GLOBAL IGBP CHANGE

IGBP Report 55

International Geosphere-Biosphere Programme

Science Plan and Implementation Strategy

GLOBAL IGBP CHANGE

Citation

This report should be cited as follows:
IGBP (2006) Science Plan and Implementation Strategy. IGBP Report No. 55. IGBP Secretariat, Stockholm. 76pp.

Front Cover Illustration

The cover illustration is a depiction of the Earth System, highlighting the complexities of and cross-scale interactions between the different elements of the system. The structure of the illustration mirrors the programme structure of IGBP, which is built around the Earth System compartments of land, atmosphere and ocean, the interfaces between these compartments, and system-wide integration. At the centre of the illustration is the Earth – reflecting the IGBP focus on the Earth System – with a superimposed grid indicating the importance of Earth System modelling. The illustration emphasises the importance of physical, chemical and biological processes from the molecular to the global scale. Evidence of human activities is apparent in each Earth System compartment, reflecting the growing focus of IGBP and research partners on the coupled human-environment system. The illustration was commissioned by IGBP to help communicate IGBP science and to strengthen visual integration across IGBP products.

Publication Details

Published by:
IGBP Secretariat
Box 50005
SE-104 05, Stockholm, SWEDEN
Ph: +46 8 166448
Fax: +46 8 166405
Web: www.igbp.net

Editors:
Bill Young, Kevin Noone and Will Steffen
Series Editor: Bill Young
Graphic Design: Hilarie Cutler

ISSN 0284-8105

Copies of this report can be downloaded from the IGBP website and hard copies can be ordered from the IGBP Secretariat.

Prepared by IGBP Secretariat staff:

Wendy Broadgate

Susannah Eliott

João Morais

Kevin Noone

Will Steffen

Bill Young

and the following SC-IGBP members (past and present):

Meinrat Andreae, Germany

Guy Brasseur, United States

Sandra Lavorel, France

Karin Lochte, Germany

Carlos Nobre, Brazil

Berrien Moore III, United States

Katherine Richardson, Denmark

Mark Stafford Smith, Australia

An Zhisheng, China (Beijing)

with contributions to text boxes also provided by:

Robert Buddemeier, United States

James Galloway, United States

Roger Hanson, United States

Timothy Jickells, United Kingdom

Bernd Kromer, Germany

Steven Smith, United States

Andrew Watson, United Kingdom

Preface

This Science Plan and Implementation Strategy sets out the research agenda for the second phase of IGBP. This phase will need to be even more integrative than the first, and therein lies a major challenge. We cannot lose sight of the need for focused, disciplinary research in areas where process-level Earth System understanding is poor. Yet at the same time, we must address over-arching questions that require a systemic – not just a systematic – approach. We must combine research on Earth System components (atmosphere, land and ocean) with research on processes occurring at the interfaces between components, and we must integrate across all of these to develop diagnostic and predictive capabilities for the Earth System.

Herein, we describe our strategy for producing high quality, unbiased, credible, fundamental scientific research in the area of global change: a strategy centred on ten projects, to be carried out by the several thousand scientists worldwide who are part of the IGBP network. Further, we describe how we will communicate the results of this research to different audiences, in order to realise our vision: "to provide scientific knowledge to improve the sustainability of the living Earth".

This should be considered a living document. Like IGBP itself, is has evolved considerably since the first draft. It is neither a static nor an exclusive plan for the second phase of IGBP, but rather, is a guide book for our continued scientific journey. We describe how IGBP developed over the years and moved into its second phase, how we responded to the changing research landscape and our plans for the evolution of the network. As with any good guide book, we have tried to identify the major vistas that IGBP will visit in the next eight years, but have purposefully left ample opportunity for further exploration. We expect the guidebook to be updated as the journey continues and as new territory is explored.

This document is the work of many hands and minds. As such, it illustrates one of the greatest strengths of IGBP: the willingness of a large number of scientists around the world to voluntarily give their time and expertise to the common endeavour of building the scientific infrastructure necessary to conduct global change research. We believe the document reflects the diversity of expertise, disciplines and cultures that characterises our scientific community, and their commitment to addressing some of the most important scientific issues of our time: understanding how our planet functions in a holistic sense including the important role of humans, and mapping out a sustainable future for humankind.

Carlos Nobre, Chair SC-IGBP
Kevin Noone, IGBP Executive Director

Guy Brasseur, Past Chair SC-IGBP
Will Steffen, IGBP Executive Director (1998–2004)

Acknowledgements

This Science Plan and Implementation Strategy has benefited from varying types and levels of input, advice and comment from many people during the several years over which it evolved. The authors and editors thank all SC-IGBP members during 2003–05 – especially the chairs of IGBP project SSCs – for their contributions and guidance, including during discussion groups at the 2005 SC-IGBP meeting. All Executive Officers of IGBP projects and ESSP projects during 2003–05 are similarly thanked for their contributions and comments. From the IGBP Secretariat, John Bellamy, Sofia Roger and Charlotte Wilson-Boss assisted in preparation of the document. The several people who provided constructive reviews (in late 2004 and late 2005) are thanked for their time and contributions.

Importantly, the science agenda outlined in this document is largely based on the science agendas of IGBP projects, and thus thanks are extended to the scientific committees of these projects and to cosponsoring organisations. The cosponsoring organisations include IHDP, SCOR, WCRP, IOC (of UNESCO) and CACGP (of IAMAS). Additionally, as articulated in this document, ESSP is increasingly important for the integration and policy relevance of IGBP science; IGBP thanks its ESSP partners (DIVERSITAS, IHDP and WCRP) for their support.

Finally of course, none of this would have been achieved without the continued financial support from over forty countries, the financial and institutional support from ICSU, and the support for the IGBP Secretariat of the Royal Swedish Academy of Sciences in Stockholm.

Contents

Executive Summary

IGBP is an international research programme formed in 1987 by ICSU to study the phenomenon of global change; its vision is:

to provide scientific knowledge to improve the sustainability of the living Earth.

IGBP studies the interactions between biological, chemical and physical processes and human systems, and collaborates with other programmes to develop and impart the understanding necessary to respond to global change. In the context of its vision the research goals of IGBP are:

to analyse (i) the interactive physical, chemical and biological processes that define Earth System dynamics; (ii) the changes that are occurring in these dynamics; and (iii) the role of human activities in these changes.

The first phase of IGBP was completed in 2003, and was marked by the publication of a comprehensive book series synthesising IGBP and closely related research. The second phase of IGBP (2004–13) began with an intensive period of scientific planning, based on the research and synthesis of the first phase. This Science Plan and Implementation Strategy briefly summarises the key findings of the first phase synthesis which provide the foundation for the second phase, and then presents the outcomes of the second phase planning process.

The major outcomes of the research of the first phase of IGBP were (i) an improved understanding of the systemic behaviour of the Earth System; (ii) quantification of the extent of Earth System variability at various time scales, (iii) elucidation of the important role of the biosphere in Earth System functioning; and (iv) a far clearer picture of the changing degree of human influence on the Earth System.

The most compelling picture of Earth System behaviour comes from Antarctic ice cores that reveal strong global environmental oscillations, and provide considerable evidence for the linkages between the physical climate and global biogeochemical cycles over the last 740,000 years. Other palaeo records show strong variations at millennial time scales, including examples of abrupt changes that reflect the complex behaviour of the Earth System. While previously the biosphere was considered to simply be the passive recipient of geophysical changes, it is now recognised that biological processes are intimately coupled to physical and chemical processes in Earth System dynamics. Although analysis of past variability shows that distinguishing human-driven change from natural variability is not straightforward, there is now ample evidence that human activities are having a major influence on the Earth System, such that it has moved well outside the range of variability exhibited over at least the last half million years.

The major outcomes of the planning for the second phase of IGBP based on these findings have been (i) the definition of a new scientific structure that reflects far more clearly and completely the structure and functioning of the Earth System; and (ii) the development of a interdisciplinary and integrative Earth System science agenda necessary for addressing the challenge of global change.

The new scientific structure is based on a suite of both new and refocused projects that reflect the three major Earth System compartments (land, ocean and atmosphere), the interfaces between these compartments and system-level integration through time and space. There are nine separate IGBP projects spanning the Earth System compartments, interfaces and system-wide integration:

- the International Global Atmospheric Chemistry (IGAC) project which continues from the first phase of IGBP but with a refocused research agenda;
- the new Global Land Project (GLP) which builds on the two land-oriented projects of the first phase of IGBP;
- the Global Ocean Ecosystem Dynamics (GLOBEC) project (initiated in the first phase of IGBP and planned to conclude in 2009) and the new Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project which collaborate on ocean research;

- the new Surface Ocean–Lower Atmosphere Study (SOLAS);
- the new Integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS);
- the Land-Ocean Interactions in the Coastal Zone (LOICZ) project which continues from the first phase of IGBP but with a much broader scope;
- Past Global Changes (PAGES) which continues its integrating palaeo research; and
- Analysis and Modelling of the Earth System (AIMES) which spearheads integrative activities of IGBP at the Earth System level.

In addition to these long-term projects, IGBP uses Fast-Track Initiatives to start research on key cross-cutting issues in Earth System science and to foster integration across projects and disciplines.

IGBP recognises that collaboration between a range of research partners is increasingly necessary for comprehensive Earth System science – especially collaborations between the natural and social sciences in order to achieve a balanced analysis of the coupled human-environment system. While many collaborations will be important for the second phase of IGBP, participation in the Earth System Science Partnership (ESSP) of the global change programmes of ICSU is expected to be increasingly important, while ongoing collaborations with SCOR will continue to underpin IGBP marine research.

As well as being increasingly important for integrative Earth System science, participation in ESSP will be a key mechanism by which IGBP seeks to provide relevant research results to guide policy formulation, particularly with respect to sustainable development. To this end IGBP will continue to actively support and work with the ESSP projects on global sustainability (carbon, food, water and human health) and with existing and forthcoming integrated regional studies.

IGBP will continue many of its successful approaches to implementation from its first phase including: building research networks to tackle focused scientific questions; promoting standard methods; undertaking long time-series observations; guiding and facilitating construction of global databases; establishing common data policies to promote data sharing; undertaking model inter-comparisons and comparisons with data; and coordinating complex, multi-national field campaigns and experiments. In addition, IGBP will facilitate comprehensive interactions between modellers and experimentalists and will forge an international institutional network for Earth System science.

IGBP and Global Change National Committees will continue to be essential to research planning and implementation in IGBP, enabling a dialogue between national and international levels of global change research. IGBP will continue to invest strongly in research capacity building activities (particularly in less developed countries), with capacity building occurring primarily through project-level activities, and often in collaboration with START or regional capacity building organisations and networks.

As an apolitical but politically-relevant organisation IGBP will work to help bridge the gap between the international scientific community, policy makers and the public. IGBP will work to establish itself as a credible source of Earth System science and to provide policy-relevant (but not policy-prescriptive) information on global change to policy makers and the public.

Introduction

During the 1980s it became apparent that humankind had begun to match, and often exceed, the natural forces that regulate the Earth System. Human activities had pushed the Earth System well outside its normal operating range. This is reflected, for example, in changes in atmospheric composition, climate and terrestrial, coastal and marine ecosystems. This phenomenon is referred to herein as "global change"; although it is recognised that some groups prefer "global environmental change".

In the late 1980s ICSU decided that an international collaborative research endeavour on the phenomenon of global change was required, and so initiated planning for the International Geosphere-Biosphere Programme (IGBP) (Figure 1). Nearly twenty years after IGBP was first conceived, global change is more acute than ever. Townships on the Arctic coast have lost infrastructure to melting permafrost and storm surges; over 30,000 people in France died prematurely in a heat wave in 2003; many South American countries face dwindling water resources as glaciers retreat; and during 2003–05 eastern Australia suffered a severe drought possibly linked to rising sea surface temperatures.

The human population continues to grow (although more slowly than in previous decades) and in an uneven manner that is altering the population balance between poor and rich nations. The proportion of elderly is increasing (especially in the developed world), and for the first time the urban population exceeds the rural population. Despite water resources development and remarkable increases in agricultural production, inadequate and polluted water supplies and insufficient food production remain major causes of poverty in the developing world.

In spite of economic development, around 15% of the global population still earn less than US$1 per day, and in spite of medical advances and vaccination campaigns, infectious diseases and global pandemics remain a serious threat. Non-renewable resources are being depleted, and within fifty years a shift will be required from an energy system based on carbon-rich fossil fuels to one based on low-carbon energy sources. Human activities are causing extinctions at an unprecedented rate, irreversibly depriving us of ecosystem goods and services.

These multiple and complex problems mean Earth System science is no longer only curiosity-driven, but strongly issue-driven. The scientific challenges posed by these issues will require close collaboration between biophysical and social scientists. The recognition that economic development is constrained by environmental issues, means investigations of how global change will affect food security, water availability, energy consumption and human health are central concerns.

Decision makers are increasingly calling for scientific advice on environmental issues. In its second phase IGBP will continue to provide fundamental knowledge on the role of biological, physical and chemical processes in the Earth System, and on their interactions with human systems. Additionally, as a partner in the Earth System Science Partnership (ESSP) of the global environmental change programmes of ICSU (DIVERSITAS, IGBP, IHDP and WCRP), IGBP will investigate the implications for global sustainability of Earth System changes.

In the face of the challenges presented by global change, the vision of IGBP is *to provide scientific knowledge to improve the sustainability of the living Earth.* IGBP studies the interactions between biological, chemical and physical processes and human systems, and collaborates with other programmes to develop and impart the understanding necessary to respond to global change.

In the context of this vision the research goals of IGBP are *to analyse (i) the interactive physical, chemical and biological processes that define Earth System dynamics; (ii) the changes that are occurring in these dynamics; and (iii) the role of human activities in these changes.* To achieve these goals IGBP will foster collaboration amongst biophysical and social scientists, and will strive to build and support an expanding international community of scientists, particularly in the developing world.

The scientific basis, research structure and the implementation strategies for the second phase of IGBP (2004–2013) are presented in this Science Plan and Implementation Strategy. This second phase is based on overarching scientific questions generated by the first phase synthesis (Figure 2) and organised within a new scientific structure.

Figure 1. Timeline of the first and second phases of IGBP, indicating planning, implementation and synthesis stages.

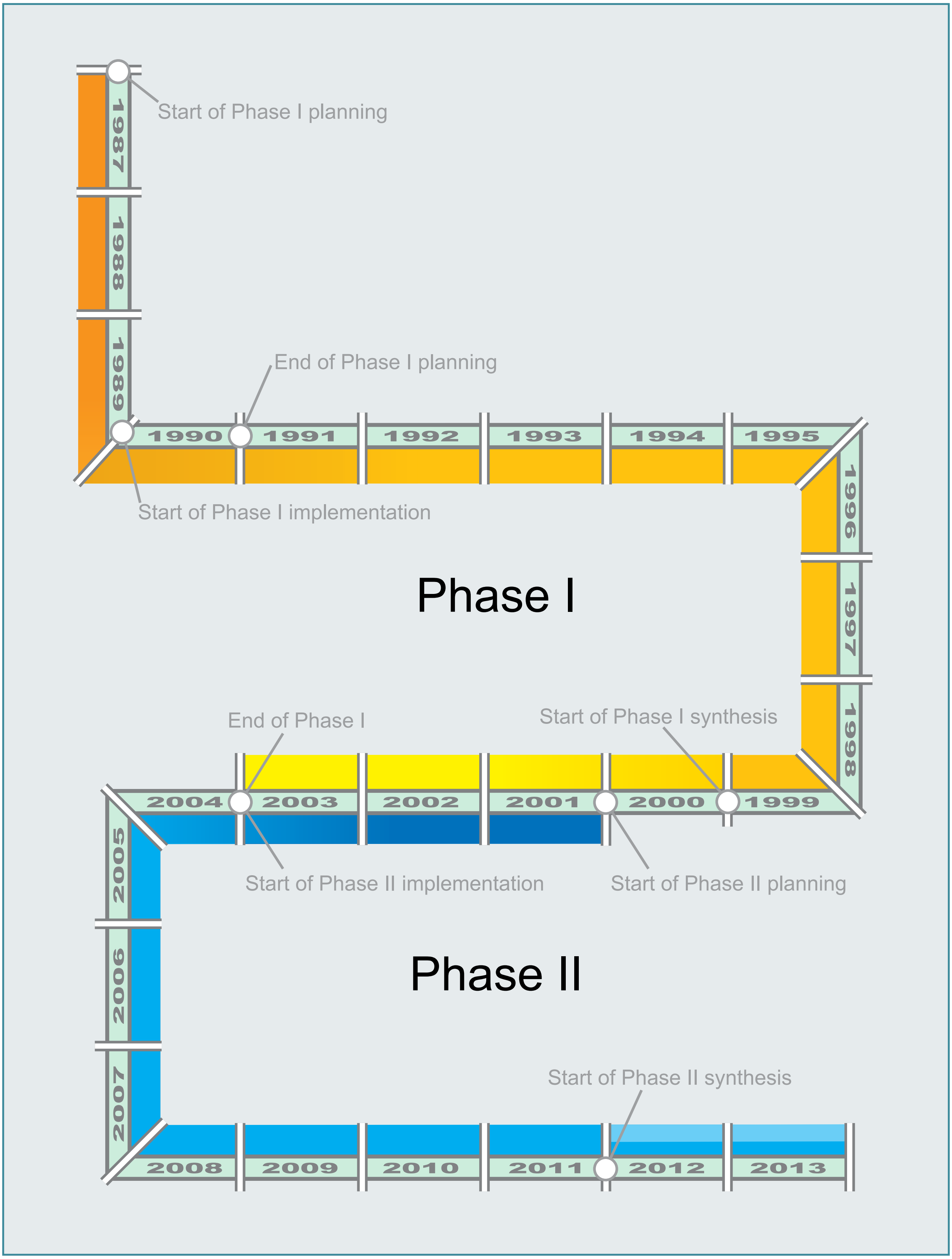
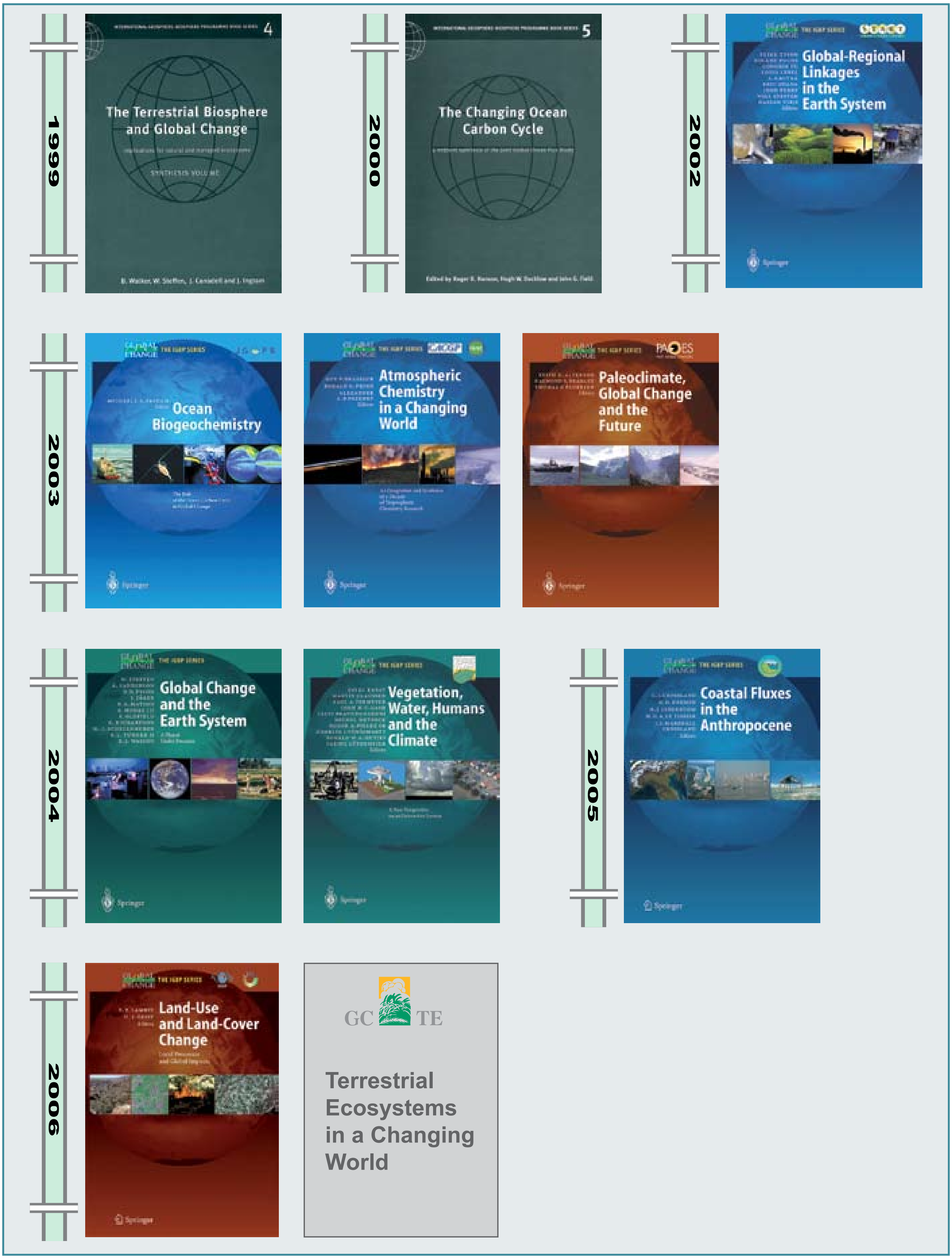


Figure 2. The IGBP synthesis activity generated eleven comprehensive project syntheses published between 1999 and 2006. These represent one of the major scientific outputs of the first phase of IGBP.



The Scientific Basis

In its early years IGBP recognised that the Earth behaves as a single, global-scale system in which the atmosphere, oceans, biosphere, cryosphere and lithosphere are linked. Beyond this conceptual framework however, there was little detailed understanding of the importance of these components, how they are connected, their forcings and feedbacks and the Earth System dynamics that emerge from their interactions. The first phase of IGBP made major advances in Earth System understanding, including showing how small and apparently unimportant activities could cause a cascade of long-term, large-scale Earth System changes, which could be abrupt, surprising and very difficult to manage. A summary of these advances in Earth System understanding is given below, which provides the foundation for the second phase of IGBP.

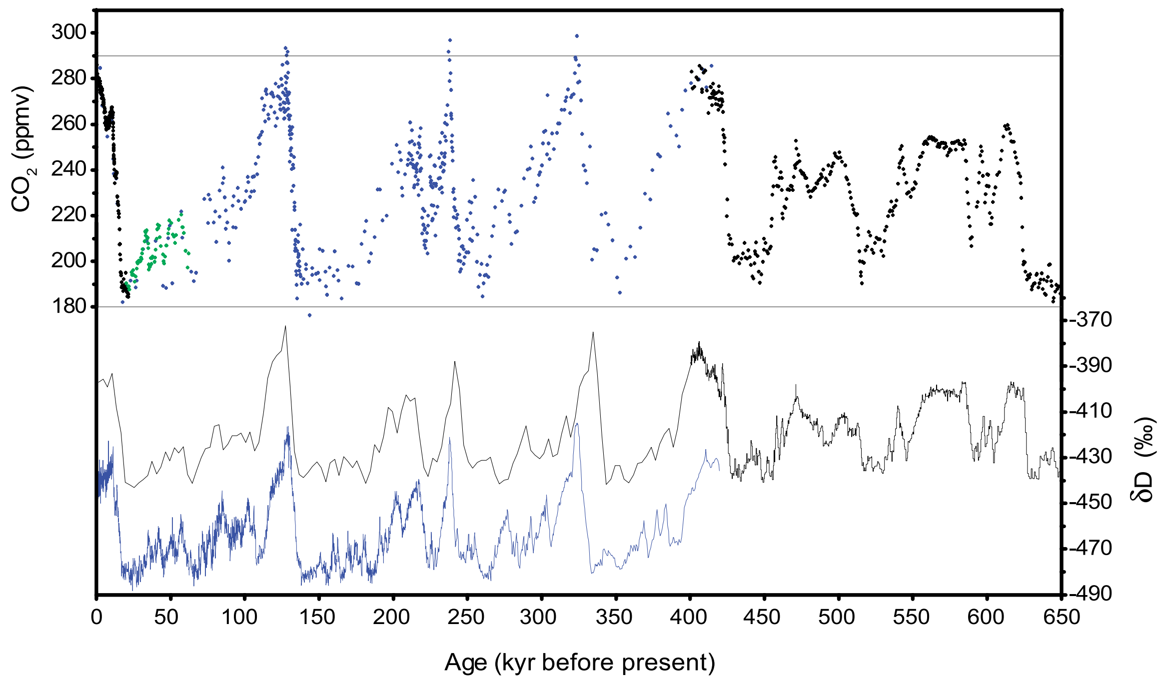
Systemic Behaviour

The clearest picture of Earth System behaviour comes from Antarctic ice cores that reveal global environmental oscillations between glacial and interglacial states. The Vostok core (Petit et al., 1999) provided concurrent records of inferred temperature, trace gas concentration and aerosol (dust and sulphate) levels for the last 420,000 years. These data provide considerable evidence for the linkages between the physical climate and global biogeochemical cycles (Steffen et al., 2004).

For example, climate (indicated by inferred temperature) and the carbon cycle (indicated by atmospheric carbon dioxide and methane concentrations) show largely parallel variations. Furthermore, the main maxima and minima of temperature and trace gas concentrations, which mark the alternation between glacial and interglacial states, follow a regular, cyclic pattern through time, with each major cycle lasting approximately 100,000 years.

The smooth changes in the eccentricity of the Earth's orbit that are believed to be the primary forcing mechanism for this dominant periodicity, are too slight and too

Figure 3. Composite carbon dioxide record from Antarctic ice cores from Dome Concordia (black, 0–22 thousand and 390–650 thousand years ago), Vostok (blue, 0–420 thousand years ago) and Taylor Dome (green, 20–62 thousand years ago); and composite delta deuterium record from Dome Concordia (0–650 thousand years ago) and Vostok (0–420 thousand years ago). From Siegenthaler et al. (2005) with permission from AAAS.



smooth to generate the changes recorded without strong modulation by internal feedbacks. This is especially so when the abrupt shifts to interglacial conditions at each the end of each glacial period are considered. This highly non-linear response of the Earth System to external forcing must involve interactions among biological, chemical and physical components. Finally, the range over which inferred temperature and trace gas concentrations vary is limited. The four cycles in the record have similar maxima and minima, pointing to a high degree of self-regulation.

The Dome Concordia core extends inferred temperature and carbon dioxide records back to 740,000 and 650,000 years before present respectively (EPICA, 2004; Siegenthaler et al., 2005). The Dome Concordia core confirms the Vostok data and reveals different behaviour for the pre-Vostok record (Figure 3): pre-Vostok interglacial periods were cooler but longer, and the dominant periodicity is less clear, apparently a mix of the 40,000-year periodicity of the Quaternary period and the 100,000-year periodicity of the Vostok record.

The Earth System dynamics that give rise to cycling recorded in the Antarctic ice cores are not completely understood, however, significant advances have been made in describing some of the main feedbacks. For example, in the transition to glacial conditions the oceans absorb increasing amounts of carbon dioxide from the atmosphere, since carbon dioxide is more soluble in colder water. Lower atmospheric carbon dioxide concentrations then lead to a cooler climate, creating a positive feedback. Secondly, in this transition to glacial conditions, northern land ice sheets begin to form and expand, as does sea ice in the Arctic Ocean and around Antarctica. This ice reflects nearly all the incoming solar radiation, further cooling the Earth's surface. Both these feedbacks operate in reverse during the more abrupt transition back to interglacial conditions.

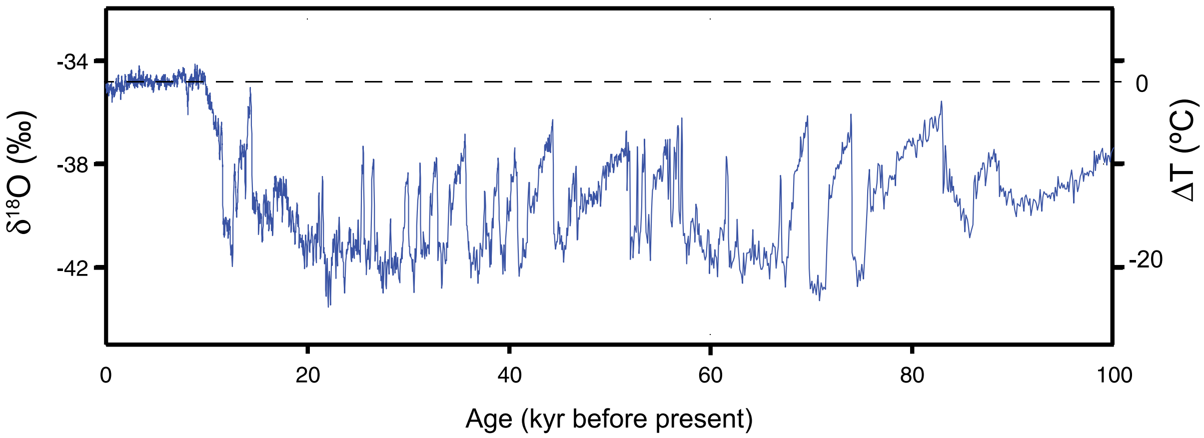
The processes that slow these positive feedbacks and constrain the temperature and trace gas concentration extremes are less well understood. However, it is clear that these limits are not simply related to changes in incoming solar radiation caused by the orbital changes which trigger glacial-interglacial cycling. It is not yet clear why the upper temperature extreme is lower in the pre-Vostok period of the Dome Concordia record.

Natural Variability

A feature of the Earth System apparent from palaeo analyses is the considerable natural variability on all time scales (Alverson et al., 2003). The Antarctic ice cores show strong temporal changes in climate proxies and trace gas concentrations over hundreds of thousands of years, and northern hemisphere temperature records demonstrate natural climate variability on millennial time scales. Although different proxies and different analytical techniques yield different millennial scale temperature records, it is clear that northern hemisphere surface temperatures varied naturally by 0.7°C on centennial time scales (Mann and Jones, 2003).

The isotopic record for the Holocene from Greenland ice cores shows much lower temperature variability than during glacial periods (Figure 4). It is tempting to assume that this relatively benign climate allowed agriculture and civilisations to develop, however, low-latitude palaeo records reveal similar hydrologic cycle variability during both the early Holocene and the glacial-interglacial transition. Other evidence shows significant hydrological variability persisted into the later Holocene, particularly in temperate and low-latitude regions where most of the human population lives (Alver-

Figure 4. Delta ^{18}O data and inferred temperature from the ice core recovered from Summit, central Greenland. From Johnsen et al. (1997).



son et al., 2003). Much of this variability is larger than that captured in the comparatively short instrumental record.

Abrupt changes are a prominent feature of Earth System variations, the best-studied examples perhaps being the rapid, high amplitude switches between glacial and interglacial conditions in the North Atlantic region during the most recent glacial period (Grootes et al., 1993; Figure 4). In these transitions temperatures increased by 6–8°C in a few decades.

The North Atlantic region has also experienced rapid cold shifts, the most recent of which occurred during the transition to the Holocene about 11,600 years ago when the regional temperature dropped by at least 10°C within a decade (Alley, 2000). These temperature increases and decreases are probably associated with instabilities in the North Atlantic thermohaline circulation.

Analysis of past variability shows that distinguishing human-driven change from natural variability is not straightforward, and that natural variability is usually considerably greater than that captured in the instrumental record.

The Role of The Biosphere

Biological processes are now known to be intimately coupled to physical and chemical processes in Earth System dynamics, with evidence that biological processes sometimes play a regulatory or buffering role. Previously the biosphere was usually considered to simply be the passive recipient of geophysical changes.

The biosphere affects Earth System behaviour through biogeophysical and biogeochemical processes and through biological diversity. Biogeophysical processes operate primarily by: (i) absorption or reflection of incoming solar radiation; (ii) evaporation and transpiration of water; and (iii) transfer of momentum from atmospheric flows. Terrestrial and marine biota can significantly affect any of these processes. Biological processes are important for the global-scale biogeochemical cycling of carbon, nitrogen, phosphorus, silicon and iron. Although much less is known about the role of biological diversity *per se*, experimental work has shown that biodiversity can affect productivity and nutrient cycling, and may buffer ecosystems against sudden abiotic changes.

Biota strongly influence atmospheric composition. The switch of the atmosphere from a reducing to an oxidising medium billions of years ago was caused by cyanobacteria, and its maintenance in a highly non-equilibrium, oxidising state is still controlled by biological processes. Marine and terrestrial biota continuously emit carbon, nitrogen and sulphur-based compounds, influencing atmospheric composition and chemistry. Terrestrial biological processes influence the amount of water vapour in the atmosphere, particularly at local and regional scales.

The interaction of vegetation and the hydrological cycle in the Amazon Basin provides an example of the multiple ways in which biological processes affect abiotic processes. About half the water which falls as rain in the Amazon Basin originates from the vegetation itself through transpiration; it is recycled continuously from the vegetation to the atmosphere and back again. More subtly, the vegetation affects the hydrological cycle through the emission of volatile organic compounds, which promote the formation of aerosol particles which provide cloud condensation nuclei and enhance the eventual formation of water droplets and thus rainfall. Human modification of land-cover in the Amazon Basin shows striking nonlinearities in the interaction between vegetation and the hydrological cycle. If conversion of tropical forest to crops or grasslands is sufficiently limited and fragmented, the conversion actually increases rainfall due to enhanced convective activity caused by surface warming. Enough water vapour remains in the atmosphere to provide moisture for clouds and rain to form. If however, land conversion is extensive, the amount of water vapour from evapotranspiration drops below a critical threshold and rainfall drops sharply, leading to increased fires and drought, further enhancing the conversion of rainforest to savannah or grassland in a positive feedback. Changes in vegetation due to land cover conversion also affect soil moisture through changes in rooting depth and density, and modify the amount of water that runs off the land surface into river networks.

The global iron cycle is another excellent example of the central and complex role of biology in the Earth System (Box 1). Although the role of the biosphere has become clearer, many fundamental questions are yet to be answered.

Human Influence

Humans have always influenced their environment, however, early human impacts were mostly local, fragmented, transitory and insufficient to affect Earth System behaviour. The advent of modern science and the discovery and widespread exploitation of fossil fuel began to alter the

Box 1. The Global Iron Cycle

Iron is an essential nutrient for all organisms; for marine phytoplankton, separated from iron-rich sediments by considerable water depths, it must be sourced from the water column. Iron is generally sparse in the marine water column and hence availability limits phytoplankton growth over vast areas of the ocean. Iron reaches the oceans mainly as suspended sediment from rivers, however, this supply is mostly trapped in near-coastal areas, and so aeolian dust is the dominant input of iron to the open ocean.

