may also wish to meet in parallel sessions to national members meeting to discuss coordination and complementary/cooperative activities in relation to global change research in a context wider than that provided by the IGBP in an ICSU Global Change Forum.

In addition, relevant UN organizations, international social science organizations with research programmes in the human dimensions of global change, other international bodies and representatives of industry will also be invited to attend the SAC meetings.

Scientific and Executive Committees

The Scientific Committee for the IGBP (SC-IGBP), which replaces the Special Committee, has overall responsibility for the development of the IGBP including planning and implementation. It will meet at least once a year.

The SC-IGBP will be composed of:

- SC-IGBP Executive Committee, to direct ongoing affairs of the IGBP, consisting of no more than 15 persons: a Chairman, two or three Vice-Chairmen, Treasurer, Executive Director (the Officers) and up to nine additional members. Members of the Executive Committee are appointed by the ICSU Executive Board. A scheme for rotation of membership will be implemented when the new set of members are appointed in 1990. Members of the EC-IGBP are to be scientists active in research areas that are particularly relevant to the present and future plans of the IGBP. The EC-IGBP is expected to meet twice a year.

- Additional members of the SC-IGBP will be chairpersons of Scientific Steering Committees and Standing Committees. Chairpersons of these Committees are appointed by the SC-IGBP upon recommendations from the SSC. In the case that a Core Project is organized in collaboration with another body, the SSC Chairperson(s) will be appointed in consultation with that body.

- Ex officio members of the SC-IGBP will be the chairman of WCRP/IGBP and a designated representative of the ICSU Advisory Committee on the Environment (ACE).

The IGBP Secretariat

The IGBP Secretariat will be headed by an Executive Director, appointed by the ICSU Executive Board, and staff appointed by the Executive Director with the approval of the EC-IGBP. It is expected that the staff will include the Executive Director, a Deputy Executive Director, two Programme Officers with a PhD in a subject area of relevance to the IGBP, an Assistant to the Executive Director, a Finance Officer and two Secretaries. In addition to these persons, it is anticipated that a special officer will be hosted with responsibilities for promoting and establishing linkages to endeavours in the social sciences that address the human dimensions of global change research. This person will be selected and supported through mechanisms external to the IGBP and ICSU.
The Executive Director is responsible, under the guidance of the EC-IGBP, for the overall administration and coordination of the IGBP. The Deputy Executive Director is responsible for the general management of the Secretariat. These two persons together with the Programme Officers serve as contact persons between the Secretariat, the Core projects and other external organizations.

IGBP Funding Mechanisms

The implementation of the IGBP will require the commitment of major resources to support the research activities of the Core Projects of the programme. Funding for IGBP research activities will be raised by two different mechanisms. The majority of the research activities of Core Projects will be funded through affiliated national research programmes, with a small fraction set aside for international planning, coordination and synthesis efforts managed by Core Project offices and the IGBP. In some instances, however, centralized funding will be needed for specific research activities. In such cases, arrangements will be made through IGBP for the appointment of a coordinating body, responsible for project management and funding. The financing of the IGBP Regional Research Centres is an example of this need.

The task of sustaining an international programme of research that is funded principally by national efforts with national research priorities is a major challenge of the IGBP. The need to coordinate observational campaigns and other implementation aspects of the IGBP (including satellite schedules, ship operation plans, coordination of short- and long-term budget development and planning) requires an effective coordinating mechanism among federal agencies. For this reason, an Interagency Resource Committee (IRC) with members from participating nations should be formed to coordinate national efforts. In view of the complementarity of the IGBP and WCRP, the IRC should address both programmes as well as certain global change initiatives. A first meeting of national funding agency representatives was held in Washington, January 1990, in parallel with the meeting of national IGBP committees. The IRC should meet annually and also in conjunction of SAC meetings. It is appropriate that this committee includes initially the nations that will provide major funds for the IGBP Core Projects and WCRP research programmes, with membership expanded in the future to include all participating nations.

