ESSP Report No.1

GCP Report No.1

The Global Carbon Project



A framework for Internationally Co-ordinated Research on the Global Carbon Cycle

Earth System Science Partnership

www.globalcarbonproject.org

Global Carbon Project

The Science Framework and Implementation

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Please, cite this document as:

Global Carbon Project (2003) Science Framework and Implementation. Earth System Science Partnership (IGBP, IHDP, WCRP, DIVERSITAS) Report No. 1; Global Carbon Project Report No. 1, 69pp, Canberra.

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Preface

We are pleased to launch the Earth System Science Partnership (ESSP) report series with the publication of the Science Framework and Implementation Strategy of the Global Carbon Project. This report marks the beginning of a new era in international global change research, as well as a significant departure from the usual way of treating the carbon cycle.

The ESSP, comprising four global change programmes - the International Programme of Biodiversity Science (DIVERSITAS); the International Geosphere-Biosphere Programme (IGBP); the International Human Dimensions Programme on Global Environmental Change (IHDP); and the World Climate Research Programme (WCRP) - has been formed for the integrated study of the Earth System, the changes that are occurring to this System, and the implications of these changes for global sustainability. The Global Carbon Project, along with other ESSP projects on food systems, water resources and human health, are designed to make the links between the fundamental research on global change and the Earth System carried out in the programmes themselves and issues of vital concern for people.

Carbon cycle research is often carried out in isolation from research on energy systems and normally focuses only on the biophysical patterns and processes of carbon sources and sinks. The Global Carbon Project represents a significant advance beyond the *status quo* in several important ways. First, the problem is conceptualised from the outset as one involving fully integrated human and natural components; the emphasis is on the carbon-climate-human system (fossil-fuel based energy systems + biophysical carbon cycle + physical climate system) and not simply on the biophysical carbon cycle alone. Secondly, the development of new methodologies for analysing and modelling the integrated carbon cycle is a central feature of the project. Thirdly, the project provides an internally consistent framework for the coordination and integration of the many national and regional carbon cycle research programmes that are being established around the world. Fourthly, the project addresses questions of direct policy relevance, such as the management strategies and sustainable regional development pathways required to achieve stabilisation of carbon dioxide in the atmosphere. Finally, the Global Carbon Project goes beyond the traditional set of stakeholders for a global change research project by seeking to engage the industrial and energy sectors as well as the economic development and resource management sectors in the developing regions of the world.

We believe that this document will help to encourage, promote and shape carbon cycle research around the world for at least the next decade. Furthermore, we believe that it will provide the framework for a substantially enhanced knowledge base for dealing more effectively with the challenge of transforming energy systems and managing the global carbon cycle.

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The carbon cycle is central to the Earth system, being inextricably coupled with climate, the water cycle, nutrient cycles and the production of biomass by photosynthesis on land and in the oceans. A proper understanding of the global carbon cycle is critical for understanding the environmental history of our planet and its human inhabitants, and for predicting and guiding their joint future.

Human intervention in the global carbon cycle has been occurring for thousands of years. However, only over the last two centuries have anthropogenic carbon fluxes become comparable in magnitude with the major natural fluxes in the global carbon cycle, and only in the last years of the 20th century have humans widely recognised the threat of adverse consequences and begun to respond collectively. This development adds a new feedback into the global carbon cycle that will have a profound influence on the future of the Earth system, as humankind begins to grapple with the challenge of managing its planetary environment.

The Global Carbon Project

The challenge to the scientific community is to monitor (quantify), understand (attribute) and predict the evolution of the carbon cycle in the context of the whole Earth system, including its feedbacks with human components. This demands new scientific approaches and syntheses that cross disciplinary and geographic boundaries, and place particular emphasis on the carbon cycle as an integral part of the coupled carbon-climate-human system.

Three international global environmental change research programmes have come together to bring a coordinated programme into reality: the International Geopshere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), and the World Climate Research Programme (WCRP). The result is the Global Carbon Project (GCP). The present document outlines the project's framework for research and its implementation strategy. The document is addressed to the large research and agency communities, including multiple disciplines of natural and social sciences, and policy makers.

Science Themes

The goal of the GCP is to develop comprehensive, policy-relevant understanding of the global carbon cycle, encompassing its natural and human dimension and their interactions. This will be accomplished by determining and explaining three themes:

1. ***Patterns and Variability:*** What are the current geographical and temporal distributions of the major pools and fluxes in the global carbon cycle?
2. ***Processes and Interactions:*** What are the control and feedback mechanisms - both anthropogenic and non-anthropogenic - that determine the dynamics of the carbon cycle?
3. ***Carbon Management:*** What are the likely dynamics of the carbon-climate-human system into the future, and what points of intervention and windows of opportunity exist for human societies to manage this system?

Implementation Strategy

The GCP will implement its research agenda through collaborative efforts with national and international carbon programmes and funding agencies, and by leading a limited number of difficult and highly interdisciplinary new research initiatives that are feasible within a 3-5 year framework. The implementation strategy is organised around the three science themes.

Theme 1: Patterns and variability

Quantify current geographical and temporal distributions of the major carbon pools and fluxes through compiling new sectorial and regional budgets and developing model-data fusion.

- ***Major carbon stocks and fluxes.*** Provide a coordinated international effort to complement and strengthen regional and national carbon cycle programmes by fostering common protocols, sharing data, promoting rapid transfer of information on new applications and techniques, and leveraging resources in joint projects.
- ***Model-data fusion.*** Develop and implement methods for assimilating atmospheric, ocean and terrestrial data into carbon-climate-human system models, with particular emphasis on the application of multiple constraints (from the simultaneous use of atmospheric, oceanic and terrestrial data and models) to the problem of determining patterns and variability in the carbon cycle.

- ***Comprehensive national, regional and sectoral carbon budgets.*** Promote the harmonisation of existing approaches to national, regional and basin-scale carbon budgets to ensure comparability amongst regions.

Theme 2: Processes and Interactions

Promote new research and synthesis to increase understanding of the controls on natural and human-driven sources and sinks of carbon, and the spatially explicit links between causes and effects, with particular emphasis on understanding the interactions among mechanisms and feedbacks among components of the coupled carbon-climate-human system.

- ***Mechanisms and feedbacks controlling carbon stocks and fluxes.*** Promote research and synthesis to identify the source and sink mechanisms, their relative importance and their interactive effects. Explore how the processes of the carbon system work, both individually and collectively.
- ***Emergent properties of the coupled carbon-climate system.*** Investigate additional system properties that emerge when the perturbed carbon cycle is included as an interactive element in the full carbon-climate system; in particular, investigate whether thresholds, instabilities and surprises could emerge from this full-system coupling.
- ***Emergent properties of the coupled carbon-climate-human system.*** Initiate cross-disciplinary research on the coupling of models (quantitative or qualitative) of the physical, biochemical and human components of the carbon cycle, and highlight novel behaviours that emerge when all these subsystems are coupled. Stimulate the development of more detailed predictive tools and conceptual frameworks.

Theme 3: Carbon management

Identify and quantify points for intervention and windows of opportunity in the carbon cycle to steer the evolution of the coupled carbon-climate-human system.

- ***Points of intervention and options for mitigation.*** Identify and assess specific points of intervention at which the future evolution of the carbon cycle might be influenced, and critically assess the achievable mitigation potential of the options, once sustainable development concerns are considered (i.e., triple bottom line: economy, society, and environment).
- ***Carbon management in the context of the whole Earth system.*** Develop a framework to assess the best mix of mitigation options in a full-system analysis framework, design dynamic portfolios of carbon mitigation options for specific regions, and analysis/design appropriate institutions for carbon management.
- ***Carbon consequences of regional development pathways.*** Undertake a comparative analysis of a network of regional case studies to understand:
  - The consequences of different pathways of regional development on carbon stocks and fluxes.
  - The critical processes and interactions in development that result in pathways with widely differing carbon consequences.
  - The trade offs and synergies between changes in carbon stocks and fluxes with other ecosystem services, especially the provision of food, water and clean air, and the maintenance of biodiversity.

Synthesis and communication

The GCP will deliver high-level syntheses of information on the carbon cycle aimed at the research and assessment communities. Written products and web-based resources will be developed for policy makers, educators and general public. Specific products for multidisciplinary audiences will be developed to foster a common understanding and language.

Capacity building

The GCP will develop a number of capacity building activities associated with the main research themes. This will promote the development of a new generation of young and senior scientists trained in the highly interdisciplinary topics of the carbon-climate-human system.

Products

The products of a 10-year research programme are envisioned as being:

- Improved knowledge of the coupled carbon-climate-human system with increased capacity to quantify, attribute and predict.
- A systemic framework, implemented in a suite of linked models, of the coupled biophysical and human interactions controlling the carbon cycle.
- Improved coordination between the research, monitoring and assessment communities, leading to a capability for rapid assessments and responses to trends in the carbon cycle.
- Improved outputs from national and international research and monitoring programmes, through better coordination, linkage and information exchange.
- Outreach and communication products, including synthesis of research in journal issues and books; electronically available resources (e.g., data, graphics and presentation material), quality websites including a carbon portal, educational resources (e.g., posters and leaflets) and opportunities for higher education through the various research activities.

Stakeholders

Major stakeholders of the GCP are the scientific, assessment and policy communities dealing with:

- Quantifying and predicting carbon budgets from local to global scales.
- Policies to reduce net greenhouses gas emissions.
- Development of, and compliance with, international conventions.
- Regional development aimed at meeting environmental, economical and social goals.

Connections with national and international programmes

Because of the integrative nature of the project, there will be a need to build upon many existing projects and to work with communities whose spheres of interest intersect (but do not necessarily coincide) with that of the GCP. In particular, the GCP will work with:

- Research communities coordinated through IGBP, IHDP, WCRP and other members of the Integrated Global Observing Strategy Partnership (IGOS-P).
- National and regional carbon cycle programmes.
- Assessment and policy communities dealing with the consequences of changes in the carbon cycle, vulnerability and the links to water resources, food systems and biodiversity.

The GCP Mandate

- To develop a research framework for integrating the biogeochemical, biophysical and human components of the global carbon cycle, recognising the need for work across disciplines, and temporal and geographical boundaries.
- To provide a global platform for coordinating international and national carbon programmes to improve the design of observation and research networks, data standards, information transfer, and timing of campaigns and process-based experiments, and the development of model-data fusion techniques.
- To strengthen the carbon-related research programmes of nations, regions, and international programmes such as IGBP, IHDP, WCRP, DIVERSITAS and the observation community, through better coordination, articulation of goals and development of conceptual frameworks.
- To foster research on the carbon cycle in regions that are poorly understood but have the potential to play important roles in the global carbon cycle.
- To synthesise and communicate new understanding of the carbon-climate-human system to the broad research and policy communities.

1 Introduction

This document outlines the research framework of the Global Carbon Project (GCP), a research project on the global carbon cycle developed jointly by the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), and the World Climate Research Programme (WCRP). The GCP is also one of the first projects established under the Earth System Science Partnership (ESSP) sponsored by IGBP, IHDP, WCRP and DIVERSITAS. This document is, therefore, addressed to the large research and agency communities, including multiple disciplines of natural and social sciences, and policy makers.

The document is organised in three major sections. Section 1 (Introduction) gives an overview of the project, the motivation, vision and the main strategic elements. Section 2 (Science themes) outlines the three science themes of the GCP, which together provide a comprehensive picture of the global carbon cycle and its interactions with climate and human activities. For each of these themes, there are subsections on the relevant knowledge base, current research areas, uncertainties and research priorities. Section 3 (Implementation strategy) outlines the initial activities that the GCP, in coordination with a number of other projects and programmes, will execute over the next 3-5 years, and includes a vision that extends to the full life time of the project (about 10 years). At the end of the document, there are a number of appendixes containing information on national and international programmes and networks relevant to global research of the carbon cycle, and therefore, relevant to the GCP.

The carbon challenge

The carbon cycle is central to the Earth system, being inextricably coupled with climate, the water cycle, nutrient cycles and the production of biomass by photosynthesis on land and in the oceans. This production sustains the entire animal kingdom, including humans through their dependence on food and fibre. Hence, a proper understanding of the global carbon cycle is critical for under-

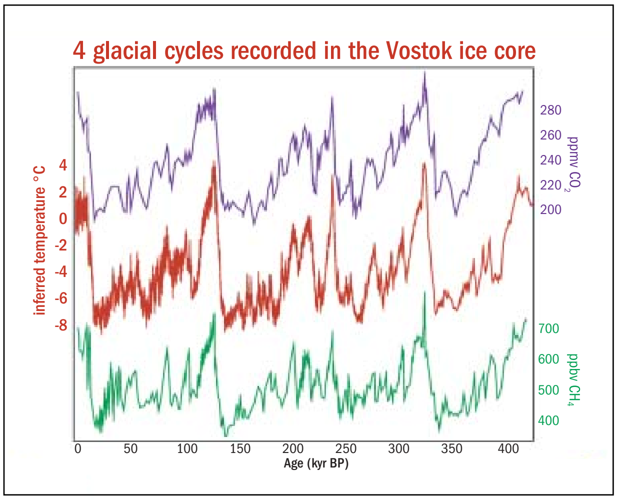


Figure 1

Changes in atmospheric carbon dioxide, isotopically inferred temperature and methane from a 420,000 year record from the Vostok ice core. For a detailed report of these measurements see Petit et al (1999). Image compliments of IGBP/PAGES.

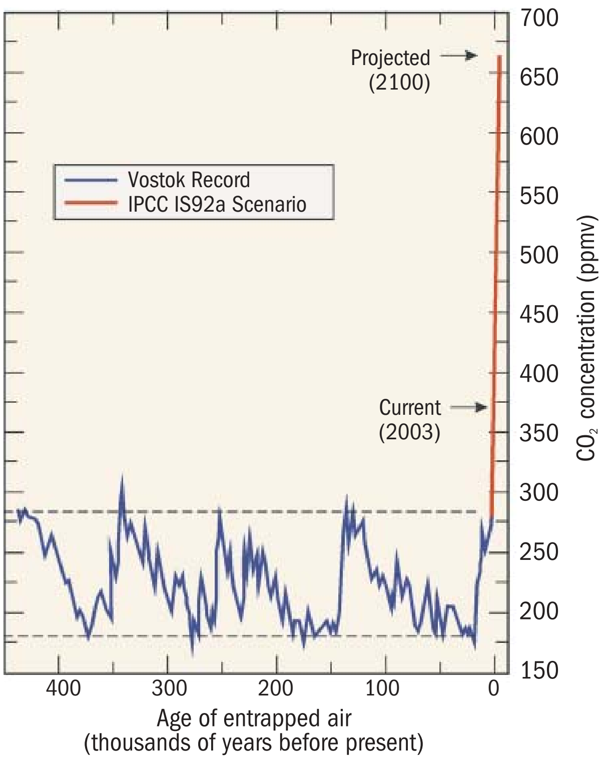


Figure 2

The Vostok ice core record for atmospheric concentration (Petit et al 1999) and the 'business as usual' prediction used in the IPCC third assessment (IPCC 2001a). The current concentration of atmospheric carbon dioxide (CO_2) is also indicated.

standing the environmental history of our planet and its human inhabitants, and for predicting and guiding their joint future.