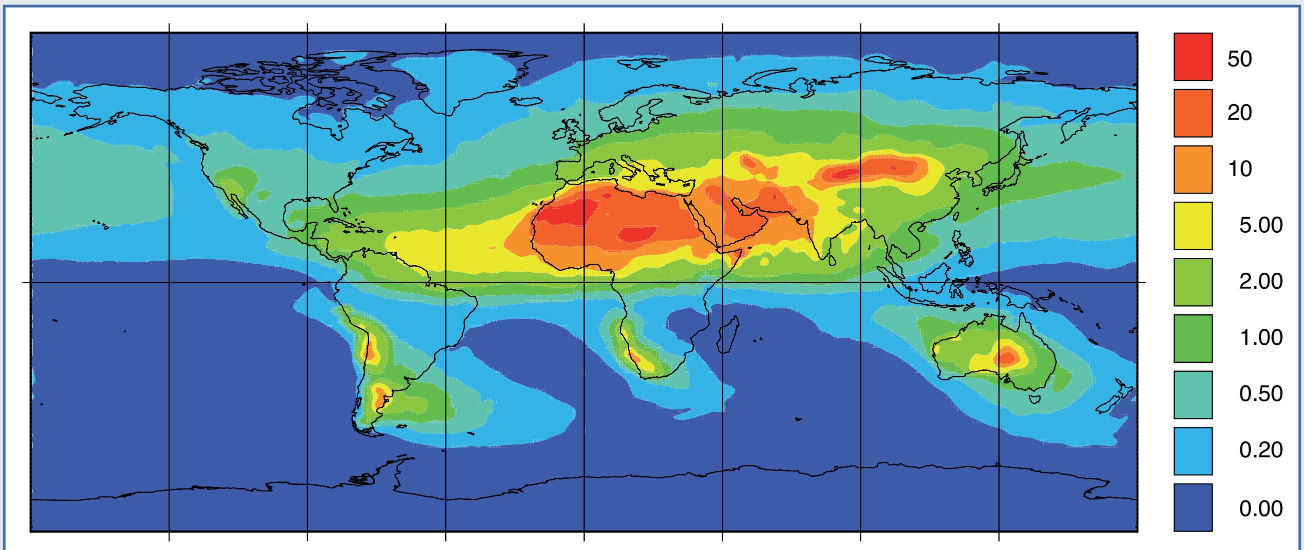
Terrestrial vegetation affects the amount of iron available for global cycling through the stabilisation of soil by root activity, thus reducing the amount of soil susceptible to wind and water erosion. Globally, dust is largely produced by short dust storm events in the great desert areas of the world, with North Africa being the predominant source region (Figure 5).

Only a small fraction of the iron transported with dust dissolves in surface ocean waters, but this fraction stimulates significant phytoplankton growth in regions (such as the high latitudes) where iron availability is low (Box 10). In nutrient-poor tropical waters dust can stimulate nitrogen fixation which stimulates production. The marine impacts of dust deposition are therefore spatially heterogeneous and depend upon nutrient availability.

Stimulation of plankton growth in the oceans can affect the atmosphere by changing oceanic uptake and release of climatically active gases, which can affect the global climate and hence dust production itself, creating the potential for large-scale, multiple and complex climate feedbacks. The complexity of these linkages and feedbacks means that the global iron cycle cannot be studied in isolation, but must be considered in the context of the overall biogeochemistry of the Earth System.

Dust production rates are linked to rainfall and wind, and have varied considerably through time – particularly on the time scale of glacial-interglacial cycles. Because of these links, the potential for global change pressures to modify dust production is substantial

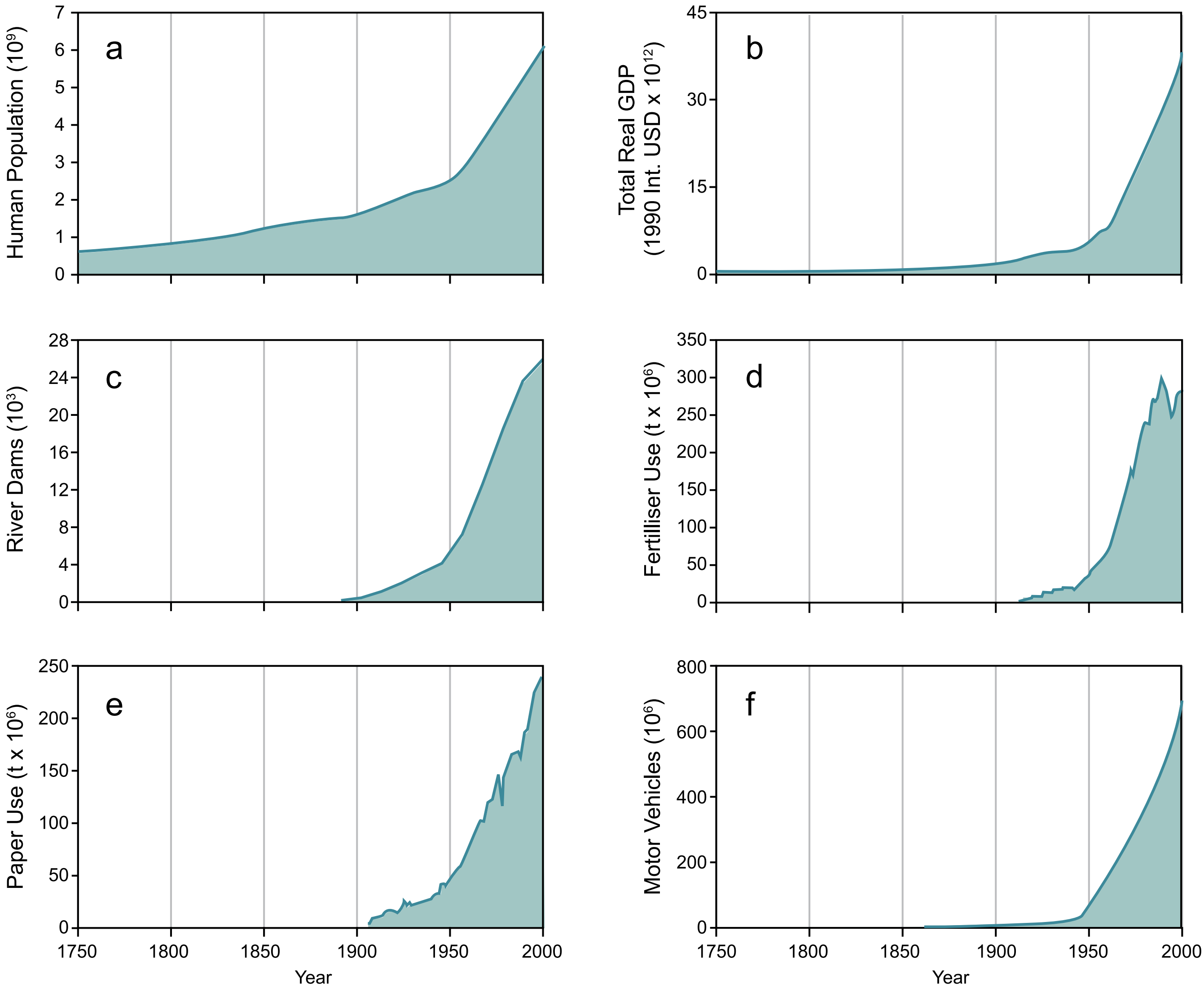
Figure 5. Global dust deposition (g m^{-2} yr^{-1}) based on a composite of three modelling studies that match satellite optical depth, *in situ* concentration and deposition observations. Reproduced from Jickells et al. (2005) with permission from AAAS.



human-environment relationship. The explosion of the human enterprise over the last few centuries and its remarkable global-scale environmental and socio-economic impacts characterise global change (Figures 6 and 7).

Although human impacts are discernable in all parts of the Earth System, land systems and the coastal zone have been the most heavily impacted. About half of the ice-free land surface has been converted or significantly modified by humans (Klein Goldewijk and Battjes, 1997), while most of the rest is managed to some extent. Upwards of half the terrestrial net primary productivity is directly used, co-opted or diverted by human activities (Rojstaczer et al., 2001), and the only relatively pristine coasts outside the polar regions are remote areas of Australia and southern South America (Crossland et al., 2005). Increasing coastal urbanisation will continue to drive coastal impacts. The flux of nitrogen from the land

Figure 6. Some global-scale indicators of human activity from 1750 to the present: (a) human population (USBC, 2000); (b) total real Gross Domestic Product (Nordhaus, 1997); (c) damming of rivers (WCD, 2000); (d) fertiliser use (IFIA, 2002); (e) paper use (PPI, 1993); and (f) number of motor vehicles (UNEP, 2000).

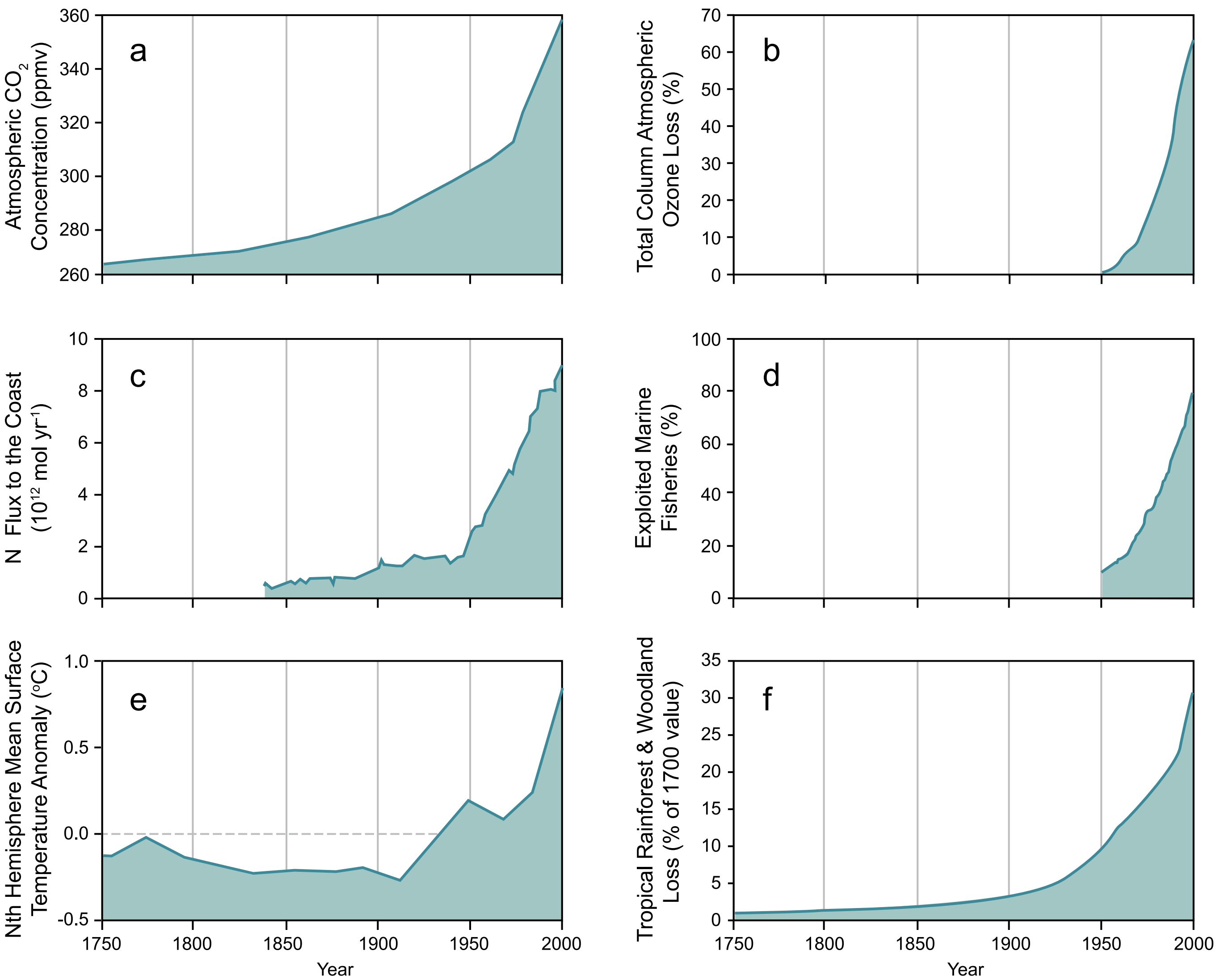


to the coastal zone has increased by an order of magnitude during the last century (Mackenzie et al., 2002), and many other parts of the global nitrogen cycle have been perturbed (Box 2). Human activities have increased extinction rates by between one hundred and one thousand times the natural rate (MEA, 2005).

Increases in the atmospheric concentrations of greenhouse gases, most notably carbon dioxide, are well-known. However, human activities have influenced atmospheric composition and chemistry in many other ways, including depletion of stratospheric ozone and increases in tropospheric ozone (Brasseur et al., 2003).

Collectively, the global impacts of human activities mean the Earth System is currently operating in a no-analogue state and has moved well outside the range of variability exhibited over at least the last half million years (Steffen et al., 2004).

Figure 7. Some global-scale indicators of change in the Earth System: (a) atmospheric carbon dioxide concentration (Etheridge et al., 1996); (b) percentage of total column atmospheric ozone loss based on an average annual total column ozone of 330 (courtesy of JD Shanklin, British Antarctic Survey); (c) modelled anthropogenic nitrogen flux to the global coastal zone (Mackenzie et al., 2002); (d) percentage of global marine fisheries fully exploited, over-exploited or collapsed (FAOSTAT, 2002); (e) Northern Hemisphere average surface temperature anomalies (Mann et al., 1999); and (f) estimated loss of tropical rainforest and woodland for Africa, Latin America, South Asia and Southeast Asia (Richards, 1990; WRI, 1990).



Box 2. The Global Nitrogen Cycle

In the late 20th century human activities surpassed natural terrestrial processes in converting unreactive nitrogen gas to reactive nitrogen (Nr)*, with major implications for both ecosystem productivity (often Nr-limited) and environmental problems (Galloway et al., 2004). In 1860 the global population was 1.5 billion, anthropogenic Nr creation was about 15 Tg yr^{-1} and was almost entirely for food production through "cultivation-induced biological nitrogen fixation" (CBNF). At this time the rate of Nr creation by natural terrestrial BNF was about ten times higher, hence human activities accounted for only about 10% of the global terrestrial Nr creation.

By the early 1990s however, anthropogenic Nr creation had increased about 10-fold while the global population had increased 3.5-fold. Around 15% of the anthropogenic Nr creation was associated with energy production and most of the remainder with food production. About one quarter of the Nr creation for food production was by CBNF, and three quarters by fertiliser production via the Haber-Bosch process. Coupled with these Nr creation increases was a decrease of about 10% in natural terrestrial BNF due to conversion of natural grasslands and forests to agricultural uses.

The benefit from these human alterations to the nitrogen cycle is food production to support an increasing population and a rising *per capita* food consumption. However, problems have arisen due to both nitrogen shortages and excesses. Many regions of the world (e.g. Africa) have insufficient nitrogen for adequate food production, and nitrogen supply to these regions must be increased. Conversely, in other regions there is an excess of nitrogen, in part because all the nitrogen mobilised by energy production and most of the nitrogen used in food production is lost to the environment. Nitrogen loss to the environment can contribute to a host of problems, which are all linked through the global nitrogen cycle via the "nitrogen cascade" (Figure 8). For example, a nitrogen atom released to the atmosphere from fossil fuel combustion can, in sequence, increase atmospheric ozone concentration, decrease atmospheric visibility and increase precipitation acidity. Following deposition it can increase soil acidity, decrease biodiversity, pollute groundwater and cause riverine, estuarine and coastal eutrophication. Finally, once emitted back to the atmosphere it can contribute to greenhouse warming and decrease stratospheric ozone. Because nitrogen is linked to so many of the current global and regional environmental challenges, nitrogen issues are extremely important in environment policy.

Anthropogenic Nr creation will continue to increase as the global population increases. Even after the global population has peaked, Nr creation is likely continue to increase due to rising *per capita* consumption of both food and energy. The maximum Nr creation rate will depend to a very large extent on how the world manages its use of nitrogen for food production and its control of nitrogen in energy production. If the global population peaks around 9 billion, and if subsequently the average *per capita* Nr creation rate reaches that of North America in 1990 (around 100 kg $person^{-1}$ yr^{-1}), then the global total will reach around 900 Tg yr^{-1}, with about half occurring in Asia. The potential for this large increase emphasises the need for policies that focus on how to maximise the benefits of nitrogen, while minimising the environmental and human health impacts.

*Herein Nr refers to all biologically active, photochemically reactive, and radiatively active nitrogen compounds in the atmosphere and biosphere, including inorganic reduced forms (e.g. NH_3 and NH_4^+), inorganic oxidised forms (e.g. NO_x, HNO_3, N_2O, and NO_3^-), and organic compounds (e.g. urea, amines and proteins).

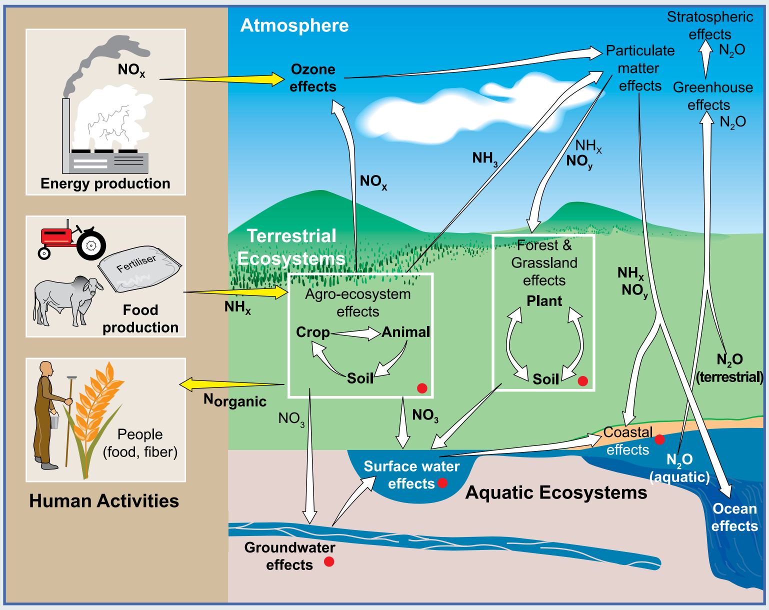


Figure 8. The cascade of nitrogen through the environment and the associated environmental impacts. The red dots indicate denitrification potential. From UNEP (2003) based on Galloway et al. (2003) with permission from UNEP.

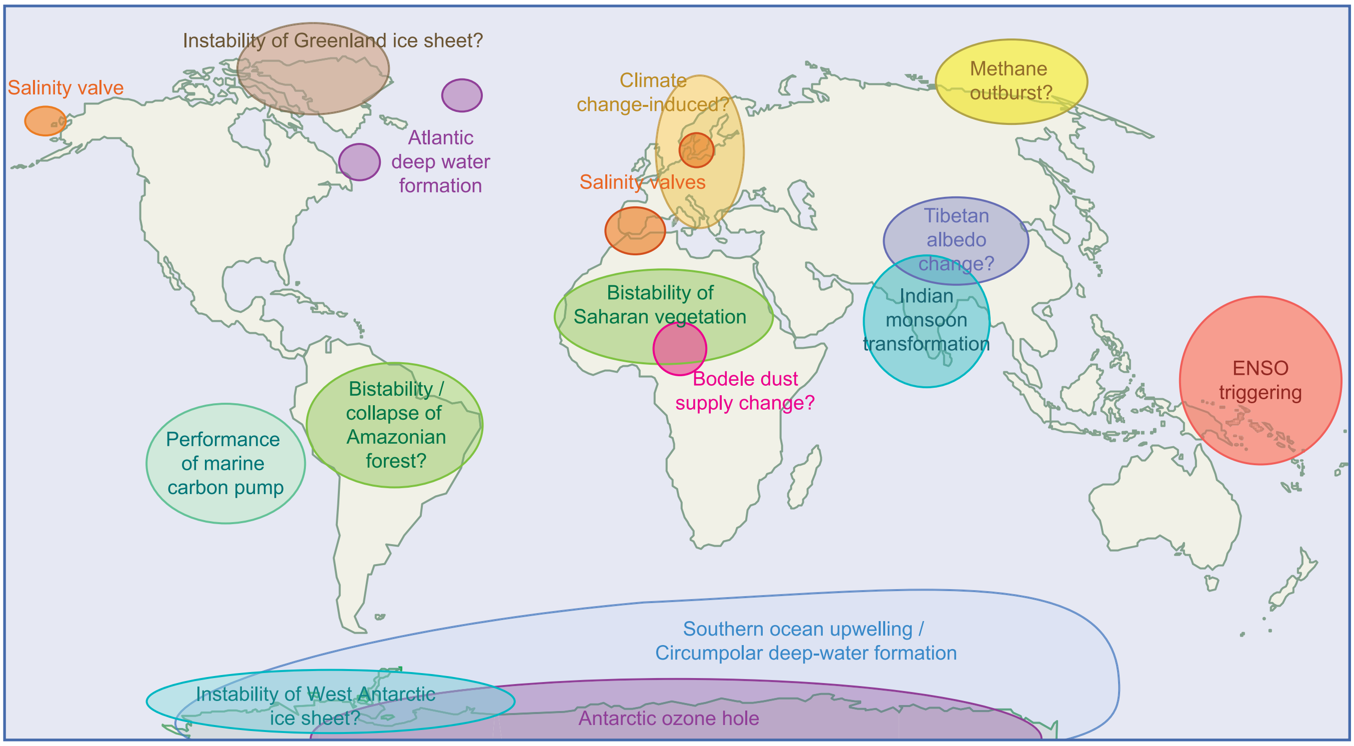
The Research Challenge

The ultimate aim of the United Nations Framework Convention on Climate Change is the stabilisation of greenhouse gases in the atmosphere at a level that will “prevent dangerous anthropogenic interference with the climate system” (UNFCCC, 1992). The Millennium Ecosystem Assessment (MEA) reported significant anthropogenic degradation of many ecosystem services, substantial and largely irreversible loss of biodiversity, and the potential for diminished benefits from ecosystem services for future generations (MEA, 2005). The concept of “dangerous anthropogenic interference” can therefore be extended beyond the climate system to the entire Earth System. Society should determine what level of interference is “dangerous”, however, this determination should be informed by science. A key role of IGBP is to help plan, coordinate, facilitate, integrate, synthesise and communicate the science necessary to inform this debate.

Additionally, Earth System science and global change research are required to guide sustainable development, and IGBP (together with research partners, see below) will increasingly work to address key issues in global sustainable development. The United Nations has established eight so-called Millennium Development Goals (MDG) which aim to liberate over 500 million people from poverty by 2015, and integrate sustainable development into national and international agendas to reverse the loss of environmental resources. The MDG are ambitious, and progress to date indicates major challenges for the coming decade. Accelerated progress will require a greater injection of relevant scientific research, as well as scientific capacity building in less developed countries. This will require not only more focused research, but a more concerted effort to communicate the implications of research results to policy makers, resource managers and international aid agencies in a timely manner.

Earth System science has already contributed much to the societal debate on climate change and global change, and predictions, projections and scenarios for the Earth

Figure 9. Regions known or anticipated to have strong influences on the Earth System. Courtesy of HJ Schellnhuber.



abound. However, these still range from global catastrophe to equitable sustainability, and even the fundamental biophysical variables are difficult to predict. For example, estimates for increases in global mean surface temperature expected this century range from 1.4 to 5.8 °C (IPCC, 2001), and even this range may be too narrow (Andreae et al., 2005). Two fundamental issues underlie the current range of Earth System futures. The first is the resilience of the coupled human-environment system, and the second is the nature of the human response to global change.

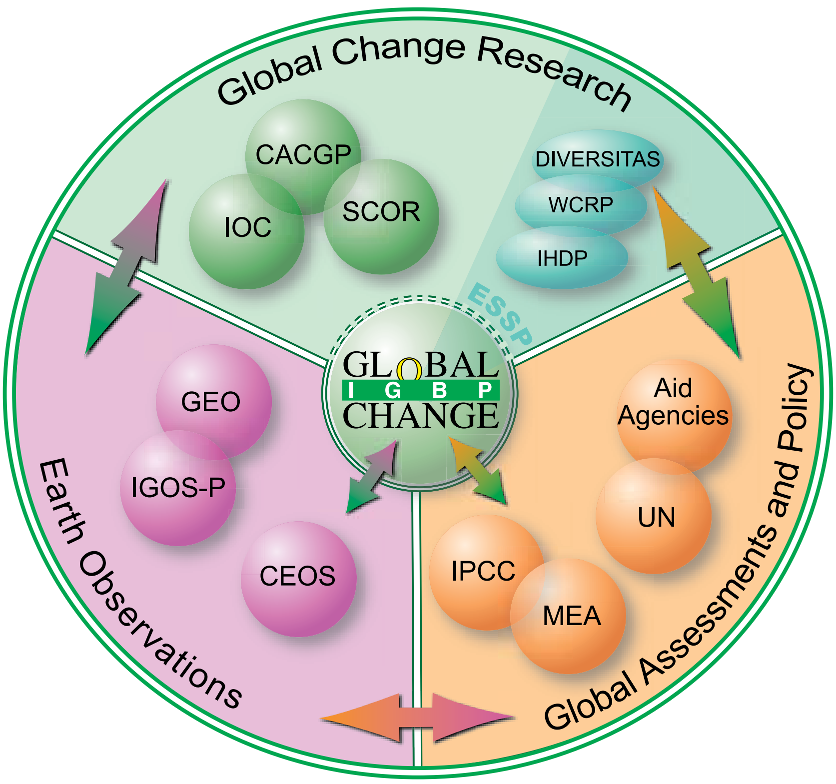
Addressing these issues requires conceptualising the Earth as a complex, non-linear system with strongly interacting biophysical and socio-economic components, and building the science of integration necessary to make the coupled human-environment system the fundamental unit of study. This will require greater study of thresholds and abrupt changes, of regional-global linkages via teleconnections and of sensitive regions that act as "switch and choke points" in the Earth System (Figure 9).

The second phase of IGBP will focus more on regional studies, on the integration of observations, process and case studies and modelling, and on development of simulation tools that capture the richness of past Earth System behaviour. These aspects are highlighted in *IGBP Projects and Activities*.

Additionally however, IGBP will, in its second phase, forge closer and stronger collaborations with key research partners in order to comprehensively study the Earth System and to meet the challenges posed by global change. To this end, most IGBP projects are now cosponsored, and all are developing and strengthening links with other relevant projects, especially projects of the other international global environmental change programmes (IHDP, WCRP and DIVERSITAS).

A key aspect of the collaborations of the second phase of IGBP is the push to achieve a deeper understanding of processes and systems-level behaviour, with particular emphasis on the coupling between natural and human systems. Hence two projects are cosponsored by IHDP.

Figure 10. An IGBP-centric view of the triangulation between global change research, Earth observations and global assessments and policy.



In addition to cosponsorship from other global change programmes and increasing levels of collaboration with their various activities, several projects are broadened and strengthened by cosponsorship from the Scientific Committee on Oceanic Research (SCOR), the Commission on Atmospheric Chemistry and Global Pollution (CACGP) of the International Association of Meteorology and Atmospheric Sciences (IAMAS) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO. These arrangements are detailed under the individual project descriptions.

While Earth System science has made considerable contributions to raising the awareness of, and informing the debate onglobal change, it has been less influential on policies for sustainable development, particularly in less developed countries. IGBP will therefore work to increase the relevance of its research for sustainable development policy, and will increase its efforts to effectively communicate research results to the appropriate audiences.

ESSP provides a general framework for collaborative Earth System science and sustainable development policy guidance (see Box 12). IGBP will continue to fully participate in the development and evolution of ESSP, including working actively to refine and further develop ESSP projects. IGBP, where possible, will consolidate activities with ESSP partners, increasing the efficiency and effectiveness of research, and strengthening the structural links between the programmes.

In addition to working with research partners, IGBP recognises that progress in Earth System science will increasingly require integration of observations (especially spaced-based) and modelling. To this end IGBP will participate in the Group on Earth Observations (GEO), will remain a member of the Integrated Global Observing Strategy Partnership (IGOS-P), and will remain an associate of the Committee on Earth Observation Satellites (CEOS). The IGBP involvement in these initiatives has two primary purposes: firstly, to facilitate greater input by Earth System scientists to defining Earth observation requirements; secondly, to improve access to the resulting data by scientists. Participation in these groups is also a key element of the IGBP data management strategy (see *Data Management*).

Given the above-stated aim of contributing to the science that guides the societal determination of what constitutes dangerous interference with the Earth System, it is critical that IGBP increasingly engage with global environmental assessment processes and with policy makers. This completes the triangulation between global change research, Earth observations and global environmental assessments and policy (Figure 10). Through publications and working group participation IGBP will continue to contribute to the assessments of IPCC and MEA, and will increasingly work to communicate Earth System science to policy makers and resources managers (see *Communication and Outreach*).

IGBP Projects and Activities

The second phase of IGBP has been planned on the basis of the research and synthesis of the first phase. IGBP will continue to pursue focused, disciplinary research that contributes to Earth System understanding, but will also address over-arching questions that require a systemic approach. IGBP will combine research on Earth System components (atmosphere, land and ocean) with research on interface processes and research that integrates across these components and interfaces. This overall integration will underpin development of diagnostic and predictive capabilities for the Earth System. IGBP recognises that progress must be supported by theoretical and laboratory studies, *in situ* measurements, modelling and remote sensing, and hence will combine these approaches from the outset.

IGBP provides the Earth System science framework within which projects and activities are planned and integrated. This framework allows projects to develop their own scientific profiles, while simultaneously fostering systemic, integrative Earth System analyses. Integration and systems-level analysis are themselves important scientific activities, which require firm foundations in disciplinary science. The three primary modes of IGBP activity (described below) are IGBP projects, Fast-Track Initiatives (FTIs) and integration and synthesis.

The projects for the second phase of IGBP reflect the three major Earth System compartments (land, ocean and atmosphere), the interfaces between these compartments and system-level integration through time and space (Figure 11). This structure reflects the emphasis being placed on Earth System functioning and on processes within Earth System compartments.

A phased approach has been adopted to implementing this structure, with some projects continuing from the first phase of IGBP (although with new research agendas) and several new projects having beginning launched.

Figure 11. Scientific structure of IGBP projects.

A single atmosphere project – the International Global Atmospheric Chemistry (IGAC) project – continues from the first phase of IGBP. The new Global Land Project (GLP) builds on the two completed land-oriented projects of the first phase of IGBP: Global Change and Terrestrial Ecosystems (GCTE) and Land-Use and Cover Change (LUCC). Ocean research is conducted by the Global Ocean Ecosystem Dynamics (GLOBEC) project which was initiated in the first phase of IGBP and the new Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project, which builds on the successes of the Joint Global Ocean Flux Study (JGOFS) but has a much broader focus. In 2009 GLOBEC will conclude its work, leaving a single ocean project.

Two new interface projects have been initiated in the second phase of IGBP: the Surface Ocean–Lower Atmosphere Study (SOLAS) and the Integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS). The Land-Ocean Interactions in the Coastal Zone (LOICZ) interface project continues from the first phase with a much broader scope encompassing the coupled human-environment coastal system.

Past Global Changes (PAGES) continues its integrating palaeo research, providing an improved picture of past Earth System behaviour, and guiding assessments of future sustainability. Analysis, Integration and Modelling of the Earth System (AIMES) builds on the work of the earlier Global Analysis, Integration and Modelling (GAIM) task force, and spearheads modelling and other integrative activities of IGBP at the Earth System level.

All IGBP projects will be guided by individual Science Plans and Implementation Strategies developed by project research communities. Brief summaries of these are given in the sections below, starting with the underpinning work of PAGES, moving through the component and interface projects and concluding with the integrative work of AIMES.

The Past Global Changes (PAGES) project was founded in 1991 during the first phase of IGBP. It will play a similar role in the second phase of IGBP, albeit with refined research directions which focus more strongly on Earth System behaviour. At the time of writing, formal documentation of the PAGES science agenda was in preparation. The International Project Office (IPO) is based in Bern, Switzerland.

Rationale

The palaeo sciences have revolutionised the understanding of the Earth System, the central role of biogeochemical cycling and the history of abrupt climate changes on time scales and of amplitudes relevant for human societies. One of the most important roles of palaeo studies is to estimate the envelope of natural variability (including solar variability, Box 3) and the rate of environmental change to which human perturbations can be compared. Palaeo records also enable testing and refinement of Earth System models.

Oceans modulate the climate-environment system (for example, by varying the meridional transport of heat and by sequestering atmospheric carbon dioxide), and much has been learned about past ocean circulation, marine carbon cycling and other processes from various palaeo records. Nevertheless, many fundamental issues remain unresolved, including the role of marine biota and the carbonate system in past changes, and the palaeo hydrography and circulation of critical regions, such as the tropical oceans and the Southern Ocean. Similarly, past temperatures and carbon cycle variations (and the coupling of these) are increasingly well quantified and understood, but a more detailed understanding of natural (and anthropogenic) forcings and responses of climate system is needed to provide a sound context for global change.

Variations in the hydrological cycle are of considerable socio-economic importance. Reconstructions demonstrate the instability of the hydrological cycle during the Holocene, especially in low latitude regions where precipitation is controlled by monsoon systems, the position of the inter-tropical convergence, or inter-annual climate oscillations. As persistent droughts are among the most devastating hazards faced by society, there is an urgent need to understand the mechanisms of past regional climatic and hydrologic change.

Because humans have become an increasingly significant factor in the Earth System in the last few millennia, the synthesis of past environmental change studies with archaeological and historical evidence and documentary data provides insights on the role of humans in climatic and environmental change.

Key Questions

- What is the history of climate forcing factors and the sensitivity of the climate system to these forcings?
- What are the causes of natural greenhouse gas and aerosol variations?
- What was the precise sequence of past changes in forcings, surface climate and ecological systems?
- How have global climate and the Earth's natural environment changed in the past?
- What are the main modes of variability at orbital to sub-decadal time scales, and how do these relate to each other and to the mean state of the climate system?
- How have different parts of the Earth System interacted to produce feedbacks on regional and global scales?
- What are the causes and thresholds of rapid transitions between quasi-stable climatic and environmental states (particularly on time scales relevant to society), and how reversible are these changes?
- To what extent, and since when, has human activity modified climate and the global/regional environment?
- How can human-induced change be disentangled from natural responses to external forcing mechanisms and internal system dynamics?