Particular measures need to be taken to enlist the collaboration of scientists from developing countries. For this it will be necessary that governments of all nations identify global change research as a national priority, regardless of the size of expenditure that is allowed. If national priorities are set, it will be considerably easier to fund the research through bilateral or multilateral arrangements. The SAC and IRC meetings will constitute suitable fora for discussions of such funding.

The SC-IGBP and Secretariat will primarily be financed through national contributions. National Committees for the IGBP need to convince their funding bodies of this necessity. Funding secured from private foundations and industry has as yet been modest. In the initial years of programme planning and administration, the national committees will need to make major contributions to support the Secretariat.

IGBP at the National Level

Core Projects of the IGBP will require the support of many participating nations if they are to be successfully implemented. Each participating nation, although subscribing to the overall priorities of the IGBP, will place different degrees of emphasis on the various programme elements, consistent with its own needs and capabilities. National IGBP committees will constitute the crucial link between the national and international efforts. Many such committees have already been established. It is a responsibility of the IGBP Secretariat to identify key contact persons in countries where national committees do not yet exist and to promote the establishment of such committees.


Regional meetings constitute an important mechanism to create awareness of the scientific challenge of global change research, stimulate nations in the region to become involved in IGBP Core Projects, promote the establishment of national committees and foster increased regional collaboration within the IGBP and with other relevant research programmes. Such meetings have already been organized for the Southern Hemisphere (Swaziland, December 1988) and South America (Brazil, March 1990) and meetings are now planned for Asia (February 1991) and Africa (January 1991).

Annual meetings of representatives of national IGBP committees will be convened to coordinate national efforts that contribute to the international programme. The first such meeting was held in Washington at the invitation of the US National Committee in January 1990; the second is planned for the UK in early 1991. These meetings, attended by scientists from the national committees and national funding agency counterparts, will review the status of the international planning, coordination and synthesis efforts in the context of planned and ongoing national research, analyze and discuss the commonality of national programme elements, design mechanisms for supporting critical programme elements, and develop multinational and regional programme linkages.
While these meetings of national members, as well as those of the IGBP Scientific Advisory Council, will provide input into the overall IGBP operations and strategic planning, specialized attention must be given to the individual Core Projects of the IGBP. For this purpose, periodic meetings of appropriate specialists from National Committees as well as appropriate ICSU and other relevant organizations will be convened. These Core Project Open Meetings (see above) will provide the mechanism for coordinating the collaborative efforts of the scientists who will be active in the research components of individual projects.

It is essential that national funding agencies are involved in the international discussions on programme development and implementation. The IGBP implementation plan calls for a close partnership between national IGBP committees and the funding agencies, both in context of national planning and through meetings of the SAC.

Many of the ICSU scientific members carry out substantial activities of their own that relate to studies of global change, efforts that lie outside the scope of the two major research programmes of ICSU, the IGBP and WCRP.

The Scientific Committee on Problems of the Environment (SCOPE) plays a special role through its charter "to advance knowledge of the influence of humans on their environment ... and to serve as a source of advice ... with respect to environmental problems." A fundamental difference between IGBP and SCOPE is that the former has been set up to conduct a research programme, while SCOPE focuses on interdisciplinary analyses of environmental problems that often lead to the identification of research needs. As two examples, SCOPE is now conducting surveys of our present state of knowledge on the effect of UV-B on organisms and ecosystems and the effect of global change on ecological complexity. In both instances, the IGBP will use the results from these studies when deciding on whether these research questions should be covered by IGBP Core Projects.

In developing plans for Core Projects under the guidance of the IGBP objective and underlying philosophy, the SCO-IGBP has relied on planning efforts in other ICSU scientific bodies. The following merit special mention:

- SCOR: Responsible for planning and implementing JOIFS.
- IUGG/IAMAP /CACC: Responsible for planning the major proportion of IGAC and SCOPE that is under IGBP responsibility for its implementation.
- IUCS: Has provided major inputs to the planning for PAGES and is, together with Unesco, making a feasibility study for a complementary programme.
- SCOPE: Apart from the two above-mentioned activities, SCOPE has made a major contribution to the development of the biological component of IGAC; it has initiated, together with Unesco, the discussions on needs for Geospheric-Biosphere Observatories (now developed into the RRC concept); it is developing generic simulation models for primary production/decomposition in boreal forests and grasslands, which will be important inputs to GCET; it has addressed the issue of large-scale ecological experiments, which has guided the development of certain core activities in GCET; it has addressed the need for long-term ecological research, which is of special interest to the development of RRC networks.
- WDC: A major component in the development of IGBP-DIS.
- IUGG-IAGA/IAMAP/SCOSTEP: Contributed to the plans for STIB.