The Vostok ice core record (**Figure 1**) illustrates the limits and patterns of natural variability of atmospheric carbon dioxide (CO_2) and the correlation of atmospheric CO_2 and methane (CH_4) concentrations to inferred temperature over the last 420,000 years. From about one-half million years ago until about 200 years ago, the climate system has operated within a relatively constrained range of temperature and concentrations of atmospheric CO_2 and CH_4. In the pre-industrial world, atmospheric CO_2 concentrations oscillated in roughly 100,000-year cycles between 180 and 280 parts per million by volume (ppmv), as the CO_2 climate system pulsed between glacial and interglacial states. The ice core record clearly illustrates that atmospheric composition and climate (especially temperature) are closely linked.

Comparison of the Vostok record with contemporary measurements of atmospheric CO_2 concentration reveals that the Earth's system has dramatically left this regular domain of glacial-interglacial cycling (**Figure 2**). Atmospheric CO_2 concentrations are now nearly 100 ppmv higher than at the interglacial maximum, and the rate of increase has been at least 10, and possibly 100, times faster than at any other time in the past 420,000 years. Concentrations of other greenhouse gases, including CH_4 and N_2O, are increasing at comparable rates. These increases are unquestionably due to human activities, and are already having consequences for climate. For example, a temperature record for the past millennium indicates that the contemporary climate system is now responding to changing greenhouse gas concentrations in the atmosphere. Far greater changes are predicted over a time scale of centuries, with a confidence that has increased substantially between the second and third assessments of the Intergovernmental Panel on Climate Change (IPCC 1996; 2001a,b,c). These changes indicate that the Earth system has moved well outside the range in which the carbon cycle operated over the past half million years. Change has been unidirectional and of unprecedented rate; that is, humans have pushed the Earth system into uncharted territory.

The role of humans in the carbon cycle is not new. Human activities have influenced it for thousands of years through agriculture, forestry, trade and energy use in industry and transport. However, only over the past two or three centuries have these activities become sufficiently widespread and far reaching to match the great forces of the natural world. Moreover, human societies and institutions (social, cultural, political and economic) are not unidirectional drivers of change: they are impacted upon by changes to the carbon cycle and climate, and respond to these impacts in ways that have the potential to feed back on the carbon cycle itself (Young 2002; **Figure 3**). One example is the attempt to manage greenhouse gas emissions as part of the global atmospheric commons.

Efforts to identify the location and magnitude of carbon exchanges between atmosphere, land and ocean illustrate the complex interactions between the natural and human aspects of the system, and the difficulty of separating them. The locations of current terrestrial CO_2 sinks (i.e., areas of land that take up CO_2 from the atmosphere) may be largely due to historic patterns of land-use change, and their magnitudes the result of physiological response to repeated disruption. Patterns of oceanic CO_2 sinks may also be modified by atmospheric transport of iron-laden dust from continents, which, in turn, is influenced by land-use and climatic variability. Areas where humans might manipulate the carbon cycle include enhancing sequestration of carbon in terrestrial ecosystems and the oceans, and minimising the massive emissions from fossil fuel combustion.

Research is focusing on monitoring and understanding these patterns and processes in the global carbon cycle, and their environmental impacts. Different research communities are using a variety of resources and methods. For example, satellite data, air sampling networks and inverse numerical methods ('top-down' approaches) allow the strength and location of the global and continental-scale carbon sources and sinks to be determined. Surface monitoring and process studies ('bottom-up' approaches) provide estimates of land-atmosphere and ocean-atmosphere carbon fluxes at finer spatial scales, and allow examination of the mechanisms that control fluxes at these regional and ecosystem scales (**Figure 4**). An understanding of the natural dynamics and the potential for mitigation in the carbon cycle will ultimately allow pathways for decarbonisation to be developed that can be implemented through policy instruments and international regimes.

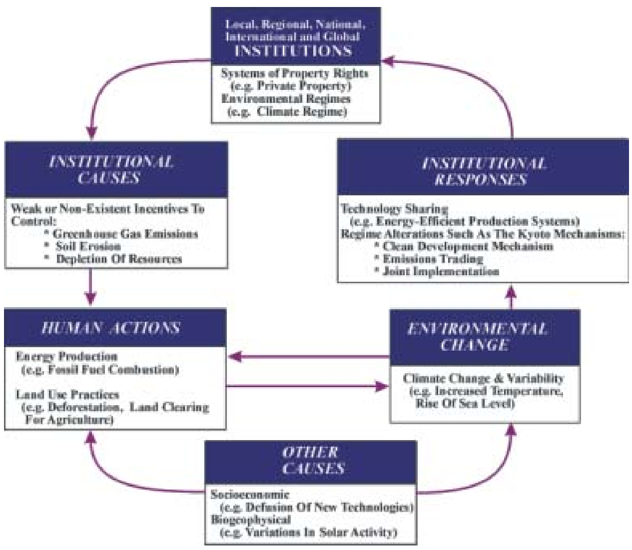


Figure 3

Institutions and their effects on the carbon cycle (adapted from Young 2002).

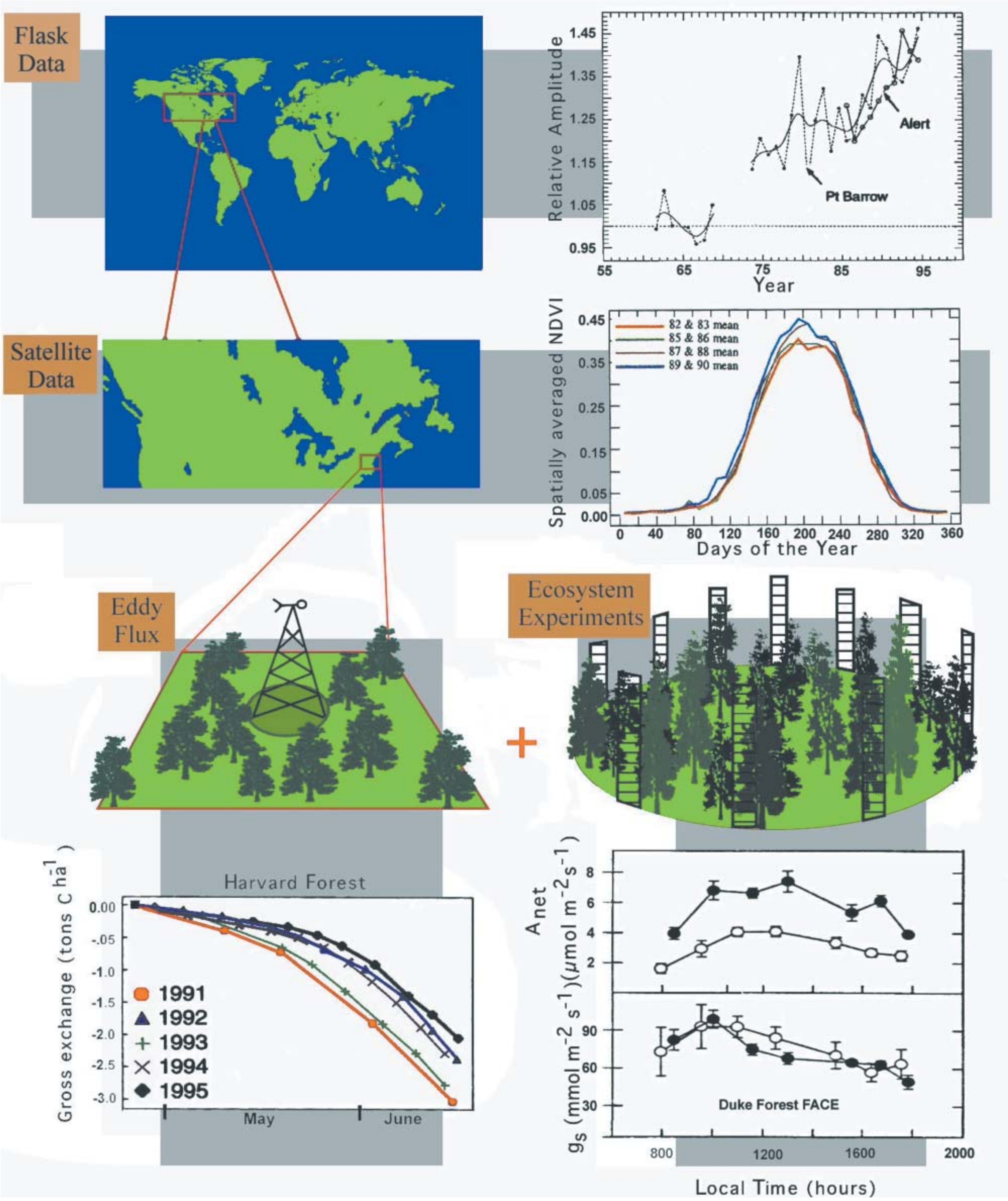


Figure 4

Measuring the carbon metabolism of terrestrial ecosystems: Techniques and results (Canadell et al. 2000).

The Vision

The central vision of the GCP is to develop comprehensive, policy-relevant understanding of the global carbon cycle, encompassing its natural and human dimension and their interactions.

Achieving this vision will require coordination by the international scientific community across all relevant disciplines and regions, and application of a large number of available resources and techniques. At present, no single international research programme provides this framework. The GCP was created to fill this gap and provide overall coordination to address highly interdisciplinary and complex problems of the carbon-climate-human system.

The GCP will to take an interdisciplinary approach to understanding the natural unperturbed carbon cycle, the perturbed carbon-climate-human system, and the feedbacks between societies' responses to a perceived or real threat and the dynamics of the natural system (**Figure** 5).

Through a series of workshops from 1999 to 2003, the scientific community identified three broad science themes for carbon cycle research. These themes define the scientific scope of the GCP and contribute to the development of a strong capacity for detection, attribution and prediction. The prediction component focuses strongly on where and how humans can intervene in the future dynamics of the perturbed carbon cycle. Each of the themes is described by an overarching question, as follows:

1. Patterns and variability: *What are the current geographical and temporal distributions of the major pools and fluxes in the global carbon cycle?*

2. Processes and interactions: *What are the control and feedback mechanisms - both anthropogenic and non-anthropogenic - that determine the dynamics of the carbon cycle?*

3. Carbon management: *What are the likely dynamics of the carbon-climate-human system into the future, and what points of intervention and windows of opportunity exist for human societies to manage this system?*

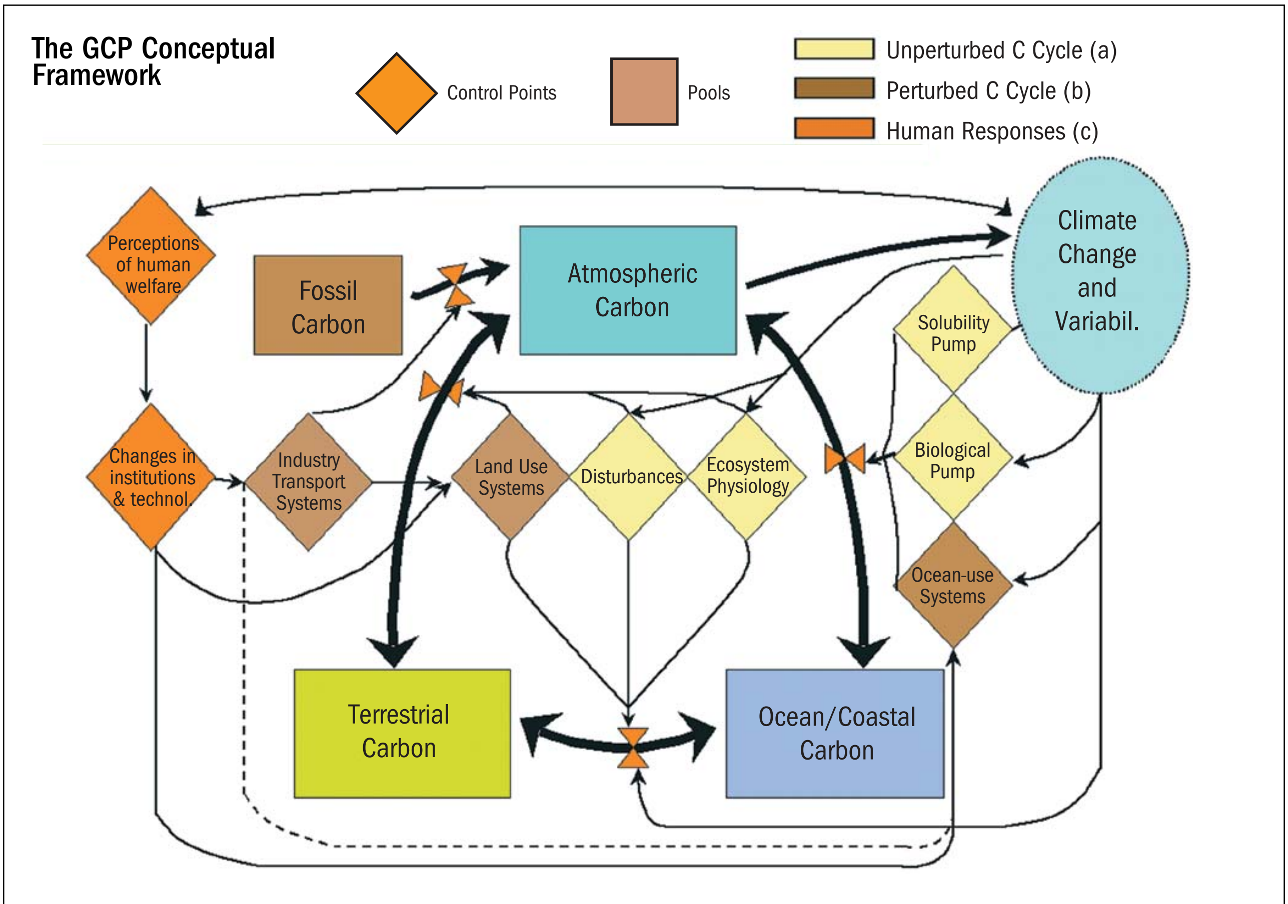


Figure 5

The global carbon cycle from three perspectives over time. (a) During glacial-interglacial periods and before significant human activities, the global carbon cycle was a linked system encompassing stocks in the land, oceans and atmosphere only. The system was (and still is) controlled or driven through climate variability as well as its own internal dynamics. For example, the ocean carbon system was tightly coupled to air-sea gas exchange as well as physical and biological 'pumps' that transport carbon. Interactions of the land surface and atmosphere were driven by land and ecosystem physiology as well as disturbance. (b) Starting about 200 years ago, industrialisation and accelerating land-use change complicated the global carbon cycle by adding a new stock - fossil carbon. However, humans did not initially perceive that their welfare might be endangered. Regardless of how society responds to increased fossil fuel inputs to the atmosphere, or the consequences of intensification of current land-use practices, the global carbon cycle has been seriously impacted. (c) Over recent decades, humans have begun to realise that changes in climate variability and the Earth system may significantly affect their welfare as well as the functionality of the global carbon cycle. The development and implementation of institutions and regimes to manage the global carbon cycle coherently provides a new set of feedbacks in the contemporary era.