Objectives and Structure

The objective of PAGES is to provide regional and global information on the past behaviour of the Earth System to enable assessment of its future sustainability, based on reconstruction, systemic analysis and modelling of past scenarios. The scope includes the physical climate system, biogeochemical cycles, environmental processes and human dimensions. To achieve its objective PAGES is organising its activities under the following four foci:

Focus 1: Past climate forcings. This focus aims to produce improved, extended and consistent time series of climate forcing parameters (natural and anthropogenic), including solar insolation and irradiance intensity (or luminosity), volcanic activity, land use, greenhouse gas and aerosol concentrations.

Focus 2: Reconstruction and modelling of regional climates and modes of variability. This focus will develop the understanding of past climate dynamics (climate modes, low-to-high latitude and longitudinal linkages, and global teleconnections) by comparison of reconstructions and model simulations. Activities will contribute towards a global coverage of high-resolution, well-dated reconstructions of past climate state parameters (temperature, precipitation, atmospheric pressure fields) and of past modes of climate variability based on natural archives and documentary data. The emphasis is on the last 2,000 years, but earlier periods are also considered.

Focus 3: Land-ocean-cryosphere dynamics and linkages. This focus includes activities that reconstruct and model abrupt changes and quantify the associated thresholds. Key issues include ocean circulation changes, droughts, ice sheet stability, land surface responses and processes, monsoon changes and dynamics, and permafrost changes.

Focus 4: Past human-climate-environment interactions. This focus addresses the long-term interactions between past climate, other environmental processes and human activities. It emphasises comparisons of regional-scale reconstructions of environmental and climatic processes (from natural archives, documentary and instrumental data) with evidence on past human activity (from historical and archaeological records). This focus promotes dynamic modelling to better understand

Box 3. Solar Variability and Holocene Climate

Solar forcing of the climate is unresolved. Eddy (1976) was among the first to postulate a link between widespread cooling and the low level of solar activity suggested by sunspot absence in the 17th century (the Maunder Minimum). Cosmogenic isotopes (e.g. ^{14}C and ^{10}Be) preserved in well-dated archives are the only proxy from times prior to observations of solar activity. Cosmogenic isotope production rates depend on the solar wind and the shielding of the Earth by its magnetic field.

Solar activity for the past 12,000 years has been inferred from atmospheric ^{14}C fluctuations determined from decadal tree-rings and tree-ring climate proxies during periods of high and low solar activity (Bond et al., 2001). Comparisons of ice-drift indices and ^{14}C and ^{10}Be production rate variations provide strong evidence for solar forcing of cooling events in the North Atlantic, with Holocene cooling events coincident with intervals of low solar activity.

To test the solar forcing hypothesis a time series of solar irradiance – scaled with respect to ^{14}C production changes (Bard et al., 2000; Crowley, 2000) – was created for the Holocene and input to a climate model of intermediate complexity (CLIMBER-2). Because the model shows no free decadal and centennial variability, results clearly show the response of the climate system to solar forcing. These include a linear, positive response of surface air temperatures in the North Atlantic (Figure 12a) and a negative response of North Atlantic overturning (Figure 12b).

Carbon and oxygen isotopes from tree rings have been analysed for periods of strong solar variation (e.g. 11,310–10,880 BP – German pine chronology, and 4,900–4,700 BP and 2,930–2,570 BP – German oak chronology). The information from ^{13}C and ^{18}O is complex, with strong variations due to physiological processes within the tree that are not directly related to climate forcing. However, the early Holocene record is striking because of dramatic drops in $\delta^{13}C$ and subsequent recoveries. Similar behaviour is observed for $\delta^{18}O$, although the variations do not correlate with those of $\delta^{13}C$.

Although many questions remain unanswered, analyses and modelling have provided strong support for solar forcing of decadal to multi-centennial aspects of the global climate.

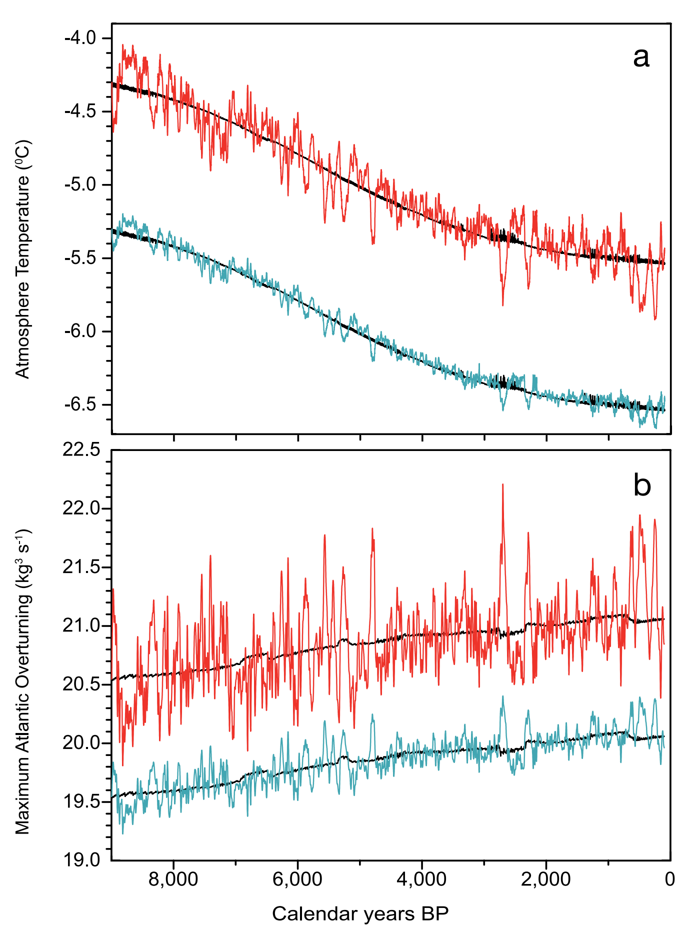


Figure 12. (a) Modelled North Atlantic surface air temperatures comparing control runs (black lines) to runs with irradiance changes based on calculated ^{14}C production rate changes. Blue line: 0.24% irradiance change between the Maunder minimum and the present. Red line (1°C offset): 0.65% irradiance change between the Maunder minimum and the present. (b) Modelled maximum of North Atlantic overturning comparing control runs (black lines) to runs with irradiance changes as above. Red line offset 1 km^3 s^{-1}. From Kromer et al. (2004).

processes of climate-human-environment interactions, to quantify the relative roles of different drivers in forcing change, and to provide integrated datasets for model comparison and verification.

In addition to the above foci PAGES has established four cross-cutting themes of relevance to all four foci and to palaeo science in general. Two of these are described below, and two which relate to research implementation are described in the following sub-section.

Theme 1: Chronostratigraphy. Chronology underlies most palaeo scientific research and often limits the strength of conclusions based on palaeo environmental reconstructions. This theme encourages activities that improve tools for absolute and relative dating, and encourages reference time scales and creative new approaches.

Theme 2: Proxy development, validation and calibration. This theme supports improvements in the precision and accuracy of palaeo environmental proxies as a basis for high quality records of past global change that complement instrumental and documentary data. Activities include efforts on proxy interpretation and development, analytical innovation, inter-laboratory comparisons and calibration refinement.

Research Approaches

PAGES promotes integrative research that is global in scope and based on temporally and spatially well-resolved data and model simulations. PAGES facilitates international collaborations and interdisciplinary science, especially between individuals involved in national programmes with overlapping interests. PAGES collaborates with other IGBP projects on palaeo biogeochemical and palaeo hydrological cycles, ocean-atmosphere circulation, sea-level changes, the role of the biosphere in the Earth System, the carbon cycle and palaeo hazards and recovery. The PAGES online databases and other web services help facilitate collaboration and coordinate international palaeo research.

PAGES facilitates workshops, symposia and conferences that unite scientists from different countries to share, compare and synthesise results. Effort will be put into strengthening national/regional sub-networks and integrating them into the international palaeo community. Efforts will also be made to involve scientists from developing countries and to enhance worldwide partnerships.

The third and fourth cross-cutting themes of PAGES address data management and communication activities as follows:

Theme 3: Data management. This theme promotes the availability of, and access to palaeo data, as well as the creative use of these data. The theme mediates between the scientific community and international data centres such as the World Data Centers and PANGAEA, as well as regional, topical and national databases.

Theme 4: Dissemination and outreach. PAGES is committed to communicating data products and their implications to policy makers and the public, and will continue to describe and promote palaeo research and associated activities on the PAGES website and in the PAGES newsletter. PAGES will continue to organise outreach activities.

The International Global Atmospheric Chemistry (IGAC) project was created in the late 1980s during the first phase of IGBP. It is jointly sponsored by CACGP of IAMAS. Its research agenda for the second phase of IGBP is documented in IGAC (2006) and its IPO is based at the Pacific Marine Environmental Laboratory of the National Oceanic and Atmospheric Administration in Seattle, United States.

Rationale

Atmospheric chemistry and composition help determine conditions in the biosphere. For example, atmospheric trace gases thermally insulate the biosphere and stratospheric ozone protects life from harmful levels of ultraviolet radiation. A suite of chemical reactions, many of them involving the hydroxyl radical, cleanse the atmosphere of pollutants and prevent pollutant accumulation to lethal levels. The atmosphere is also critical for transfers of materials and energy between the land and ocean.

Atmospheric chemistry and composition are changing rapidly. In addition to the recognised importance of increasing greenhouse gas concentrations, awareness of the role of aerosols is growing (Box 4). Aerosol production in the Northern Hemisphere in recent decades probably contributed to the severe droughts in the Sahel (Rotstyn and Lohmann, 2002), and aerosol-driven cooling over Europe and North America from the 1960s to the 1980s changed the latitudinal temperature differential between the North Atlantic region and the tropics and subtropics. This latter change affected atmospheric circulation and led to a shift in the positioning of the African monsoon, which led in turn, to a drying climate in the Sahel with severe environmental and human consequences.

Recognition of the role of reactive compounds in the climate system is also growing, however, the interactions are complex and remain poorly understood. Tropospheric ozone – which appears to have increased substantially over the last century – is a good example. Ozone is a greenhouse gas, but also affects climate because it is a powerful oxidant, undergoing chemical reactions that affect hydroxyl radical concentrations. Hydroxyl radicals, in turn, react with climatically important gases such as methane.

The formation of new particles – secondary organic aerosols – has been observed in a variety of locations (e.g. marine, coastal, forested regions and free troposphere) around the world (Kulmala et al., 2004). But only for the marine environment are the compounds and reaction schemes accounting for secondary aerosol formation sufficiently well understood to examine the effects on the Earth System. Formation and growth of new particles from various precursor gases, as well as heterogeneous modification of existing particles, are linked to the oxidation of a myriad of gaseous and particle phase organic compounds by atmospheric oxidants such as the hydroxyl radical, ozone, the nitrate radical and nitrogen oxides. Recent observations of aerosol particles in the upper troposphere (e.g. Ström et al., 1999; Lee et al., 2004) inspire further studies.

Apart from climate, changing atmospheric composition has other implications for Earth System functioning. One is the ability of the atmosphere to cleanse itself of a wide range of natural and anthropogenic emissions, via oxidation of the emissions, dissolution in water droplets and removal via precipitation. Decadal-scale estimates of hydroxyl radical concentrations suggest little change over the past 30–40 years (Prinn et al., 2001), but it is unknown whether this due to the inherent robustness of the atmospheric chemical system, or to opposing anthropogenic effects. Understanding the nature of this oxidising-cleansing system, especially its response to changing climatic and anthropogenic drivers, is essential.

The atmosphere transports energy, gases and particles over long distances. Airborne and satellite data have demonstrated that aerosols generated in eastern North America are transported to Western Europe and North Africa, pollutants from Europe are deposited in Asia, and dust storms generated in arid Asia are carried over the Pacific Ocean to the Rocky Mountains and beyond. Palaeo studies have also revealed long-range transport of aerosols, and thus regional air quality cannot be completely managed by regions themselves.

Box 4. The Effects of Aerosols on Climate

Aerosols affect the Earth's energy balance directly by scattering or absorbing incoming solar radiation, and indirectly by helping to determine cloud properties. In general, these effects act in opposition to the effects of greenhouse gases; that is, aerosols generally cool the Earth's surface. The effect is well-known in the case of sulphate aerosols. For other aerosols however, the situation is less straightforward. For example, carbonaceous particles produced from fossil fuel or biomass burning absorb both solar and infrared radiation, and can lead to warming at the surface, while the same combustion processes produce organic carbon particles which act to cool the Earth's surface.

The several indirect effects are complex, potentially more important than the direct radiative effects, and far less understood. One indirect effect is increases in cloud reflectivity due to increases in aerosol particle concentration (especially when starting in clean conditions). This effect causes "ship tracks" – clouds that form around the exhaust released by ships into the ocean air (Figure 13), and has been the focus of a number of large experimental campaigns.

Figure 13. Increases in cloud reflectivity due to aerosols emitted from ships forming "ship tracks" over the Atlantic Ocean off the east coast of the United States. Courtesy of NASA.

A second indirect aerosol effect is the influence on cloud and precipitation formation. Increased aerosol particle concentrations can sometimes suppress precipitation in marine clouds. Precipitation and cloud formation itself can be perturbed, as seen for example, in cloud suppression in forest fire plumes in the Amazon Basin (Andreae et al., 2004).

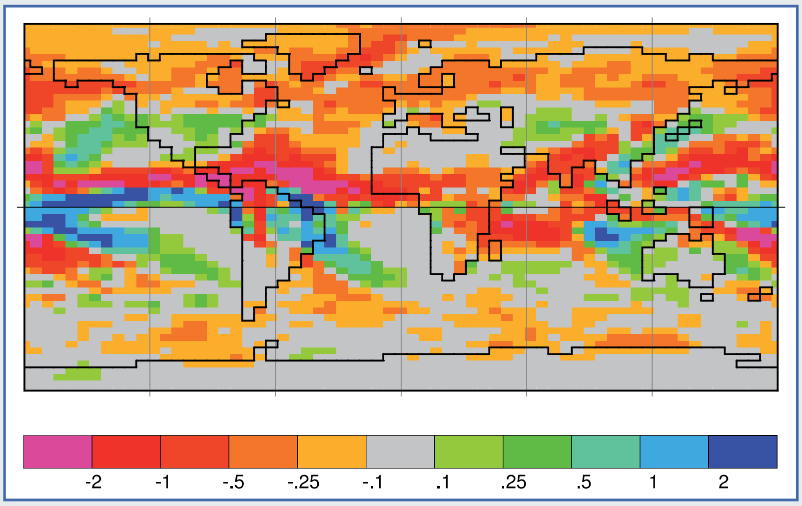


Figure 14. Modelled difference in annual mean precipitation (mm day^{-1}) between pre-industrial and current conditions due to aerosols. From Rotstayn and Lohmann (2002) with permission from the American Meteorological Society.

Modelling these effects – especially globally – is challenging. Cloud formation, cloud reflectivity and precipitation formation all depend directly or indirectly on cloud droplet number, which itself depends on aerosol particle number concentration and chemical composition. The few attempts at treating these effects in global models indicate that the potential effects can be large, both in terms of radiative effects (e.g. Ghan et al., 2001) and in terms of precipitation (Figure 14).

Human activities of the past two centuries have led to a much greater chemical burden for the atmosphere, even in remote areas. Key drivers are widespread industrialisation, growth in the transport sector, biomass burning and the expansion and intensification of agriculture (particularly fertiliser use).

Key Questions

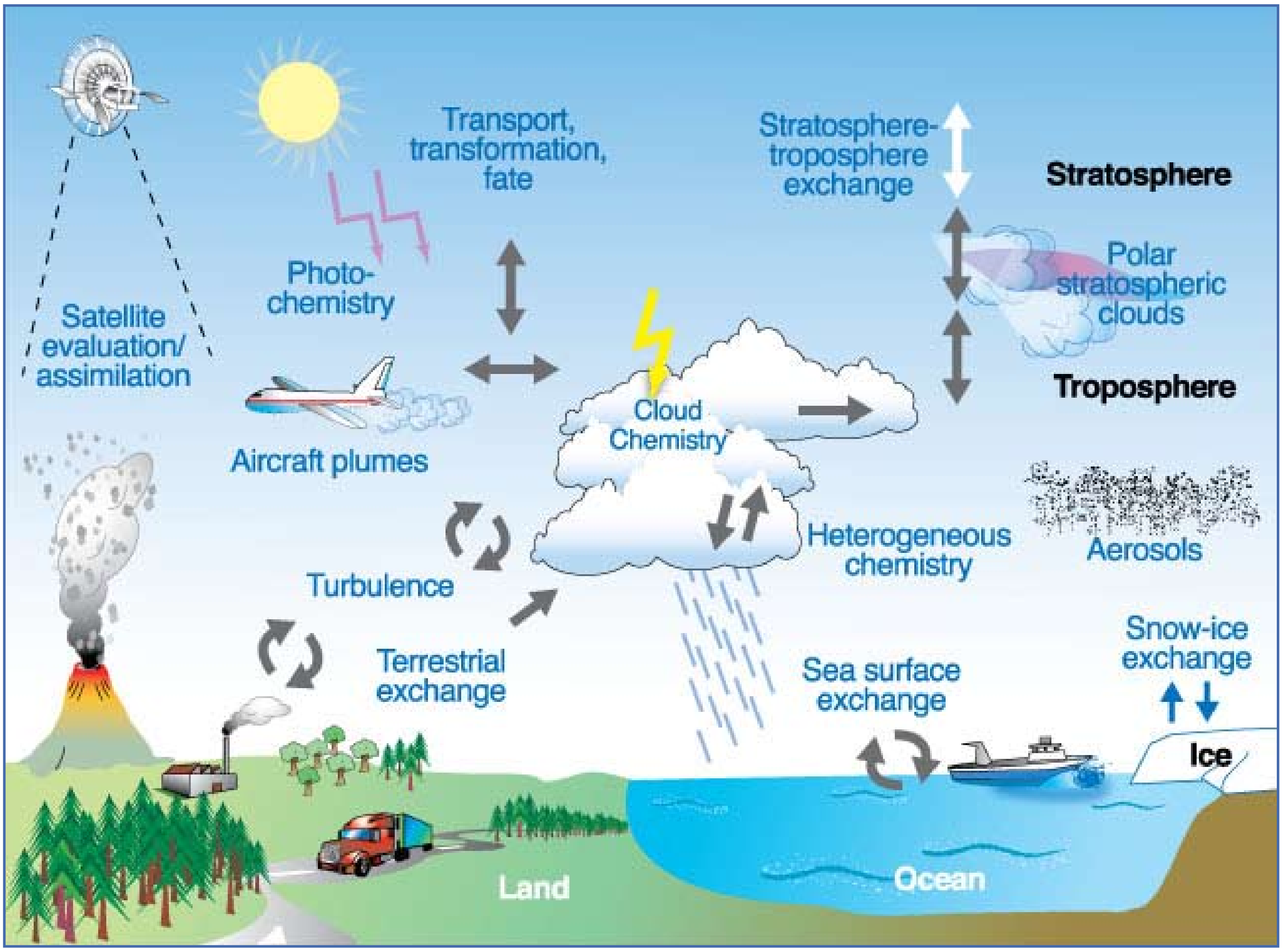
- How does atmospheric chemistry affect the radiative balance of the atmosphere and the physical climate system?
- What are the direct and indirect effects of aerosols on climate?
- How do emissions, long-range transport and chemical transformation of trace gases and aerosols affect surface air quality?
- How stable is the cleansing capacity of the atmosphere in the face of both direct human perturbations and changing climate?

Objectives and Structure

The objective of IGAC is to understand the role of atmospheric chemistry in the Earth System and to determine the effects of changing regional emissions and depositions, long-range transport and chemical transformations on air quality. To address this objective IGAC has developed a series of specific questions, organised as follows under two primary themes:

Theme 1: What is the role of atmospheric chemistry in amplifying or damping climate change? This primary question gives rise to four subsidiary questions: (i) what are the relative roles of stratosphere-troposphere exchange, anthropogenic and natural precursor emissions, and *in situ* photochemical processes in controlling ozone and its effects on climate change? (ii) what are the sources, sinks, distributions and properties of aerosol particles and their direct radiative effects on climate? (iii) what are the effects of aerosol particles on clouds, precipitation

Figure 15. The major atmospheric processes being investigated by IGAC.



and regional hydrological cycles? and (iv) how will changing emissions and depositions of gases and aerosol particles affect spatial patterns of climate forcing?

Theme 2: Within the Earth System, what effects do changing regional emissions and depositions, long-range transport and chemical transformations have on air quality and the chemical composition of the planetary boundary layer? This primary question gives rise to three subsidiary questions: (i) what are the export fluxes of oxidants, aerosol particles and their precursors from continents (e.g. mega-cities, biomass burning and desert dust) to the global atmosphere? (ii) what are the impacts of intercontinental transport on surface air quality? and (iii) how will human activities transform the cleansing capacity of the atmosphere?

Research Approaches

To address these questions, the atmospheric chemistry research community needs to (i) accurately determine global distributions of both short- and long-lived chemicals in the atmosphere and document their changing concentrations over time; (ii) provide a fundamental understanding of the processes that control the distributions of chemicals in the atmosphere and their impact on global change and air quality; and (iii) improve the ability to predict the chemical composition of the atmosphere over the coming decades by integrating understanding of atmospheric processes with the responses and feedbacks of the Earth System. The atmospheric processes being investigated by IGAC are illustrated in Figure 15.

A number of common research approaches are required for most of the above questions. Long-term measurements of atmospheric composition are being made using surface-based platforms and satellite remote sensing. The latter are advancing rapidly and promise a revolution in terms of the amount, consistency and coverage of data. Intensive, short-term field campaigns involving aircraft, ships and other platforms are another important tool that have the advantage of providing more detailed spatial coverage for regions of specific interest. Climate and Earth System models are now poised to incorporate atmospheric chemistry in a more complete fashion, providing further stimulus to the development of global atmospheric chemistry and transport models.

Within the broad field of global change research in atmospheric chemistry the role of IGAC is to focus on issues that require a global strategy. From a practical perspective, IGAC research is organised on a task basis, directed towards answering more specific questions that fall within the overall IGAC framework. A wide variety of tasks are being undertaken including: (i) international networks (e.g. for wet and dry deposition in the tropics, where consistency and comparability of measurements, quality assurance and central and long-term archiving are important); (ii) field campaigns (e.g. the Aerosol Characterisation Experiments of the 1990s, involving coordination of surface-based and aircraft measurements); (iii) coordination of measurements by commercial aircraft fitted with appropriate instrumentation to regularly sample the upper troposphere over long periods; (iv) model development and intercomparisons; and (v) short-term synthesis tasks where a specific question is addressed and a synthesis paper published within a 2–3 year period. Tasks are approved and periodically reviewed by the IGAC Scientific Steering Committee (SSC), have finite lifetimes, and aim to culminate in peer-reviewed journal publications.

The Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS) is an interface project initiated in the second phase of IGBP. The iLEAPS agenda is documented in iLEAPS (2005) and its IPO is based in the Department of Physical Sciences at the University of Helsinki, Finland.

Rationale

The transport and transformation of energy and matter across the land-atmosphere interface play major roles in controlling atmospheric composition. Processes in both the atmosphere and in terrestrial ecosystems drive transport and transformation, with biological processes playing an especially important role in terrestrial ecosystems. Rather than being a passive recipient of changes in atmosphere and climate, the terrestrial biosphere strongly influences the atmosphere and climate. Biota and their geophysical and geochemical environments have co-evolved, resulting in many complex feedbacks. Many of the linkages that connect the terrestrial biosphere to the atmosphere operate through the emission of a wide range of gases and particles at the land surface, their transport into the troposphere, subsequent chemical and physical reactions, and the implications of these processes for radiation transmission, precipitation and gaseous and particle deposition at the land surface. iLEAPS research emphasises the importance of connections, feedbacks and teleconnections between the numerous processes of the land-atmosphere interface.

Land use and land cover play a key role in emissions of gas-phase compounds, primary and secondary aerosol particle emissions, atmospheric composition and oxidative capacity, and a variety of deposition processes. Deforestation and desertification increase dust emissions, decrease the amount of carbon fixed by photosynthesis, and change atmospheric water vapour content due to changes in evaporation and transpiration. Deforestation and expansion of agriculture alter the amount and type of emissions from land to the atmosphere, thus affecting the concentrations of volatile organic compounds, nitrogen oxides and other compounds. This in turn influences the formation and concentrations of ozone, hydroxyl radical and nitrate radical – the key species determining atmospheric oxidation capacity, and hence the type, amount and lifetime of reaction products, and finally the nature of deposition. Through the hydrologic cycle, deforestation also influences the lower atmosphere, for example, affecting transfers of water vapour, energy and momentum that determine boundary layer height and cloud formation. Fire also generates aerosol particles and carbon, especially in boreal forests, grasslands, tropical savannas and woodlands. The radiative properties of the atmosphere are affected by emissions of gases and particles from the land surface, which in turn feed back on atmospheric processes and interactions (for example, photochemistry) and land surface processes (for example, photosynthesis). The radiation balance is affected by changes in albedo caused variations in glaciers and snow-ice cover.

Much of the terrestrial influence on the atmosphere operates through aerosol emissions that are transported into the troposphere, where as cloud condensation nuclei they influence climate in complex ways depending on their composition and size distribution (Glantz and Noone, 2000). A broad distribution tends to produce a broad cloud droplet size distribution, which tends to promote precipitation. However, other aerosol mechanisms tend to reduce precipitation, for example, when particles strongly absorb radiation leading to atmospheric heating and cloud evaporation, or when particle numbers increase, increasing droplet numbers but decreasing droplet radii, with fewer droplets coalescing into raindrops. Reducing the uncertainties surrounding these processes is a high priority, as they present major impediments to improved global and regional climate change predictions.

Feedbacks to terrestrial ecosystems operate primarily through the amounts of incoming radiation and precipitation. Greater cloud extent (due to vegetation-sourced aerosols) enhances diffuse radiation, and thus enhances photosynthesis and vegetation growth. Precipitation can also be positively influenced by vegetation due to emission of precursor compounds that contribute to formation of sufficient aerosol particles to maintain a low number of cloud condensation nuclei, and thus form clouds that are efficient in producing rain. It may be that terrestrial ecosystems have developed in synergy with the atmosphere,

Box 5. The Great Tropical Reactor

Because of the high levels of ultraviolet radiation and water vapour in the tropics, hydroxyl radical concentrations are highest here, and most of the oxidation of methane, carbon monoxide, and other trace gases occurs in the "Great Tropical Reactor" – the region of high hydroxyl concentrations in the tropical troposphere. This region is thus important not only in regulating climate, but also in maintaining the chemical composition of the atmosphere.

Under pristine conditions, the biosphere is the dominant source of both hydrocarbons and nitrogen oxides in the lower and mid-troposphere. The relative amounts emitted are such that nitrogen oxide concentrations are low, and consequently the troposphere is in a low-ozone state. In tropical rainforests this is achieved by a tight interaction of biological, chemical and physical processes, which allow efficient turnover of nitrogen but limit loss to the atmosphere. Nitrogen oxide is produced during breakdown of soil organic matter, and a fraction of this typically escapes into the air just above the soil. Here, it reacts with ozone to form nitrogen dioxide, which is efficiently deposited on plant surfaces in the forest canopy, and made available for plant growth. Only a small fraction of the nitrogen oxide emitted from the soil therefore escapes to the atmosphere to contribute to ozone formation (Figure 16a).

The conversion of rainforest to grasslands and croplands and the resulting removal of the tree canopy breaks open this tight recycling system for nitrogen oxides. Because of the short distance from the soil to the top of the grass canopy, there is little opportunity for oxidation of nitrogen oxide to nitrogen dioxide and the deposition of nitrogen dioxide on leaves. Biogenic hydrocarbon emissions are reduced because of the change from trees to grass or crops. However, biomass burning (deforestation and land management) and fossil fuel use in the developing tropics supply additional nitrogen oxides and hydrocarbons to the regional atmosphere. The consequence is a transition from the low-ozone state of the Great Tropical Reactor to a high-ozone photochemical smog (Figure 16b).

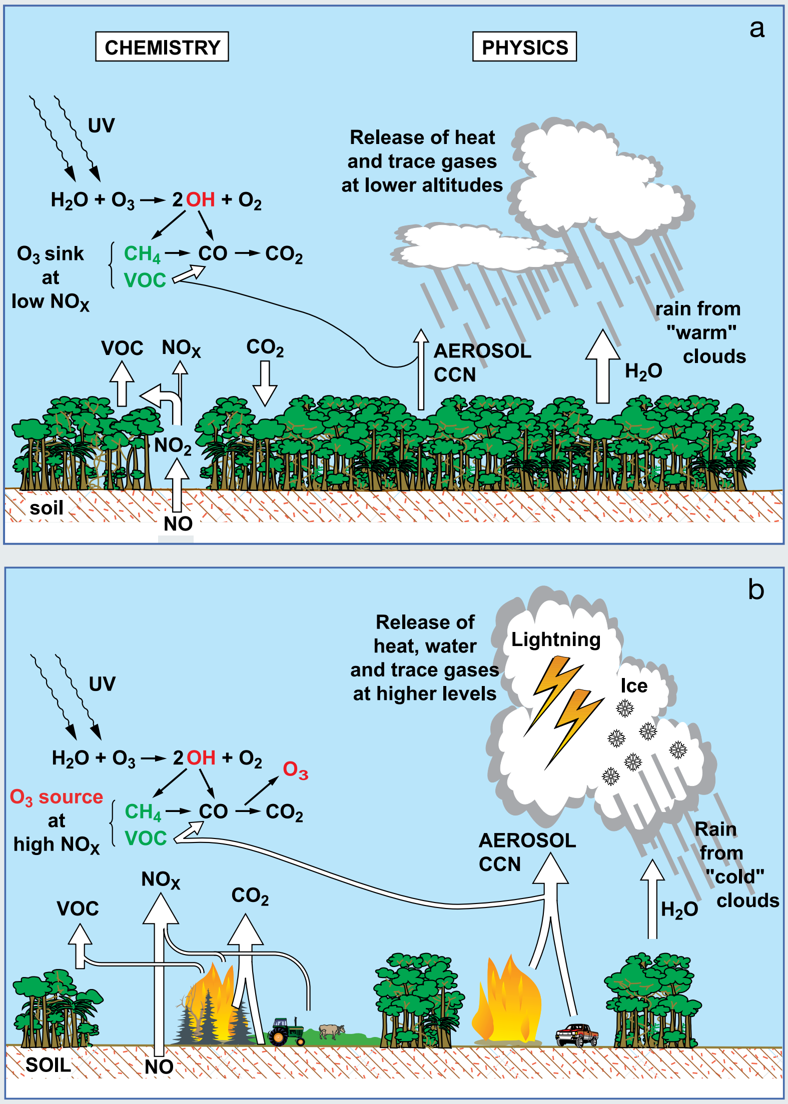


Figure 16. The Great Tropical Reactor – biosphere-atmosphere interactions for trace gases, aerosols and clouds over the tropics under (a) natural conditions, and (b) after deforestation and development. Courtesy of MO Andreae.

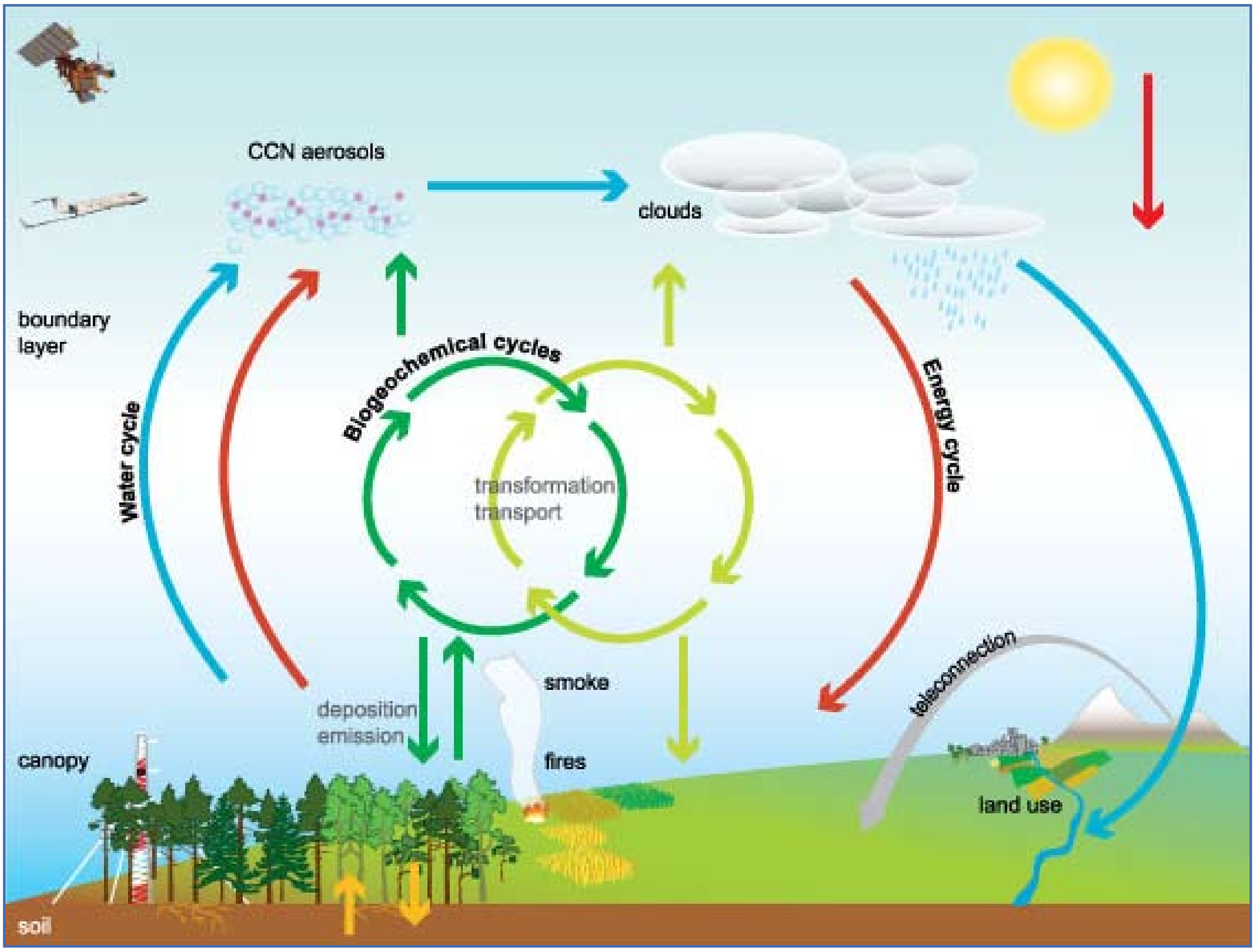
with aerosol particle concentrations and distribution regulated by the interplay of emissions, particle formation, transport and removal processes (Andreae et al., 2002).