Many other ICSU bodies have developed important research programmes of relevance to global change research, although they fall outside the specific objectives and priorities of the IGBP (e.g. STEP of SCOSTEP).

It is essential that the IGBP maintains close contacts with the scientific members of ICSU. To this end ICSU scientific members with activities relevant to global change research have been invited to appoint liaison representatives to the IGBP. Their role is to foster efficient communications between their parent body and the IGBP. The IGBP Secretariat will ensure that they are kept informed of current developments within the programme.

The scientific member liaison persons and other representatives of ICSU scientific members are invited to the SAC meetings. In addition, they will be invited to the Core Project Open Meetings, where further discussions can develop plans for specific collaborative activities.

Discussions between ICSU scientific members and the IGBP will also be possible at the annual ICSU meetings (General Assembly or General Committee).

In addition, the ICSU Global Change Forum offers a platform for discussions of additional global change activities, which are not explicitly included in IGBP Core Projects.

Three United Nations bodies are essential for the implementation of an international programme of global change research: the World Meteorological Organization (WMO); the United Nations Educational, Scientific and Cultural Organization (Unesco) and the United Nations Environment Programme (UNEP). Of special relevance in this context is the Intergovernmental Panel on Climate Change (IPCC). Cooperation with other bodies of the United Nations system, such as FAO, will be needed to facilitate the implementation of certain IGBP projects.

It is important to identify those activities of intergovernmental bodies, which relate directly to the IGBP and to define mechanisms through which the IGBP can be strengthened by collaboration with focused research projects of intergovernmental bodies. A key component of an international global change research effort and a close counterpart to the IGBP is the World Climate Research Programme (WCRP) of ICSU and WMO. The Intergovernmental Oceanographic Commission (IOC), the Man and Biosphere Programme (MAB), the International Hydrological Programme (IHP), the International Geological Correlation Programme (IGCP) and other Unesco programmes have great potential to contribute to the overall global change research effort. The Global Environmental Monitoring System (GEMS), the Global Resource Information Database (GRID), and other UNEP programmes can also make important contributions.

These organizations also provide a vehicle for multinational coordination. This could be particularly useful in developing the active interest and involvement of developing countries in the IGBP. Thus, Unesco has supported the IGBP regional meeting in South America and a planning meeting for Africa. For this group of countries, but also in general, IGBP will need to work together with the relevant intergovernmental institutions with extensive experience in coordination, environmental education and scientific training activities. The intergovernmental bodies can help to communicate IGBP and other global change research results to governments and their agencies. The UN bodies can be instrumental in...
formulating internationally agreed upon response measures and legal agree­ments to deal with global change. For this reason, close links have already been developed between IPCC and IGBP/WCRP, who have jointly developed the chapter on research needs for the IPCC report to the 2nd World Climate Conference.

An Interagency Coordinating Committee (ICC) for the IGBP has been set up to facilitate exchanges between the UN system and IGBP. This body has comprised the Executive Committee of the IGBP and representatives from UNEP, Unesco and WMO. The ICC is now under review to determine how it can provide the most efficient mechanism for such interaction between IGBP and the UN bodies with major interests in global change research.

The IGBP now collaborates with several bodies outside the ICSU and UN system and hopes to further develop such links. IIASA has, for example, cosponsored a meeting on RRCs and activities within their environment programme have directly influenced the planning for GCTE. SC-IGBP also serves as one of ICSU's two focal points with SAFETY. IGBP will continue to maintain close contacts with IUCN in questions related to conservation issues.