Mandate and approach

To implement the GCP vision and cover the three major themes, the GCP will be driven by the following scientific mandate:

- To develop a research framework for integrating the biogeochemical, biophysical and human components of the global carbon cycle, recognising the need for work across disciplines, and temporal and geographical boundaries.
- To provide a global platform for coordinating international and national carbon programmes to improve the design of observation and research networks, data standards, information transfer, timing of campaigns and process-based experiments, and the development of model-data fusion techniques.
- To strengthen the carbon-related research programmes of nations, regions, and international programmes such as IGBP, IHDP, WCRP, DIVERSITAS and the observation community, through better coordination, articulation of goals and development of conceptual frameworks.
- To foster research on the carbon cycle in regions that are poorly understood but have the potential to play important roles in the global carbon cycle.
- To synthesise and communicate new understanding of the carbon-climate-human system to the broad research and policy communities.

Approach: The GCP will implement its research agenda in two ways. First, the more disciplinary-oriented research on the carbon cycle is already implemented through a number of projects under the auspices of the GCP's sponsoring programmes (**Appendix A1**), and sub-global research efforts are implemented through many national/regional carbon programmes (**Appendix A2**). The GCP will enhance and add value to this research by facilitating collaboration towards a higher-level integration, supporting the GCP's mandate of putting together the broader picture of the global carbon cycle. Secondly, the GCP will initiate and lead a limited number of new research initiatives that are feasible within a 3-5 year framework on difficult and highly interdisciplinary problems of the carbon cycle.

Scientific guidance: The work of the GCP is guided by a scientific steering committee (SSC) made up of scientists covering the main interdisciplinary areas of the GCP science framework. The SSC will also consider recommendations made by its sponsor programmes and their projects.

Governance and time frame: The GCP answers to a committee made up of the chairs and directors of its three sponsoring programmes (IGBP, IHDP, WCRP). A time frame of 10 years is envisioned for the GCP, beginning in 2002. A mid-term review by the three sponsoring programmes will assess how well the project has met its near-term objectives, monitor progress towards the longer term goals and suggest modifications needed to enhance the effectiveness of the project.

Institutional linkages: In a broader context, *research* on the carbon cycle is an essential component of many activities addressing the environmental science of the whole Earth system and the sustainable development agenda at an international level. The GCP will establish formal and informal partnerships to work with a number of observation, assessment and policy bodies:

- An integrated strategy for observing the global carbon cycle (Integrated Global Carbon Observation, IGCO) is under active development within the Integrated Global Observation Strategy Partnership (IGOS-P), with contributions by the global observing systems (Global Ocean Observing System (GOOS), Global Terrestrial Observing System (GTOS), Global Climate Observing System (GCOS)) and the GCP (Appendix B).
- The global carbon cycle is at the centre stage of *policy* development for climate mitigation, sustainable development and the provision of ecosystem services, both at national and international levels. There is a need to connect, through appropriate assessment bodies, with international and national policy communities.
- *Assessment* of scientific research on the carbon cycle, and its interpretation for the policy community, is carried out by the IPCC as requested by the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the United Nations Framework Convention on Climate Change (UNFCCC), the Millennium Ecosystem Assessment (MA) and other assessment programmes.

2 Science Themes

The science framework of the GCP is organised around three themes: patterns and variability; processes and interactions; and carbon management. This section describes, for each theme, the knowledge base (what we already know from past work), current or planned research, and the main areas where important knowledge is lacking, described here as areas of uncertainty. The definition of areas of uncertainty leads finally into a number of questions that define research priorities for each theme. It is notable, however, that many of the research questions bridge across the three themes.

Theme 1: Patterns and Variability

Motivation

The basic structure of the carbon cycle is determined by the flows of carbon between major pools, including carbon in the atmosphere (mainly as CO_2); in the oceans (surface, intermediate waters, deep waters and marine sediments); in terrestrial ecosystems (vegetation, litter and soil); in rivers and estuaries; and in fossil carbon, which is being remobilised by human activities. Both the flows of carbon among these pools and their carbon content have a rich spatial and temporal structure reflecting natural dynamics and human activity (**Figure 6**). An understanding of the patterns and variability in this structure is crucial for defining the basic anatomy of the carbon cycle, providing diagnostic insight into the driving processes and underpinning reconstructions of past and predictions for the future - especially a future subject to anthropogenic perturbations outside the range experienced by the Earth system in recorded history.

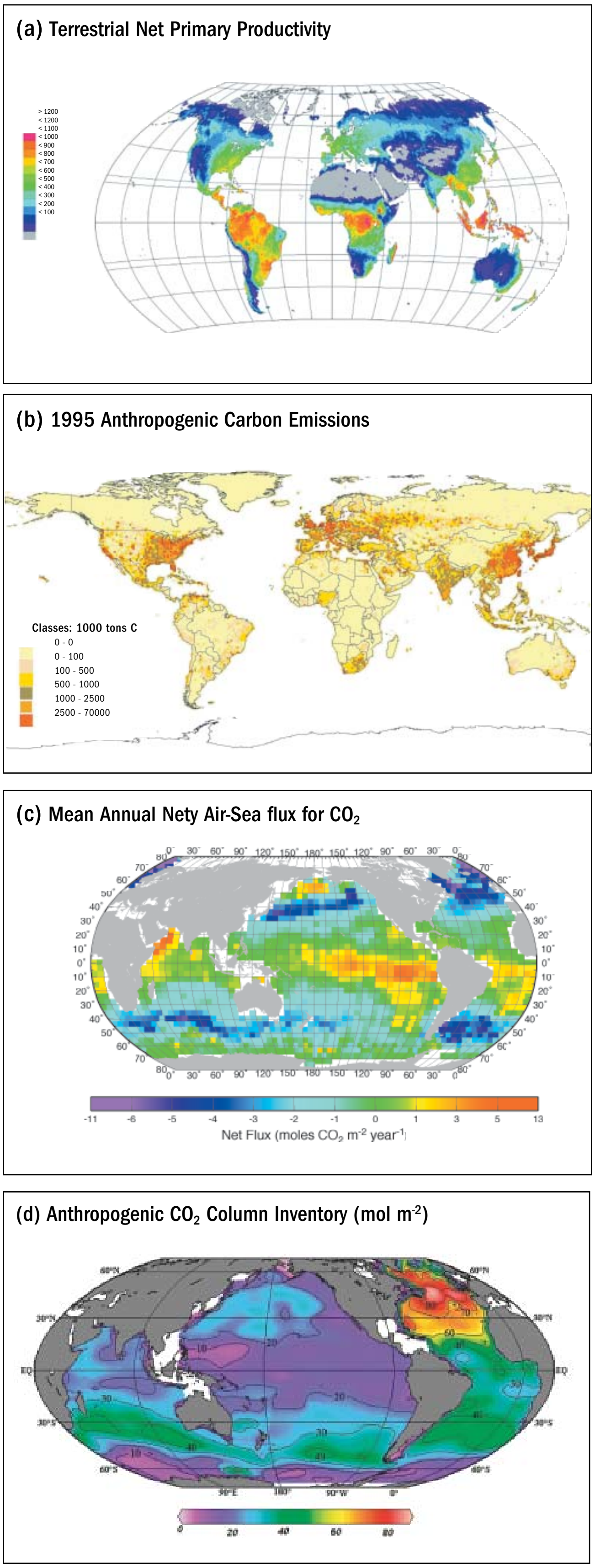
Knowledge base

Present understanding of the patterns and variability of global carbon fluxes is based on:

- Global observations, including the atmospheric concentrations of CO_2 and other gases, satellite observations, and in situ terrestrial and oceanic measurements.
- Modelling of atmospheric and oceanic dynamics and biogeochemical processes.
- Mass balance principles.

Together, these provide strong evidence to support the following points (IPCC 2001a; Field and Raupach 2003; CDIAC 2003):

1. Global fossil fuel emissions have been rising since pre-industrial time and were 5.2 petagrams of carbon (PgC) in 1980 and 6.3 PgC in 2002, with the vast majority occurring in the northern hemisphere.
2. Atmopheric carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased by 31%, 150%, and 16% since 1750, respectively.
3. About half of the CO_2 emitted to the atmosphere by fossil fuel sources is taken up by a combination of terrestrial and oceanic sinks.
4. Observed distributions of atmospheric CO_2 and the oxygen/nitrogen ratio (O_2/N_2), together with atmospheric model inversion studies, suggest that the terrestrial sink occurs predominantly in the northern mid-latitudes.
5. Land-use change results in significant emissions of atmospheric CO_2 in tropical latitudes, whereas land-management change is responsible for a significant carbon sink in northern mid-latitudes.
6. For the last few decades, observed changes in atmospheric CO_2 concentrations have varied widely (**Figure 7**); the implied rate of carbon accumulation in the atmosphere varies between years by nearly as much as average annual fossil fuel emissions.
7. The interannual variability in carbon exchange with the atmosphere is dominated by terrestrial ecosystems rather than the ocean.
8. Imports and exports of cereals, wood and paper products accounted for about 0.72 PgC yr^{-1} of 'embodied' carbon trade in 2000, affecting regional sinks (production), sources (consumption) and temporary storage (e.g., furniture) (**Figure 8**).
9. The net global air-sea flux is 2.2 PgC (-19% to +22%) into the ocean for the reference year 1995; ocean models and observations suggest that the interannual variability of the global ocean CO_2 flux is around 0.5 PgC yr^{-1}, with the largest interannual variability apparently occurring in the equatorial Pacific Ocean.
10. The broad pattern of oceanic sources and sinks of atmospheric CO_2 are known: tropical waters generally act as sources and higher latitude waters act as sinks; the strongest oceanic CO_2 sink is the North Atlantic Ocean and the strongest source is in the equatorial Pacific Ocean.
11. Lateral fluxes in rivers are important in explaining patterns and distribution of the carbon sources and sinks; carbon exports from rivers to the coastal ocean are higher than 1 PgC yr^{-1}.



Current research

The above conclusions are largely based on observation and modelling. This section describes continuing work on carbon cycle patterns and variability using these two approaches, including observations of human interactions with the carbon cycle and strategies for combining observations with models.

Global monitoring

Long-term monitoring is an essential research tool for detecting, attributing and predicting the spatial and temporal patterns in the global carbon cycle. Major time series have become touchstones for the science of the carbon cycle and the Earth system (IPCC 2001a). Examples include the multidecadal records of atmospheric composition (notably CO_2 concentrations) from baseline observing stations at Mauna Loa, Cape Grim and elsewhere (e.g., Keeling and Whorf 2000); and the 420,000-year Vostok ice core record shown in **Figure 1** (Petit et al 1999). Spatial data are also critical, for example, the global net terrestrial primary production (NPP) inferred from a number of biogeochemical models (**Figure 6a**).

The global observation tools necessary to understand the Earth system (including the global carbon cycle and human impacts on it) are being assembled in a cooperative global observing strategy, the Integrated Global

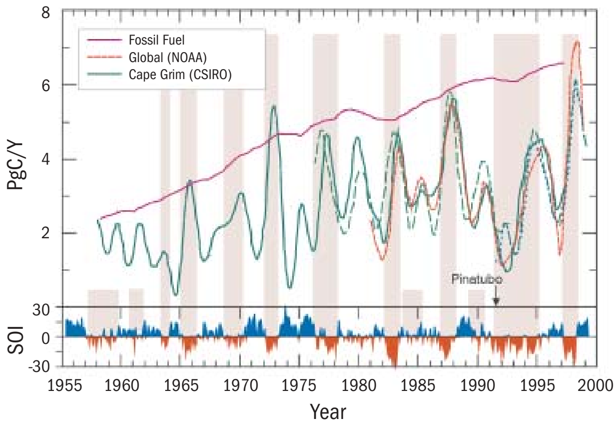


Figure 7

The CO_2 global growth rate (expressed here as 10^{15} g/yr of carbon accumulating in the atmosphere since the start of direct CO_2 monitoring) is compared to fossil fuel emissions over 4 decades. On average, 55% of the anthropogenic carbon is retained in the atmosphere, but with large interannual variability related to the southern oscillation index (SOI). (The very low growth following the Pinatubo volcanic explosion in 1991 is an exception). All CO_2 data are deseasonalised and smoothed over 650 days. The records collected by SIO/NOAA from Mauna Loa, by NOAA from 50 global sites, or by CSIRO from Cape Grim all closely track the global growth rates (Source: R J Francey, presented at the EC-IGBP-GTOS Terrestrial Carbon Meeting, 22-26 May 2000, Costa da Caparica, Portugal).

Figure 6

Spatial observations critical to determining patterns and variability in the stocks and fluxes making up the carbon cycle. (a) Global map of terrestrial net primary production (NPP) from the IGBP Potsdam NPP Model Intercomparison, gC m^2 (Cramer et al 2001); (b) 1995 carbon dioxide emissions from fossil-fuel burning, cement production, and gas flaring at one degree grid basis emissions (Brenkert 1998 [http://cdiac.esd.ornl.gov/], map prepared by R J Olson, Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States); (c) Mean annual net-air sea flux for CO_2 (mole CO_2 m^2 yr^{-1}) for 1995 (Takahashi et al 2002); and (d) Anthropogenic CO_2 column inventory (mol m^2) (Sabine et al 2003).

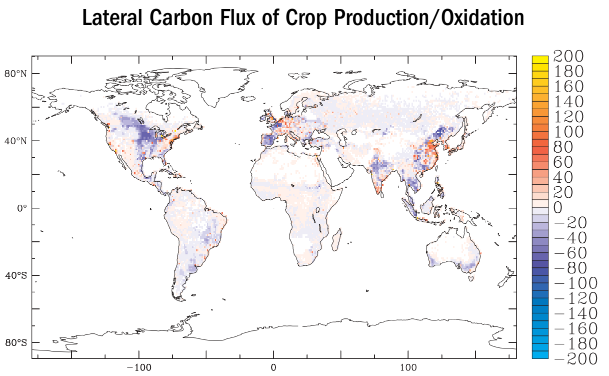


Figure 8

Sources and sinks induced by the production and metabolisation of food products (gC m^{-2} yr^{-1}) (Ciais et al 2001)

Observing Strategy Partnership (IGOS-P). The principle behind IGOS-P is to develop a strategy for coupling major Earth and space-based systems for global environmental observations of the land, oceans and atmosphere.