Removal processes are important for system stability, for preventing gases from reaching toxic levels and for preventing aerosols from substantially reducing radiation or rainfall. Removal occurs through oxidation into water-soluble substances and subsequent precipitation. The process is not, however, unidirectional. The concentration of the oxidising hydroxyl radicals is dependent on complex reaction sequences, which in turn, partly depend on the nature and amount of emissions. Thus the cleansing efficiency is significantly influenced by strong feedbacks coupling the land to the atmosphere, and this emission-oxidation-deposition feedback is tightly linked to the vegetation-aerosol-cloud-climate feedback (Box 5).

Key Questions

- How tightly coupled are terrestrial ecosystems and the atmosphere through gas and particle emissions, transformations and deposition?
- To what extent does vegetation optimise its physical and chemical environment?
- What are the implications of land-atmosphere interactions for Earth System functioning?
- How are human activities influencing the land-atmosphere system?
- How well buffered is the land-atmosphere system?

Figure 17. iLEAPS science spans from molecular-scale measurements to global-scale modelling.



Objectives and Structure

The objectives of iLEAPS are to determine (i) how interacting physical, chemical and biological processes transport and transform energy, momentum and matter through the land-atmosphere system; (ii) the implications for the dynamics of the Earth System; (iii) the functioning of the land-atmosphere system in pre-industrial conditions and under the influence of human activities; and (iv) the extent to which vegetation determines its own physical and chemical environment on different temporal and spatial scales. To achieve these objectives iLEAPS is organising its research activities within the framework of the following four foci:

Focus 1: Land-atmosphere exchange of reactive and long-lived compounds: key interactions and feedbacks in the Earth System. This Focus has four sub-foci: (i) carbon dioxide; (ii) methane; (iii) volatile organic compounds; and (iv) nitrogen oxides.

Focus 2: Feedbacks between land biota, aerosols and atmospheric composition in the climate system. This Focus has two sub-foci: (i) biosphere-aerosol-cloud interactions; and (ii) surface-atmosphere exchanges and the self-cleansing mechanism of the atmosphere.

Focus 3: Feedbacks and teleconnections in the land surface-vegetation-water-atmosphere-system. This Focus has three sub-foci: (i) lateral hydrology-biogeochemistry connections; (ii) regional issues; and (iii) global issues.

Focus 4: Transfer of materials and energy in the soil–canopy–boundary-layer system: measuring and modelling. This Focus has six sub-foci: (i) development of sensors for turbulent flux measurements; (ii) measurements at tower-patch scale; (iii) non-conservative scalars; (iv) boundary-layer budget methods; (v) airborne measurements of fluxes and atmospheric composition; and (vi) remote sensing.

These four foci science span from the molecular level to global-scale integrating measurements and modelling (Figure 17).

Research Approaches

In most cases, iLEAPS research will be based around a combination of *in situ* measurements, process and case studies, satellite observations and modelling. Appropriate theoretical foundations and observational methodologies will be an important part of iLEAPS. The following principles will be applied to iLEAPS research: (i) multiple chemical species interactions and feedbacks, including energy and momentum, should be considered in each activity; (ii) research should foster process understanding at a broad range of scales, and should integrate measurements and modelling; (iii) measurements and modelling should be integrated from the outset; (iv) research should be driven by scientific questions of regional and global significance; (v) research should operate across traditional scientific and organisational boundaries; (vi) research should be international, open to participants from all countries and organisations, based on scientific contributions; and (vii) all activities should contain a capacity building component.

iLEAPS is adopting a task-oriented approach to defining its research. Tasks have clearly defined goals (e.g. peer-reviewed publications, methodological developments); are proposed, developed and implemented by individual scientists or scientific teams; and have finite lifetimes. Tasks are initially approved and periodically reviewed by the iLEAPS SSC. Tasks include field campaigns, modelling (tool development, validations, inter-comparisons), long-term integrated field studies, large international cross-disciplinary campaigns, synthesis studies, databases, conferences on specific scientific questions and synthesis meetings. Certain tasks, such as the development and maintenance of global networks (e.g. flux measuring sites) and of global databases (e.g. surface emissions, depositions) will be ongoing over the lifetime of iLEAPS. Regular open science conferences will be organised around the world to promote exchange of scientific results and ideas, and to support interaction amongst the community dealing with land-atmosphere issues.

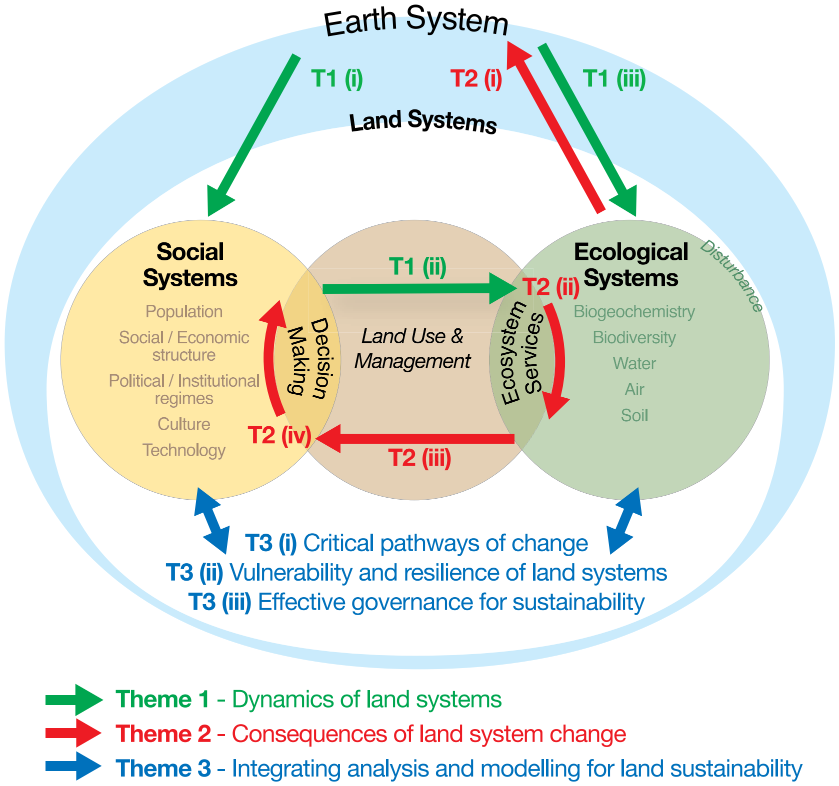
The Global Land Project (GLP) is a second phase IGBP project which builds on the two land oriented first phase projects: LUCC and GCTE. GLP is jointly sponsored by IHDP and its research agenda is documented in GLP (2005). At the time of writing an IPO had not been established.

Rationale

The extent of human impact on terrestrial systems has led to the emergence of land-change science – the linking of natural, social and geographical information sciences to study land surface changes and their consequences (Gutman et al., 2004). Land research in an Earth System context focuses on the coupled human-environment system (Turner et al., 2004). Furthermore, over the past decade the dominant paradigm for land research has shifted from one of homogeneity and equilibrium towards one of spatial and temporal heterogeneity, complex systems and nonlinear dynamics. The new paradigm considers global change as one of several interacting stresses (e.g. social and economic collapse, globalisation, episodic disturbances, land use shits) at various scales that cause cascading change in land systems, often with unforeseen system-level consequences. The feedbacks from land change are equally complex, with implications for ecosystem services, economic outputs and Earth System function. This new paradigm underpins the analytic structure of GLP (Figure 18).

Global environmental change affects the coupled human-environment system differently in different regions of the world. Responses to biophysical changes and social forces differ between the Northern and Southern Hemispheres, between urban and rural environments, and between developed and developing countries. These in turn, influence local land use decisions and ecosystem service provision. The resulting environmental changes can either increase or decrease the rate of environmental change. Links between decision making, ecosystem services and global change define important cross-scale feedback pathways in the coupled human-environment system.

Figure 18. The analytical structure of GLP, indicating the links and feedbacks between human and environment subsystems and across scales to the Earth System.



At present, and for the next several decades, land use change will continue to be an important driver of change in terrestrial ecosystems. Semi-arid and arid lands are extremely vulnerable to land use changes due to climate variability and water availability. In addition, the people of these regions are highly dependent on land productivity for livestock and crops. Tropical deforestation is a primary component of global change and is likely to continue into the foreseeable future. The knowledge base on the rates and patterns of deforestation, and importantly, on the socio-economic factors that drive deforestation and its feedbacks through the coupled human-environmental system, has improved enormously in recent years. Different combinations of proximate causes and underlying drivers occur in different geographical and historical contexts, with specific regions showing a surprising level of coherence in cause-driver patterns. A major challenge is to integrate the work on causes and drivers with studies of rates and patterns of change, to produce robust models of land use change for interpretion and projection studies.

Land system change alters biogeochemical cycling, with complex responses in the coupled human-environment system. For example, human activities now fix more nitrogen directly and indirectly than is fixed naturally in all terrestrial ecosystems (Box 2). Most of the extra nitrogen is added as synthetic agricultural fertiliser, however, much of this is lost to the atmosphere or rivers, or accumulates in soils with global-scale consequences. Desertification due to climate and land use change is altering material exchanges in dust aerosols and key nutrients. Land systems in the high latitudes are being affected by climate changes resulting in permafrost thaw that affects biogeochemical and hydrological fluxes. These changes are not only affecting biogeochemistry, but also the coupled social-environmental system as evidenced by changes in policies, institutions, vegetation dynamics and delivery and maintenance of ecosystem services. Research into the terrestrial phases of these cycles and their implications for the coupled human-environment system is needed.

Coupled human-environment system changes have impacted terrestrial biodiversity for millennia, but in the past century the extent of change has lead to extinctions that rival the five major global extinction events in the Earth's history. The implications for ecosystems and indeed Earth System function, are poorly known. For example, it is unknown whether general relationships exist between biological diversity and ecosystem processes and mechanisms. The first generation of biodiversity-ecosystem experimentation suggests that increasing numbers of species lead to asymptotic increases in plant biomass. This research is however, in its infancy, and it is rarely known *a priori* which species are critical for which ecosystem functions, or which are resilient or resistant to environmental change. A key issue is how much and which types of biological complexity are required to maintain Earth System functioning within limits acceptable for human society.

Land system dynamics are strongly affected by both natural and anthropogenic disturbances that alter the structure of the physical environment and the distribution of organisms. The magnitudes and frequencies of natural disturbances (e.g. fire (Box 6), permafrost thaw, storms and insect attacks) appear to be changing due to climate change, whilst anthropogenic disturbances (e.g. resource extraction and land use change) are also increasing. The interactions of these disturbances can be synergistic, with significant consequences for ecosystem services (locally and regionally) and Earth System functioning.

Overall, there is a need for improved understanding of how human actions affect natural processes in the terrestrial biosphere, and an even greater need to evaluate the consequences of these changes for humans. This must include process-level biogeochemistry, but also studies of a wide range of land systems (from near-natural reserves through managed production systems to urban ecosystems) and studies of the interaction of land change with climate change.

Key Questions

- What are the causes of land system changes and what is the role of global change in these changes?
- What are the consequences of land system changes for ecosystem services?
- What are the feedbacks to Earth System functioning, especially biogeochemical cycling?
- How vulnerable are land systems to global change and how can their resilience be enhanced?
- What are the thresholds, abrupt changes and emergent properties that may be exhibited by changing land systems?

Box 6. Fire – A Coupled Human-Environment Disturbance

Fire is critical for two important feedbacks in the Earth System. Firstly, fire regimes are linked to atmospheric and climate dynamics, and secondly, fire regimes affect ecosystem services and thereby impact on human systems, where institutions may influence feedbacks to fire regimes themselves. Quantifying the consequences of changed fire regimes for Earth System dynamics requires considering all these feedbacks to land cover.

It is well known that fire is a key determinant of land cover. Furthermore, palaeo ecological evidence and models of the future show that during periods of rapid climate change, fire can accelerate vegetation change and may in fact trigger this change much faster than the direct effects of climate change on vegetation.

Biomass burning contributes significantly to greenhouse gas and pollutant emissions, and the magnitude of the associated carbon flux can determine whether a region is a carbon source or sink. For instance, the net carbon sink calculated for the United States may result from the suppression of fire, whilst in Canada recently there has been a net carbon loss due to widespread fires. Biogenic emissions and trace gas production from fire also alter atmospheric chemistry and climate more directly, smoke aerosols impact regional and probably global radiation budgets, and in the longer term, fires can alter regional climate by modifying ecosystem properties such as albedo, temperature and hydrology.

Fire regimes also shape and modify the structure and functioning of terrestrial ecosystems, so as to affect biodiversity, primary productivity, soil nutrient dynamics and catchment runoff. In turn, these have significant economic impacts via changes in production of food and fibre, carbon sequestration, maintenance of soil fertility, provision of clean water, regulation of atmospheric quality and climate, and aesthetic or spiritual values of biodiversity.

Finally, fire as a natural disturbance is greatly affected by changes in anthropogenic disturbance regimes. For example, where clearing for agriculture fragments the original vegetation, fire frequencies in residual natural landscape pockets are often suppressed, leading to a loss of fire-dependent species. In contrast, forest areas near cities may be managed to suppress fire for the sake of amenity values, such that when a fire does occur it has a particularly destructive impact (Figure 19). In these cases, human institutions such as regional farmer groups and forest management agencies have an intimate impact on how fire affects the biosphere.

Figure 19. Pine forest in eastern Oregon, two years after the catastrophic fires of 2002. The intensity of these fires was in part due to 100 years of fire suppression, leading to greater emissions and land cover impacts than would otherwise have occurred. The fires resulted in a loss of ecosystems services such as timber production, and a re-appraisal of the managing institutions, thus completing several feedback loops. Courtesy of K Hibbard.

Objectives and Structure

The objectives of GLP are to (i) identify the agents, structures and nature of change in coupled terrestrial human-environment systems and quantify their effects on the coupled system; (ii) assess how the provision of ecosystem services is affected by these changes; and (iii) identify the character and dynamics of vulnerable and sustainable coupled human-environment land systems to interacting perturbations, including climate change.

To meet these objectives GLP is organising its research into the three themes described below. The key issues of linking human and environmental domains, understanding decision making and management, handling cross-scale issues and seeking syndromes, are threads throughout these themes that will be addressed using comparative case studies, learning from the past and integrated model development.

Theme 1: Dynamics of land systems. This theme addresses three issues: (i) how do globalisation and population change affect regional and local land use decisions and practices? (ii) how do changes in land management decisions and practices affect biogeochemistry, biodiversity, biophysical properties and disturbance regimes of terrestrial and freshwater aquatic ecosystems? and (iii) how do the atmospheric, biogeochemical and biophysical dimensions of global change affect ecosystem structure and function?

Theme 2: Consequences of land system change. This theme addresses four issues: (i) what are the critical feedbacks to the coupled Earth System from ecosystem changes? (ii) how do changes in ecosystem structure and functioning affect the delivery of ecosystem services? (iii) how are ecosystem services linked to human well-being? and (iv) how do people respond at various scales and in different contexts to changes in ecosystem service provision?

Theme 3: Integrating analysis and modelling for land sustainability. This theme addresses three issues: (i) what are the critical pathways of change in land systems? (ii) how do the vulnerability and resilience of land systems to hazards and disturbances vary in response to changes in human-environment interactions? and (iii) which institutions enhance decision making and governance for the sustainability of land systems?

Research Approaches

GLP has a strong legacy (existing networks and ongoing research which emerged from GCTE and LUCC) on which implementation will be based. In addition, coordinated or joint activities will be developed with AIMES, PAGES, iLEAPS, LOICZ, ESSP projects (GECAFS, GCP and GWSP) and activities within DIVERSITAS and IHDP.

GLP employs working groups and networks of researchers in the implementation of its science plan. The guiding principles are that studies should (i) be place-based; (ii) use interdisciplinary teams; (iii) be cognisant of the need to scale up, down and across disciplines; and (iv) define the relationship of the research to the broader coupled human-environment framework.

Research activities include case studies, experimental studies, comparative studies, coordinated regional studies, and land use meta-analyses. Networks of experimental and case studies are employed across land system gradients, and both long-term observations and integrated regional studies are promoted. GLP develops process models (e.g. vegetation-ecosystem, agro-ecosystem, agent-based), integrated analytical tools (including field techniques) and decision-making models. Effort is being put into interdisciplinary database development and archival systems.

The Land-Ocean Interactions in the Coastal Zone (LOICZ) project was initiated in 1993 during the first phase of IGBP. For the second phase of IGBP the research agenda of LOICZ has been broadened with a comprehensive inclusion of human dimensions and joint sponsorship from IHDP. The project research agenda is documented in LOICZ (2005) and the IPO is based at the Institute for Coastal Research at the GKSS Research Centre in Geesthacht, Germany.

Rationale

Coastal zones (excluding Antarctica) occupy less than one fifth of the global land area (Shi and Singh, 2003) yet accommodate over half the global population. There are virtually no long coastal stretches without significant human influence outside of Greenland, northern Canada, Siberia and remote areas of South America and Australia. About half of all mangrove ecosystems have been converted to other uses and close to 30% of coastal land (excluding Antarctica) is classified as altered or semi-altered, with much of the rest significantly influenced by human activities.

The marine and terrestrial biospheres are connected by rivers which transport nutrients essential for marine ecosystems. Many anthropogenic impacts in the coastal zone originate far upstream, where land use and cover change (including urbanisation and sewage disposal) alter the timing, flux and dispersal of water, sediments, nutrients and contaminants (Figure 20). In many catchments increased soil erosion (driven by agriculture, forestry and urban development) has increased sediment delivery to the coastal zone, however, in other catchments sediment trapping in dams has decreased sediment delivery. For dissolved compounds the story is simpler; for example, riverine nitrogen delivery has increased sharply since 1950 and is predicted to continue to increase at least until 2020. Increased nutrient delivery also occurs through atmospheric deposition of agricultural, industrial and transport emissions of nitrogen oxides. Physical changes within the coastal zone – due to dredging, land reclamation, port facilities and other engineering – affect biogeochemical cycling through changes in flow patterns and sedimentation. Understanding biogeochemical cycling of coastal seas is critical for understanding global biogeochemistry (Box 7).

Human activities in the coastal zone and in river basins can affect the biogeochemistry of continental shelf seas. For example, the Three Gorges Dam in China is expected to have significant effects on the productivity and hence carbon sink strength of the South China Sea (Chen, 2002). Most of the nutrients driving the high productivity of the South China Sea come from coastal upwelling not riverine inputs, but the Three Gorges Dam will significantly reduce water efflux to the Sea, thereby reducing the buoyancy effect and consequently decreasing upwelling.

Like the land, the coastal zone is best considered as a coupled human-environment system that provides ecosystem goods and services under growing local and global pressures. Global change will become an increasingly important driver of coastal zone change, and understanding altered coastal zone biogeochemistry – in the context of Earth System changes (e.g. climate change and sea-level rise) and changing local pressures – is essential for improved integrated coastal management.

Key Questions

- What are the magnitude and variability of terrestrial material delivery to the coastal zone?
- How is biogeochemical cycling changing within coastal seas?
- What is the fate of terrestrial and atmospheric materials in continental shelf seas?
- What are the implications of these changes for Earth System function?
- How can knowledge of changing coastal biogeochemistry improve resource management and sustainability?

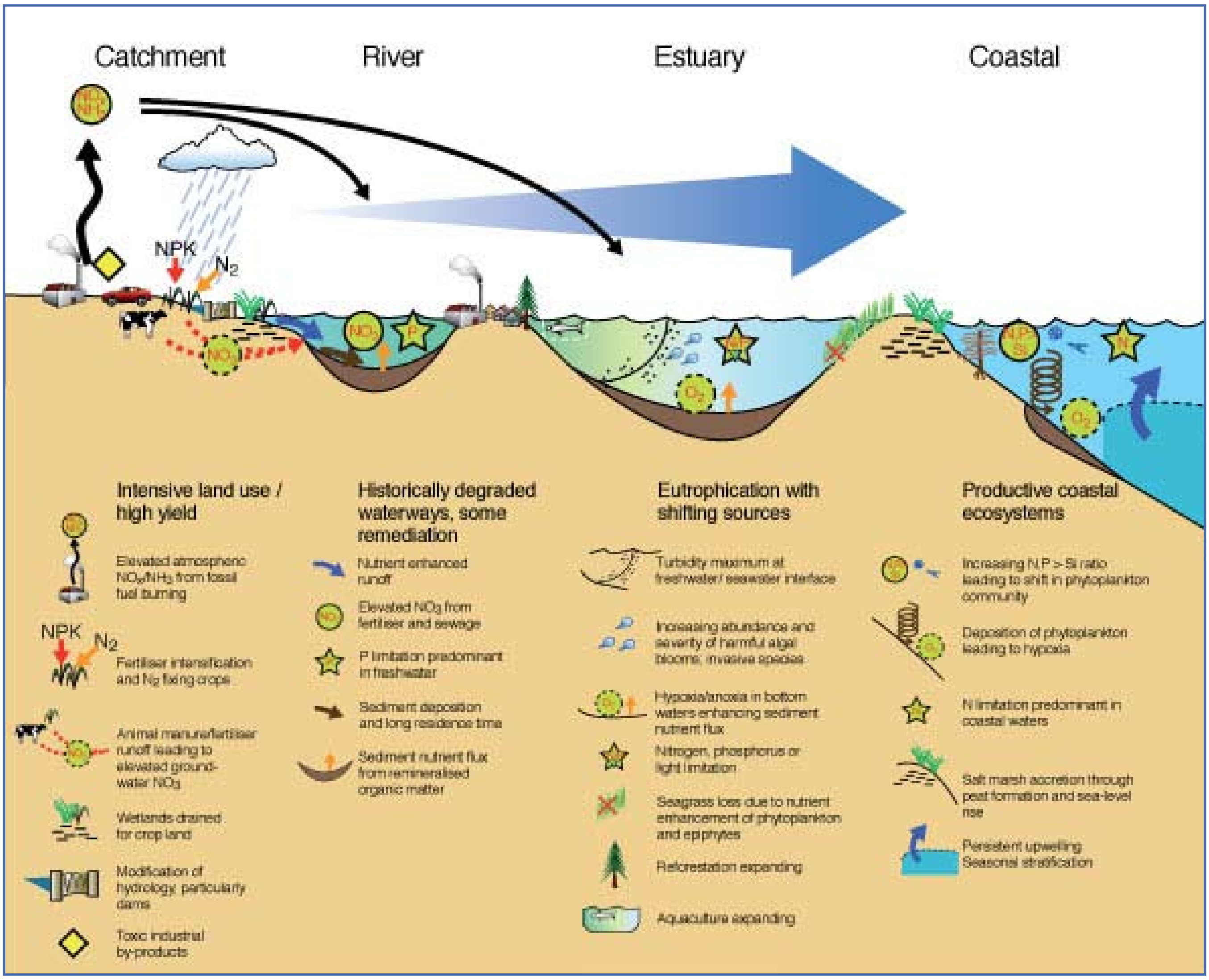
Objectives and Structure

The objective of LOICZ is to provide the knowledge, understanding and prediction needed to allow coastal communities to assess, anticipate and respond to the interaction of global change and local pressures in determining coastal change. To meet this objective LOICZ is organising its research around the following five themes:

Theme 1: Vulnerability of coastal systems and hazards to human societies. This theme sets the stage for the subsequent themes which address the wider coastal domain. It considers the hazards to humans from coupled human-ecosystem change, carrying capacities and vulnerability issues, including the risk of degrading the sustainability of coastal goods and services. Key issues include (i) the effect of non-linearities and uncertainties on vulnerability of coastal societies and ecosystems to global change hazards; (ii) the community's stakes in the coastal zone including resources, goods and services; and (iii) external and internal factors of human and coastal vulnerability.

Theme 2: Implications of global change for coastal ecosystems and sustainable development. This theme focuses on conflicting spatial, temporal and organisational issues of coastal change, land and sea use, and how these exert pressures on coastal systems and influence natural resource availability and sustainability. Key issues include (i) characterising the nature and location of coastal environmental and social systems and their tapestry of interactions; (ii) assessing system sensitivity and robustness to reveal critical thresholds for changes to biogeochemical and/or hydrological cycles that cause permanent state changes; (iii) quantifying human impacts on coastal areas through natural science methods

Figure 20. Major processes and conditions affecting the biogeochemical fluxes in temperate coastal environments. Courtesy of W Dennison.



Box 7. Biogeochemical Budgets of the Coastal Zone

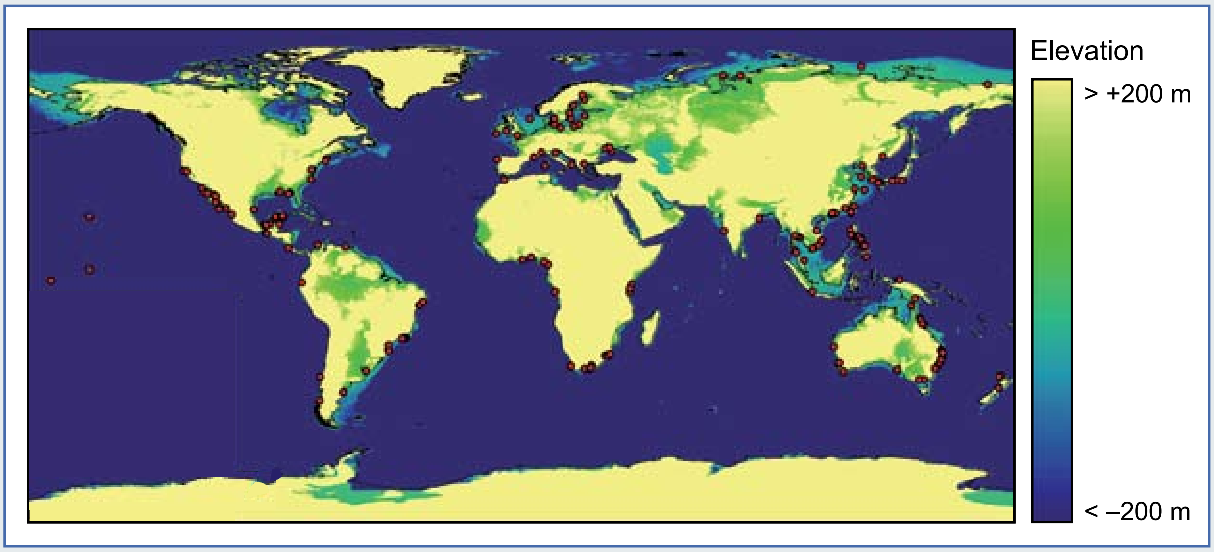
Material fluxes to and from the coastal ocean are largely lateral inputs from land and exchanges with the open ocean. The coastal ocean, to a nominal shelf-edge depth of 200 m, has an average width of about 25 km along a coastline of about 10^6 km (at 1 km resolution). Its characteristics are not well described in global ocean data sets, which are typically at 50 km grid resolution or coarser. Furthermore, coastal zones are very heterogeneous, largely because of heterogeneity of morphology, runoff distribution and population density.

Two approaches have been adopted for biogeochemical studies of coastal zones. Firstly, a simple material budgeting procedure has been developed for specific coastal sites – largely bays and estuaries. To date, about 200 sites have been assessed. Secondly, a coastal typology has been developed at 0.5 degree resolution.

The budgeting procedure uses water and salt budgets to describe delivery of freshwater from land and exchanges between the site of interest and adjacent marine waters. Material fluxes (particularly dissolved inorganic phosphorus and nitrogen; DIP, DIN) are estimated on the basis of the water fluxes. Deviations of DIP and DIN fluxes with respect to water and salt exchange are attributed to net uptake or release within the system. The non-conservative behaviour of DIP is attributed to net organic carbon metabolism, while non-conservative behaviour of DIN includes both organic carbon metabolism and transfers to and from nitrogen gas (i.e. fixation and denitrification). Results suggest that small, rapidly exchanging systems are generally more variable and more biogeochemically active than large shelf seas.

Budgeting is only possible for sites for which adequate data exist (Figure 21). The coastal typology (using environmental data and techniques such as geospatial clustering) allows budget results to be extrapolated. Budgeted sites serve as representatives for particular coastal zone types, and their results are up-scaled to similar but data-poor regions. This approach has been successful in terrestrial parts of the coastal zone, as high-resolution global datasets are available to describe the system and critical forcings. However, the lower resolution of most available marine datasets has limited the success of upscaling the coastal ocean. A promising avenue is the development of higher resolution coastal grids together with GIS analyses and typological comparisons to populate grid cells with derived data.

Figure 21. Global coastal zone and location of LOICZ budget sites (red dots). Courtesy of S Smith and R Buddemeier.



and ecological-economic indicators; (iv) identifying options to design and manage system robustness, through a scenario approach that considers critical thresholds and sustainability; and (v) evaluating the effects of changing inputs on ecosystem health and coastal zone goods and services, including the links between biological functioning, geochemistry and human drivers.

Theme 3: Human influences on river basin–coastal zone interactions. This theme considers river basin drivers and pressures that influence and change the coastal domain. The entire water continuum is considered as a single system. Processes of material transport to the ocean and human influences due to activities in the exclusive economic zone are considered through links to Themes 2 and 4. Key issues include (i) disentangling the cause-effect relationships of those impacts and human activities which are strictly coast or river basin oriented (regional) from those which result from wider external pressures on the river-coast system; (ii) modelling coupled human-ecosystems in river basins using the Driver-Pressure-State-Impact-Response assessment framework in order to identify links between major anthropogenic and natural pressures in catchments that affect coastal ecosystems; (iii) developing scenarios of future coastal change due to land use, climate change and management options; and (iv) evaluating societal and institutional dimensions and changes in order to establish basin-coast linkages.

Theme 4: Biogeochemical cycles of coastal and shelf waters. This theme focuses on the cycling of carbon, nutrients and sediments in coastal and shelf waters, and their exchange with the ocean. This recognises the vital and changing benthic processes that influence shelf ecosystems and global chemical cycles. Key issues include (i) quantifying material transport within and across the continental shelf, transformation of materials within the water column and sediments, storage of materials in the coastal zone and air-sea exchange; (ii) assessing regional differences and understanding why some shelf waters are more resilient or resistant to change than others; (iii) defining the terrestrial boundary condition for nutrient fluxes by better integration of river basin information including sediment dynamics and organic inputs; and (iv) developing regional budgets and flux estimates for shelf and coastal waters in order to understand and predict the impacts of global and basin-scale changes in ocean climate and biogeochemical cycles.

Theme 5: Towards coastal system sustainability by managing land-ocean interactions. This theme integrates across the other four themes and provides a platform for considering coastal zone development and management (including resource users) in the context of "strong" and "weak" sustainability options. Key issues include (i) considering how temporal and spatial scales, including those of institutional dimensions, affect scientific and management perspectives of coastal change; (ii) classifying and comparing different settings of drivers-pressures in coastal system state interactions and existing responses using typologies; (iii) linking natural, economic and human dimension sciences into "futures" scenarios; and (iv) developing management response options and participation derived from "futures" scenarios, developed and assessed in collaboration with relevant policy, management and investment communities.

Research Approaches

LOICZ engages in global change science that derives new knowledge and understanding and make its results and outputs available to the wider scientific community. LOICZ also strives to facilitate the adoption and application of its scientific outcomes within policy and management realms. Major coastal change issues drive the science, and outcomes inform management of land-ocean interactions in order to reduce vulnerability of human activities in coastal regions and enhance opportunities for sustainable development. In seeking to provide improved scientific information for advanced Earth System analysis and modelling, and better science for better management, LOICZ uses an "adaptive" science approach that recognises short-term information needs.

Ocean research in the second phase of IGBP is initially being undertaken jointly by the Global Ocean Ecosystem Dynamics (GLOBEC) and Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) projects. GLOBEC will conclude in 2009, and hence from 2010 there will be a single ocean project. GLOBEC was originally established in 1991 by SCOR and by IOC of UNESCO. IGBP became a cosponsor of GLOBEC in 1995. The research agenda of GLOBEC is documented in GLOBEC (1997) with a separate implementation plan (GLOBEC, 1999). These documents will continue to guide GLOBEC activities during the second phase of IGBP. The GLOBEC IPO is based at the Plymouth Marine Laboratory in Plymouth, United Kingdom. IMBER is a project of the second phase of IGBP and is cosponsored by SCOR. The IMBER research agenda is documented in IMBER (2005) and the IPO is based at the European Institute of Marine Studies, Technopôle Brest-Iroise in Plouzané, France.

Rationale

The ocean is the most extensive and least-known part of the biosphere; it can buffer or amplify physical and chemical signals from atmosphere and land. For example, in the past relatively small changes in freshwater input have interrupted the thermohaline circulation in the North Atlantic Ocean causing abrupt climate shifts, and linear stochastic physical fluctuations are known to cause non-linear biological responses and regime shifts (Hsieh et al. 2005). The ocean storage of heat and gases and the fluxes of these within the ocean and between the ocean and atmosphere exert major controls on climate. Palaeo records show that oceanic processes link the dynamics of atmospheric carbon dioxide to those of dust-borne iron fluxes to the ocean – one of several poorly understood Earth System feedbacks.

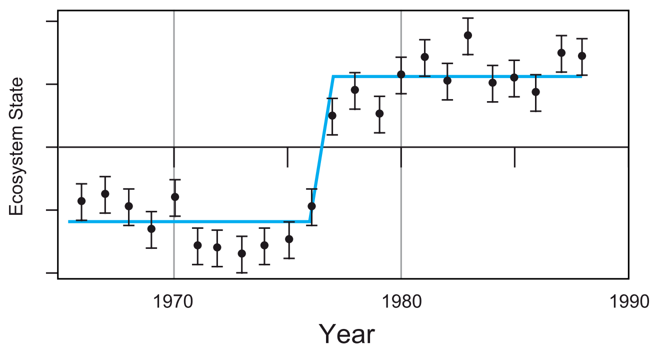
The ocean contains by far the largest pool of active carbon in the Earth System. Uptake by, release from, and storage of carbon in the ocean are controlled by interacting physical, chemical and biological processes. The largest carbon sinks occur in areas where physical, chemical and biological processes work in concert, such as the North Atlantic.