IGBP and Industry

In recent years private industry has become more involved in the analysis of environmental issues, including global change. In the next decades, with possibly great environmental changes, industry will need to be fully apprised of the best available scientific knowledge concerning environmental changes and the research that is planned to increase our understanding and predictive ability. Industry must know, on global as well as regional scales, the anticipated impacts of environmental change.

The IGBP and WCRP endeavours, to carry out major research programmes and to provide a focus for global change studies, should be of service to the private as well as the public sector. At present, few people directing these industries are sufficiently aware of ICSU's plans for global change research in general and the IGBP in particular. There is a large potential interest in industries that could be harnessed to aid the IGBP research effort. The IGBP Secretariat should make efforts to develop closer links to industry.

It is in the interest of both parties, the natural sciences represented by IGBP and the increasing group of large industrial companies much affected by global changes, to consider the mutual advantages of collaboration. In this regard, industry can contribute in kind to the IGBP effort with their expertise in data management and model development, provide access to large computers and instruments, advise on public affairs aspects, fund raising and management, and contribute to needed technological development.
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1st SC-IGBP Paris (France) 16-19 July, 1987
2nd SC-IGBP Cambridge, MA (USA) 8-11 February, 1988
3rd SC-IGBP Stockholm (Sweden) 23-26 October, 1988
4th SC-IGBP Brussels (Belgium) 13-16 June, 1989
5th SC-IGBP Berlin (West) 6-11 November, 1989
6th SC-IGBP Moscow (USSR) 21-24 March, 1990

Executive Committee for the IGBP (EC-IGBP)
1st EC-IGBP Cambridge, MA (USA) 4-5 December, 1987
2nd EC-IGBP Budapest (Hungary) 4-5 June, 1988
3rd EC-IGBP London (UK) 12-13 January, 1989
4th EC-IGBP Lisbon (UK) 15 October, 1989

Interagency Coordinating Committee (ICC)
1st ICC London (UK) 11 January, 1989
2nd ICC Lisbon (Portugal) 14 October, 1989

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Southern Hemisphere

Regional Meetings for the IGBP
Southern Hemisphere
Swaziland, 11-16 December, 1988
South America
Sao Jose dos Campos (Brazil), 5-9 January, 1990
Africa (planning)
Lomé (Togo) 13-14 March, 1989

CP1: Terrestrial Biosphere-Atmospheric Chemistry Interactions
CP1 Snowmass (USA) 13-14, 20-21 August, 1988
IGAC Dookie (Australia) 7-11 November, 1988
CP1 Mainz (FRG) 26 January-1 March, 1989
CP1 Woods Hole, Mass. (USA) 25-27 October, 1989
Join CP1/SCOPE Sigtuna (Sweden) 19-25 February, 1990

CP2: Marine Biosphere-Atmosphere Interactions
CP2 Tokyo (Japan) 19-21 September, 1989
JGOFS/IGAC San Francisco (USA) 6 December, 1989 JGOFS
London (UK) 12-13 March, 1990

CP3: Biospheric Aspects of the Hydrological Cycle
CP3 Cambridge (USA) 12-13 February, 1988
CP3 Potsdam (DDR) 7-9 June, 1988
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Joint CP3/CP4/CP5/WG1
CP3
CP5/IGBP/IAH/HP
CP4: Effects of Climate Change on Terrestrial Ecosystems
CP4
CP4 Joint CP3/CP4/CP5/WG1
CP4
CP4
CP4

CP5: Global Analysis, Interpretation and Modelling
Joint CP3/CP4/CP5/WG1
CP5
WG1: Data and Information Systems
WG1
WG1/IGBP Remote Sensing
Joint CP3/CP4/CP5/WG1
WG1
WG2: Regional Research Centres
WG2
WG2/IBSA/Unesco

SSC: Global Changes of the Past
SSC
SSC
SSC

Other IGBP Scientific Planning Meetings
Land-Ocean Interactions in the Coastal Zone
IGBP/WCRP Group on
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Meetings of the Editorial Committee for the SAC II Report
1st
2nd

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