As part of IGOS-P, a strategy for international global carbon cycle observations over the next decade is being developed through an IGCO theme, in close collaboration with the GCP (**Appendix B**). This strategy will:

- Integrate remote and in situ observations.
- Link ocean, terrestrial and atmospheric observing strategies.
- Involve close collaboration with the international carbon cycle research and assessment communities.

Towards these goals, a Terrestrial Carbon Observation (TCO) component of the GTOS component has already been developed to provide information on the spatial and temporal distribution of carbon sources and sinks in terrestrial ecosystems, using data obtained through ground and satellite-based observations.

The new products from the Moderate Resolution Imaging Spectroradiometer (MODIS) and other satellites will provide an important dynamic long-term record of the terrestrial and ocean metabolism. This record will include a number of consistent, calibrated and near-real-time measures of major components of the global carbon cycle including global net primary productivity (NPP) at 1x1 km resolution every eight days (**Figure 9**).

Atmospheric observations

Numerous countries currently sponsor measurements of atmospheric trace gas concentrations, in most cases as part of research programmes. These data have made pivotal contributions to the awareness and understanding of climate change. The atmosphere is an excellent filter of spatially and temporally varying surface fluxes, integrating short-term fluctuations while retaining the large-scale signal (Tans et al 1990). The distribution of CO_2 in the atmosphere and its time evolution can thus be used to quantify surface fluxes.

Regional carbon budgets are currently calculated from CO_2 measurements at about 100 sites, supplemented by a few tall towers and aircraft programmes, using atmospheric inversion methods. Among the most significant impacts to date of network observations (and their interpretation by inversion methods) has been the discovery of major CO_2 net sinks in the northern hemisphere, both terrestrial and oceanic (IPCC 2001a; Gurney et al 2002; Rödenbeck et al 2003) However, retrieval of the space-time patterns of surface fluxes is highly uncertain. Without the use of additional constraints, it is hardly possible to resolve sources or sinks within longitudinal zones or between oceans and continents, even in the most densely sampled regions, the northern mid-latitudes. Even when such constraints are available from local process-oriented studies (e.g., Wofsy et al 1993), it is difficult to connect this understanding to global CO_2 patterns (Braswell et al 1997). Without a comprehensive spatial coverage of CO_2 measurements, uncertainties cannot be localised unequivocally to transport model or data error, or inversion procedures.

To overcome accuracy and consistency problems in these measurements, GLOBALVIEW-CO_2 was established as a cooperative atmospheric data integration project. It presently involves approximately 24 organisations from 14 countries (**Figure 10**). An internally consistent 21-year global time series has been compiled. In addition to CO_2, the observing system includes measurements of ^{13}C and ^{18}O in CO_2, CH_4, CO, the O_2/N_2 ratio, and many other species. Measurements of ^{13}C and O_2/N_2 provide information on the partition of net carbon fluxes into the atmosphere between fossil fuel emissions, land-atmosphere exchange and ocean-atmosphere exchange. Measurements of ^{18}O are used

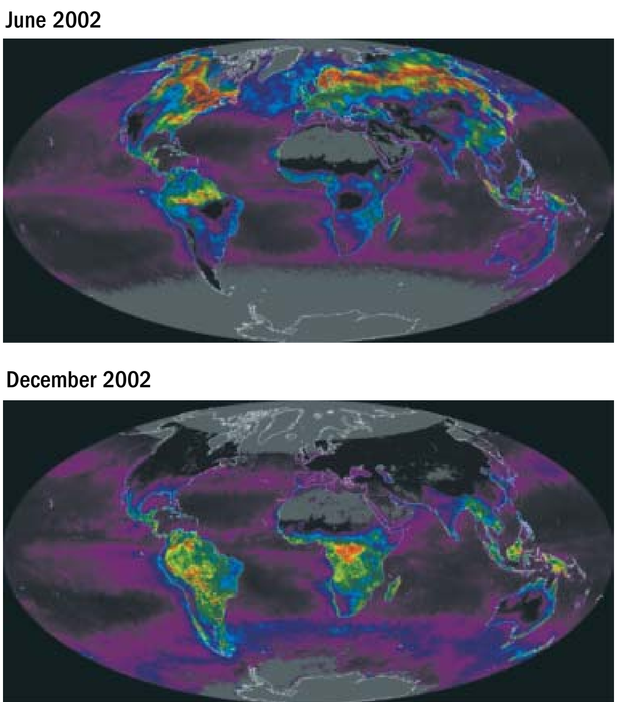


Figure 9

Global net primary productivity (NPP) for the months of June and December of 2002 based on space-based measurements taken by the Moderate Resolution Imaging Spectroradiometer (MODIS) with algorithms developed by the NASA Earth Observing team that use a suite of other satellite and surface-based measurements. (Kg C m^{-2} yr^{-1}) (Source: NASA Earth Observatory).

to estimate gross primary production, as opposed to net ecosystem exchange. The CH_4 and CO measurements are used to estimate the contribution of combustion, in addition to the significance of CH_4 as a greenhouse gas. In addition, GLOBALHUBS has outlined a plan for global intercalibration of CO_2 concentrations and isotopes.

Three significant developing contributions to atmospheric observation are as follows:

- Continental and opportunistic measurements of atmospheric composition will extend the network of observations not only for CO_2 but also for other gases mentioned above. Existing atmospheric observing networks focus largely on measurements in the remote marine boundary layer, to avoid contamination by local sources and sinks. These data are invaluable in providing a baseline. However, there is a need for additional measurements over the continents. These are more complicated, due to strong variability in space and time caused by surface heterogeneity and diurnal cycling of the atmospheric boundary layer between convective and stable states, which affects the mixing of CO_2. Developments in sampling strategies are likely to progressively overcome these difficulties. Such measurements are commencing, using a combination of flask-sampled and continuous data from Fluxnet sites (see below), commercial and specially deployed aircraft, and Ships of Opportunity (SOOP). For continuous CO_2 measurements, a key technological development is the recent availability of lightweight, low-maintenance CO_2 sensors with precision comparable to present continuously attended baseline instrumentation.
- Methods for network optimisation will improve the next generation of upgrades to existing sampling networks. These rely on the use of data-assimilation methods as a primary technique to optimise network design.
- The measurement of CO_2 from space will have major impacts in filling the present sparse and uneven ground-based atmospheric sampling network on land, at sea and in the atmosphere, which, as noted above, severely limits the atmospheric-inverse approach (Rayner and O'Brien 2001).

Satellite observations of atmospheric CO_2

Remote sensing of the Earth's surface and atmosphere by space-borne instruments will improve all aspects of carbon cycle research. Two new infrared instruments for operational meteorological soundings are currently being devel-

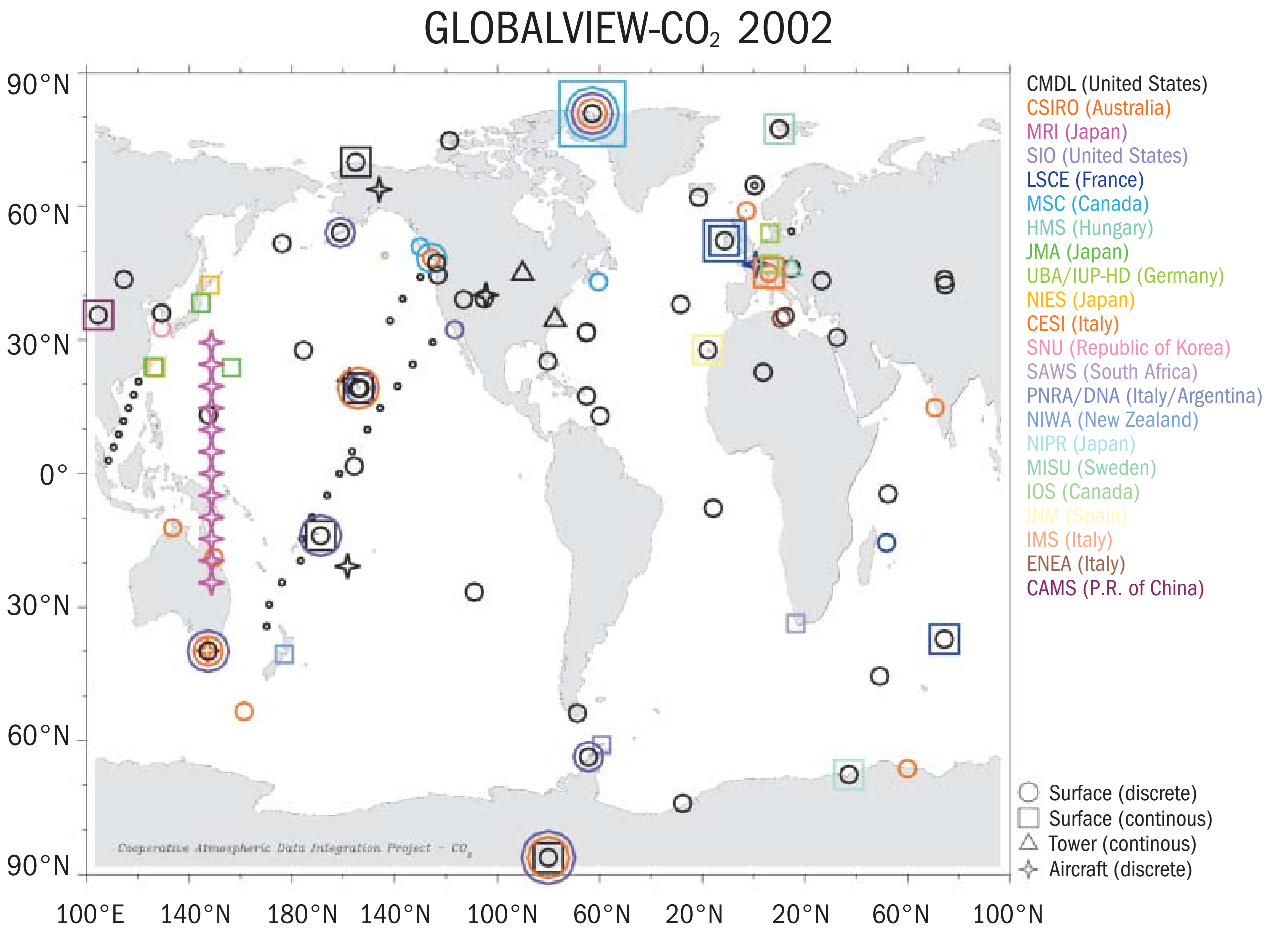


Figure 10

Global distribution of atmospheric CO_2 concentration flask sites. Note the paucity of stations in the southern hemisphere, as well as Eurasia, Africa and South America (GLOBALVIEW-CO_2 2002) [http://www.cmdl.noaa.gov/ccgg/globalview/index.html].

oped for the measurement of CO_2 from space: the Atmospheric Infrared Sounder (AIRS), launched on board the Earth Observing System (EOS) satellite EOS-Aqua in March 2002; and the Infrared Atmospheric Sounder Interferometer (IASI), on board the first Meteorological Operational Polar Satellite (METOP) in 2005. Both instruments will measure most of the infrared spectrum at high spectral resolution and will be accompanied by the Advanced Microwave Sounding Unit (AMSU), a microwave sounder that can be used synergistically with either AIRS or IASI. The significance of this is that AMSU detects only the atmospheric temperature, while AIRS and IASI are also sensitive to CO_2 concentration. It is anticipated that additional properties of CO_2 will be retrieved from these sensors (Chedin et al 2003a).

A proof of concept study has been completed with existing instruments such as the Television Infrared Observational Satellite-Next (TIROS-N) Operational Vertical Sounder (TOVS), flown on board the United States National Oceanic and Atmospheric Administration (NOAA) polar meteorological satellites since 1978. Despite the quite limited spectral resolution of these space-based radiometers, clear signatures of the seasonal cycles and trends in CO_2 and other greenhouse gases (N_2O and CO) may be extracted from TOVS measurements and interpreted in terms of seasonal and annual variations of their atmospheric concentrations (Chedin et al 2002; 2003b).

Also important for retrieving CO_2 concentrations from space is the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) launched on the Envisat platform in 2002 (Bovensmann et al 1999). This instrument will provide high-resolution spectra of the sunlight reflected by the Earth, including the absorption bands that are being considered for retrieving the greenhouse gases CO_2, CH_4, N_2O, H_2O and CO. The estimated total column precision is about 1% for CO_2, CH_4 and H_2O and about 10% for CO and N_2O (Buchwitz et al 2000). The horizontal resolution of the SCIAMACHY nadir measurements is typically 30 km _ 120 km for relevant gases (30 Km x 120 km and 30 Km x 240 Km at high latitudes). A similar passive differential absorption technique has also been recently proposed for the CARBOSAT (European Space Agency mission dedicated to monitoring the carbon cycle) and Orbiting Carbon Observatory (OCO) instruments (with greatly improved spatial and spectral resolutions).

The key assignment for each of these missions is a set of column CO_2 measurements of individual precision better than 1% (< 3ppmv). Simulations show that satellite measurements improve measurement of the carbon fluxes by a factor of up to 10 as compared to the network of surface stations. The greater coverage in time and space provided by the satellite data will improve existing estimates even though the precision of individual measurements may be an order of magnitude lower than those estimated from the air sampling network (Rayner and O'Brien 2001).

Terrestrial observations

Traditionally, the exploitation of biomass resources has been the primary reason for terrestrial carbon observations, motivating many countries to establish inventories (Cannell et al 1999; Houghton 2003) and monitoring networks to support the sustainable use of forests, croplands and grasslands. In parallel, national research programmes have initiated long-term ecophysiological observations at numerous sites, and increasingly use remotely sensed observations of land cover.

Currently, there are a number of existing internationally coordinated networks relevant to terrestrial carbon observation (data providers), including both ground networks of global scope and satellite-based observations (**Appendix C**). Among the ground-based networks, the Fluxnet programme coordinates a global network of over 200 sites, at which tower-based eddy covariance methods provide continuous measurements of the land-atmosphere exchanges of CO_2, water vapour, heat and other entities (**Figure 11**). At many of these sites, complementary measurements are made of carbon stocks and fluxes in vegetation, litter and soil pools, and other ecophysiological variables. Flux tower data with scaling techniques have been already applied successfully to calculate continent-wide fluxes (Papale and Valentini 2003) and are yielding important insights on the controls of seasonal and interannual dynamics. Fluxnet is also becoming an important validation tool for the new MODIS products (e.g., net primary productivity) which will be generated every eight days.