The biological processes of the marine carbon cycle are now reasonably well studied; for example, the so-called biological pump (Box 8) is well understood, particularly its operation in the surface ocean layer. Nonetheless, the fate of carbon in the deeper ocean requires further investigation. Recently, attention has begun to focus on the implications of changing surface ocean acidity caused by increasing oceanic uptake of atmospheric carbon dioxide. Increased acidity affects marine ecosystems in many ways, including decreasing the ability of coral organisms to form calcium carbonate shells (Box 9).

The marine biogeochemistry of other elements – particularly over longer time scales – has received little attention, and the biological processes affecting the structure and functioning of marine food webs are poorly studied. Biogeochemical and ecosystem regime shifts have been observed (e.g. Figure 22; Folke et al., 2004), but the causes and consequences remain largely unknown. Documenting and modelling such changes are important for understanding the role of the ocean in the Earth System.

Remarkable advances have been achieved with coupled physical-biological ocean models, but these cannot yet adequately address key ecological questions or issues of material sources and sinks. Positive and negative feedbacks between Earth System components are particularly important, as are abrupt changes in ecosystem dynamics. Feedbacks and abrupt changes can be seen in palaeo records (e.g. Baumgartner et al., 1992) and emerge from models, but are impossible to identify from short-term measurements.

Figure 22. Sharp and synchronous change in "ecosystem state" (composite of over one hundred biological and environmental variables) in the North Pacific Ocean. Adapted from Hare and Mantua (2000) with permission from Elsevier.



Marine ecosystems experience non-linear changes in food web structure and composition due to atmospheric forcing and related changes in ocean circulation (Hare and Mantua, 2000; Beaugrand, 2004). These changes however, are not well understood and cannot yet be predicted. In addition, human activities are having increasing impacts on ocean ecosystems and biogeochemistry, due to fishing pressure, material transport through the coastal zone and climate change.

Ocean fisheries provide 16% of the animal protein in the global human diet (FAO, 2004), harvesting the equivalent of 8% of oceanic primary production, biased towards upwelling and continental shelf areas (Ryther, 1969). About 52% of the major marine fish stocks are fully exploited, 17% are overexploited and 7% are depleted or are recovering from depletion (FAO, 2005). Commercial fisheries also affect non-target species populations, with discarded bycatch being equivalent (by weight) to 8% of the total marine fisheries production (FAO, 2004).

Fish population dynamics are however, a complex interaction of fisheries impacts and longer-term productivity cycles related to environmental conditions, particularly climate (Lehodey et al., 2006). These interactions are poorly understood, as are marine food web dynamics in response to external forcing. It is unclear whether upper trophic level changes significantly affect ocean biogeochemistry.

Box 8. The Marine Carbon Cycle

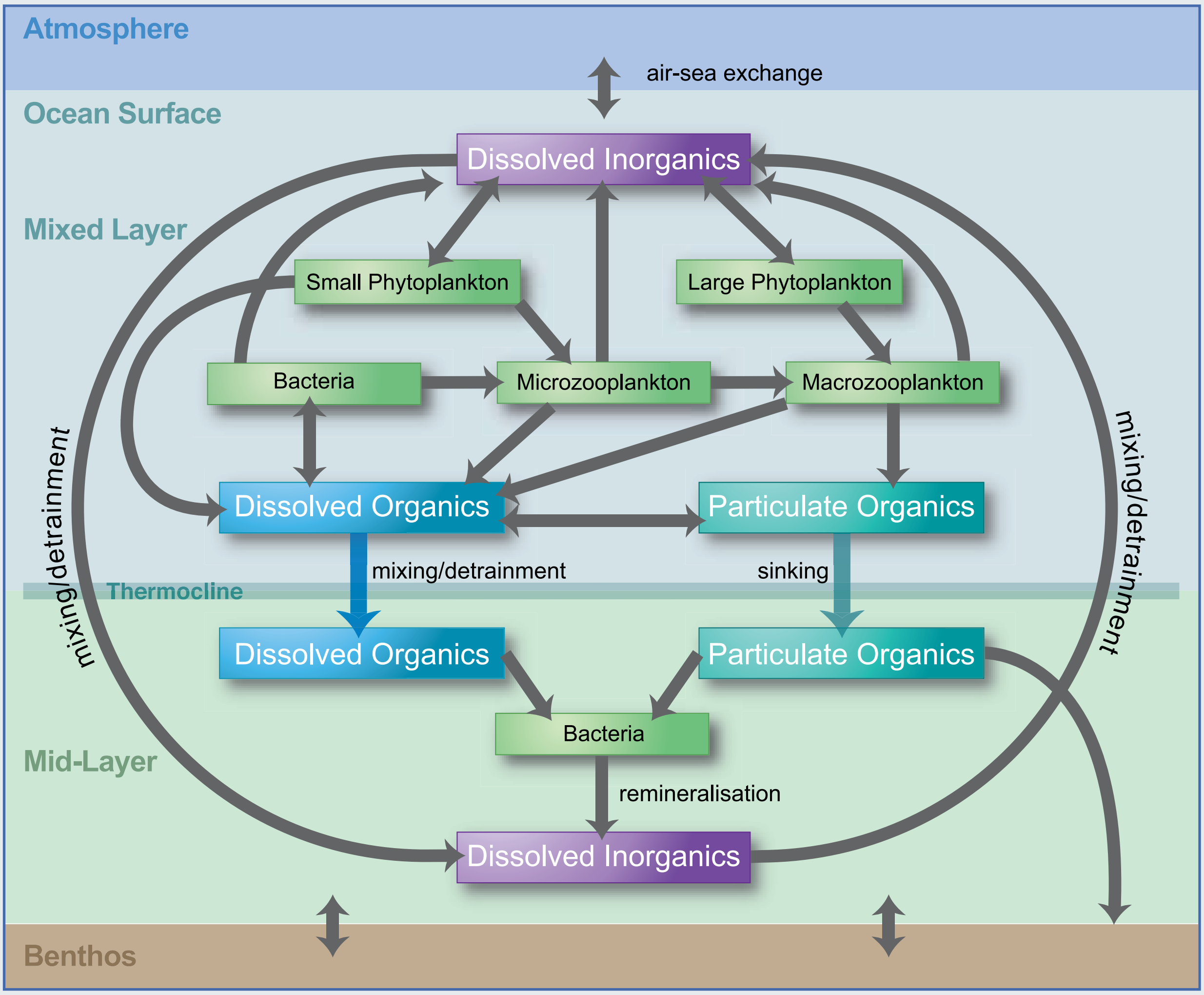
Most marine carbon is in dissolved inorganic forms, of which less than 1% is carbon dioxide, around 90% is bicarbonate ions and the remainder is carbonate ions. These exist in a pH-dependent equilibrium. The bicarbonate capacity to buffer changes in carbon dioxide is limited by calcium, and to a lesser extent by magnesium, from slow rock weathering. This constrains ocean absorption of excess carbon dioxide on short time scales.

Marine primary production (approximately 50 Pg C yr^{-1}) is the major input of organic carbon to the marine system, and carbon fixed at the surface is transported slowly to ocean depths. Most marine carbon is in intermediate and deep waters, remaining there for decades to centuries. The higher concentrations of inorganic carbon in the ocean depths are due to solubility and biological pumping (Fasham et al., 2001), the rates of which differ temporally and spatially across the ocean giving rise to source and sink regions.

The solubility pump is due to thermohaline circulation and latitudinal and seasonal changes in ocean ventilation. Carbon dioxide is more soluble in cold, saline waters, and so is sequestered to deeper waters by the formation of cold, dense water at high latitudes. Hence the largest sink is the North Atlantic, where the Gulf Stream and the North Atlantic Drift transport warm water northward. The biological pump operates by the biological assimilation of dissolved carbon dioxide which enhances air-sea gas exchange, and contributes to the vertical transport of carbon via physical processes (Figure 23). It functions through a complex food web of small plankton which recycle carbon dioxide primarily within the photic zone, and larger plankton which generate most of the particulate and dissolved carbon that sink to ocean depths.

About one quarter of the carbon fixed by phytoplankton in the upper ocean layer sinks to ocean depths (Falkowski et al., 1998), where it is oxidised and recycled by bacteria and other heterotrophs

Figure 23. Conceptualisation of the marine biological carbon pump. Courtesy of the Joint Ocean Flux Study.



into dissolved inorganic and organic forms. Only 1–2% reaches the ocean floor. The deep benthos consumes and recycles most of what sinks, while the remainder is buried in ocean sediments. Food webs dominated by large phytoplankton and macrozooplankton generate the largest downward fluxes (Fasham, 2003), with global flux estimates being around 10 Pg C yr^{-1} (Falkowski et al., 2000; Laws et al., 2000; Schlitzer, 2002).

Carbon in deeper waters is transported laterally, hence dissolved carbon dioxide is prevented from re-equilibrating with the atmosphere until transported back to the surface. Along the Equator, vigorous upwelling warms deep water as it rises to the surface, decreasing the solubility of carbon dioxide and thus releasing it to the atmosphere. Along many ocean margins intense seasonal upwelling supports a strong phytoplanktonic and heterotrophic food web, referred to as the continental carbon pump. These food webs absorb upwards of 0.2–1 Pg C yr^{-1} – a significant component of the global carbon cycle (Fasham, 2003). In many regions, eastern and western ocean boundary currents sweep carbon deep offshore, while in high latitude margins, cold water sinks into intermediate layers of the open ocean. Globally, the lateral and vertical flux at the sea floor is less than 0.2 Pg C yr^{-1}, which agrees well with benthic respiration, sediment trap and primary production data (Fasham, 2003).

Box 9. Ocean Acidification

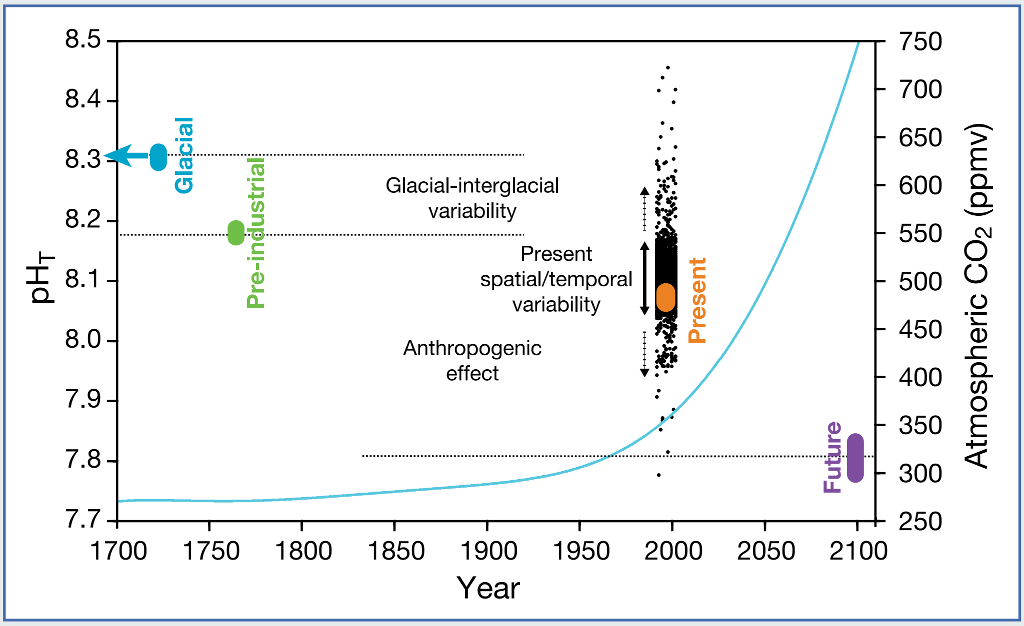
An often overlooked effect of rising atmospheric carbon dioxide is its absorption into the ocean and the resulting acidification of the ocean. Over the past 200 years, the ocean has taken up half of the carbon dioxide produced by human activities, reducing the pH of the surface ocean by 0.1 units, equivalent to a 30% increase in the concentration of hydrogen ions (Figure 24). If global carbon dioxide emissions continue to rise, the pH of the ocean could fall by 0.5 units by 2100 (equivalent to a three-fold increase in hydrogen ions since pre-industrial times). This would be a lower ocean pH than at any time in the last several hundred thousand years, and would be a rate of pH change probably one hundred times greater than at any time during this period.

The effects of these changes on the Earth System are currently difficult to predict. It is known however, that the ability of the ocean to absorb atmospheric carbon dioxide is significantly reduced at low pH values, with consequences for global warming. Ocean acidification will also affect calcification in the ocean – the ability of organisms such as corals and phytoplankton to make shells and plates. The potential effects are damage to coral reefs and calcifying plankton, with consequences for tourism, fisheries and the entire marine ecosystem.

A SCOR-IOC symposium (Cicerone et al., 2004) and a study by The Royal Society (2005) both concluded that research into the impacts of high carbon dioxide concentrations in the ocean is in its infancy, and should be developed rapidly. The consequences of continued carbon dioxide emissions or purposeful carbon dioxide sequestration in the ocean are currently unpredictable, and a major internationally coordinated effort is required to address this issue, including global monitoring and laboratory, mesocosm and field studies.

Several projects (in particular SOLAS and IMBER) and a Fast-Track Initiative on Ocean Acidification will investigate the consequences of ocean acidification for marine ecosystems and the Earth System.

Figure 24. Surface seawater pH (temperature compensated) and atmospheric carbon dioxide concentrations. pH values are for 1990–2002 for the upper 25 m across all oceans calculated from measured dissolved inorganic carbon and alkalinity. Future pH values are based on a simple exponential increase in atmospheric carbon dioxide. Courtesy of A Körtzinger; based on data from Schlitzer (2000).



Understanding the role of the ocean in the Earth System requires comprehensive studies of marine ecosystems and their interactions with biogeochemical cycles and the physical environment, in the context of global change. A palaeo perspective is required, since for example, the carbon dioxide currently out-gassing from the ocean was taken up by the ocean many centuries (perhaps millennia) ago. Palaeo studies can help elucidate the full range of variability, determine critical components and reveal non-linear behaviours. System-level integration of palaeo studies, process studies, observations and modelling is required for a comprehensive understanding of the ocean in the Earth System.

Key questions

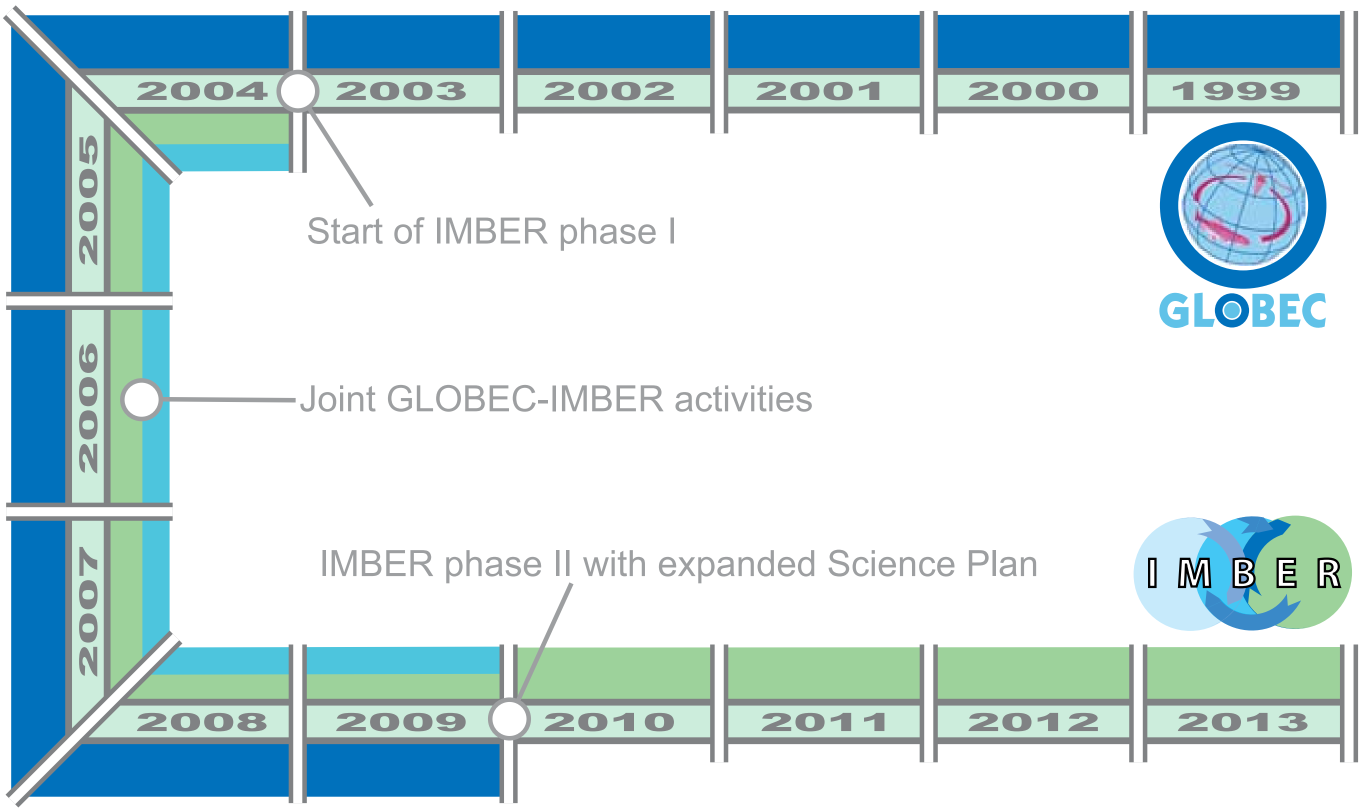
- What are the critical components of the marine system for Earth System functioning?
- What are the major feedbacks between the ocean and other Earth System components and how will human societies adapt to changes in the marine system?
- How will global change affect the structure and function of marine ecosystems, particularly the interactions between ecosystem components, at biogeochemical, individual and population levels?
- What are the interactive impacts of human, climatic and biogeochemical factors on end-to-end food webs?
- How will the ocean buffer global change and how will it trigger further change?

Objectives and Structure

In the second phase of IGBP ocean research is initially being undertaken jointly by GLOBEC and IMBER, with close collaboration on a number of activities. GLOBEC will conclude in 2009, and thus from 2010 there will be a single project (Figure 25). To maximise the opportunities for interaction the Executive Committees of the two projects will hold back-to-back meetings, and in 2007 a joint transition team will be formed to develop an addendum to the IMBER Science Plan to reflect the broader science of IMBER during its second phase.

The goal of GLOBEC is to advance the understanding of the structure and function of the global ocean ecosystem, its major subsystems and its response to physical

Figure 25. GLOBEC-IMBER interactions and transition to a single ocean project.



forcing, so that a capability can be developed to forecast marine ecosystem responses to global change. This goal gives rise to the four primary GLOBEC objectives: (i) to better understand how multi-scale physical environmental processes force large-scale changes in marine ecosystems; (ii) to determine the relationships between structure and dynamics in a variety of oceanic systems which typify significant components of the global ocean ecosystem, with emphasis on tropho-dynamic pathways, their variability and the role of nutrition quality in the food web; (iii) to determine the impacts of global change on stock dynamics using coupled physical, biological and chemical models linked to appropriate observation systems, and to develop the capability to predict future impacts; and (iv) to determine how changing marine ecosystems will affect the Earth System by identifying and quantifying feedbacks. To meet its goal GLOBEC uses an integrated suite of six regional programmes (described below under *Research Approaches*), national activities and the following four cross-cutting foci:

Focus 1: Retrospective analyses and time series studies. The identification and understanding of the characteristic natural modes of physical forcing and marine ecosystem variability over a range of temporal and spatial scales.

Focus 2: Process studies. Experimental approaches to investigating specific mechanisms which are thought to link ecosystem responses with environmental variability.

Focus 3: Predictive and modelling capabilities. To elucidate ecosystem dynamics and responses on a range of time scales.

Focus 4: Feedbacks from changes in marine ecosystem structure to the Earth System.

The goal of IMBER is to investigate the sensitivity of marine biogeochemical cycles and ecosystems to global change, on time scales ranging from years to decades. In pursuit of its goal IMBER is structuring its research under the following four themes, each addressing a number of specific issues:

Theme 1: Interactions between biogeochemical cycles and marine food webs. The guiding question for this theme is: what are the key marine biogeochemical cycles, ecosystem processes and their interactions, that will be impacted by global change? This theme addresses three issues: (i) the transformation of organic matter in marine food webs; (ii) transfers of matter across ocean interfaces; and (iii) material flows in end-to-end food webs.

Theme 2: Sensitivity to global change. The guiding question for this theme is: what are the responses of key marine biogeochemical cycles, ecosystems and their interactions with global change? The theme addresses four issues: (i) effects of climate change on the physical dynamics of the ocean; (ii) effects of increasing carbon dioxide levels and decreasing pH; (iii) effects of changes in macro- and micronutrient inputs to the ocean; and (iv) impacts of marine harvesting.

Theme 3: Feedbacks to the Earth System. The guiding question for this theme is: what is the role of ocean biogeochemistry and ecosystems in regulating climate? The theme addresses three issues: (i) the varying capacity of the ocean to store anthropogenic carbon dioxide; (ii) ecosystem feedbacks on ocean physics and climate; and (iii) how changes in low-oxygen zones affect the nitrogen cycle, especially transformations involving nitrous oxide.

Theme 4: Responses of society. The guiding question for this theme is: what are the relationships between marine biogeochemical cycles, ecosystems and the human system? The overall goals of this theme are to promote an understanding of the multiple feedbacks between human and ocean systems, and to clarify what human institutions can do, either to mitigate anthropogenic perturbations of the ocean system or to adapt to such changes.

Research Approaches

IMBER and GLOBEC are working collaboratively to achieve a complete understanding of end-to-end food web structure and function. IMBER is conducting major hydrographic surveys of carbon (with CLIVAR and SOLAS) and trace elements (with GEOTRACERS) and conducting sustained observations of several variables through established and new long-term time-series sites, remote sensing and autonomous *in situ* instrumentation. Process studies and palaeo oceanography are key elements of both projects, and ongoing modelling and synthesis activities are critical for testing hypotheses, extrapolating data and identifying gaps that to be filled by observations and experiments. Biogeochemical models and marine food web models are being coupled to advance understanding of the ocean system and its interactions in the Earth System. IMBER is conducting mesoscale manipulative experiments to complement laboratory and mesocosm studies, and is developing data management activities consistent with existing and ongoing marine research and observation programmes.

GLOBEC and IMBER are both implemented through national and regional activities. The six regional activities of GLOBEC are (i) the Small Pelagic Fishes and Climate Change (SPACC) activity that aims to understand and predict climate-induced changes in marine fish production; (ii) the Cod and Climate Change (CCC) activity that aims to understand how climate variability affects the productivity and distribution of cod stocks; (iii) the Climate Change and Carrying Capacity (CCCC) activity that aims to forecast the consequences of climate variability on the ecosystems of the sub-Arctic Pacific; (iv) the Southern Ocean activity that aims to study the life cycle of Antarctic zooplankton; (v) the Ecosystem Studies of Sub-Arctic Seas (ESSAS) activity that aims to investigate how global change will influence the sub-Arctic seas and their ability to support resources of value to people; and (vi) the Climate Impacts on Oceanic Top Predators (CLIOTOP) activity that aims to determine the impact of both climate variability (at various scales) and fishing on the structure and function of open ocean pelagic ecosystems and their top predator species.

During its final five years GLOBEC is undertaking an extensive integration and synthesis effort in an Earth System context, focused on the comparative dynamics of regional ecosystems. From 2010 the single ocean project will comprise (i) ongoing IMBER research; (ii) ongoing research in the CLIOTOP and ESSAS regional programmes; and (iii) research questions identified during the GLOBEC synthesis.

The Surface Ocean–Lower Atmosphere Study (SOLAS) is a second phase IGBP project which is cosponsored by SCOR, WCRP and CACGP. The SOLAS research agenda is documented in SOLAS (2004) and the IPO is based at the University of East Anglia in Norwich, United Kingdom.

Rationale

Climate change can alter ocean-atmosphere exchanges of many reactive particles and gases. During glacial-interglacial transitions large amounts of carbon are transferred directly from the atmosphere to the ocean. The current net carbon transfer is about 2 Pg yr^{-1}, but it is unclear in which ocean basins carbon is primarily stored, and which processes are responsible for the sinks. Furthermore, there is little understanding of how transfers will respond to climate change.

Sea-salt particles and sea ice release gases and provide surfaces for heterogeneous chemical reactions, and changes in emissions of marine biogenic gases alter the radiative environment, chemical cycles, acidity and the oxidative capacity of the atmosphere. Significant exchanges of these gases occur between the atmosphere and both open waters and sea ice. Changes in the spectral quality and intensity of radiation in the atmosphere as a result of stratospheric ozone depletion and climate-driven tropospheric change, can have significant impacts on photochemical atmospheric processes and cloud cover. These in turn, can alter physiology, community structure and photochemical processes in the marine photic zone. Deposition of gases and particles from the atmosphere (such as iron-laden mineral dust) has significant impacts on surface ocean processes (Boxes 1 and 10).

Phytoplankton in ocean surface waters are responsible for the production of dimethylsulphide (DMS), which is subsequently oxidised in the atmosphere to sulphate aerosol. Sulphate aerosols affect the radiative properties of the atmosphere and cloud albedo which in turn affect the climate. Climate changes affect distribution patterns and productivity of phytoplankton, thus closing the feedback between marine production and climate. The strength of this feedback remains to be determined, but it hints at the importance of the ocean-atmosphere interface in terms of buffering or accelerating changes in the Earth System.

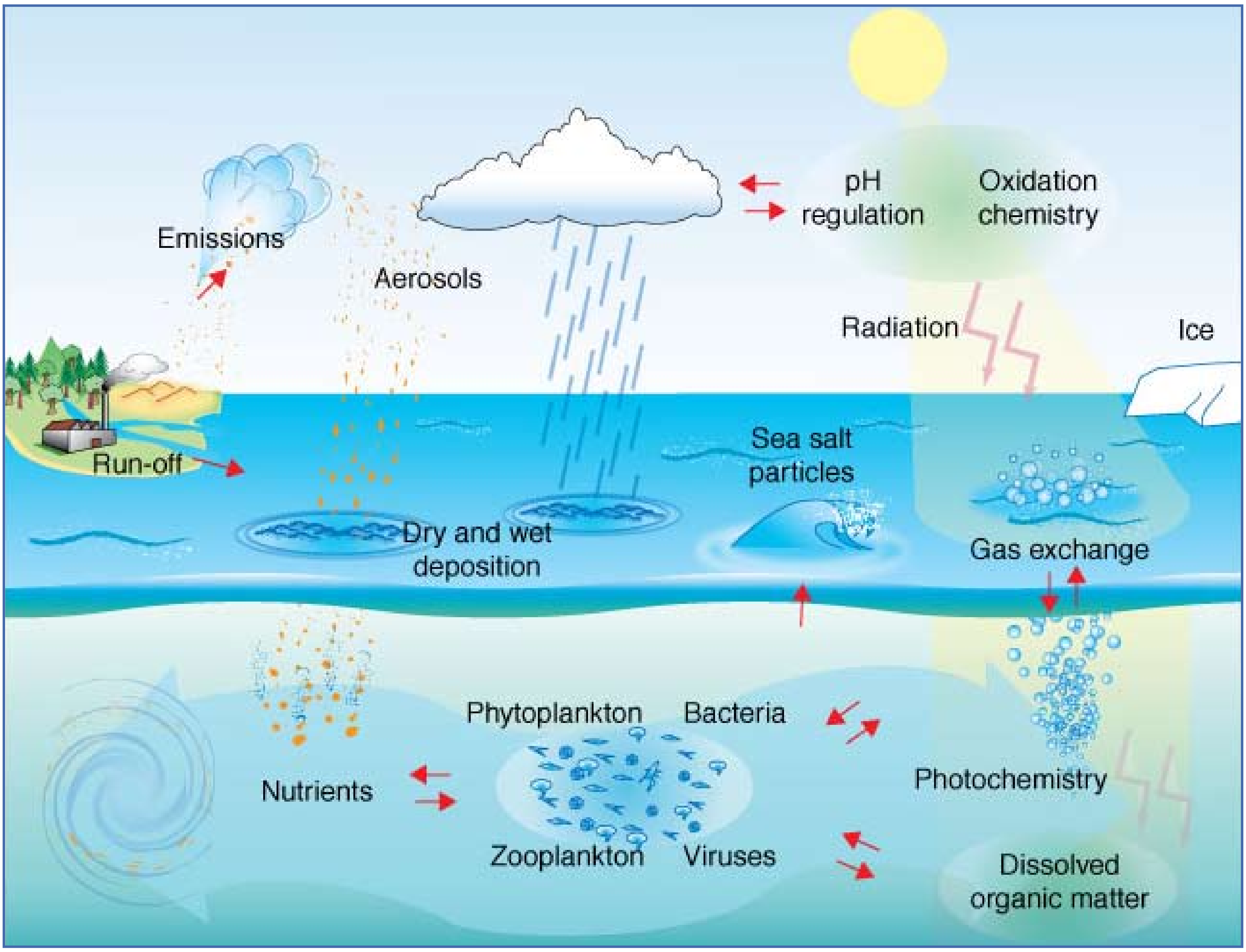
Climate simulations are just beginning to incorporate biological and chemical feedbacks in atmosphere-ocean responses to climate forcing. Currently, climate simulations differ depending on which feedbacks are included and how they are modelled. Climate change is likely to induce substantial changes in natural sources and sinks of climatically active gases. Carbon dioxide is the best studied example, but less studied gases (DMS and other chemically active trace gases) may have important effects.

Mass, momentum and energy exchanges need to be better understood across a wide range of scales. Sound physical and biogeochemical principles must be developed to underpin parameterisations of processes in models, and quantitative measurements made to characterise the interface and its controlling processes. This requires simultaneous study of the physics and biogeochemistry of the ocean-atmosphere interface. SOLAS will address these issues to substantially reduce the uncertainties in predictions of the timing and effects of global and climate change (Figure 26).

Key Questions

- What are the key biogeochemical ocean-atmosphere interactions and feedbacks, particularly those involving trace gases?
- What are the processes that control transport and transformation across the air-sea interface?
- What are the interactions and feedbacks between biogeochemical and physical processes?
- What is the two-way interaction between the coupled ocean-atmosphere system and climate?

Figure 26. The main air-sea exchange processes which affect Earth System functioning.



Box 10. Iron Fertilisation Experiments

In the late 1980s laboratory experiments showed that addition of iron to incubations of phytoplankton substantially increased biological production relative to controls (Martin and Fitzwater, 1988; Martin et al., 1990). However, the implications of these experiments were uncertain, since conditions inside an incubator are very different from those in the ocean. The very low concentrations of iron (order 0.1 nM) of some open ocean regions makes it possible to enrich an experimental area of hundreds of square kilometres with very modest iron additions. Using sulphur hexafluoride as a tracer enables patch experiments to be tracked for several weeks in real time from a ship (Watson et al., 1991).

In iron enrichment experiments iron salts are dissolved in tanks of seawater on a ship, a tracer solution is prepared, and the two solutions are pumped over the stern while the ship tracks a path around a drifting buoy. Once the release is complete, shipboard analytical instruments map the initial shape of the patch, and then continue chemical and biological measurements within the patch over several weeks.

Such experiments have been performed in the equatorial Pacific (Martin et al., 1994; Coale et al., 1996), the Southern Ocean (Boyd et al., 2000; Watson et al., 2000) and the northeast Pacific. These are high-nutrient–low-chlorophyll regions, where nitrate and phosphate – the nutrients which often limit plankton growth – are abundant in surface waters. In these experiments iron addition caused dramatic ecosystem shifts beginning with diatom blooms. Under bloom conditions diatoms can rapidly reach a large biomass and remove carbon and nutrients from the water, causing nutrient drawdown and potentially, uptake of atmospheric carbon dioxide. The fates of diatom blooms in these experiments varied. In the equatorial Pacific the blooms faded within a fortnight, but in the Southern Ocean they lasted much longer (Figure 27).

Iron supply can switch a marine ecosystem from a recycling mode in which the plankton community is relatively self-contained, to an export mode in which carbon and nutrients are stripped from the surface waters and exported to depth (Landry et al., 1997). This has important Earth System consequences, as the biological export in the Southern Ocean is a key factor in setting natural concentrations of carbon dioxide in the atmosphere, and the supply of iron in atmospheric dust to the Southern Ocean has an important role in explaining why carbon dioxide varied between glacial and modern pre-industrial times (Martin, 1990; Watson et al., 2000).

Although deliberate ocean fertilisation could be used to sequester atmospheric carbon dioxide, this potential has been greatly exaggerated, as there are limitations to how quickly the ocean can take up carbon dioxide (Peng and Broecker, 1991). Furthermore, little is known about other ecological consequences of large-scale ocean fertilisation.

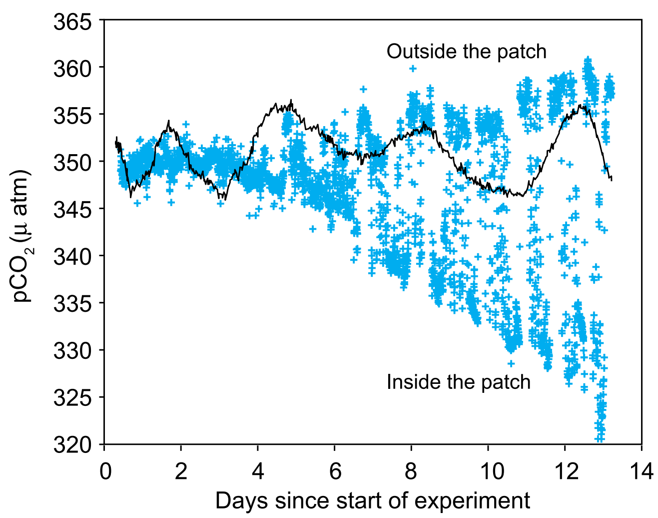


Figure 27. Partial pressure of carbon dioxide (pCO_2) in the surface of the Southern Ocean following release of iron. The blue crosses indicate pCO_2 at the water surface; the black line indicates pCO_2 in the overlying air (reflecting atmospheric pressure changes). From Abraham et al. (2000) with permission from Macmillan Magazines Ltd.

Objectives and Structure

The objective of SOLAS is to achieve quantitative understanding of the key biogeochemical-physical interactions and feedbacks between the ocean and atmosphere, and of how this coupled system affects, and is affected by climate and environmental change. To meet this objective SOLAS is organising its research into the following three foci:

Focus 1: Biogeochemical interactions and feedbacks between ocean and atmosphere. This focus seeks to quantify feedback mechanisms involving biogeochemical coupling across the air-sea interface, including emissions of trace gases and particles, their reactions of importance in atmospheric chemistry and climate, and deposition of nutrients that control marine biological activity and carbon uptake. The focus has five activities: (i) sea-salt particle formation and transformations; (ii) trace gas emissions and photochemical feedbacks; (iii) DMS and climate; (iv) iron and marine productivity; and (v) ocean-atmosphere cycling of nitrogen.