The International Long-term Ecological Research Network (ILTER) provides a far more extensive network of lower technology ecophysiological observations, together with measurements of ecological changes. Harmonisation of regional ground observation programmes is being addressed by GTOS, as part of the GT-Net programme (**Appendix C**). Some research programmes are also addressing the harmonisation of data collected nationally; for example, a comparison of national forest inventories in North America and Asia (Goodale et al 2001), and a comparison of datasets from a number of countries on soil organic matter (Smith et al 2001).

Data users are agencies and programmes requiring information on the carbon cycle in terrestrial ecosystems (**Appendix C**). Data requirements differ in coverage (global, continental and national), type of product and the user group. For certain activities, national agencies require consistent information beyond their territories.

In addition to the above acquisition and product generation programmes, a number of projects have been undertaken that contribute to the development of systematic global observing capabilities, such as the Global Observations of Forest Cover (GOFC) project; the World Fire Web, providing data and information about biomass burning; the GTOS net primary production (NPP) project, providing data to support NPP estimation; and the IGBP NPP-intercomparison project, contributing to the improvement of algorithms for ecosystem productivity (Cramer and Field 1999).

Several major emerging trends in the observation of terrestrial carbon pools and fluxes are likely to accelerate in the next few years:

- Increased attention will be given to methods for combining measurements at multiple scales, such as eddy covariance, ecophysiological and process-level data, and remotely sensed data (see Current research: Scale interactions, in Theme 2).

- A closely related direction will be the synthesis of observations and models, through inversion, data assimilation and multiple-constraint approaches applied to a combination of terrestrial models and observations (see Current research: Synthesis of observations and models, in Theme 1).
- The use of isotopes and other tracers (^{13}C, ^{14}C, ^{18}O, ^{15}N, ^{2}H, ^{3}H) will provide additional measurement possibilities and constraints on models.
- There will be an increasing diversity of terrestrial observations, as nations implement carbon monitoring programmes for determining stocks and fluxes in the mandated categories for greenhouse gas emission estimations under the Kyoto Protocol.

Ocean observations

Traditional oceanographic surveys are a necessary element of any sampling strategy, providing continuity with historical data and the capability for full water column sampling, high accuracy and precision laboratory measurements, and detailed process studies. A continuing global survey programme is under way, to be coordinated by the International Ocean Carbon Coordination Project (IOCCP), a pilot project of the GCP and the SCOR-IOC Advisory Panel on Ocean CO_2. The IOCCP will work in collaboration with CLIVAR, which is making plans to re-occupy some of the World Ocean Circulation Experiment (WOCE) hydrographic lines.

Higher resolution spatial data is available for some in situ surface measurements, in particular the sea surface CO_2 partial pressure (pCO_2) required for air-sea carbon flux estimates. Shipboard underway pCO_2 systems are commonly used on oceanographic research cruises (a recent example being the WOCE-Joint Global Ocean Flux Study (JGOFS) hydrographic survey), as well as a growing effort with Ships of Opportunity (SOOP). The quantity of such measurements will increase in the future and will need better coordination to optimise the basin-scale and global coverage.

Because of their expense and logistic requirements, large-scale shipboard surveys are conducted only infrequently. Such temporally limited measurements offer a picture of the approximate average state of the ocean but do not resolve well the variability on seasonal, interannual and decadal time scales. To resolve these temporal patterns, long-term time-series measurements of carbon and other biogeochemical variables at fixed locations are crucial. The best-known open-ocean time series at present are the more than decade-old United States JGOFS stations near Hawaii (Hawaii Ocean Time-series programme - HOT) and Bermuda (Bermuda Atlantic Time-series Study - BATS). The HOT and BATS monthly data include carbonate system parameters and other traditional biogeochemical data, such as primary productivity, chlorophyll, nutrients, and near-surface sediment traps. They have led to a number of key discoveries, including the demonstration of increasing surface dissolved inorganic carbon (DIC) concentrations and the importance of nitrogen fixation in the subtropical Pacific Ocean. To be most effective, these time-series sites should be thoroughly integrated into the hydrographic and SOOP survey programmes, including measurements from moorings and drifters. The time-series data can provide the temporal context for the spatial surveys and vice versa.

A number of satellite data sets have direct applicability to

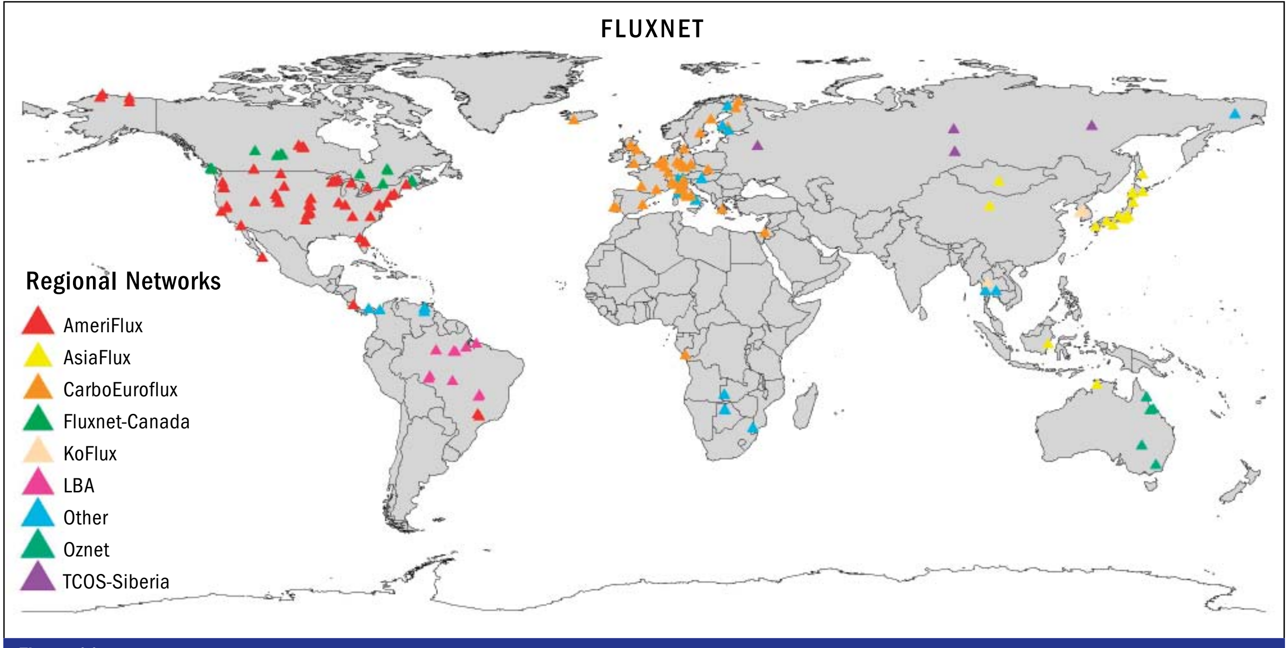


Figure 11

Spatial distribution of Fluxnet sites and their representative sponsor countries. There is a strong movement to standardise ecophysiological and ecosystem measurements and observations among the various networks. Fluxnet is a key example of how international coordination can facilitate communication and information across national boundaries and scientific disciplines. One of the aims of the Global Carbon Project is to encourage and foster the successful development, coordination and expansion of successful networks such as Fluxnet [http://www-eosdis.ornl.gov/FLUXNET/].

the ocean carbon system (**Appendix C**). The most obvious are ocean colour data, which were collected beginning with Coastal Zone Colour Scanner Data (CZCS) (1979-1986) and have been greatly expanded in recent years (Ocean Colour and Temperature Scanner, OCTS, 1996-1997; Polarization and Directionality in the Earth Reflectances, POLDER; Sea-viewing Wide Field-of-view Sensor, SeaWiFS, late 1997 to present). Relevant physical data sets include sea surface altimetry (TOPEX, a United States/French mission to track sea-level height with radar altimeters/Poseidon, a satellite research programme; and the European Remote Sensing programme) for mesoscale variability and physical circulation, sea surface temperature (Advanced Very High Resolution Radiometer (AVHRR) and other platforms), and surface wind speed (National Aeronautics Space Agency Scatterometer, NSCAT; QuickScat). New developments may make it possible to measure salinity from satellites.

Major emerging directions for ocean observations include the following:

- Continuing expansion of ocean observations, in temporal and spatial density, and in the range of chemical and biological parameters measured. Satellite data on sea surface temperature (SST), winds and ocean colour will continue to provide critical information on large-scale patterns and variability of upper ocean physics and biology. For those quantities that cannot be resolved from space, in situ autonomous measurement/sampling technologies are being developed. Particularly promising directions for in situ chemical sampling include new autonomous sensors (e.g., pCO_2, DIC, nutrients, particulate inorganic carbon, particulate organic carbon (POC), bio-optics) and ocean platforms (e.g., moorings, drifters, profiling floats, gliders and autonomous underwater vehicles).
- Enhanced methods for the interpretation of ocean observations will provide additional information on regional interannual variability in air-sea fluxes. Such information is now emerging from repeat observations of surface water pCO_2. Estimates of changes in ocean carbon inventories and transports are needed to contribute to basin-scale carbon budgets for the ocean.
- The development of a comprehensive ocean carbon observing system can be advanced through improved organisation and coordination. This will involve (1) identifying and supporting those programme elements that are currently in operation (such as time-series stations, hydrographic sections and SOOP lines) or in the planning stages; (2) convening and encouraging international meetings of expert groups to refine observing system requirements for scientific and operational monitoring goals; and (3) developing cooperative relationships with other physical, chemical and biological ocean field efforts, with special emphasis on CLIVAR and GOOS. Projects are presently underway in both the North Atlantic and North Pacific to continuously monitor properties on the basin-scale from SOOP lines. However, these programmes need long-term support to build and maintain available datasets.
- The development of ocean carbon assimilation and inverse models is advancing rapidly (as for atmospheric and terrestrial observations). The inclusion of enough process-level information will be critical to address spatial-temporal patterns and detection-attribution of controls of fluxes. As the observational programmes mature, they will provide an unprecedented data stream that can be quickly fed into data-driven models. These models can help provide the time and space scale interpolation to evaluate global fluxes and inventories of carbon.

Observations of human interactions with the global carbon cycle

The human components of the global carbon cycle include emissions, sinks, lateral flows, commodity production and consumption. These human-induced carbon fluxes interact with a range of other human variables including population, wealth, energy systems, technological pathways, and environmental values and constraints (Dietz and Rosa 1997). Such interactions occur both through perceptions of the consequences of human-induced changes in the carbon cycle, and through other major factors such as economic and social drivers, and water and food supplies.

A range of existing systems provide relevant data on these human-mediated carbon fluxes. These systems include inventories of national emissions, forestry and land-use; national carbon accounting systems, regional environmental reporting, and data on trade and commodity production. The challenge is clearly to integrate these disparate and often indirect data sources.

In the area of observations of human interactions with the carbon cycle, major emerging directions include:

- The differing roles of countries, regions and sectors in the carbon cycle. For example, the vast majority of fossil fuel emissions occur in the northern hemisphere, while land use change dominates carbon emissions in tropical latitudes. International corporations are key contributors of data and analyses of such trends (Mason 1997).
- Increasingly refined assessment of regional impacts and vulnerability to climate and carbon-cycle changes. Although there are already different documents on this issue, a major challenge will be to explore the ways in which different regions, sectors, ecosystems and social groups will be confronted by, and/or be able to manage, changes in the carbon cycle (O'Brien and Leichenko 2000).

Synthesis of observations and models

Only a few of the observations described above give direct information on the fluxes and stocks that constitute the global carbon cycle, and none offer an adequate direct picture of spatial and temporal patterns. It is therefore necessary to infer these indirectly. Numerous methods have been developed for this, all based on the synthesis of information from both observations and models. The term "model-data fusion" is sometimes used as an umbrella descriptor for these activities. The general principle is to find an optimal match between observations and model by varying one or more than one property of the model. All applications of this principle involve two basic choices, the first being the model property (or properties) to be varied. There are four broad options: parameters (notionally constant quantities entering the model equations); boundary conditions in space; initial conditions in time; or the model state variables themselves. The second choice is the search method for finding the optimum values of these properties, for which there are many options depending on the formulation and complexity of the problem. In all cases the optimising process should provide three kinds of output: the optimal values of the varied quantities, uncertainty statements about these values, and an assessment of whether the model fits the data, given prior specified uncertainties on the data.

There are several well-established pathways among this suite of possibilities. Three are summarised briefly below.

Atmospheric and Oceanic Inverse Methods: Global atmospheric inversions use observations of atmospheric composition from global flask and baseline networks, together with global atmospheric transport models, to infer spatially averaged net fluxes of CO_2 and other entities between the surface and the atmosphere (Enting 2002; Gurney et al 2002). The principle is to seek the source-sink distribution of a passive tracer, typically CO_2, which, together with a transport model, provides maximum consistency with global concentration measurements. Thus, in this case, the model property being varied is a boundary condition. The term "inverse" refers to the search method, which in essence is to run the transport model backwards.

Atmospheric inversions provide constraints on total carbon sources and sinks, but do not offer information on the processes responsible. Currently, their spatial resolution is extremely coarse. They can partition between the tropics and northern and southern hemisphere extratropical regions, and between land and ocean exchanges, but they do not provide a tropical carbon balance and cannot satisfactorily resolve longitudinal patterns (Schimel et al 2001). Their regional resolution is highly limited by lack of data, particularly in the tropics and the interiors of continents. There is an ongoing effort to use vertical profiles to help fill this gap. Inversions also depend on the choice of atmospheric transport model, especially on scales of ocean basins, continents or smaller.

Atmospheric inversion methods have also been applied regionally, using mesoscale models (Gloor et al. 2001) and atmospheric boundary-layer budget approaches (e.g., (Lloyd et al 1996). Plume studies of forest fires and urban areas have also been used to obtain otherwise unavailable information on gaseous sources, through species and isotopic measurements. Applications at the scale of vegetation canopies have been used to partition sources and sinks between vegetation and soil (e.g., Raupach 2001).

Ocean inversions use similar principles to infer ocean-atmosphere CO_2 exchanges, using ocean pCO_2 and other data. Their data requirements are broadly similar to those of atmospheric inversions. In particular, the accuracy and density of measurements is a major issue, and results are sensitive to the ocean transport model employed.