Focus 2: Exchange processes at the air-sea interface and the role of transport and transformation in atmospheric and oceanic boundary layers. This focus aims to develop a quantitative understanding of the physical, biological and chemical processes responsible for air-sea exchange of mass, momentum and energy to permit accurate calculation of regional and global fluxes. The focus has three activities: (i) exchange across the air-sea interface; (ii) processes in the oceanic boundary layer; and (iii) processes in the atmospheric boundary layer.

Focus 3: Air-sea flux of carbon dioxide and other long-lived radiatively active gases. This focus aims to characterise the air-sea flux of carbon dioxide and other long-lived radiatively active gases, including nitrous oxide and to some extent methane, and the boundary-layer mechanisms that drive them, in order to assess their sensitivity to variations in environmental forcing. The focus has three activities: (i) geographic and sub-decadal variability of air-sea carbon dioxide fluxes; (ii) surface layer carbon transformations in the oceans; and (iii) air-sea flux of nitrous oxide and methane.

Research Approaches

To address these foci SOLAS will (i) study the ocean and atmosphere simultaneously to determine the connections between the processes and fluxes (of aerosols and gases) in both media; (ii) provide a fundamental understanding of the dependence of interfacial transfer mechanisms on physical, biological and chemical factors within the boundary layers; (iii) establish the horizontal and vertical transport and transformation processes that regulate air-sea exchanges; and (iv) improve the ability to predict the role of biogeochemical interactions between the atmosphere and ocean in the Earth System.

Understanding the processes that occur at the ocean-atmosphere interface requires an enhanced level of cooperation in planning and execution of research among different Earth System disciplines. SOLAS depends on the effective cooperation between scientists to integrate measurements and analyses of many types. A wide variety of tasks is being conducted including: (i) coordinated laboratory work and mesocosm studies; (ii) field studies – in many cases using simultaneous observations on multiple platforms, for example, ships, aircraft, buoys and satellites; (iii) long time-series observations; (iv) palaeo studies; and (v) models for upscaling to regional and global scales, which are vital components for Earth System models.

SOLAS is implemented through networks of national and international groups, and implementation groups that coordinate work in each of the three research foci. A Model and Data Management group cooperates closely with other international projects and creates Task Teams for shorter-term activities.

Analysis, Integration and Modelling of the Earth System (AIMES) is a project of the second phase of IGBP which continues and extends the work of the Global Analysis, Integration and Modelling (GAIM) task force of the first phase. At the time of writing, formal documentation of the AIMES science agenda was in preparation. The International Project Office (IPO) is based at the National Center for Atmospheric Research in Boulder, United States.

Rationale

There is a growing recognition that global change must be studied in a holistic and integrated way, since it is now understood that the Earth is a single system in which the biosphere is an active and essential component, and that human activities are now so pervasive and profound that they affect the entire Earth System in complex, interactive and apparently accelerating ways. This recognition suggests that it is no longer appropriate to consider humans as an outside force perturbing a natural system, but rather, to consider a coupled, interactive human-environment system. Representing human activities in this way presents daunting challenges for Earth System analysis and modelling. Understanding carbon cycle dynamics may offer the best initial opportunity for integrating human and natural drivers of global biogeochemical cycles (Box 11). Ultimately however, Earth System modellers must engage with the social and economic science communities to develop integrated assessments of the full spectrum of linkages between human activity and Earth System functioning.

These challenges may be met in part by application of complex systems theory and new mathematical and computer tools. One potentially useful approach is "agent-based" modelling in which humans or groups of humans interact through specified rules. The agent-to-agent interactions in the virtual world generate emergent properties of groups of agents, such as an economy or social system. Network dynamics provide another potential approach, where the topology of the network and the rules by which nodes interact are both important, and give rise to complex, nonlinear dynamics.

Objectives and Structure

The overall objective of AIMES is to obtain a deeper and more quantitative understanding of the how human perturbations to biogeochemical cycles alter the coupled physical climate system. Specifically, this will require developing quantitative understanding under the following five themes:

Theme 1: Understanding the operation and interactions of global biogeochemical cycles, including material transfers between the land, ocean, atmosphere and lithosphere, and their linkages to the physical climate.

Theme 2: Understanding the causes and consequences of atmospheric composition changes through glacial-interglacial cycles (and thus the biophysical coupled system), as a basis for modelling climate-biogeochemistry interactions on long time scales.

Theme 3: Understanding the interplay of environmental changes with human activities in history and prehistory, including the interaction between the physical environment, human decision making and consequent human forcings back to the physical system.

Theme 4: Understanding the operation of the contemporary Earth System, as perturbed by, and influencing human actions, during both the industrial era and the more recent observational period.

Theme 5: Developing scenarios for the interaction of climate, biogeochemistry and society during the 21^{st} century, and their implications for the sustainable use of natural resources.

Research Approaches

AIMES interacts and collaborates closely with other projects and activities of IGBP and ESSP. In all cases, the reciprocal advantage of information and data sharing from local and regional studies is the global context for regional processes that AIMES provides. AIMES has adopted four templates for interaction and collaboration:

Template 1: Process and Parameterisation.
Earth System models require observations and process understanding for model development, parameterisation, testing and evaluation. Datasets and process knowledge for global model improvement and development need not

Box 11. C4MIP

In the early 1990s GAIM and the WCRP Working Group on Coupled Models (WGCM) collaborated on the Coupled Carbon Cycle–Climate Model Intercomparison Project (C4MIP), which compared and analysed feedbacks between the carbon cycle and climate in the presence of external climate forcing. The project incorporated models of the terrestrial and ocean carbon cycles in existing ocean-atmosphere global circulation models, and ran the augmented models with and without active feedbacks. Initial protocols included the consideration of carbon dioxide, radiative and biogeochemical forcing and using tracer carbon dioxide for diagnostic surface fluxes.

C4MIP simulations (Friedlingstein et al., 2006) agree unanimously that future climate change will reduce the efficiency of the Earth System to absorb anthropogenic carbon perturbations (Figure 28a). A larger fraction of anthropogenic carbon dioxide will remain in the atmosphere. All models simulate a negative sensitivity for both the land and the ocean carbon cycle to future climate (Figure 28b and c). However, there are large uncertainties in the magnitude of these sensitivities. The attribution of the land sensitivity to changes in net primary productivity versus changes in respiration is still a subject of debate, as no consensus has emerged from the models.

AIMES will continue and extend the model intercomparison project to integrate the fate of methane, nitrous oxide, aerosols, ozone and other important greenhouse gases into coupled models. This will require the development of emission models of these species and their precursors for land and the ocean, as well as models of the interactive chemistry in the atmosphere. The interactions between climate and fire regimes (and the trace gases emissions, including carbon dioxide, methane and aerosols) will be investigated to quantify the feedbacks to the climate system.

Existing coupled models have only very crude representations of how humans manage ecosystems. Land cover change (e.g. deforestation) and agricultural management (e.g. irrigation and harvesting) affect the climate system and hence should be included in coupled models. Similarly, ecosystem services (e.g. agricultural and marine fisheries production) may be affected by climate change and biogeochemistry changes, and so should be incorporated into coupled models. AIMES will guide the modelling community to improve representations of human-environment interactions and ecosystem services in coupled climate-biogeochemical models.

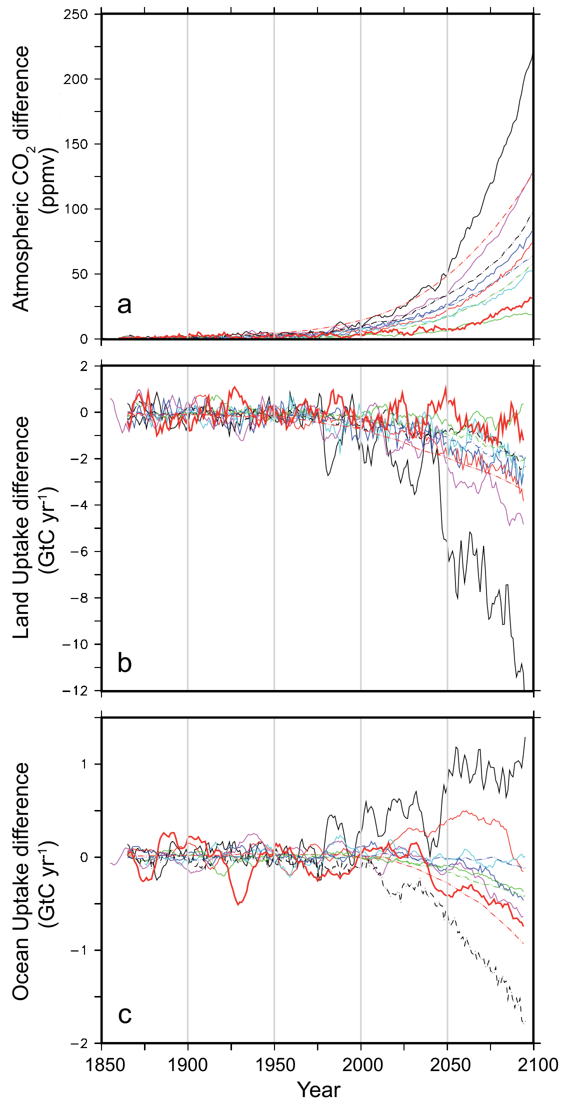


Figure 28. (a) Atmospheric carbon dioxide differences between coupled and uncoupled carbon cycle-climate simulations; (b) land carbon uptake for coupled runs; and (c) ocean carbon uptake for coupled runs. From Friendlingstein et al. (2006) with permission from the American Meteorological Society.

be localised – they can include global data networks. This template provides a mechanism to improve global representations of process mechanisms in Earth System models by speeding the transfer of local and regional process understanding to global models.

Template 2: Regional-Global Interactions. This template focuses on the impacts and feedbacks in regions where rapid rates of human development trigger changes in the atmosphere or biosphere, and where rapid local and regional changes have global consequences. Regional to global interactions include:

(i) Where rapid change in a human system triggers a global response, either directly through transport, or indirectly through teleconnections in the climate system. In order to understand the significance of the regional study, it has to be embedded in a global context.

(ii) Where global changes trigger rapid changes in a region with subsequent global feedbacks (for example, recent changes in the northern high latitudes). The emphasis here is on human consequences rather than on human causation.

(iii) Where regional impacts of global change need to be understood at high resolution. This template utilises an Earth System approach to downscaling: if global changes are recognised this template will endeavour to understand the regional effects and feedbacks to changes in human behaviour.

Template 3: Applied Earth System Science. This template translates region- or process-specific global change responses into global understanding of assessment, mitigation and management. Integrative models will enable transfer of information to global ecosystem services and integrative problem-solving by harnessing the energy of IGBP.

Template 4: Integrative Earth System Science and Modelling. Incremental problem-focused additions to coupled models (of climate biogeochemistry, ecology and human dimensions) will lead to a greater capability to understand human-environment interactions and coupled behaviour of the biogeosphere. Integrative modelling will be a component of all applied activities.

Important early (and ongoing) activities for AIMES implementation include C5MIP, IHOPE and GEIA. C5MIP is the first phase of the extension to C4MIP (Box 11), that will integrate more complete atmospheric chemistry and terrestrial biosphere dynamics into coupled models. IHOPE – Integrated History and Future of People on Earth – is a wide collaboration among natural scientists, social scientists, archaeologists and historians to construct an integrated history of human activities and environmental change. IHOPE will attempt to unravel the complex causes of the collapses of past civilisations, to help guide options for future sustainability. GEIA – the Global Emissions Inventory Activity – will continue to build global databases of gridded emissions inventories for use in Earth System modelling and analysis.

Additionally, IGBP has identified the need for a digital Earth System Atlas to provide scientists with a single source for high-quality, peer-reviewed global data sets of important Earth System variables (including palaeo environmental observations and socio-economic variables). While the development of this tool involves collaborations across and beyond IGBP, AIMES is leading and coordinating IGBP contributions to the endeavour. AIMES is also coordinating a network of Earth System science institutions (see page 55) which will benefit all IGBP projects, and building research capacity by developing a network of young Earth System scientists.

Fast-Track Initiatives

Fast Track Initiatives (FTIs) were established in 2003 by the SC-IGBP to foster integration and synthesis of IGBP science, and to offer a means for SC-IGBP members to actively contribute to IGBP scientific activities. FTIs help identify new issues for research within the IGBP network. They are designed to advance Earth System understanding and address innovative, cross-cutting issues in Earth System science not being addressed by IGBP or ESSP projects. FTIs are thus "nurturing grounds" for innovative research activities both within and outside the programme.

FTIs are initiated by the SC-IGBP, but usually involve multiple IGBP projects (with participation from several countries) as well as scientists from beyond the IGBP community. FTIs are often cosponsored by partner organisations. It is recommended that one or both of the IGBP integration projects (PAGES and AIMES) be involved in each FTI, and that capacity building elements be included. FTIs are short-lived (maximum lifetime of three years) and are expected to generate significant outputs such as review articles, books or major databases. After completion, FTIs may expand into new research activities, potentially as an integral part of an IGBP or ESSP project.

Proposals for FTIs are submitted to the IGBP Secretariat and considered for approval at the annual SC-IGBP meeting. Proposals outline the key questions and objectives, planned products, the scientific expertise required to achieve the goals, timeline, budget, termination/transition plan, interactions with stakeholders and the involvement of integration projects. If the FTI leader is not an SC-IGBP member, then an ICSU-appointed SC-IGBP member will monitor and report on the FTI to the SC-IGBP. FTIs receive seed funding from IGBP; additional funding is usually required.

Initial FTIs considered the global iron cycle (2003–05; a collaboration with SCOR; see Box 1), the global nitrogen cycle (2003–05; a collaboration with SCOPE; see Box 2) and the role of fire in the Earth System (2003–06; see Box 6). These produced several synthesis papers, a book and a Declaration on Nitrogen Management. Work initiated by the "Iron FTI" continues, largely with SOLAS. The "Nitrogen FTI" developed into a major international initiative – the International Nitrogen Initiative – which continues some of its activities within IGBP under the umbrella of AIMES.

Other FTIs at the time of writing are an: (i) *An Investigation of Ocean Acidification over Time* (2005–07; a collaboration with SCOR); (ii) *Refining Plant Functional Classifications for Earth System Modelling* (2006–08; a collaboration with DIVERSITAS) and (iii) *The Earth in 2030–50* (2006–08).

Integration and Synthesis

Scientific integration and synthesis are fundamentally important activities for IGBP, and both require careful and early planning and adequate resourcing. The ultimate goal of these activities is to provide policy and resource management communities with useful global change and Earth System information. One important avenue for this has been, and will continue to be, contributions to global environmental assessments such as IPCC and MEA. Nonetheless, advances in global change understanding at all levels (science, policy and public) over the last decade, and the changing organisational landscape of Earth System science mean additional approaches to integration and synthesis are required.

Integration

IGBP will use a range of activities and approaches for integration, both within the programme and through collaborations – particularly participation in the ESSP. Within the programme, AIMES and PAGES have the roles of undertaking Earth System-level research, and integrating the work of other IGBP projects. To facilitate this integration an AIMES representative will, wherever possible, attend the SSC meetings of other IGBP projects, especially in the initial stages of research implementation.

As in its first phase, IGBP will organise a congress every four years. IGBP congresses assemble the SC-IGBP, all project SSCs and other key scientists in the IGBP community to share progress, jointly plan ongoing and new implementation activities, and facilitate integration of Earth System science. IGBP and Global Change National Committee (NC) representatives attend these congresses to foster national-international linkages and to facilitate regional-global integration of research findings. In its second phase IGBP will consider (where appropriate, practical and resource-efficient) to co-convene its congresses with key partner research programmes. The first congress for the second phase of IGBP is planned for early 2008; a second is envisioned for 2012 or 2013.

Beyond the programme, IGBP will foster integration by strategic collaborations with key partners. The most important strategic collaboration for the second phase of IGBP is participation in ESSP. Established in 2001, ESSP

Box 12. ESSP Projects on Global Sustainability

ESSP projects on issues of global sustainability address the global change aspects of a number of issues critical for human well-being: the carbon cycle, food systems, the global water system and human health. These projects go beyond the scope of the individual partner programmes, but draw heavily on the research of the projects of the partners, integrating this research around questions on the nexus between Earth System function and human and societal well-being. These projects tackle the two-way interaction between global change and global sustainability by researching both the impacts of a changing global environment on human societies, and the implications of human-driven changes in these societal systems for the functioning of the Earth System.

Global Carbon Project (GCP)

GCP is developing a comprehensive, policy-relevant understanding of the global carbon cycle, encompassing its natural and human dimensions and their interactions. GCP is organised around three themes:

- Patterns and variability: what are the current geographical and temporal distributions of the major pools and fluxes in the global carbon cycle?
- Processes and interactions: what are the control and feedback mechanisms – both anthropogenic and natural – that determine carbon cycle dynamics?
- Carbon management: what will be the future dynamics of the carbon-climate-human system, and what points of intervention and windows of opportunity exist for management of this system?

Global Environmental Change and Food Systems (GECAFS)

GECAFS is determining strategies to cope with the impacts of global environmental change on food systems, and is assessing the environmental and socio-economic consequences of adaptive responses aimed at improving food security. GECAFS is organised around three major questions:

- How will global environmental change affect the vulnerability of food systems in different regions?
- How can food systems be adapted to cope with global environmental change so as to enhance food security?
- How will various adaptation options feedback on environmental and socio-economic conditions?

Global Water System Project (GWSP)

GWSP is addressing how human actions are changing the global water system, and is considering the environmental and socio-economic feedbacks arising from anthropogenic changes in this system. GWSP is organised around three major questions:

- What are the magnitudes of anthropogenic and environmental changes in the global water system, and what are the key mechanisms by which these changes are induced?
- What are the main linkages and feedbacks within the Earth System arising from changes in the global water system?
- How resilient and adaptable is the global water system to change, and what are sustainable water management strategies?

Global Environmental Change and Human Health (GECHH)

GECHH will identify the risks to human health posed by global environmental change, and will investigate potential ways to minimise these risks. GECHH will be launched at the Second ESSP Open Science Conference in late 2006.

provides the framework for DIVERSITAS, IGBP, IHDP and WCRP to collaborate on integrated Earth System research, including consideration of the changes that are occurring to the system and the implications for global sustainability. ESSP supports projects on issues of global sustainability (Box 12), global change research capacity building, integrated regional studies (IRS) and open science conferences.

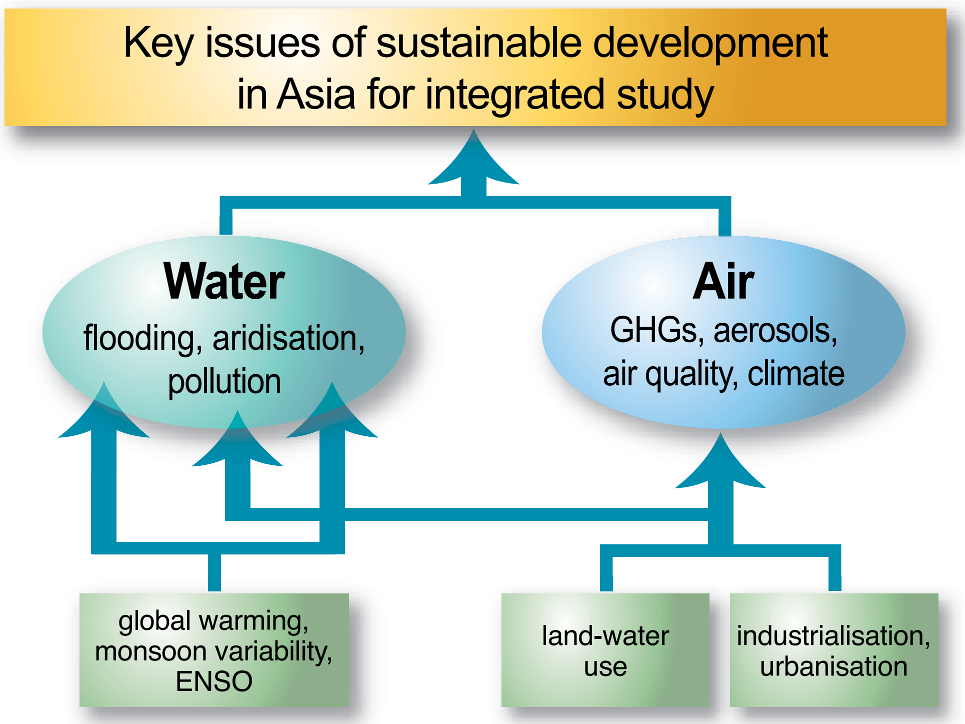
Recognising the increasing importance of regional aspects of global change, ESSP promotes and facilitates IRS. IRS are based on the concept of the region as a holistic entity in the context of the Earth System, and are intended to contribute scientific understanding in support of sustainable regional development. IRS consider integration and processes within and across a region, and integration between a region and the global system. IRS contribute to understanding regional-global linkages and the consequences of changes in these linkages.

IRS are developed and led by scientists in a particular region, and reflect the characteristics, interests, scientific capabilities and development priorities of the region. By addressing the same overall goals, IRS are amenable to cross-comparisons and the construction of a global synthesis. In addition to their scientific objectives, IRS are important for capacity building, as they help to develop regional scientific infrastructure for global change research.

IRS transcend disciplinary boundaries and address aspects of marine, terrestrial, atmospheric, social, economic, cultural and historical components of the Earth System. They reflect the particular socio-economic and biophysical characteristics of a region, and address regional Earth System research all the way from planning to synthesis. IRS explicitly consider major features of Earth System (e.g. the Asian monsoon system, the Amazon Basin, the Antarctic cryosphere) and consider regions where small changes may lead to profound Earth System change.

The Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) which was initiated in the middle of the first phase of IGBP, exemplifies many of the key aspects that ESSP expects from IRS. LBA comprises over eighty closely linked and coordinated research groups involving 600 scientists from South and North America, Europe and Japan, all focussed on studying how Amazonia functions as a regional entity within the larger Earth System, and how changes in land use and climate will affect the biological, physical, and chemical functioning of the region's ecosystem.

Figure 29. Initial foci for MAIRS.



The first IRS approved by ESSP is the Monsoon Asia Integrated Regional Study (MAIRS). MAIRS seeks to improve the understanding of how human activities in Monsoon Asia are interacting with and altering the natural variability of atmospheric, terrestrial and marine components of the monsoon system. From this, MAIRS will develop a capacity to predict changes in global-regional linkages and their consequences. Together these will build the scientific basis for sustainable development in Monsoon Asia. Initially MAIRS will focus on issues related to air and water, considering how Earth System changes affect the Asian monsoon region (Figure 29).

ESSP also sponsors open science conferences to promote integration and to cross-fertilise Earth System science. The first conference – *Challenges of a Changing Earth* – was held in 2001 and attracted 1,400 participants across science, policy and resource management from 105 countries. The second conference – *Global Environmental Change: Regional Challenges* – will occur in late 2006.

Synthesis

One of the key functions of IGBP is to coordinate and facilitate periodic syntheses of global change research and Earth System science. In the first phase of IGBP this was a major focus during 1999–2003 and generated eleven major books for a scientific audience (Appendix 2). In addition, 32-page summaries of six of these books were produced for policy and education audiences.

In the second phase of IGBP synthesis will continue to be important, and will be the focus during 2012–2013 (Figure 1). The exact nature of the outputs from this synthesis phase will be decided by the SC-IGBP. While major book publications are possible in the later stages of the second phase, the changing emphasis of the IGBP communication effort (See *Communication and Outreach*) means these are unlikely to be targeted solely at a scientific audience. In addition, greater effort will be invested in synthesis as an ongoing activity, rather than solely as a culminating activity. For example, it is envisioned that the IGBP Secretariat will produce a new series of two-page Earth System science summaries for policy makers (see *Communication and Outreach*). In addition, a range of ongoing synthesis activities will be undertaken by individual IGBP projects.

Implementation Strategy

Conducting Earth System science is often expensive and research budgets around the world are under increasing pressure. The fraction of research funds available for international activities is even more tightly constrained, and hence it is imperative that available funding is used efficiently. One of most important roles of IGBP is to work with the international scientific community to develop scientifically effective and resource-efficient implementation strategies. IGBP will work to ensure that national funding agencies adopt a global perspective in their funding of global change research.

Implementation of IGBP science primarily occurs through the activities of the IGBP projects, which have developed and published project-specific science plans and implementation strategies. Each project has developed its own approach to achieving its scientific goals, within the overall IGBP scientific structure and aims. Additionally however, there are some implementation strategies that are common to most projects that were developed during the first phase of IGBP, and some new programme-level strategies. Together these form a powerful toolkit for international Earth System science. These strategies are described in this section and include:

- developing international frameworks for collaborative research based on agreed agendas;
- building research networks to tackle focused scientific questions;
- building an international institutional network for Earth System science;
- promoting standard methods;
- undertaking long time-series observations;
- guiding and facilitating construction of global databases;
- establishing common data policies to promote data sharing;
- undertaking model inter-comparisons and comparisons with data;
- facilitating comprehensive interaction between modellers and experimentalists; and
- coordinating complex, multi-national field campaigns and experiments.

NCs are essential to the implementation of IGBP, providing a two-way conduit between national and international levels of global change research. NCs input advice, research capacity and research projects, and IGBP provides an agreed international framework to facilitate the international collaborations of researchers from many countries. A key component of the IGBP implementation strategy will continue to be building research capacity – particularly in less-developed countries.

International Frameworks for Collaborative Research

Researching Earth System science issues across national boundaries requires an agreed research framework and common science questions. IGBP projects have developed through a thorough process of discussion and consultation with the scientific community, involving hundreds of scientists from all continents. This has ensured the development of truly international research frameworks that help to orient national and regional research efforts in ways that facilitate international collaboration. It has also fostered the building of the international and interdisciplinary networks needed to undertake the research.

The IGBP project science plans and implementation strategies are good examples of IGBP international frameworks for collaborative research. For example, the SOLAS Science Plan and Implementation Strategy was the result of several years of consultation and iteration within the SOLAS community, including an Open Science Meeting in 2000 and a meeting of SOLAS National Representatives in 2002. Through plenary presentations and working group discussions at the Open Science Meeting scientists agreed upon the over-arching questions for SOLAS research. This led to a draft science plan which was revised based on feedback from the community. In 2001 the SSC invited national representatives to participate in the ongoing and planned national research activities of relevance to SOLAS, and thus providing a realistic implementation strategy. The document was reviewed in 2003, and after final revisions and approval was published in early 2004. The scientists who participated in the consultative development of the framework formed the initial SOLAS network, which continues to expand as activities progress.

Research Networks to Tackle Focused Scientific Questions

Many global change questions are best addressed by the long-term coordinated efforts of an international research community. Thus networks focused on critical, well-posed scientific questions are central to the implementation of many IGBP projects. IGBP networks share expertise on experimental technologies, help transfer this expertise to developing countries (especially where relevant to local science and policy), interact with relevant modelling communities to ensure the latest understanding is used, and conduct periodic syntheses on focused topics. This approach leads to faster scientific progress and more comprehensive understanding of global processes and their regional variations.

An example of this approach is the FLUXNET network of eddy covariance flux measurements, which is a global network of over 240 flux towers across all major biomes continuously measuring exchanges of carbon dioxide, water vapour and energy between the biosphere and the atmosphere. Initiated by BAHC and GCTE and now supported by iLEAPS, the goals are to quantify the temporal dynamics, spatial patterns and biotic and abiotic forcings of carbon dioxide, water vapour and energy fluxes between the land surface and the atmosphere, and to provide data for validation of remote sensing products used to infer fluxes of carbon dioxide.

FLUXNET has made major contributions to the understanding of processes that control water, energy and carbon dioxide exchange. For example, FLUXNET has helped to (i) reveal the effect of changing growing season length on net carbon dioxide exchange; (ii) quantify variations in light use efficiency (and hence gross primary production) with cloudiness; and (iii) test remote sensing algorithms used in seasonal forcing of models for computing carbon exchange. In some locations clusters of measuring stations allow vegetation succession to be studied.

Institutional Network for Earth System Science

Many pressing Earth System science issues (such as environmental sustainability) extend beyond the remit of any single global change research programme or institution. To help facilitate Earth System science research and education and to promote systems-level analysis and integration, IGBP will work to establish a global network of leading Earth System science research institutions. The goals of this institutional network are primarily to enhance existing international research and education efforts to address systems-level themes including: (i) biogeochemistry-climate interactions (past, present and future); (ii) social-biogeophysical interactions (past, present and future); and (iii) strategies for Earth System modelling. Additionally, the network will help (i) formulate strategies for future global observation systems; (ii) develop collaborative international research projects amongst network participants; (iii) augment educational curricula in Earth System science; and (iv) promote stakeholder interaction and communication of scientific results beyond the scientific community.

The institutional network will use the IGBP umbrella to structurally link leading institutions via agreements that enhance the mobility of personnel and the sharing of resources. The network will provide participants with access to the AIMES post-doctoral network, facilitate their participation in other IGBP and ESSP activities and provide a link via IGBP to global observing systems. The network will improve access to institutional facilities, enhance computer infrastructure for Earth System modelling and provide a neutral platform for model intercomparisons. The network should help share perspectives between developed and developing countries, help facilitate building centres of excellence in developing countries, and create a lasting forum for dialogue between leadingglobal change institutions and stakeholders.

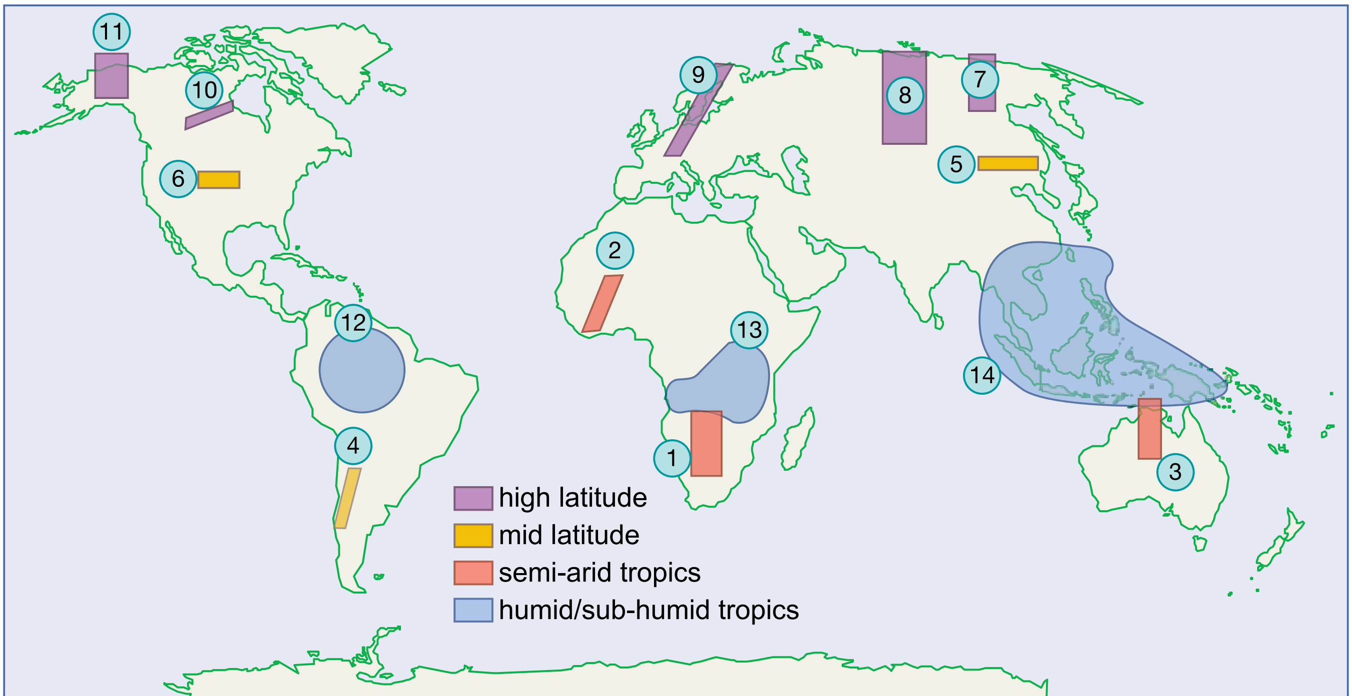
Standard Methods

Earth System science often requires a large number of process or case studies at multiple sites under different conditions around the world, and their subsequent comparison and integration. An essential component in this approach is the development and use of standard research methods. The initial phase is method development, usually based on broad consultation. The method is then communicated widely (for example, by publication of on-line and hard copy guidelines), and regional workshops held to promote the method's use.

An example of a standard method developed and promoted by IGBP is the LOICZ biogeochemical budgeting method for coastal seas. A global study of biogeochemical fluxes in coastal seas is difficult because of the strong heterogeneity of the coastal zone, hence application of a standard method by an international network of researchers is very effective. The international LOICZ community developed and applied a standard method based on conservation of mass for estimating coastal biogeochemical fluxes, especially within the bays and estuaries of the inner coastal zone. The method provides estimates of carbon, nitrogen and phosphorus fluxes into and out of the coastal zone, including the emission of gases to the atmosphere. Because nutrients undergo reactions in coastal waters, budgeting is complicated. The method therefore relies on measuring fluxes for one nutrient species (usually phosphorus) and applying scaling ratios to estimate the fluxes of other nutrient species.

The method uses small, or moderate amounts of existing or easily obtainable data, and is widely applicable enabling cross-site comparisons. Cross-site comparisons have been possible across widely differing sites, for example, from local lagoons and estuaries to the large East China Sea; from pristine sites to sites degraded by high anthropogenic nutrient loadings; from shallow water bodies to water bodies hundreds of metres in depth; and from tropical to arctic environments. Many regional workshops have been conducted to communicate and promote the method, and a web site provides method details and updates, tools for implementation, training materials and results from completed studies. More than 200 coastal budgets have been determined by around 180 scientists (see Figure 21, Box 7).

Figure 30. The IGBP terrestrial transects.



1. Kalahari Transect (KALA)
2. Savanna on the Long-Term (SALT)
3. North Australian Tropical Transect (NATT)
4. Argentina Transect
5. North East Chinese Transect (NECT)
6. North American Mid-Latitude Transect (NAMER)
7. Siberia Far East Transect
8. Siberia West Transect
9. Europe Transect
10. Boreal Forest Transect Case Study (BFTCS)
11. Alaskan Latitudinal Gradient (ALG)
12. Amazon (LBA)
13. Miombo Woodlands Transect
14. South East Asian Transect

Long Time-series Observations

Complementary to intensive field campaigns are long time-series observational stations and networks. These are important for detecting long-term trends, particularly where anthropogenic forcings may be driving change on top of considerable natural variability. They also provide long-term environmental baselines for intensive field campaigns and process studies. Examples of long time-series observations include monitoring of atmospheric carbon dioxide via the global flask network, the IGBP terrestrial transects and long time-series oceanic stations for marine processes. All of these require a significant international coordination to achieve global comparability and applicability. A important issue is determining when and how to move long time-series observations from the research domain to the operational observation domain.

An example of the promotion of long time-series observations are the IGBP terrestrial transects (Figure 30). These were established in the mid-1990s to support the land-focussed IGBP projects, and as such will be important for GLP and iLEAPS. They are generally of around 1000 km long and 200–300 km wide, and are aligned along important environmental gradients. For example, north-south transects in the high latitudes encompass the boreal forest and tundra biomes and capture temperature variation as an important controlling factor. Transects in the mid-latitudes and semi-arid tropics are based on moisture gradients, while other transects follow gradients of land use intensity. Land use intensity gradients are conceptual and are spatially more complex than those based on quasi-linear biophysical gradients, but they are exceptionally important for studying tropical land use change.

Each transect is based on long-term observational sites distributed along the primary gradient. On some transects each site consists of a major observational station with a cluster of ancillary sites to examine secondary gradients and local variability. Intensive manipulative experiments or field campaigns are sometimes embedded within transects using longer-term observations as an environmental baseline. To maximise the value of the transects, observational data and experiments or field campaigns are usually coupled with modelling and periodic syntheses of large-scale land system response to global change.

Global Databases and Policies to Promote Data Sharing

Earth System understanding requires globally consistent data describing critical parameters and processes of biogeochemical cycles. The advent in recent decades of remotely sensed data has revolutionised Earth System understanding, and led to a burgeoning number of global databases. *In situ* observation systems have been established to complement remotely sensed data. IGBP projects have helped guide and facilitate the construction of many relevant global databases including: (i) high resolution land cover; (ii) reactive trace gases and aerosols in the atmosphere; (iii) soil structure and mineral/chemical composition; and (iv) surface ocean partial pressure of carbon dioxide. IGBP has played a central role in the design, construction, archiving and dissemination of a wide range of palaeo environmental records that have become critical for supporting the global change research across and beyond IGBP.

An example of a global database to promote data sharing is the PAGES palaeo database. PAGES, together with the World Data Centre network of ICSU, has established a long-term repository for palaeo data critical for Earth System studies. PAGES continues to promote the move towards multi-proxy and interdisciplinary databases, and to facilitate the construction of spatially explicit, well-calibrated data against which model simulations can be tested. PAGES will make special efforts to retrieve the key palaeo archives that are themselves disappearing due to global change, such as glaciers, coral reefs, coastal tropical wetlands and boreal peat lands.

Model Intercomparisons and Comparisons with Data

Earth System models are essential tools in global change research, integrating current understanding in internally consistent ways, supporting hypothesis testing and providing plausible scenarios of future Earth System evolution. These models however, must be rigorously tested to improve confidence in their ability to simulate Earth System functioning. IGBP provides an international platform for the comparison of such models with each other and with data. Model intercomparisons help identify the strengths and weaknesses of different modelling approaches, share knowledge on modelling techniques and structures, and accelerate model development. Testing models against data is crucial for model performance and for the consistency and usefulness of different databases. Model intercomparisons and comparisons with data are undertaken in every IGBP project, but such work within GAIM and AIMES in particular has significantly enhanced the ability to understand and simulate Earth System functioning.

An example of the model intercomparison approach is C4MIP (Box 11) initiated by GAIM and WGCM. A common protocol has been used for comparing the results of coupled models and exploring the reasons for divergence of results. Early results showed a positive feedback between an interactive carbon cycle and climate, with all models simulating increased atmospheric carbon dioxide and stronger warming by 2100 compared to uncoupled model runs. In addition, all models show the terrestrial biospheric response dominating the feedback effects. The next stage in complex model development – coupling full atmospheric chemistry into models – will also be coordinated by an AIMES-WGCM partnership.

Modeller-Experimentalist Interactions

IGBP will actively foster interactions between modellers and experimentalists, and will seek to ensure such interactions are carefully planned and implemented to maximise their benefits. The planning of these activities will seek an experimental design for the minimum combination of observations and models needed to ensure comparability, yet without preventing the addition of observations/models to address questions specific to a particular experiment. These activities are expected to bring together laboratory studies, *in situ* observations, remote sensing, and both detailed process modelling and global-sale modelling.

These activities are expected to enhance the interactions between IGBP and key partners, for example, IGAC-SPARC collaborations on atmospheric chemistry and climate and iLEAPS-GEWEX collaborations on land-atmosphere interface processes. A major such activity involving IGBP and WCRP is envisioned to investigate aerosol-cloud-climate-health interactions. Already, many large field campaigns have investigated aerosol-cloud interactions in different locations including areas of mid-latitude marine stratocumulus, areas of tropical convection, the mid-latitude upper troposphere and Arctic stratus near the ice margin. Many of these campaigns either directly involved modelling studies or spawned modelling activities, however, it has been difficult to directly compare them to learn about the relative importance of different processes in different geographical areas and under different dynamic and thermodynamic conditions. In addition, the issue of air quality and health has seldom been an integral part of any of these studies. Fostering dialogue and interactions between experimentalists and modellers will greatly enhance the explanatory power of these approaches.

Multinational Field Campaigns and Experiments

Earth System process studies and targeted observations often require techniques, specialised equipment or instrumentation that are limited in number or availability. Furthermore, Earth System processes do not operate within national boundaries and thus often require multi-national cooperation. In these cases, the best approach is intensive, highly coordinated field campaigns in which resources from several countries are pooled. Coordination avoids unnecessary duplication of effort and maximises the scientific value of the campaign. IGBP projects are an ideal platform for such multi-investigator and multi-national campaigns. Examples include: (i) land surface experiments to measure water, energy and trace gas fluxes at different scales; (ii) airborne measurement campaigns to characterise the composition and chemistry of the troposphere; and (iii) biomass burning experiments in remote areas. Increasingly, these experimental campaigns are planned and executed together with modelling exercises to more fully integrate model and experimental activities.

Examples of multi-national field campaigns from the first phase of IGBP are the IGAC Aerosol Characterisation Experiment (ACE) campaigns. These sprang from the recognition that progress in tropospheric chemistry required a more coordinated approach to aerosol measurement, by the coordinated deployment of multiple individual measurement platforms. IGAC coordinated large-scale, intensive field campaigns involving research teams from many countries. ACE was able to capture significant aerosol processes that occur over large geographical areas by coordinating ships, aircraft, surface stations, satellites, specialised instruments and large numbers of investigators. The international approach also promoted active participation by meteorologists (to provide the descriptions of transport fields necessary for interpretation of observations) and modellers able to integrate process-level understanding and provide model-based projections to guide the observations themselves. ACE facilitated the open sharing of data between researchers and the broader scientific community, greatly enhancing the usefulness and value of the data. In the second phase of IGBP similar campaigns are envisaged, for example, to better characterise global ocean-atmosphere exchanges.

Data Management

Since its formation in the late 1980s, IGBP has placed a high priority on data issues, and a data management strategy is also part of the general terms of reference for IGBP projects. The strategy entails establishing a data management and archiving system for the project. Data systems should address the issues of data quality, creation of data sets, metadata and catalogues, data archiving, data standards, data sharing, external co-operation and linkages to data agencies, networking and distribution of data, and future instrumentation needs.

One of the programme's original framework activities was Data and Information System (DIS), the goal of which was to support the IGBP projects in defining, developing and accessing global databases to aid their work. DIS played a strong role in linking the IGBP scientific community with satellite remote sensing agencies to help ensure that databases produced from satellite observations were suitable for global change research. In addition, DIS brokered access for IGBP scientists to high resolution satellite data, which in the early 1990s was both costly and difficult to obtain. In terms of non-remotely sensed data, DIS played a leading role in building two important land-oriented databases, one on land cover (including a widely used classification scheme) and the other on soil characteristics.

By 2001 however, the data world had changed considerably and access to global databases for individual scientists was much more open, inexpensive and convenient. Around that time, IGBP concluded DIS and focused instead on participation in the Integrated Global Observation Strategy Partnership (IGOS-P). IGOS-P has facilitated the coordination of multiple databases around major Earth System themes, such as oceans, atmospheric chemistry and the carbon cycle. IGBP has already led the development of the carbon cycle observation theme, and has contributed strongly to themes on atmospheric chemistry, the coastal zone and terrestrial ecosystems.

More recently IGBP became a participating organisation in the Group on Earth Observations (GEO) – an international partnership which in 2006 included 60 countries and 43 international organisations. GEO aims to build a Global Earth Observation System of Systems (GEOSS) by 2015. GEOSS will work with, and build upon existing national, regional and international systems to provide comprehensive, coordinated Earth observations from thousands of instruments worldwide, transforming the data they collect into vital information for society. As one of the participating organisations, IGBP is committed to contributing to the GEOSS effort the data and information gathered through IGBP research. As GEOSS develops, the strategies for IGBP and its projects will be adapted to the overall GEOSS approach.

IGBP is also an associate of the Committee on Earth Observing Satellites (CEOS) – an international coordinating mechanism charged with coordinating international civil space-borne missions designed to observe and study the Earth. CEOS has 25 members (mostly space agencies) and 20 associates (associated national and international organisations), and is recognised as the major international forum for the coordination of Earth observation satellite programs and for the interaction of these programs with users of satellite data worldwide. Involvement in CEOS will help IGBP improve satellite data access for the research community, and help IGBP communicate the data requirements of the research community to the observing community.

Capacity Building

IGBP is committed to capacity building to address the imbalance between the scientific capabilities of developed and developing countries. There are several aspects to this imbalance which should be addressed: (i) differences in the level of research resources; (ii) differences in research infrastructure; (iii) differences in opportunities to participate in international initiatives; and (iv) insufficient exchange of people and ideas between developed and developing countries. IGBP will use different and complementary approaches to address these imbalances and to help enhance research institutions in developing regions.

Research-driven capacity building has proven to be an effective way to improve the scientific capacity of less developed countries (LDCs). Approximately one quarter of IGBP committee members come from LDCs, and thus contribute to the planning, coordination and evaluation of IGBP research. LDC scientists are members of most IGBP research networks and participate in observational campaigns and process studies. Meetings of the SC-IGBP and IGBP Officers are often held in developing countries, allowing interaction between the IGBP leadership and scientists from the region.

IGBP projects have undertaken, and will continue to undertake a range of capacity-building activities. In the first phase of IGBP for example, GAIM conducted Earth System modelling workshops in Brazil and Kenya, GCTE established the Global Change Impacts Centre for Southeast Asia and LOICZ ran many biogeochemical budgeting training workshops. In the second phase of IGBP similar efforts will continue and will be expanded, including: (i) establishment by AIMES of an international post-doctoral network for Earth System science; (ii) the recurrent summer schools of SOLAS and iLEAPS; and (iii) continued cosponsorship by LOICZ of a Masters programme in Water and Coastal Management. In addition to these specific examples, all IGBP projects will increasingly develop regional activities that promote capacity building, and will use a variety of training methods (including workshops and web-based learning) to build scientific capacity within their communities, especially in LDCs.

The need for regionally-based training and exchange programmes, facilitation of regional interdisciplinary research, and regional modelling and synthesis activities, led in the first phase of IGBP to the establishment of START as an IGBP project. Initially cosponsored by IHDP and WCRP, START is now an ESSP project and has evolved to focus on regional research, assessments for policy makers and research-driven capacity building. START undertakes fundamental capacity building in areas where the scientific base is too weak to allow participation in international programmes. Many bilateral activities are undertaken by START and IGBP projects, and many LDC scientists who gained their first experience in international global change science via START are now members of IGBP research networks and committees.

Regional research and capacity building in global change science is also supported at the inter-governmental level by the Inter-American Institute for Global Change Research (IAI) and the Asia-Pacific Network for Global Change Research (APN). IGBP benefits strongly from its close interaction with these organisations, with IGBP projects obtaining funding from them for regionally-oriented research activities. IGBP scientists contribute time and expertise to developing the regional research agendas of these organisations. In addition to IAI and APN, IGBP will continue its efforts (begun in 2005) to assist in the establishment of an organisation to coordinate and foster-global change research in Africa. This network or organisation is likely to focus on strengthening collaboration between scientists in Africa and Europe, and will most importantly improve the access to Earth System science and global change funding for African researchers.

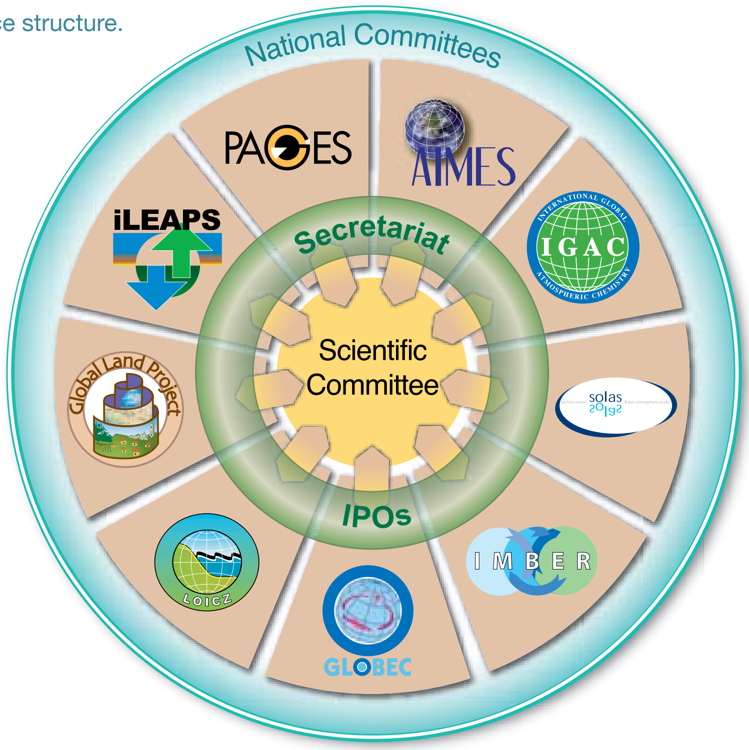
Organisation and Infrastructure

IGBP has a simple governance structure (Figure 31) that enables efficient implementation of its scientific structure (Figure 11) and promotes internal communication and integrative and interdisciplinary activities. Core aspects of IGBP governance are described in the IGBP Constitution (see www.igbp.net).

The SC-IGBP is the central governing body of IGBP. Most of the scientific effort of IGBP is organised into projects, many of which are cosponsored by other organisations, and these projects are represented on the SC-IGBP (the teeth on the SC-IGBP cog; Figure 31) by their SSC chairs. The Secretariat and the IPOs facilitate information exchange through the IGBP network and scientific synthesis and integration. The Secretariat directly supports the activities of the SC-IGBP, including managing the records and information relating to SC-IGBP meetings and memberships and project SSC memberships. The Secretariat also promotes IGBP and disseminates its scientific results to different audiences. NCs are points of contact in the countries and regions that participate in the network, help initiate and organise activities at the local and regional level and are an important interface with the wider international research community.

In addition to its internal structure, IGBP must, in order to achieve its goals, operate in a much larger inter-organisational structure (Figure 32). This structure is conceptual rather than formal, but is important to understand, as it influences the modes of operation of IGBP, and the different relationships maintained with different organisations. In the "big picture", IGBP is influenced by its parent body (ICSU) and by various funding bodies, including the International Group of Funding Agencies for Global Environmental Change (IGFA). Close collaborations and formal project cosponsorship arrangements exist with several research organisations, including the other global change research programmes which together form the ESSP. IGBP seeks to influence, and to some extent depends upon organisations involved in Earth observations (IGOS, GEO, CEOS). To facilitate capacity building IGBP interacts with regional networking organisations for global change research (IAI, APN).

Figure 31. IGBP governance structure.



Scientific Committee

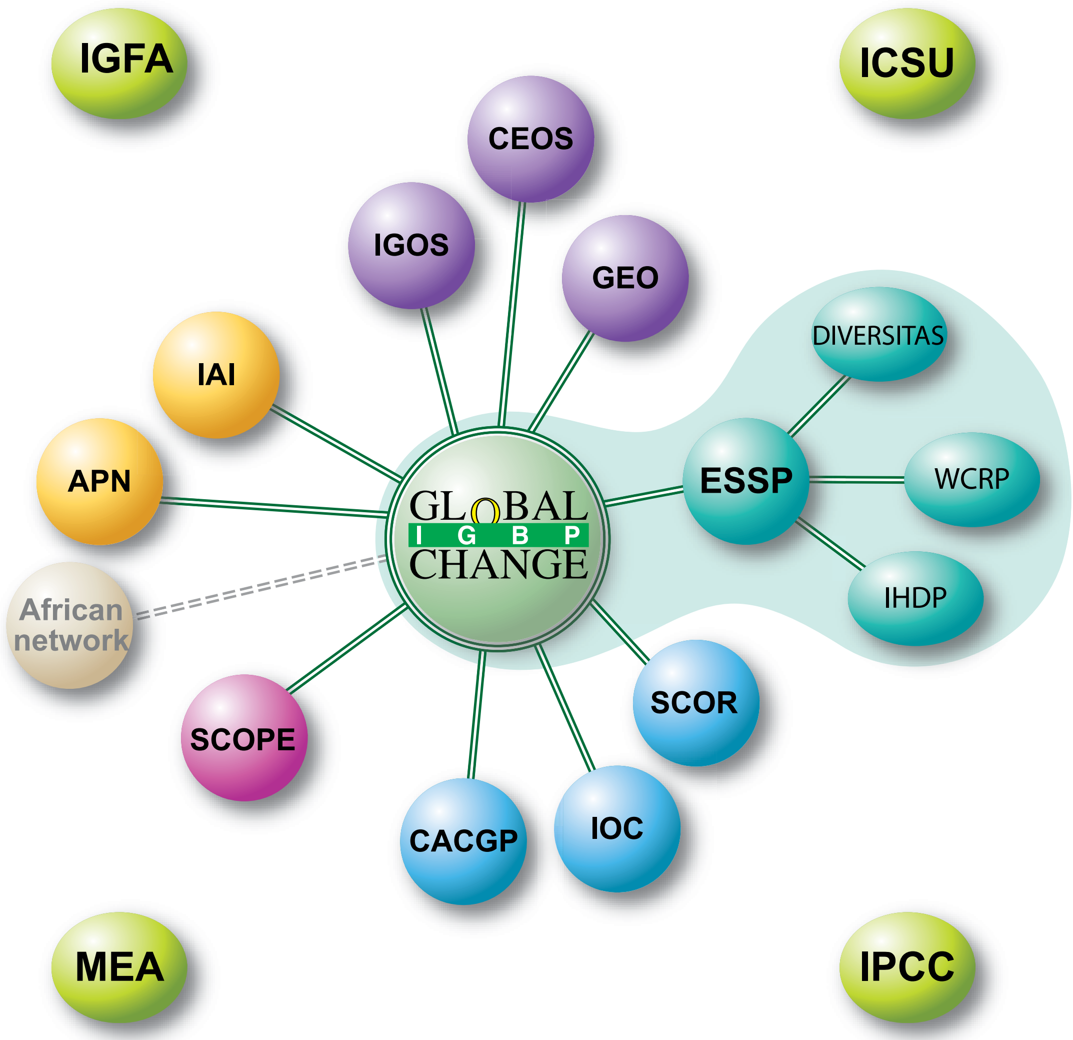
The SC-IGBP is responsible for the scientific oversight and strategic development of IGBP and for helping to ensure that IGBP research results are published and used. Members of the SC-IGBP promote and coordinate the national, regional and international activities of the network, and act as liaisons with other national and international organisations. The SC-IGBP meets at least once per year.

Beyond its governance function the SC-IGBP is an important forum for further developing the interdisciplinary science of IGBP, being comprised of experts from many disciplines and geographic regions. Each IGBP project is represented and reports at SC-IGBP meetings, providing the opportunity to initiate integrative research (such as FTIs) spanning the more disciplinary efforts of the projects.

The SC-IGBP consists of approximately 30 members, 15 of whom are appointed by the Executive Board of ICSU primarily on the basis of scientific excellence, but with consideration of disciplinary, geographical and gender balances. In addition to the 15 ICSU-appointed members, other members include the Chairs of the IGBP project SSCs (and any Standing Committees) and the Chairs of the Scientific Committees of WCRP, IHDP and DIVERSITAS. Memberships are normally for three years, renewable once. Several guests are normally invited to the annual meeting of the SC-IGBP, including the Executive Officers of the IGBP and ESSP projects, the Chairs of the ESSP project SSCs, and representatives of important cosponsors of IGBP projects such as SCOR.

The Officers of the SC-IGBP are the Chair, up to three Vice-Chairs, the Treasurer and the Past-Chair (*Ex officio*,

Figure 32. The inter-organisational structure within which IGBP operates.



normally for a period of one year). The IGBP Chair is appointed by ICSU, and the Officers (under leadership of the Chair) are responsible for conducting the affairs of the SC-IGBP between meetings.

Project Scientific Steering Committees

Project SSCs are comprised of experts in disciplines relevant to the project, with attention to discipline, geographic and gender balances. SSCs set the project's scientific agenda, guide the organisation and implementation of activities, and assist in raising funding for project activities including the IPO. SSC members are usually involved in analysing, integrating and publishing project results, and assembling the myriad of individual project investigations in a broader context.

SSCs typically have around 15 members, appointed by the IGBP Officers and the executive bodies of any cosponsors. Many SSCs have an Executive Committee that conducts the affairs of the SSC between meetings with assistance from the project Executive Officer and the IPO. SSC memberships are normally for three years, renewable once. SSCs normally meet at least once per year.

IGBP Secretariat

The IGBP Secretariat is hosted by the Royal Swedish Academy of Sciences in Stockholm, Sweden. As its primary function, the IGBP Secretariat assists the IGBP Officers in ensuring implementation of SC-IGBP decisions. Secretariat members prepare, attend and document the outcomes of the SC-IGBP and Officers meetings. The Secretariat also undertakes scientific communication within and beyond the IGBP network (see Section 8).

Each IGBP project has a scientific contact at the Secretariat and these liaisons help channel information between the projects (IPOs and SSCs), the SC, NCs and partner organisations. The Secretariat helps promote IGBP and ensure project research results are communicated outward, organises the periodic IGBP scientific congresses and assists with the organisation of ESSP open science conferences. Secretariat staff represent IGBP at international and national fora as required by the SC-IGBP. The Secretariat raises and manages the funds for the operation of the Secretariat and the SC-IGBP.

The Secretariat has around ten staff covering scientific liaison, communications and administration. It is headed by an Executive Director appointed by ICSU to a three-year (renewable) term of office. The Executive Director is responsible for managing the Secretariat, aiding in the strategic development of IGBP, coordinating preparation of the SC-IGBP and Officers meetings and preparing the annual report.

International Project Offices

Each IGBP project is supported by an IPO (led by an Executive Officer) and in some cases, regional project offices. Regional offices are additional project contact points that share the project administrative work load, support project Co-Chairs and improve access to national funding. The main functions of IPOs are to:

- administer the project on a day-to-day basis, under the overall guidance of the SSC;
- coordinate research efforts including research campaigns and field programmes;
- promote and advocate for the project, enlisting wide international participation;
- maintain connections with relevant international, national and regional projects;
- ensure effective coordination within IGBP;
- disseminate project information and research results;
- monitor and assess project progress and SSC activities; and
- secure financial support for the IPO.

IPOs collaborate closely with the IGBP Secretariat on scientific integration. Executive Officers usually meet with the Secretariat annually in addition to interactions at annual SC-IGBP meetings.

IGBP and Global Change National Committees

NCs are the grassroots of the IGBP network and contribute to the development of the research agenda through participation in IGBP congresses, scientific conferences and open meetings at programme and projects levels. They actively encourage national scientific communities to participate in IGBP projects and thus often have specific project representation.

IGBP research is mainly implemented through nationally funded projects. Whilst NCs are not always involved in the funding process, they are usually aware of the relevant national research effort and thereby assist IGBP projects identify planned and ongoing research that addresses IGBP priorities. NCs help raise central funds for IGBP, both by helping to secure national contributions and by informing national funding agencies of the nature and importance of IGBP research. NCs often initiate regional collaborations with START, IAI, APN and emerging scientific networking partners.

Endorsement Process

IGBP encourages and facilitates international, interdisciplinary collaboration, and hence external projects or programmes ("external projects") often solicit formal endorsement from IGBP. Endorsement should be mutually beneficial: external projects benefit by assess to, and support from, the international IGBP research network; IGBP benefits by access and input to research activities initiated outside the network that contribute to the IGBP goals. Endorsement by IGBP obliges an external project to conform to the scientific aims, criteria of scientific scope and excellence, principles of openness, geographic and gender balance, and free exchange of data, as expressed in the science plans and implementation strategies of IGBP and its projects.

IGBP will consider external projects for endorsement at both the project and programme level – the appropriate level depending on the scope and focus of the external project. Endorsement will be most common at the project level, where the majority of IGBP scientific activity takes place, and where the greatest opportunities for interaction exist. Endorsement by more than one IGBP project may be appropriate. Programme-level endorsement will only be considered for international external projects where the scope requires expertise from most or all IGBP projects, or where the goals closely match the goals of IGBP as a whole.

When an external project applies (either directly, or on the recommendation of the IGBP Secretariat) to one or more the IGBP projects for endorsement, an endorsement decision will be made by the project SSC(s). The IPO(s) will inform the IGBP Secretariat of the request and later of their SSC decision. The IGBP Secretariat will forward this information to other IPOs, appropriate NCs and the SC-IGBP. External projects endorsed by an IGBP project are required to provide a short annual report to the annual meeting of the project SSC, and acknowledge endorsement in project products.

When an external project applies for programme-level endorsement, initial contact should be with the IGBP Secretariat, either directly or via a member of the SC-IGBP. The IGBP Secretariat will inform the full SC-IGBP and all IPOs of the request, and solicit input and recommendations for consideration by the IGBP Officers. Programme-level endorsement decisions will be made by the IGBP Officers and communicated to the external project, appropriate NCs and all IPOs. External projects endorsed at programme level are required to provide a short annual report to the annual SC-IGBP meeting, and to acknowledge endorsement in project products.

A more detailed description of the endorsement procedure (including assessment criteria) can be obtained from the IGBP Secretariat.

Information Management

The IGBP Secretariat maintains the IGBP "corporate memory", including documentation of the constitution, terms of reference, important procedural guidelines (including for committee memberships), records of meetings and decisions (especially of the SC-IGBP and the IGBP Officers), official correspondence, agreements, contracts and financial records. The Secretariat also manages and archives copies of IGBP publications (in printed and electronic forms), databases of contacts and publications, presentation and educational materials, and records of IGBP communications activities including media and outreach work. In addition to hard copy archives, the Secretariat maintains electronic records on the Secretariat server with regular tape back-ups.

The Secretariat will increasingly use the internet to manage information for access by the IGBP network and by external audiences. For use within the IGBP network, the Secretariat will make its publications and contacts databases accessible via the website, and seek to integrate these with similar databases maintained by IPOs. The contacts database will be redesigned to improve its flexibility and usefulness within the IGBP network, for example, to enable the Secretariat to quickly put journalists in touch with relevant experts. The Secretariat will continue to promote and rely upon an IGBP extranet facility for communications and information exchange within the IGBP network.

Wherever possible, IGBP publications and presentation materials will be made available on the website in electronic forms for free download. The website – redesigned site launched in 2006 – includes "resource rooms" for the scientific community, media, education and policy makers.

Evaluation

The IGBP publications database will enable IGBP to document and report on its scientific output and to properly attribute this output to different projects and activities. As the primary output of IGBP is scientific knowledge, the publications database will provide primary information to help evaluate progress and output. Overall progress will be evaluated by the number of papers in refereed scientific journals arising from research of IGBP and ESSP projects and IGBP FTIs, the number of books and reports published based on IGBP-related research and the number and type of major field campaigns and modelling activities organised by IGBP and its projects. Progress reporting will occur by publication of an annual report, annual progress reports to major funding agencies and annual progress presentations to IGFA. The approaches to be adopted for the evaluation of IGBP progress in science communication are described in *Communication and Outreach*.

In addition to output, IGBP will evaluate its international diversity and reach. This will be assessed by the level of international participation in the IGBP network, diversity of IGBP committee memberships and the number of active NCs. Independent evaluations of IGBP will be undertaken by ICSU. The first such review will occur in late 2007 or early 2008, and will guide the implementation of IGBP. This first review will consider the scientific progress and the appropriateness of the IGBP structure, and the degree of successful of the initial stages of implementation.

Finances

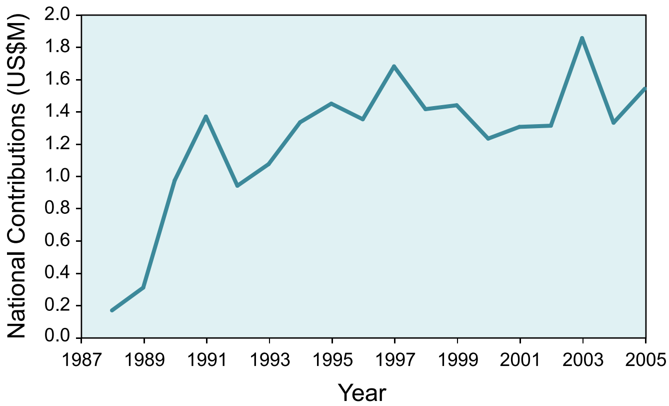
The IGBP Secretariat, the SC-IGBP and some project activities are financed primarily by contributions from around forty countries. Since 2001 these national contributions have averaged about US$1.5M per year (Figure 33). The variations in this income between years are largely because some "annual contributions" for a given year are received in the following year. National contributions typically represent 60–70% of the total central income. The remaining fraction of the income comes from specific grants to support IGBP projects (where funds are simply administered by the Secretariat), research activities and conferences.

Typically, around one third of the unencumbered income is spent on Secretariat salaries (a significant fraction of which directly supports scientific activities), and around half is spend on non-salary scientific and communication activities. About 10% of the income covers Secretariat operating expenses, and the remainder (around 5%) funds IGBP publications and the website. The scientific activities funded include project activities, workshops and conferences, meetings, contributions to ESSP, GEO and IGOS and other partners, and integrative research efforts.

Maintaining the current income level is increasingly challenging. IGBP will work with the International Group of Funding Agencies (IGFA) to develop a funding strategy that will enable IGBP to (i) fully implement this Science Plan; (ii) contribute to the evolution of the ESSP, (iii) increase support of science in developing countries; and (iv) broaden engagement with stakeholders. IGBP will also seek to expand its funding base beyond the IGFA community, and will increasingly seek in-kind support from those developing countries unable to make direct financial contributions.

As well as strategies to maintain funding, IGBP will work to reduce costs, for example, by using new communication technologies (e.g. video and web-conferencing) to lessen travel and the associated costs. To the same end, IGBP will where possible, consolidate common activities between the IGBP Secretariat and IPOs, and work together with the ESSP partners to hold joint meetings, workshops and conferences. While one-off events (such as IGBP congresses) will require additional funding, these demands are met by specific grants; IGBP does not foresee any overall substantial growth in costs to implement the science agenda described herein.

Figure 33. History of national contributions to IGBP.



Communication and Outreach

Earth System science is critical for the development of effective policy to address global change and sustainability. As an apolitical but politically-relevant organisation IGBP aims to bridge the gap between the international scientific community, policy makers and the public. Communication of Earth System science is therefore a key activity of IGBP.

The communication strategy follows from the long-term communication goals, which in turn follow from the IGBP vision. The long-term communication goals of IGBP are to:

- establish IGBP as a credible source of Earth System science;
- promote Earth System science and demonstrate a scientific structure that supports Earth System science;
- position IGBP within the scientific community as a primary organisation that adds value to national and international projects by providing the global context and the integrative framework for national and regional research efforts; and
- provide policy-relevant (but not policy-prescriptive) information on global change to policy makers and the public.

IGBP communication activities occur at multiple levels. Firstly, IGBP contributing scientists publish the results of their work in the peer-reviewed literature, and contribute to the assessment processes of IPCC and MEA. At the IGBP project level, scientific results are also synthesised and communicated to a wider range of audiences, for example, via project newsletters and websites. The communication strategies of IGBP projects are detailed in their respective science plan and implementation strategies. The IGBP Secretariat undertakes and facilitates programme-level communication activities. The strategy and implementation tactics described herein focus on these programme-level communication activities, with a strong emphasis on communication of the Earth System science that emerges from programme-wide scientific interactions, synthesis and integration. Additionally, the IGBP Secretariat will work closely with IGBP core projects to highlight their achievements to the scientific community and other audiences, and to support programme-wide integration, especially by improving inter-project communication.

At the programme-level, both internal and external communications are important. Internal communications target project SSCs, IPO staff, contributing research scientists and funding agencies, via meetings and workshops, electronic communication and scientific documents (newsletters, journal articles and science plans). External communications target the scientific community, decision makers (e.g. politicians and resource managers), funding agencies, the education sector and the public.

IGBP has eight programme-level communication objectives: (i) improve communication within the IGBP community; (ii) update and revitalise IGBP communication tools; (iii) develop the visual identity of IGBP; (iv) promote Earth System science to the broader scientific community; (v) inform policy makers on key global change issues; (vi) influence the next generation of Earth System scientists; (vii) extend IGBP outreach efforts amongst agencies, decision makers, schools and the public; and (viii) develop new tools to communicate uncertainty, risk and vulnerability in global change.

Meeting these objectives, has been, and will continue to be achieved via three-year implementation plans, with guidance provided by a “Think Tank” of IGBP scientists and communications professionals. The eight objectives have been phased in with successive three-year plans as the communications effort developed and as resources allowed. Objectives (i)–(iii) have been addressed since 2001, objectives (iv)–(vi) have been addressed since 2004 and objectives (vii)–(viii) will be addressed from 2007 onwards. All objectives remain current and ongoing. Below, the focus is on the communications plan for 2007–09.

Numerous tactics are in use or are planned for achieving each of the above communication objectives. Internal communication will be improved via (i) refinements to the quarterly Global Change Newsletter, the bi-monthly email bulletin and annual reports; (ii) provision of a

Box 13. Ongoing Outreach Mechanisms

Ambassadors Network

Presentations by respected IGBP scientists can have great impact on policy makers and the public. IGBP will enlist a group of IGBP scientists as spokespeople or "ambassadors". They will be excellent presenters, have a good overview of IGBP science and be prepared to represent IGBP to politicians, political advisors and journalists in their respective countries or at international fora.