Parameter estimation: In this case the model properties being varied are parameters which are poorly constrained by process understanding. For biogeochemical and carbon cycle models, these may include quantities such as quantum yields, light use efficiencies, temperature controls on respiration or pool turnover times (Barret 2002). It is almost always necessary to choose such parameters so that the model best fits sets of test data. There are many techniques for finding the best ("optimum") parameters, ranging from simple graphical fits (such as choosing the slope of a line to give best fit) to advanced search procedures for finding multiple parameters simultaneously.

An emerging direction is the simultaneous use of multiple kinds of data in parameter estimation ("multiple constraints"). Many different kinds of data - atmospheric composition, remote sensing, in-situ measurements of pools or fluxes - are available. Different kinds of data constrain different processes in a model. For example, atmospheric concentration measurements and eddy fluxes constrain net CO_2 exchanges (Net Ecosystem Exchange) while remote sensing provides indirect constraints on gross exchanges (Gross Primary Production) through indices such as the Normalised Difference Vegetation Index (NDVI). Thus, different model parameters are constrained by different kinds of data, and the simultaneous use of several kinds of data is needed to constrain a comprehensive model adequately. Several preliminary applications of this approach have already been made, including the combined use of atmospheric concentrations and surface data at continental scale (Wang and Barret 2002), investigations of the combination of atmospheric composition, remotely sensed data and eddy flux data at global scale (Kaminski et al 2002), use of genetic algorithms to constrain terrestrial ecosystem models of the global carbon cycle with ecological data at continental scale (Kaminski et al 2002) and applications at the scale of vegetation canopies (Styles et al 2002).

The multiple-constraint approach relies on access to multiple sources of constraining data with vastly different spatial, temporal and process resolutions, thus producing more constrained predictions. The approach potentially offers a means for discriminating between important and less important avenues for research to improve the process representations in the carbon-cycle model, because the inverse techniques currently used yield uncertainties on estimated parameters. A reduction in these uncertainties constitutes an increase in the information content of the overall prediction of the model. Potential data sources can be assessed for the reduction in uncertainty they provide for model parameters. Importantly, this approach requires the uncertainty characteristics of the data but does not require actual data to be available, thus allowing preliminary testing of experimental designs.

Data assimilation methods: Data assimilation involves adjusting the (time-varying) model state variables themselves as the model is integrated forward in time. This may also be done by sequential adjustment of initial conditions, as in four-dimensional variational data assimilation (4DVAR) methods now being made operational in weather forecasting. Here, time series of global data are used to force a dynamic model into optimal conformity with the data at a given time, while respecting the conservation requirements on the various fields represented in the model, such as conservation of mass (Chen and Lamb 2000; Park and Zupanski 2003). The application of these methods to carbon cycle modelling is still in the future.

Major emerging directions in the synthesis of data and models include:

- Development of other reasonably passive tracers that will offer increased understanding of the carbon cycle (noting that some currently available carbon cycle-related tracers are still not used), and continuing improvements in measurement density, calibration and interpretation, particularly for these additional tracers, but also for atmospheric CO_2 and ocean pCO_2.
- Improved data coverage that will allow downscaling to regional estimates, although regional estimates will also require improved knowledge of the global background (roughly - improvement anywhere hinges on improvement everywhere).
- Three promising technologies to collect more data relevant to regional inversions: (1) continuous measurements, to allow synoptic variations in transport to provide regional source signatures; (2) potential global coverage of CO_2 column integrals from space; and (3) potentially disposable light-weight sensors for use in low-maintenance environments - all of these technologies can interpolate gaps in the current network but must be well linked to it and will also require a major international data management effort to cope with the associated expansion in data flow.
- Inversions regionally and in 'campaign mode' (i.e., snapshots in time in a more constrained area) that can provide information on processes (e.g., via atmospheric plume studies from fires or urban areas and regional ocean transport studies).
- Application of multiple-constraint approaches to the modelling of combined physical, biological and biogeochemical processes.
- Development of carbon cycle process models, for use in multiple-constraint studies, focused on modelling at an appropriate level of parameterisation (noting that most fully process-based models are over-parameterised for use in this way).
- Developments in practical nonlinear search methods.
- More rigorous testing for model inconsistencies by the use of subsets of multiple data sources.
- Further development of uncertainty analyses, particularly in the context of nonlinear inversions.

Areas of uncertainty and research priorities

Despite progress over the last decade, substantial uncertainties remain:

- Existing global models and observations are unable to determine carbon sources or sinks with acceptable accuracy at regional, continental or interannual time scales, largely because of the sparse observing network. For example, the partition of the northern hemisphere terrestrial sink between North America and Eurasia remains unclear.
- There is no systematic and convincing agreement between 'top-down' and 'bottom-up' approaches to determining the spatial patterns of major fluxes in the carbon cycle. Budgets at regional, continental or basin scales are not consistent with the global analysis, with major uncertainties in key regions such as the Southern Ocean and terrestrial tropics. In addition, estimates of some critical fluxes, such as those associated with land-use change, are only obtainable by bottom-up methods and remain highly uncertain in the global context. Recent evidence suggests a much larger role of lateral transport and the coastal zones for regional carbon budgets than previously thought.
- The temporal patterns of the major carbon fluxes, and their consequences for stocks, are poorly understood at time scales greater than a few years. It is unclear which major stocks, whether resolved regionally or biogeochemically, contribute to the long-term variability in atmospheric CO_2 evident in the Vostok ice core record or in shorter records.
- Global estimates of oceanic flux patterns must currently be obtained from data collected over several decades, during which time the spatial pattern of fluxes has changed. This leads to considerable uncertainty in the estimates for any given year, or even decade. Results are dependent on the assumptions made to interpolate both in time and space between the often sparse measurements.
- There are uncertainties in the spatial and temporal distributions of human-induced fluxes, and the influence of human decision processes. Examples are the fluxes associated with land clearing and anthropogenic terrestrial sinks, and fossil fuel emissions (IPCC 2000a,b).

The above assessment prompts the following research priorities for Theme 1: What are the current geographical and temporal distributions of the major pools and fluxes in the global carbon cycle?

1. *What are the spatial patterns of carbon fluxes and stocks at large scales (continents, ocean basins)?*
    - Determine the carbon budget of the terrestrial tropics, and particularly constrain carbon emissions due to land-use change.
    - Determine the longitudinal distribution of the northern hemisphere terrestrial sink between North America and Eurasia, and within Eurasia between Europe and Asia.
    - Determine the spatial patterns and magnitudes of ocean carbon sources, sinks and stocks, particularly in the Southern Ocean.
    - Determine the fluxes and stocks of carbon associated with water flow from land to terrestrial water bodies to the coastal zone, and exchanges between the coastal zone and open oceans.
    - Determine the consequences for the global carbon budget of the uplift, transport and deposition of sediments by both water and wind.
    - Determine the role of non-CO_2 gases (e.g., methane and volatile organic compounds) in the global carbon budget.

2. *How do regional and subregional patterns in carbon fluxes interact with the global-scale carbon cycle?*
   - Determine the space-time dynamics of the biological and solubility pumps in the oceans, and their relative roles in regional and global ocean carbon balances.
   - Determine current trends in the carbon budgets of key terrestrial biomes (tropical, savannah, mid-latitude, boreal, tundra) which are changing as a result of global-scale changes in the coupled carbon-climate system.
   - Develop methodologies for using regional and subregional carbon budgets to constrain the global budget, and vice versa.
3. *What are the seasonal- to decadal-scale temporal variations in the fluxes and stockss making up the carbon budget at global and regional scales, and what are the causes of these variations?*
   - Determine the relative roles of the oceans, the terrestrial biosphere and fluctuations in human emissions.

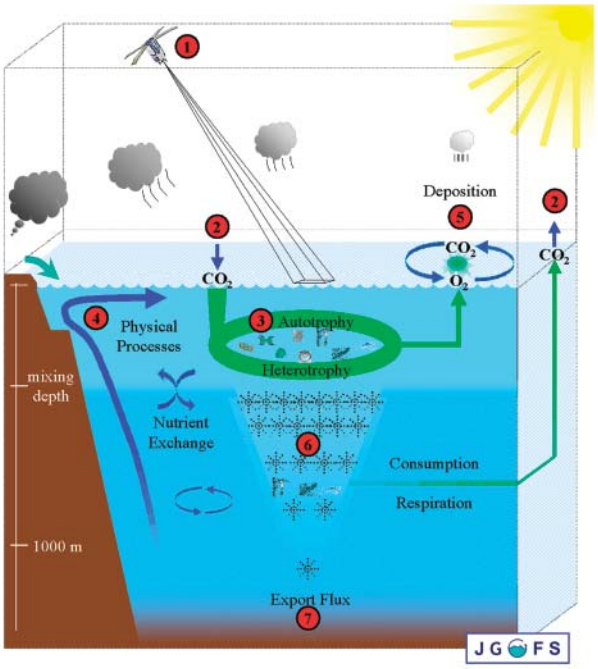


Figure 12

The oceanic 'biological carbon pump' is a collective expression for planktonic, biological processes and feedback pathways that play a role in carbon transfer from the photic zone (zone of light penetration) to the the deep ocean. This complex ecosystem begins with phytoplankton using sunlight and dissolved inorganic nutrients to photosynthetically convert atmospheric CO_2 into biogenic matter, which forms the base of the marine food web. The autotrophic and heterotrophic organisms excrete particles and dissolved matter as they grow and die. The particles sink through the water column carrying carbon to the deep ocean. Thus, the biological pump is one of the pathways that regulate atmospheric CO_2 concentrations, the other being the physical 'solubility pump'. Generally, the food web is efficient and most of the produced particles and dissolved organic matter is recycled through the microbial loop to CO_2 and released back to the atmosphere. (Courtesy of International JGOFS Project Office, Norway).

4. *What are the space-time patterns of human influences on the carbon cycle, including emissions from fossil fuel burning and land-use practices?*
   - Quantify the carbon fluxes and stocks associated with critical regions and sectors of human influence. Here regions include both rural and urban areas (especially megacities), and sectors include both industrial and agricultural activities.
   - Resolve discrepancies in measurements of the historical and current rates and patterns of land-use and land-cover change.
   - Determine the role of human activities in the terrestrial tropics, especially carbon sources due to land use change.
5. *What are the social impacts of changes in the carbon cycle?*
   - Analyse the social and regional patterns of vulnerability and adaptation to the changes in the carbon cycle.

Theme 2: Processes and Interactions

Motivation

The behaviour of the fluxes and stocks that make up the carbon cycle is governed by a set of processes. These include:

- Physical processes in the atmosphere, oceans and terrestrial hydrosphere.
- Biological and ecophysiological processes in the oceans and on land.
- Biogeochemical transformations.
- A range of natural and anthropogenic disturbances to terrestrial ecosystems, such as fire, agriculture and clearing.
- The processes associated with the release of fossil carbon by humans (i.e., energy systems).

Some of these emerge as crucial controls on the global carbon cycle and its responses to anthropogenic forcing (e.g., terrestrial sink saturation, the stability of the thermohaline circulation, and the behaviour of the oceanic biological pump).

An understanding of these processes is needed at the level of their basic mechanisms and also of factors that emerge when they act in combination. Such knowledge is central to understand current and future dynamics of the carbon cycle and includes the recognition and interpretation of past and present interactions and feedbacks among key processes and mechanisms. Process understanding is needed for the development of diagnostic and prognostic tools (Activities 1.2, 2.2 and 2.3, in section 3) that will eventually integrate the dynamics of biophysical systems and human behaviour. These tools will allow the exploration of critical system thresholds (e.g., vulnerabilities) beyond which it may be unwise to proceed (Activity 2.3) and the identification of mitigation options and their contribution to stabilising atmospheric CO_2.

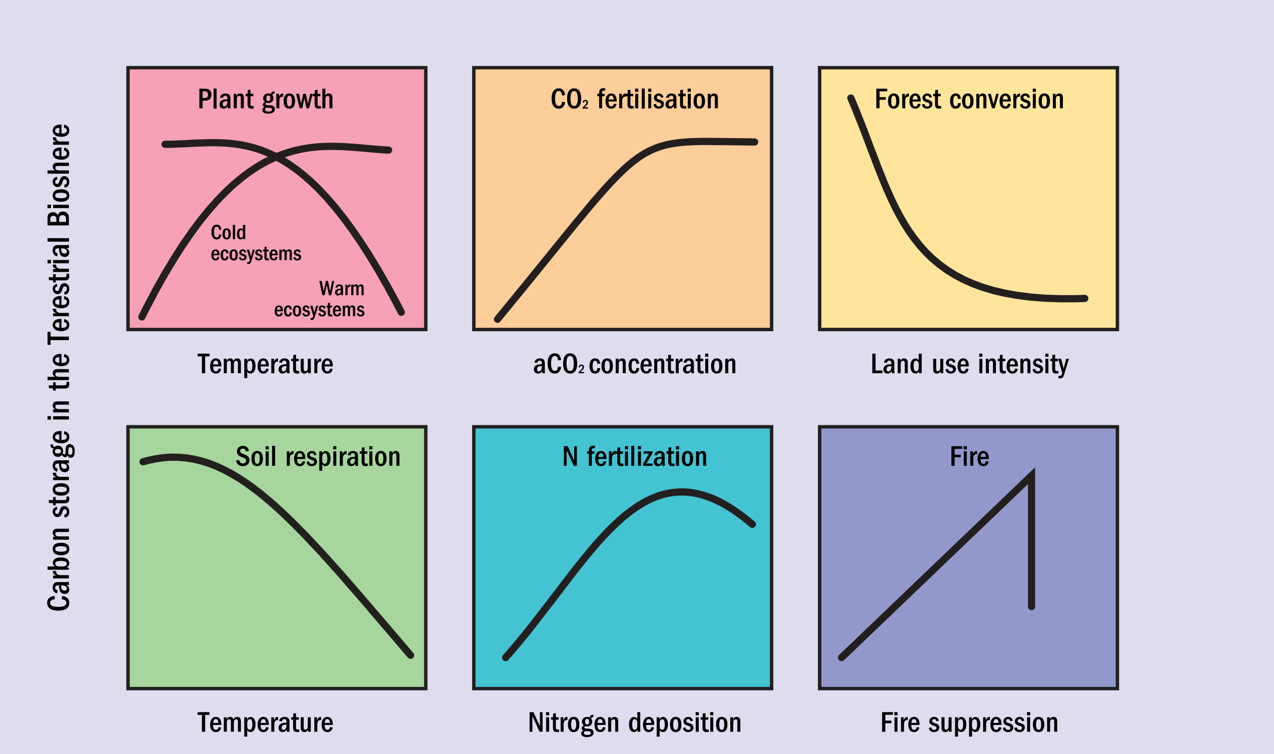


Figure 13

Multiple mechanisms responsible for the current terrestrial carbon sink and their expected future dynamics with increasing global change forcing (Courtesy of Canadell).