Policy-relevant Roundtables

Regional roundtables that bring scientists and policy makers together in two-way dialogue on neutral ground are a coordinated way to communicate IGBP science to policy makers. Collaboration with policy makers from the outset is critical. Roundtables will be tailored to a region and conducted in collaboration with IGBP projects and NCs, usually in conjunction with a scientific meeting or workshop. Roundtables will focus on critical issues relevant to the region and linked to global change.

Media Strategy

The media strategy aims to raise awareness of Earth System science and global change amongst the broader scientific community, decision makers and the public, and to raise the profile of IGBP. The strategy includes global media campaigns in association with large international open science conferences, and regional media campaigns based on local stories with underlying global change messages. Key messages will be identified to guide each campaign and create a underlying theme for all story angles. Each media campaign should have a purpose and is not intended to simply generate media coverage as an end in itself.

IGBP Media Tactics

- provide website "Media Room" with background information, press releases and images;
- monitor the media to identify hot topics and, where possible, respond quickly with accurate and accessible information for journalists;
- develop database of global media contacts and establish contact with key news, science and environment reporters;
- develop group of IGBP scientists willing and able to respond quickly to media requests (including IGBP Ambassadors);
- target specific audiences through different media;
- organise IGBP symposia at major international meetings that attract journalists;
- work with IGBP projects and NCs to publicise regional issues in global change science, especially through regional workshops and policy-relevant roundtables;
- increase the accuracy of reporting by providing well written, plain English press releases and briefing papers;
- provide IGBP Ambassadors with presentation material and media training and organise interviews with journalists; and
- work with IGBP projects to identify science stories and follow-up with media campaigns.

password-protected website; (iii) cross-project databases of contacts and publications; and (iv) development of project-specific communication plans. IGBP products will be updated based on commissioned Earth System and project-level artwork, and presentation/poster/brochure templates will be developed to create and promote the visual identity of IGBP. Earth System science will be promoted by a group of IGBP Ambassadors (Box 13) and through major synthesis publications, regional workshops and IGBP sessions at major international science/policy meetings. Global change science will be communicated to policy makers via jargon-free summary booklets and leaflets, briefings of key politicians, and policy-relevant roundtables of scientists and policy makers (Box 13). The next generation of Earth System scientists will be reached using educational packages for lecturers, web-based materials for students and project summer schools. Broader outreach efforts will include working with projects and NCs on regional activities, media briefings and translation of publications. IGBP will collaborate with risk communication institutes to develop ways to communicate risk and uncertainty, and will work with ESSP partners to develop ways to communicate vulnerability. The IGBP website will be a fundamental component of the communications effort for all audiences and all objectives, acting as a hub for IGBP products and services. Increasing emphasis will be placed on highlighting core project products and achievements on the IGBP website.

IGBP communications will be evaluated periodically. The overall communications effort will be evaluated via web statistics and feedback from the SC-IGBP, the Think Tank and IGBP scientists. Internal communication will be assessed via feedback to the IGBP Secretariat and by confidential telephone surveys of IPO staff and NCs. IGBP products will be evaluated through surveys, review articles in magazines and journals and through unsolicited feedback. Profile-raising activities and Earth System science promotion will be evaluated via media monitoring, and outreach to policy-makers will be evaluated through unsolicited feedback, number of requests for information, extent of collaborations with policy departments and agencies, number of links to the IGBP website and number of downloads from the IGBP website.

A communications crisis is generally a false or inaccurate media report. Media monitoring will enable the IGBP Secretariat to prevent most crises, but in the event of a crisis the IGBP Secretariat will organise a teleconference within 24 hours with IGBP leadership (Executive Director, Deputy Directors and SC-IGBP Chair). If necessary, the Secretariat will prepare and distribute a statement, and brief IGBP spokespeople enabling them to respond to the media, and national government agencies. The Secretariat will monitor the situation to determine any further action and provide information as required.

References

Abraham E, Law CS, Boyd PW, Lavender S, Maldonando, M and AR Bowie (2000) Importance of stirring in the development of an iron-fertilised phytoplankton bloom, Nature 407, 727–730.

Alley RB (2000) The Younger Dryas cold interval as viewed from central Greenland. Quaternary Science Review 19, 213–226

Alverson K, Bradley R and Pedersen T (Ed.s) (2003) Paleoclimate, Global Change and the Future. Springer-Verlag, Berlin, Heidelberg. 220pp.

Andreae MO, Artaxo P, Brandão C, Carswell FE, Ciccioli P, Da Costa AL, Culf AD, Esteves JL, Gash J, Grace J, Kabat P, Lelieveld J, Malhi Y, Manzi AO, Meixner, FX, Nobre AD, Nobre C, Ruivo M, Silva-Dias MA, Stefani P, Valentini R, Von Jouanne J and Waterloo MJ (2002) Biogeochemical cycling of carbon, water, energy, trace gases, and aerosols in Amazonia: The LBA-EUSTACH experiments. Journal of Geophysical Research 107(D20), DOI 10.1029/2001JD000524.

Andreae MO, Rosenfeld D, Artaxo P, Costa AA, Frank GP, Longo KM and Silva Dias MAF (2004) Smoking rain clouds over the Amazon. Science 303, 1,337–1,342.

Andreae MO, Jones CD and Cox PM (2005) Strong present-day aerosol cooling implies a hot future. Nature 435, 1,187–1,190.

Bard E, Raisbeck G, Yiou F and Jouzel J (2000) Solar irradiance during the last 1,200 years based on cosmogenic nuclides. Tellus 52B, 985–992.

Baumgartner TR, Soutar A, and Ferreira-Bartrina V (1992) Reconstruction of the history of Pacific sardine and Northern Pacific anchovy populations over the past two millennia from sediments of the Santa Barbara basin. CalCOFI Report 33, 24–40.

Beaugrand G (2004) The North Sea regime shift: evidence, causes, mechanisms and consequences. Progress in Oceanography 60, 245–262.

Bond G, Kromer B, Beer J, Muscheler R, Evans M, Showers W, Hoffmann S, Lotti-Bond R, Hajdas I and Bonani G (2001) Persistent solar influence on North Atlantic surface circulation during the Holocene. Science 294, 2,130–2,136.

Boyd PW, Watson A, Law CS, Abraham E, Trull T, Murdoch R, Bakker DCE, Bowie AR, Buesseler K, Chang H, Charette M, Croot P, Downing K, Frew R, Gall M, Hadfield M, Hall J, Harvey M, Jameson G, La Roche J, Liddicoat M, Ling R, Maldonado M, McKay RM, Nodder S, Pickmere S, Pridmore R, Rintoul S, Safi K, Sutton P, Strzepek R, Tanneberger K, Turner S, Waite A and Zeldis J (2000) A mesoscale pytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. Nature 407, 695–702.

Brasseur GP, Artaxo P, Barrie LA, Delmas RJ, Galbally I, Hao WM, Harriss RC, Isaksen ISA, Jacob DJ, Kolb CE, Prather M, Rodhe H, Schwela D, Steffen W and Wuebbles DJ (2003) An integrated view of the causes and impacts of atmospheric changes. In: Brasseur GP, Prinn RG and Pszenny AAP (Ed.s) Atmospheric Chemistry in a Changing World: An Integration and Synthesis of a Decade of Tropospheric Chemistry Research. Springer-Verlag, Berlin, Heidelberg. pp207–230.

Chen C (2002) The impact of dams on fisheries: case of the Three Gorges Dam. In: Steffen W, Jäger J, Carson D and Bradshaw C (Ed.s), Challenges of a Changing Earth. Springer-Verlag, Berlin, Heidleberg. pp97–100.

Cicerone R, Orr J, Brewer P, Haugan P, Merlivat L, Ohsumi T, Pantoja S, Poertner H, Hood M and Urban E (2004) The ocean in a high-CO_2 world. Oceanography 17(3), 72–78.

Coale KH, Johnson KS, Fitzwater SE, Gordon RM, Tanner S, Chavez FP, Ferioli L, Sakamoto C, Rogers P, Millero F, Steinberg P, Nightingale P, Cooper D, Cochran WP, Landry MR, Constantinou J, Rollwagen R, Trasvina A and Kudela R (1996) A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. Nature 383, 495–501.

Crossland CJ, Kremer HH, Lindeboom HJ, Marshall Crossland JI, and Le Tissier MDA (Ed.s) (2005) Coastal Fluxes in the Anthropocene. Springer-Verlag, Berlin, Heidelberg. 231pp.

Crowley TJ (2000) Causes of climate change over the past 1000 years. Science 289, 270–277.

Eddy JA (1976) The Maunder Minimum. Science 192, 1,189–1,201.

EPICA (2004) Eight glacial cycles from an Antarctic ice core. Nature 429, 623–628.

Etheridge DM, Steele LP, Langenfelds RL, Francey RJ, Barnola J-M and Morgan VI (1996) Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn. Journal of Geophysical Research 101, 4,115–4,128.

Falkowski PG, Barber RT and Smetacek V (1998) Biogeochemical controls and feedbacks on ocean primary production. Science 281, 200–220.

Falkowski, PG, Scholes RJ, Boyle E, Canadell J, Canfield D, Elser J, Gruber N, Hibbard K, Hogberg P, Linder S, Mackenzie FT, Moore B, Pedersen T, Rosenthal Y, Seitzinger S, Smetacek V and Steffen W (2000). The global carbon cycle: a test of our knowledge of earth as a system. Science 290, 291–296.

FAO (2004) The state of world fisheries and aquaculture. FAO, Rome. 153pp.

FAO (2005) Review of the state of world marine fishery resources. FAO, Rome. 235pp

FAOSTAT (2002) Statistical Databases, Food and Agriculture Organisation of the United Nations, Rome. Available at: www.apps.fao.org.

Fasham M (Ed.) (2003) Ocean Biogeochemistry: The Role of the Ocean Carbon Cycle in Global Change. Springer-Verlag, Berlin, Heidelberg. 297pp.

Fasham MJR, Balino BM, Bowles MC, Anderson R, Archer D, Bathmann U, Boyd P, Buesseler K, Burkill K, Bychkov A, Carlson C, Chen CTA, Doney S, Ducklow H, Emerson S, Feely R, Feldman G, Garcon V, Hansell D, Hanson R, Harrison P, Honjo S, Jeandel C, Karl D, Le Borgne R, Liu KK, Lochte K, Louanchi F, Lowry R, Michaels A, Monfray P, Murray J, Oschlies A, Platt T, Priddle

J, Quinones R, Ruiz-Pino D, Saino T, Sakshaug E, Shimmield G, Smith S, Smith W, Takahashi T, Treguer P, Wallace D, Wanninkhof R, Watson A, Willebrand J and Wong CS (2001) A new vision of ocean biogeochemistry after a decade of the Joint Global Ocean Flux Study (JGOFS), AMBIO 10, 4–31.

Folke C, Carpenter S, Walker B, Scheffer M, Elmqvist T, Gunderson L and Holling CS (2004) Regime shifts, resilience and biodiversity in ecosystem management. Annual Review of Ecology and Systematics 35, 557–581.

Friedlingstein P, Cox P, Betts R, Bopp L, von Bloh W, Brovkin W, Doney S, Eby M, Fung I, Govindasamy B, John J, Jones C, Joos F, Kato T, Kawamiya M, Knorr W, Lindsay K, Matthews HD, Raddatz T, Rayner P, Reick C, Roeckner E, Schnitzler K-G, Schnur R, Strassmann K, Weaver AJ, Yoshikawa C and Zeng N (2006) Climate-carbon cycle feedback analysis, results from the C4MIP model intercomparison. Journal of Climate. *In press.*

Galloway JN, Aber JD, Erisman JW Seitzinger SP, Howarth RW, Cowling EB, and Cosby BJ (2003) The nitrogen cascade. Bioscience 53, 341–356.

Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, Seitzinger SP, Asner G, Cleveland C, Green P, Holland E, Karl DM, Michaels AF, Porter J, Townsend A and Vörösmarty CJ (2004) Global and regional nitrogen cycles: past, present and future. Biogeochemistry 70, 153–22.

Ghan SJ, Easter RC, Chapman EG, Hayder A-R, Zhang Y, Leung R, Laulainen NS, Saylor RD and Zaveri RA (2001) A physically based estimate of radiative forcing by anthropogenic sulphate aerosol. Journal of Geophysical Research 106 (D6), 5,279–5,293.

Glantz P and Noone K (2000) A physically-based mechanism for converting aerosol mass to cloud droplet number. Tellus 52B, 1,216–1,231.

GLOBEC (1997) Global Ocean Ecosystem Dynamics (GLOBEC) Science Plan. IGBP Report 40. IGBP Secretariat, Stockholm. 82pp.

GLOBEC (1999) Global Ocean Ecosystem Dynamics Implementation Plan. IGBP Report 47. IGBP Secretariat, Stockholm. 207pp.

GLP (2005) Science Plan and Implementation Strategy. IGBP Report 53/IHDP Report 19. IGBP Secretariat, Stockholm. 64pp.

Grootes PM, Stuiver M, White JWC, Johnson S, and Jouzel J (1993) Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. Nature 366, 552–554.

Gutman G, Janetos AC, Justice CO, Moran EF, Mustard JF, Rindfuss RR, Skole D, Turner II BL, and Cochrane MA (Ed.s) (2004) Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface. Series: Remote Sensing and Digital Image Processing, Vol. 6. Kluwer Academic Publishers. 461pp.

Hare SR and Mantua NJ (2000) Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47,103–145.

Hsieh CH, Glaser SM, Lucas AJ and Sugihara G (2005) Distinguishing random environmental fluctuations from ecological catastrophes for the North Pacific Ocean. Nature 435, 336–340.

IFIA (2002) Fertilizer Indicators. International Fertilizer Industry Association. Available at: www.fertilizer.org/ifa/statistics/indicators/ind_cn_world.asp.

IGAC (2006) Science Plan and Implementation Strategy. IGBP Report 56. IGBP Secretariat, Stockholm. *In press*.

iLEAPS (2005) Science Plan and Implementation Strategy. IGBP Report 54. IGBP Secretariat, Stockholm. 52pp.

IMBER (2005) Science Plan and Implementation Strategy. IGBP Report 52. IGBP Secretariat, Stockholm. 76pp.

IPCC (2001) Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Winden PJ, Dai X, Maskell K and Johnson CI (Ed.s), Cambridge University Press, Cambridge. 944pp.

Jickells TD, An ZS, Andersen KK, Baker AR, Bergametti G, Brooks N, Cao JJ, Boyd PW, Duce RA, Hunter KA, Kawahata H, Kubilay N, Laroche J, Liss PS, Mahowald N, Prospero JM, Ridgwell AJ, Tegen I and Torres R (2005) Global iron connections between desert dust, ocean biogeochemistry, and climate. Science 308, 67–71.

Johnsen SJ, Clausen HB, Dansgaard W, Gundestrup NS, Hammer CU, Andersen U, Andersen KK, Hvidberg CS, Dahl-Jensen D, Steffensen JP, Shoji H, Sveinbjornsdottir AE, White J, Jouzel J and Fisher D (1997) The delta ^{18}O record along the Greenland Ice Core Project deep ice core and the problem of possible Eemian climatic instability. Journal of Geophysical Research 102, 26,397–26,410.

Klein Goldewijk CGM and Battjes JJ (1997) A hundred year (1890–1990) database for integrated environmental assessments (HYDE, version 1.1). Report 422514002, National Institute of Public Health and the Environment (RIVM). Bilthoven, The Netherlands.

Kromer B, Claussen M, Latuske N, Lüken M, Remmele S and Schleser G (2004) Solar variability and Holocene climate: evidence from radiocarbon, tree-ring proxies and climate system modeling. PAGES News 12(2), 13–15.

Kulmala M, Vehkamäki H, Petäjä T, Dal Maso M, Lauri A, Kerminen V-M, Birmili W and McMurry PH (2004) Formation and growth rates of ultrafine atmospheric particles: a review of observations. Aerosol Science 35, 143–176.

Landry MR, Barber RT, Bidigare RR, Chai F, Coale KH, Dam HG, Lewis MR, Lindley ST, McCarthy JJ, Roman MR, Stoecker DK, Verity PG and White JR (1997) Iron and grazing constraints on primary production in the central equatorial Pacific: an EqPac synthesis. Limnology and Oceanography 42, 405–418.

Laws EA, Ducklow H and McCarthy JJ (2000) Temperature effects on export production in the open ocean Global Biogechemical Cycles. 14(4), 1,231–1,246.

Lee S-H, Wilson JC, Baumgardner D, Herman RL, Weinstock EM, LaFleur BG, Kok G, Anderson B, Lawson P, Baker B, Strawa A, Pittman JV, Reeves JM and Bui TP (2004) New particle formation observed in the tropical/subtropical cirrus clouds. Journal of Geophysical Research 109(D20), DOI: 10.1029/2004JD005033.

Lehodey P, Alheit J, Barange M, Baumgartner T, Beaugrand G, Drinkwater K, Fromentin J-M, Hare SR, Ottersen G, Perry RI, Roy C, van der Lingen CD and Werner F (2006) Climate variability, fish and fisheries. Journal of Climate 19. *In press*.

LOICZ (2005) Science Plan and Implementation Strategy. IGBP Report 51/IHDP Report 18. IGBP Secretariat, Stockholm. 60pp.

Mackenzie FT, Ver LM and Lerman A (2002) Century-scale nitrogen and phosphorus controls of the carbon cycle. Chemical Geology 190,13–32

Mann ME, Bradley RS and Hughes MK (1999) Northern Hemisphere temperatures during the past millennium: inferences, uncertainties and limitations. Geophysical Research Letters 26, 759–762.

Mann ME and Jones PD (2003) Global surface temperatures over the past two millennia. Geophysical Research Letters 30(15), 1820, DOI:10.1029/2003GL017814.

Martin JH (1990) Glacial-interglacial CO_2 change: the iron hypothesis. Paleoceanography 5, 1–13.

Martin JH and Fitzwater SE (1988) Iron deficiency limits phytoplankton growth in the north-east Pacific sub-Arctic. Nature 331, 341–343.

Martin JH, Gordon RM and Fitzwater S (1990) Iron in Antarctic waters. Nature, 345, 156–158.

Martin JH, Coale KH, Johnson KS, Fitzwater SE, Gordon RM, Tanner SJ, Hunter CN, Elrod VA, Nowicki JL, Coley TL, Barber RT, Lindley S, Watson AJ, van Scoy K, Law CS, Liddicoat MI, Ling R, Stanton T, Stockel J, Collins C, Anderson A, Bidigare R, Ondrusek M, Latasa M, Millero FJ, Lee K, Yao W, Zhang JZ, Friederich G, Sakamoto C, Chavez F, Buck K, Kolber Z, Greene R, Falkowski P, Chisolm SW, Hoge F, Swift R, Yungel J, Turner S, Nightengale P, Hatton A, Liss P and Tindale NW (1994) Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean. Nature 371, 123–129.

MEA (2005) Ecosystems and Human Well-Being: General Synthesis. Millennium Ecosystem Assessment. Island Press, Washington DC.

Nordhaus WD (1997) Modelling-induced innovation in climate change policy: theory and estimates in the R&DICE model. Paper prepared for the Workshop on Induced Technological Change, June 1997, IIASA. Laxenburg, Austria.

Peng TH and Broecker WA (1991) Dynamical limitations on the Antarctic iron fertilization strategy. Nature 349, 227–229.

Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola J-M, Basile I, Bender M, Chappellaz J, Davis M, Delaygue G, Delmotte M, Kotlyakov VM, Legrand M, Lipenkov VY, Lorius C, Pepin L, Ritz C, Saltzman E and Stievenard M (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399, 429–436.

Prinn RG, Huang J, Weiss R, Cunnold D, Fraser P, Simmonds P, McCulloch A, Salameh P, O'Doherty S, Wang R, Harth C, Porter L and Miller B (2001) Evidence for significant variations in atmospheric hydroxyl radicals over the last two decades. Science 293, 1,048–1,054.

PPI (1993) Pulp and Paper International's international fact and price book. In: FAO forest product yearbook 1960–1991. Food and Agriculture Organization of the United Nations, Rome.

Richards J (1990) Land transformation. In: Turner BL II, Clark WC, Kates RW, Richards JF, Mathews JT and Meyer WB (Ed.s), The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere Over the Past 300 Years. Cambridge University Press, Cambridge. pp163–178.

Rojstaczer S, Sterling SM and Moore NJ (2001) Human appropriation of photosynthesis products. Science 294, 2,549–2,552.

Rotstayn LD and Lohmann U (2002) Tropical rainfall trends and the indirect aerosol effect. Journal of Climate 15(15), 2,103–2,116.

Ryther JH (1969) Photosynthesis and fish production in the sea. Science 166, 72–76.

Schlitzer R (2000) Electronic atlas of WOCE hydrographic and tracer data now available. Eos – Transactions of the American Geophysical Union 81(5), 45.

Schlitzer R (2002) Applying the adjoint method for global biogeochemical modelling. In: Kasibhatla P, Heimann M, Hartley D, Mahowald N, Prinn R and Rayner P (Ed.s), Inverse Methods in Global Biogeochemical Cycles. Geophysical Monograph Series, Vol. 114. American Geophysical Union, Washington, DC. pp107–124.

Shi H and Singh A (2003) Status and inter-connections of selected environmental issues in the global coastal zones. Ambio 32, 145–152.

Siegenthaler U, Stocker TF, Monnin E, Luthi D, Schwander J, Stauffer B, Raynaud D, Barnola J-M, Fischer H, Masson-Delmotte V and Jouzel J (2005) Stable carbon cycle–climate relationship during the late pleistocene. Science 310, 1,313–1,317.

SOLAS (2004) Science Plan and Implementation Strategy. IGBP Report 50. IGBP Secretariat, Stockholm. 88pp.

Steffen W, Sanderson A, Tyson P, Jäger J, Matson P, Moore III B, Oldfield F, Richardson K, Schellnhuber H-J, Turner II BL and Wasson R (2004) Global Change and the Earth System: A Planet Under Pressure. Springer-Verlag, Berlin, Heidelberg. 336pp.

Ström J, Fischer H, Lelieveld J and Schröder F (1999) In situ measurements of microphysical properties and trace gases in two cumulonimbus anvils over western Europe. Journal of Geophysical Research 104, 12,221–12,226.

Turner SM, Harvey M.J., Law CS, Nightingale PD and Liss PS (2004) Iron-induced changes in oceanic sulphur biogeochemistry. Geophysical Research Letters 31, DOI 10.1029/2004GL020296.

The Royal Society (2005) Ocean acidification due to increases in atmospheric carbon dioxide. The Royal Society, London. 60pp.

UNEP (2000) Global Environmental Outlook. 2000 Yearbook. Produced by GEO Section, Division of Early Warning and Assessment, United Nations Environment Programme. ISBN Paperback: 92-807-1955-6.

UNEP (2003) Global Environmental Outlook. 2003 Yearbook. Produced by GEO Section, Division of Early Warning and Assessment, United Nations Environment Programme. ISBN Paperback: 92-807-2415-0.

UNFCCC (1992) United Nations Framework Convention on Climate Change. United Nations, New York.

USBC (2000) US Bureau of the Census, International Database. www.census.gov/ipc/www /worldpop.htm.

Watson AJ, Upstill-Goddard RC and Liss PS (1991) Air-sea gas exchange in rough and stormy seas measured by a dual-tracer technique. Nature 349, 145–147.

Watson AJ, Bakker DCE, Ridgwell AJ, Boyd PW and Law CS (2000) Effect of iron supply on Southern Ocean CO_2 uptake and implications for glacial atmospheric CO_2. Nature 407, 730–733.

WCD (2000) Dams and Development: A New Framework for Decision-making. The Report of the World Commission on Dams. Earthscan Publications Ltd, London and Sterling, VA, USA. 404pp.

WRI (1990) Forest and rangelands. In: A Guide to the Global Environment. World Resources Institute, Washington. pp101–120.

Appendices

Appendix 1: Acronym List

ACE	Aerosol Characterisation Experiment
AIMES	Analysis, Integration and Modelling of the Earth System
AMMA	African Monsoon Multidisciplinary Analysis
APN	Asia-Pacific Network for Global Change Research
BAHC	Biospheric Aspects of the Hydrologic Cycle
BNF	biological nitrogen fixation
CACGP	Commission on Atmospheric Chemistry and Global Pollution
CBNF	cultivation-induced biological nitrogen fixation
CCC	Cod and Climate Change
CCCC	Climate Change and Carrying Capacity
CEOS	Committee on Earth Observation Satellites
CLIOTOP	Climate Impacts on Oceanic Top Predators
CLIVAR	Climate Variability and Predictability
C4MIP	Coupled Carbon Cycle–Climate Model Intercomparison Project
DIN	dissolved inorganic nitrogen
DIP	dissolved inorganic phosphorus
DIS	Data and Information Systems
DIVERSITAS	an international programme of biodiversity science
DMS	dimethylsulphide
ENSO	El Niño Southern Oscillation
ESSAS	Ecosystem Studies of Sub-Arctic Seas
ESSP	Earth System Science Partnership
FLUXNET	global network of tower sites measuring exchanges of energy and materials between terrestrial ecosystems and the atmosphere
FTI	Fast-Track Initiative
GAIM	Global Analysis, Integration and Modelling
GCP	Global Carbon Project
GCTE	Global Change and Terrestrial Ecosystems
GEIA	Global Emissions Inventory Activity
GECAFS	Global Environmental Change and Food Systems
GECHH	Global Environmental Change and Human Health
GECHS	Global Environmental Change and Human Security
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GEOTRACERS	a collaborative multi-national programme investigating marine biogeochemical cycles of trace elements and their isotopes
GEWEX	Global Energy and Water Cycle Experiment
GLOBEC	Global Ocean Ecosystem Dynamics

GLP	Global Land Project
GWSP	Global Water System Project
IAI	Inter-America Institute for Global Change Research
IAMAS	International Association of Meteorology and Atmospheric Sciences
ICSU	International Council for Science
IDGEC	Institutional Dimensions of Global Environmental Change
IGAC	International Global Atmospheric Chemistry
IGBP	International Geosphere-Biosphere Programme
IGFA	International Group of Funding Agencies for Global Change Research
IGOS-P	Integrated Global Observing Strategy Partnership
IHDP	International Human Dimensions Programme on Global Environmental Change
IHOPE	Integrated History and Future of People on Earth
iLEAPS	Integrated Land Ecosystem–Atmosphere Processes Study
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IOC	Inter-governmental Oceanographic Commission
IPCC	Inter-governmental Panel on Climate Change
IPO	international project office
IRS	integrated regional study
JGOFS	Joint Global Ocean Flux Study
LBA	Large-scale Biosphere-Atmosphere Experiment in Amazonia
LDC	less-developed country
LOICZ	Land-Ocean Interactions in the Coastal Zone
LUCC	Land Use and Cover Change
MAIRS	Monsoon Asia Integrated Regional Study
MDG	Millennium Development Goals
MEA	Millennium Ecosystem Assessment
NASA	US National Aeronautics and Space Administration
NC	National Committee
PAGES	Past Global Changes
PANGAEA	Publishing Network for Geoscientific and Environmental Data
SC-IGBP	Scientific Committee of IGBP
SCOPE	Scientific Committee on Problems of the Environment
SCOR	Scientific Committee on Oceanic Research
SOLAS	Surface Ocean–Lower Atmosphere Study
SPACC	Small Pelagic Fishes and Climate Change
SPARC	Stratospheric Processes and Their Role in Climate
SSC	scientific steering committee
START	Global Change System for Analysis, Research and Training
UNESCO	United Nations Educational, Scientific and Cultural Organization
WCRP	World Climate Research Programme
WGCM	Working Group on Coupled Modelling

Appendix 2: IGBP Phase I Project Synthesis Books

Canadell J, Pataki D and Pitelka L (Ed.s) (2006) Terrestrial Ecosystems in a Changing World. Springer-Verlag, Berlin, Heidelberg. *In press*.

Lambin E and Geist H (Ed.s) (2005) Land Use and Land Cover Change: Local Processes, Global Impacts. Springer-Verlag, Berlin, Heidelberg. *In press*.

Crossland CJ, Kremer HH, Lindeboom HJ, Marshall Crossland JI, and Le Tissier MDA (Ed.s) (2005) Coastal Fluxes in the Anthropocene. Springer-Verlag, Berlin, Heidelberg. 231pp.

Kabat P, Claussen M, Dirmeyer PA, Gash JHC, Bravo de Guenni L, Meybeck M, Pielke Sr RA, Vörösmarty CJ, Hutjes RWA and Lütkemeier S (Ed.s) (2004) Vegetation, Water, Humans and the Climate: A New Perspective on An Interactive System. Springer-Verlag, Berlin, Heidelberg. 566pp.

Steffen W, Sanderson A, Tyson P, Jäger J, Matson P, Moore III B, Oldfield F, Richardson K, Schellnhuber H-J, Turner II BL and Wasson R (2004) Global Change and the Earth System: A Planet Under Pressure. Springer-Verlag, Berlin Heidelberg. 336pp.

Fasham M (Ed.) (2003) Ocean Biogeochemistry: The Role of the Ocean Carbon Cycle in Global Change. Springer-Verlag, Berlin, Heidelberg. 297pp.

Brasseur GP, Prinn RG and Pszenny AAP (Ed.s) (2003) Atmospheric Chemistry in a Changing World: An Integration and Synthesis of a Decade of Tropospheric Chemistry Research. Springer-Verlag, Berlin, Heidelberg. 300pp.

Alverson KD, Bradley RS and Pedersen TF (Ed.s) (2003) Paleoclimate, Global Change and the Future. Springer-Verlag, Berlin, Heidelberg. 220pp.

Tyson P, Fuchs R, Fu C, Lebel L, Mitra AP, Odada E, Perry J, Steffen W and Virji H (Ed.s) (2002) Global-Regional Linkages in the Earth System. Springer-Verlag, Berlin, Heidelberg. 198pp.

Walker B, Steffen W, Canadell J and Ingram J (1999) The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems. Cambridge University Press, Cambridge, UK. 439pp.

Appendix 3: Contact Information

IGBP Secretariat

Royal Swedish Academy of Sciences
Box 50005, Lilla Frescativägen 4
SE-104 05, Stockholm, Sweden
Tel: +46 8 166 448
Fax: +46 8 166 405
Email: charlottew@igbp.kva.se
Website: www.igbp.net

IGBP Projects

AIMES IPO

National Center for Atmospheric Research
PO Box 3000, 1850 Table Mesa Drive
Boulder, CO 80307-3000, United States
Tel: +1 303 497 1706
Fax: +1 303 497 1695
Email: kathyh@ucar.edu
Website: www.aimes.ucar.edu

IGAC IPO

Pacific Marine Environmental Laboratory
National Oceanic and Atmospheric Administration
7600 Sand Point Way NE
Seattle, WA 98115-6349, United States
Tel: +1 206 543 6674
Fax: +1 206 543 0308
Email: igac.seattle@noaa.gov
Website: www.igac.noaa.gov

iLEAPS IPO

University of Helsinki, Department of Physical Sciences
Division of Atmospheric Sciences
PO Box 68 (Gustaf Hällströmin Katu 2B)
00014 University of Helsinki, Finland
Tel: +358 9 1915 0712
Fax: +358 9 1915 0717
Email: anni.reissell@helsinki.fi
Website: www.atm.helsinki.fi/ILEAPS

IMBER IPO

Institut Universitaire Européen de la Mer
Technopôle Brest-Iroise
Place Nicolas Copernic
29280 Plouzané, France
Tel: +33 2 9849 8672
Fax: +33 2 9849 8705
Email: imber@univ-brest.fr
Website: www.imber.info

GLOBEC IPO

Plymouth Marine Laboratory
Prospect Place
Plymouth PL1 3DH, United Kingdom
Tel.: +44 1752 633 160
Fax: +44 1752 633 101
Email: globec@pml.ac.uk
Website: www.globec.org

GLP

c/o Natural Resource Ecology Laboratory
Colorado State University
Fort Collins, CO 80523-1499, United States
Tel: +1 970 491 1976
Fax: +1 970 491 1965
Email: dennis@nrel.colostate.edu
Website: glp.colostate.edu

LOICZ IPO

GKSS-Forschungszentrum
Institute for Coastal Research
Max-Planck-Straße 1
D-21502 Geesthacht, Germany
Tel: +49 4152 87 2009
Fax: +49 4152 87 2040
Email: loicz.ipo@loicz.org
Website: www.loicz.org

PAGES IPO

Sulgeneckstrasse 38
3007 Bern, Switzerland
Tel: +41 31 312 3133
Fax: +41 31 312 3168
Email: pages@pages.unibe.ch
Website: www.pages-igbp.org

SOLAS IPO

School of Environmental Sciences
University of East Anglia
Norwich NR4 7TJ, United Kingdom
Tel: +44 1603 593 516
Fax: +44 1603 591 327
Email: solas@uea.ac.uk
Website: www.solas-int.org

ESSP Coordinator

c/o DIVERSITAS Secretariat
51 Bd de Montmorency
75016 Paris, France
Tel: +33 1 45 25 67 04
Fax: +33 1 42 88 94 31
Email: mrice@essp.org
Website: www.essp.org

ESSP Projects

GCP IPO

Earth Observation Centre
CSIRO Division of Atmospheric Research
GPO Box 3023
Canberra, ACT 2601, Australia
Tel: +61 2 6246 5631
Fax: +61 2 6246 5988
Email: info@globalcarbonproject.org
Website: www.globalcarbonproject.org

GECAFS IPO

Centre for Ecology and Hydrology
National Environment research Council
Wallingford, OX10 8BB, United Kingdom
Tel: +44 1491 692 464
Fax: +44 1491 692 313
Email info@gecafs.org
Website: www.gecafs.org

GECHH

c/o DIVERSITAS Secretariat
51, bd Montmorency
75016 Paris, France
Tel: +33 1 4525 9525
Fax: +33 1 4288 9431
Email: secretariat@diversitas-international.org

GWSP IPO

Walter-Flex-Straße 3
53113 Bonn, Germany
Tel: +49 228 73 6188
Fax: +49 228 73 60834
Email: gwsp.ipo@uni-bonn.de
Website: www.gwsp.org

IGBP

The International Geosphere-Biosphere Programme is an interdisciplinary body and one of the four global environmental change programmes of the International Council for Science (ICSU). IGBP networks scientists around the world to conduct interdisciplinary Earth System science and global change research.

For more information see:

IGBP: www.igbp.net

ICSU: www.icsu.org

ICSU
International Council for Science