Knowledge base

There is already a wealth of understanding of many of the processes governing the carbon cycle, especially at the level of detailed mechanisms. This understanding has been obtained through field observations, laboratory studies, manipulative experiments in the field and process modelling. Carbon-cycle processes that are well understood include the following (Walker et al 1999; IPCC 2001a; Field and Raupach 2003):

1. Net ocean-atmosphere exchanges of carbon are largely controlled by physical processes involving ventilation of thermocline and deeper waters (the solubility pump), with additional influences by biological processes that redistribute carbon from surface to deep waters (the biological pump).
2. A key biological control of the biological pump is the large phytoplankton cells that are responsible for much of the export of particulate carbon to the deep ocean (**Figure 12**). Apart from the effect of large-scale changes in ocean circulation on the biological pump, future oceanic uptake of carbon from the atmosphere is expected to increase as atmospheric CO_2 levels rise.
3. A suite of feedback processes control the coupled energy, water and carbon exchanges between terrestrial surfaces and the atmosphere, causing the response of these fluxes to perturbations (such as land-cover transitions or changes) to be significantly scale dependent. Significant feedbacks in this context include plant physiological responses to atmospheric temperature, humidity, and soil temperature and moisture.
4. The current northern hemisphere carbon sink is due to multiple processes including, for example, forest regrowth, CO_2 and nitrogen fertilisation, climate change, soil erosion and accumulation in freshwater bodies. The relative importance of these processes is not well known (**Figure 13**).
5. The strength of the terrestrial sink may eventually level off and then decline, despite some potential to increase due to anticipated atmospheric and climate change over the next decades.
6. Under sufficiently elevated atmospheric CO_2 concentrations (> 550 ppm), in conjunction with commonly limiting environmental conditions such as water and nutrients, photosynthetic assimilation by terrestrial plants quickly becomes physiologically saturated.
7. Deliberate land-surface modifications will constitute a large forcing of both physical climate and the carbon cycle in the medium-term future (a few decades). The climate response to this forcing may feedback onto land management practices.
8. At large (regional to continental) scales, several factors determine the magnitude and direction of CO_2 exchange between terrestrial ecosystems and the atmosphere:
   - Extreme climate events such as drought, large shifts in seasonal temperatures, or changes in radiation, induced by large-scale perturbations in levels of atmospheric aerosols (e.g., volcanic eruptions).
   - Changes in the frequency of fire, clearing and other large-area disturbances that lead to large, short-term

carbon losses followed by a long, slow recovery of carbon stocks; global NPP by land plants is about 57 PgC yr^{-1} of which approximately 5-10% returns to the atmosphere through combustion (e.g., fuel, wildfires).

- Changes in distributions and biome boundaries of plant species, induced by environmental forcing or changes in land use, which affect carbon storage and turnover over large areas (e.g., the conversion of evergreen to deciduous forest, forest to grassland or grassland to woodland) (Archer 1995; Hibbard et al 2001).
- Losses of biodiversity and invasions by exotic species that may effect the use, efficiency and retention of carbon, nutrients (particularly nitrogen) and water (Schulze et al 2000).

9. Instabilities and multiple equilibrium states can potentially occur in the coupled biophysical and biogeochemical system, consisting of the physical climate, hydrological, carbon and nutrient cycles. These can arise primarily due to the nonlinearities and feedbacks involved in the exchanges of energy and matter between atmosphere, land, oceans and ice. Suggested examples include changes to the El Niño Southern Oscillation (ENSO) phenomenon, potential slowdown or shutdown of the thermohaline circulation in the North Atlantic, ice-albedo runaway (Ghil 1994) and desertification (Ganopolski et al 1998).
10. There are strong interactions among climate, atmospheric greenhouse gas concentrations and human perturbations to the carbon cycle. This is leading to human intervention at an international level, in the form of the UNFCCC and the associated Kyoto Protocol. Both are international institutions working toward the reduction of net emissions of greenhouse gases into the atmosphere (**Figure 14**).

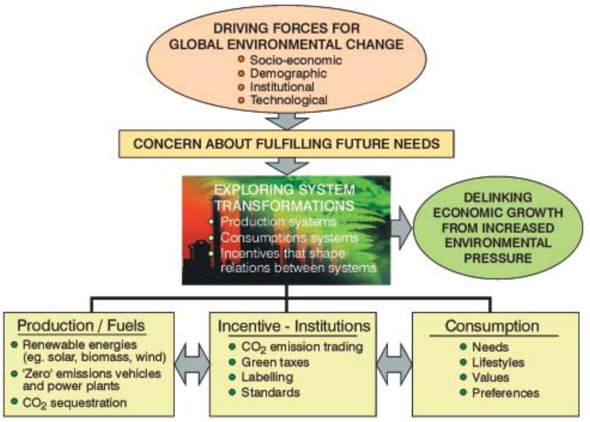


Figure 14

Decarbonising the energy system. Global environmental change driven by mainly socioeconomic, demographic, institutional and technological changes causes public concern about fulfilling future needs. Meeting current and future energy demands while minimising global environmental impacts is a challenge that requires major transformation of the energy system, including production, consumption and the incentive structures that shape the interaction between the two. Possible options for transformation include shift to renewable energies, introduction of the CO_2 emission trading and changes in lifestyle and values (Courtesy of Vellinga and Wieczorek 2002).

Current research

In a biophysical context, observational and manipulative experiments are key tools in formulating and testing hypotheses on the mechanisms that control the flows and transformations in the carbon and related cycles (water, nutrient and energy). They also underpin the formulation of parameterisations in models. In the context of human dimensions, process studies play an analogous role by motivating and testing hypotheses and models describing aspects of social, economic and organisational human behaviour.

The following subsections describe process experimentation and process model development that are key for global carbon cycle studies.

Terrestrial ecophysiological processes

There are a number of networks of physiological studies, including the previously described Fluxnet programme and ILTER. Fluxnet is providing insights on the daily, seasonal, and interannual controls on fluxes of carbon, water and energy. In addition, the Global Change and Terrestrial Ecosystems (GCTE) project of IGBP has established a number of other physiological and experimental networks to study control processes under current and future global environments. The Biosphere-Atmosphere Stable Isotope Network (BASIN) deals with isotopic discrimination in the process of photosynthesis and respiration. The aim is to use atmospheric isotopic signatures to constrain global estimates of carbon sources and sinks, and to partition ecosystem fluxes (e.g., photosynthesis and respiration). BASIN has shown that water availability is a key control on atmospheric $^{13}CO_2$ and has highlighted the potential of delta ^{13}C of ecosystem respiration as a useful tool for integrating environmental effects on dynamic canopy and ecosystem processes (Pataki et al 2003).

Manipulative experiments also play a critical role in developing and testing ecophysiological and biogeochemical models. Such experiments include warming experiments of both soils and canopies, free-air CO_2 enrichment (FACE) experiments, alteration of the water balance by irrigation or rainfall exclusion, and nutrient enrichment (Canadell et al 2002a; Norby et al 2001; Rustad et al 2001). These experiments are yielding important insights on ecosystem changes and emerging critical drivers under future environmental conditions. For example, some of these studies suggest that saturation of the CO_2 fertilisation effect will take place between 500-600 ppm atmospheric CO_2, a much lower concentration than the natural physiological saturation point at around 1000 ppm (Mooney et al 1999).

Another emerging issue from these experiments is the response of terrestrial respiration to environmental controls such as temperature, moisture and nutrient availability. Temperature responses, in particular, have been questioned recently (e.g., Valentini et al 2000), leading to the suggestion that terrestrial respiration rates have been overestimated in global carbon cycle models (Cox et al 2000). Interactions between soil respiration and dry and warm soil conditions, the effects of rains after dry periods, the effects of snow packs and length of growing season are yet to be fully understood and modelled.

Important long-term drivers of carbon exchanges between land and atmosphere are different from those controlling short-term exchanges. Long-term drivers include changes in ecosystem structure due to biome redistribution and altered disturbance regimes. Critical issues here are transient effects of biome shifts forced by climate change and the dynamics of large scale biome redistribution, given the fragmentation of current ecosystems.

Disturbance, land use and management practices

Disturbances and changes in land use or cover are important controls of carbon storage. Shifts from one type of land use or cover to another are responsible for large carbon fluxes in and out of the terrestrial biosphere (Houghton 1999; Pacala et al 2001) and can drive a region from being a carbon sink to a source (e.g., Kurz and Apps 1999).

A large body of research is focused on understanding the effects on sink strength and carbon storage of multiple land uses (IPCC 2000b; Canadell et al 2002b), as efforts to conserve forests become more important and land-based mitigation options are explored to help slow down the build up of atmospheric CO_2. Land uses include reforestation, afforestation, deforestation, agricultural practices, and succession on abandoned agricultural lands.

Biomass burning, wildfires and other disturbances are estimated to be major sources of CO_2, CO and CH_4. Efforts are underway to quantify changes in historical disturbance regimes and their contribution of greenhouse gases to the atmosphere, which in some years are comparable with the CO_2 produced from fossil fuel. Timber resources of regions such as Siberia, and farming land in Amazonia and tropical Asia are increasingly vital to the economies of those countries; however, these resources drive major changes in the frequency of disturbances and carbon potential of the altered ecosystems. The interaction of human impacts, logging, deforestation, fire, and climate variability and change are complex and are the focus of various efforts, such as those in Siberia and parts of tropical Asia, and of the Long-term Atmosphere-Biosphere Experiment in Amazonia (LBA). Special attention is being paid to carbon emissions from drained or burned peatlands.

Controls on air-sea fluxes and upper ocean biogeochemical processes

In oceanic ecosystems, interannual to decadal climatic oscillations (Arctic, North Atlantic, North Pacific and southern oscillations) and their interconnections have been identified as major controls on upper ocean biogeochemistry and air-sea fluxes of carbon (Doney et al 2000). Process tools for studying the physical and biological mechanisms that control air-sea fluxes include repeat hydrographic surveys, time-series stations and other ocean observations that incorporate an integrated programme for carbon, hydrographic and tracer measurements. The Southern Ocean Iron Release Experiment (SOIREE) illustrated the importance of iron limitation in high nutrient/low chlorophyll regions by deliberate iron fertilisation experiments in the Equatorial Pacific and Southern oceans. Such experiments found phytoplankton responses up to six weeks after iron was applied as a fertiliser in surface waters of the Southern Ocean (Boyd et al 2000). Additional investigations into the role of iron limitation used SOIREE results to probe climate switches to and from ice ages (Watson et al 2000). Of particular relevance for future oceanic process studies are insights gained into export fluxes and their dependence upon community structure (diatoms versus background microbial community); geochemical functional groups (nitrogen fixers, calcifiers); physical variability (tropical instability waves, mesoscale eddies); and trace micronutrients.

Atmospheric isotopic and tracer studies

Interpretation and integration of isotopic information has been an invaluable tool for understanding processes and diagnosing the large-scale patterns and variability of carbon fluxes (this discussion also pertains to Theme 1). In both areas, isotopic studies will continue to be of great importance with the following highlights:

- Studies of atmospheric CO_2, ^{13}C, O_2/N_2, together with mass balance calculations and atmospheric inversions, have quantified carbon fluxes into the atmosphere, due to fossil fuel, land-atmosphere exchange and ocean-atmosphere exchange (IPCC 2001a; Schimel et al 2001). In particular, atmospheric ^{13}C observations suggest that a large portion of the change in the growth rate of atmospheric CO_2 is due to variations in carbon exchange in the northern rather than the southern hemisphere, and the interannual variability in this growth rate is dominated by terrestrial ecosystems rather than the ocean.
- Substantial uncertainties are currently associated with the oxygen budget. It has become clear that a major problem with the interpretation of O_2/N_2 measurements is accounting for the secular changes in O_2 storage occurring in the oceans, due to increasing temperatures and changing circulation patterns. The current IPCC (2001a) estimates of ocean and atmospheric sink sizes, for example, appear to be in error because of this.
- Estimates of global, and to some extent regional patterns of excess CO_2 storage by the ocean, on decadal time scales, are constrained by a variety of techniques, including numerical models (often calibrated with ^{14}C and other transient tracers), temporal evolution of DIC and ocean ^{13}C fields, and data-based anthropogenic DIC estimates (Sabine and Feely 2001).
- Global estimates of terrestrial gross primary production (GPP) and the NPP/GPP ratio have been obtained from ^{18}O in CO_2 (Ciais and Meijer 1998).

Economic and technological developments governing fossil fuel emissions

Fossil fuel emissions are often taken to be an external forcing on the carbon cycle. On this level, accurate quantification is very important (Marland et al 2000). However, the future trajectory of the global carbon cycle will be determined by interactions between fossil fuel emissions and the carbon-climate-human system, as humans react to perceived dangers from inadvertent intervention. Hence, to incorporate fossil fuel emissions into models of the carbon-climate-human system is a major challenge for future predictions.

Local interactions between institutional regimes and the carbon cycle

In seeking a full understanding of the feedbacks between land management, fossil fuel emissions and the carbon cycle, it is important to recognise and include the proximate social and economic drivers of human responses. For example, a study in Chilean mixed grazing and farming systems identified the means by which biophysical, sociopolitical and economic variables influence land use and vulnerability of rural populations to climate variations (McConnell et al 2001). On one hand, rugged topography and pedogenically undeveloped soils characterise the bulk of communal lands in this area, which are typically dedicated to annual crops. On the other hand, private holdings, generally located in richer, flatter valleys, are devoted to perennial crops such as vineyards, and control almost all of the water rights. Location and crop types are thus two of the criteria that can be used to identify property regimes. The sensitivities and likely responses of these two regimes to climate change are substantially different.

Implications of this kind of study for present and future carbon stocks and fluxes emerge upon integration with process-level understanding. A comparative examination of case studies (e.g., tropical deforestation, agricultural intensification) will provide a clearer overview of the human drivers of land-cover changes and the ways that they depend on geographic and historical contexts.

Scale interactions

Process studies and models are always implicitly specific to particular space and time scales (e.g., in the case of terrestrial ecosystems, the spatial scales defined by cell, leaf, canopy, patch, region and globe). It is often necessary to apply information from one scale to a different (smaller or larger) scale in space or time. The information to be transferred across scales may include model parameters or process descriptions encapsulated in the equations of a process model. If the transfer of information is from smaller to larger scales, this is known as 'upscaling' or 'aggregation', whereas the reverse process is referred to as 'downscaling' or 'disaggregation'.

Common examples of aggregation problems include estimation of plant canopy net photosynthesis from leaf-scale models, prediction of terrestrial carbon sources and sinks for national greenhouse gas inventories from point-based models, and the specification of grid-cell averages of fluxes in large-scale atmospheric models. These problems have been the subject of major reviews in several disciplines (Bolle et al 1993; Michaud and Shuttleworth 1997: meteorological problems; Ehleringer and Field 1993: plant physiological problems; Kalma and Sivapalan 1995: hydrological problems).

Several recent and ongoing initiatives are defining methodological approaches to scaling and aggregation, and gathering data to test these approaches:

- Several large-scale campaign experiments on interactions between terrestrial ecosystems and the atmosphere have gathered numerous data at a range of scales (Hutjes et al 1998).

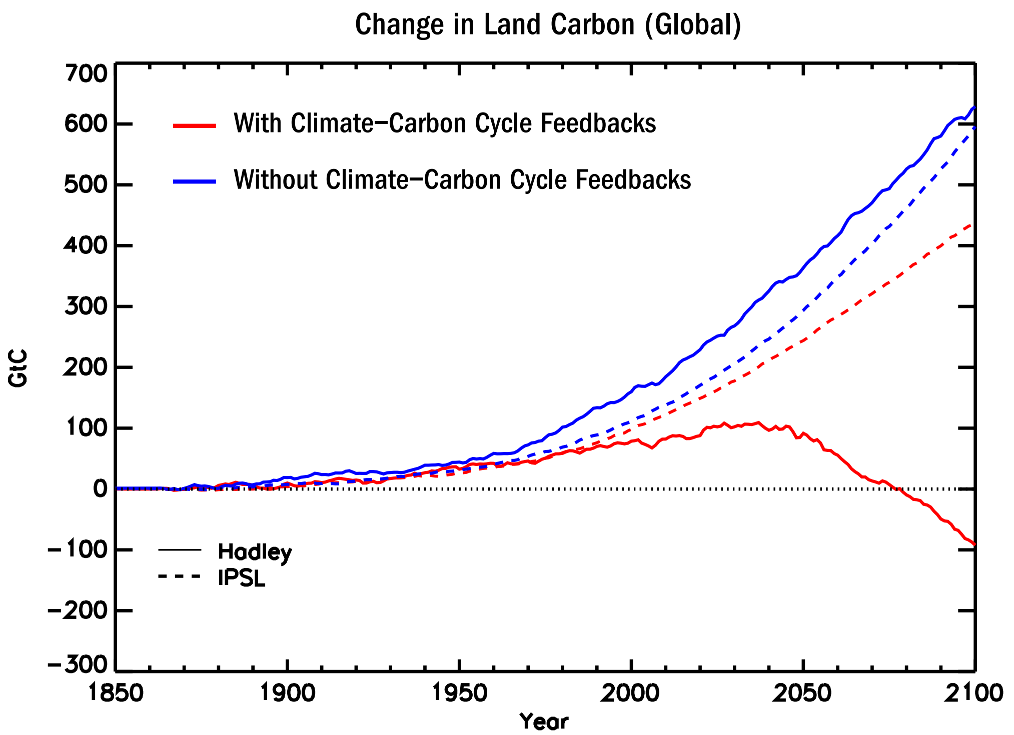


Figure 15

Predicted changes in global land carbon (vegetation plus soils) from two coupled climate-carbon cycle GCMs. Positive represents an increase in land storage. The Hadley Centre results are shown by the continuous lines and the IPSL model results by the dashed lines. Blue lines represent runs without climate change, and the red lines are from the fully coupled runs including climate-carbon cycle feedback (Cox et al 2000).

- The BigFoot project has the goal of exploring validation protocols and scaling issues that would lead to an improved understanding of several satellite products (Running et al 1999).
- Systematic approaches to aggregation are now being developed in the context of scaling models of carbon and related fluxes in terrestrial ecosystems (Baldocchi et al 1996; Raupach et al 2002).

Vulnerability of the carbon cycle: nonlinear dynamics, thresholds, and regime shifts

Dynamics of the carbon-climate-human system are likely to contain unknown surprises and thresholds induced by nonlinear feedbacks and interactions among major compartments and processes of the system (Charney 1975; Claussen 1998; Falkowski 2000). These include:

- The stability of ocean circulation (e.g., through possible slowdown or shutoff of the thermohaline circulation).
- The ability of terrestrial ecosystems to sequester carbon in the future as mechanisms responsible for current sinks saturate (CO_2 fertilisation; forest regrowth after abandonment) (Cramer et al 2001).
- The uncertain permanence of current terrestrial carbon stocks due to changes on control processes such as switches due to phenology, soil respiration, changes in seasonal freeze-thaw dynamics, thawing of permafrost, changes in water table, drought, absence/presence of snow, fire, insect infestation.
- Feedbacks between terrestrial and marine systems such as ocean NPP enhancement due to dust deposition from land.
- The societal and policy drivers for the changes in carbon systems and for carbon management (linked with the perceptions of risk, due to changing climate and consequent development of new institutional regimes to control greenhouse gas accumulation in the atmosphere).

Most of these processes are the result of interactions between the changing climate, human systems and the global carbon cycle, with the potential for accelerating or decelerating the build up of atmospheric CO_2. The implications of these interactions are that, to achieve stabilisation, an enormous reduction in fossil fuel emission and increase in carbon sequestration is urgently needed.

Although such interactions are likely to occur, their quantification is difficult and is restricted to subsets of their components for the Earth system because fully coupled carbon-climate-human models do not exist (see Integrative model development, below). Coupled carbon-climate models, however, have provided major insights on the types of possible nonlinear responses. These models show a slow down of the terrestrial sink strength by the middle of this century, with it becoming a source by the end of the century (Cox et al 2000; **Figure 15**). Coupling biophysical and decision-making models have also produced unpredicted results (Roughgarden and Schneider 1999).

Integrative model development

Understanding the global carbon cycle through Earth system modelling is motivated by our limited knowledge about the consequences of the feedbacks and interactions between biophysical components of the system. A further motivation is the need to assess the importance of large-scale perturbations of the system by human activities (e.g., fossil fuel combustion and changes in terrestrial vegetation cover). Feedbacks between changes in the Earth system and the perception of a problem by humans are equally important, because they are likely to generate major changes in policy and attitudes concerning the way we manage and use our energy systems.

Earth-system models of intermediate complexity (EMICs) are sufficiently simple to permit numerical integration over many millennia, but sufficiently complex to yield a realistic picture of the Earth system because they include more interactions than are possible using comprehensive fully coupled process-based models. To date, EMICs have focused largely on the biophysical components of the Earth system (geosphere, atmosphere, some with biosphere) with prescribed human components, such as land use and CO_2 emissions. Emerging directions in this field are the inclusion of a better representation of the living world (biosphere) and the human dimension (anthroposphere). The spatial (e.g., regional) resolution required by these models to properly capture processes with global significance remains an issue.

Comprehensive three-dimensional global climate models (GCMs) of the atmosphere, ocean, land and cryosphere, including the fully coupled carbon cycle, are now being developed. These models provide the most realistic descriptions possible of atmospheric and oceanic transport processes, and integrate the terrestrial vegetation processes into the biophysical parameterisations used in these models. Hence, they provide an interactive representation of how physical environmental parameters affect biological ones and vice versa. In the long run, such models may have the most promise as predictive tools.

A major issue of any large complex model is validation. Prognostic model components need to be robust in climates that differ from both the present and the past. Confidence in the robustness of an integrated model is currently built in four ways. First, individual components (terrestrial, oceanic, atmospheric, economic, social) are tested within and beyond the range of calibration data. Second, the ability to reproduce historical trends, either the glacial-interglacial record for the biophysical components or the industrial era for the fully coupled model, is a key test of understanding. Third, through a strategy that encourages a variety of interchangeable models or submodels, it is possible to assess the degree to which outcomes depend on the assumptions of particular models. Finally, regional model intercomparisons provide tests at the subglobal scale by exploiting the variety of biophysical and social conditions that occur at regional scales.

Other models that incorporate socioeconomic aspects with a carbon cycle perspective include integrated assessment models such as the Integrated Model to Assess the Greenhouse Effect (IMAGE) (Leemans and van den Born 1994), models of political systems that project social responses to the Kyoto Protocol based on game theory and models of industrial/energy systems and industrial transformations.

Areas of uncertainty and research priorities

Major gaps still exist in our understanding of the processes, controls and interactions that influence the global carbon cycle:

- The mechanisms underlying a number of critical biophysical processes remain poorly understood, and are therefore inadequately represented in current models. The mechanisms include:
  - the interplay between multiple land uses, ecosystem physiology and disturbances controlling carbon fluxes in and out of land systems; and the relative importance of the full suite of mechanisms contributing to current and future carbon sinks and sources
  - the dynamics and environmental responses of terrestrial carbon allocation in various components of the ecosystem
  - the dynamics and responses of heterotrophic respiration to climate forcing, particularly temperature, in terrestrial and ocean systems
  - the lateral transport of carbon across landscapes and into the coastal and open ocean
  - the roles of ocean circulation, sea ice, chemistry and ecosystem dynamics in modifying the amount and pattern of ocean uptake in response to increasing CO_2
  - the structure and dynamics of ocean ecosystems (phytoplankton and their predators at higher trophic levels)
  - the processes driving nutrient dynamics in different ocean basins which vary in time and between basins (e.g., nutrient-deficient waters in the North Pacific Ocean can switch between nitrogen and phosphorus limitation with associated ecosystem-level changes that seem to be responsible for variations in climate)
  - the biological, chemical and physical interactions that move carbon through the continuum of atmosphere, upper ocean and deep ocean.
- It is likely the global carbon cycle has highly vulnerable carbon stocks to environmental change. The release of that carbon into the atmosphere could act as a major positive feedback to climate change. Possible candidates are frozen soils, wetlands, and tropical forest.
- The scientific community is only beginning to identify the proximate and ultimate drivers of changes relevant to the carbon cycle in human systems and institutions. Such drivers include human decision processes at international, national, regional and local scales. Identifying these drivers is crucial because many of the largest sources of uncertainty and largest opportunities for intervention lie in the human domain.
- It is known from ice core records that global atmospheric CO_2 levels have maintained a range of about 180-280 ppmv over the last half million years. However, the mechanisms that determined these apparently well-constrained 'clamp points' are still a matter of debate.
- Although all the processes mentioned above are important, their implications for the emergent behaviour of the global carbon cycle and its links with climate, other major biogeochemical cycles, and human actions remain uncertain. This makes an integrated assessment of the interactions and feedbacks between the processes acting in the carbon cycle and the resulting whole-system emergent behaviour a fundamental requirement.

The above assessment prompts the following research priorities for Theme 2: What are the control and feedback mechanisms - both anthropogenic and non-anthropogenic - that determine the dynamics of the carbon cycle?

1. *What mechanisms controlled paleological and pre-industrial concentrations of atmospheric CO_2?*
   - Determine the controlling features and simulate the temporal dynamics of the glacial-interglacial carbon-climate system.
2. *What are the multiple mechanisms responsible for current aquatic (ocean and freshwater) carbon sinks? What are the relative contributions of these mechanisms, and their interactions?*
   - Quantify interactions between mechanisms controlling the biological pump, including the effects of nutrient fertilisation (iron, silicon and other elements) on net carbon uptake through changes in the structure and function of aquatic ecosystems, and the effects of climate variability and change.
   - Quantify interactions between mechanisms controlling the solubility pump and carbonate chemistry, including changes in freshwater fluxes (ice melting, river flows and precipitation) into the upper ocean; lateral transport and subduction of surface waters; ocean-atmosphere exchanges of energy, water and CO_2; and the dynamics of climate variability.
   - Identify the interactions between sediment carbon pools and aerobic and anaerobic decomposition pathways in freshwater bodies.
3. *What are the mechanisms responsible for current terrestrial carbon sinks, their relative contributions and interactions?*
   - Identify the multiple sink mechanisms responsible for the current terrestrial sink and their interactions, including climate changes (e.g., precipitation, temperature, humidity, radiation, climate variability); changes in atmospheric composition and atmospheric inputs (e.g., CO_2 and nitrogen fertilisation); and changes in land use and land management (e.g., past and present clearing, and fire management).
   - Assess how both natural and anthropogenic disturbances (e.g., fire, herbivory, harvest, storm damage) affect the sequestration and release of carbon to the atmosphere.
4. *What mechanisms control horizontal carbon fluxes in air, oceans and terrestrial water bodies?*
   - Quantify feedbacks between changes in the global carbon cycle and oceanic and atmospheric transport of carbon and energy.
   - Quantify the key processes driving land-coastal-open ocean carbon exchange and their interactions.

5. *What are the likely future dynamics of current sink mechanisms? Will current terrestrial carbon sinks saturate or reverse, and how will oceanic carbon pumps evolve over coming centuries?*
   - Using multiple data streams and improved prognostic models, develop regionalised future scenarios for the terrestrial carbon cycle on the basis of assumed scenarios for the evolution of the global carbon-climate system.
   - Integrate and test these regional scenarios for global consistency, thus constraining and feeding back on global scenario development.
   - Use long-term ocean observations (existing and future hydrographic surveys, time series stations, remote sensing records) to validate and improve prognostic ocean carbon models; then use these models to develop scenarios for the future of ocean carbon pumps over coming centuries.
6. *What mechanisms control anthropogenic carbon fluxes and storage?*
   - Explore the driving forces of different pathways of regional development on carbon stocks and fluxes.
   - Explore the drivers of patterns of production/consumption and land use change that give rise to anthropogenic emissions of greenhouse gases.
   - Explore and explain the drivers of the energy intensity of the production of wealth, and the carbon intensity of the production of energy.
   - Identify the factors explaining the mix of fuels used in the generation of electricity.
   - Determine how public and private activities and their interactions drive rates of deforestation and influence land-use practices.
   - Explain the factors governing variability in residential patterns of heating and cooling systems.
   - Quantify and explain variations in the character of transport systems.
   - Understand the effect of changing climate cycles (e.g., ENSO, the Pacific Decadal Oscillation and the North Atlantic Oscillation) on anthropogenic CO_2 fluxes (e.g., fossil fuel, land use, fire, other).
7. *How do feedbacks between natural and human processes magnify or dampen both anthropogenic and non-anthropogenic carbon fluxes?*
   - Develop simple (low-dimensional) models of the coupled carbon-climate-human system, including interactions between natural and human terrestrial processes, interactions between ocean biology, carbonate chemistry and ocean circulation, and the consequences of changes in the carbon cycle for human activities.
   - Develop Earth system models with fully coupled carbon, climate and human systems, including components of socioeconomics, human behaviour and institutions.
   - Explore with modelling tools possible feedbacks and thresholds leading to unstable behaviour that the climate-carbon-human system may possibly cross. Attempt to identify critical points for such abrupt and significant changes.

Theme 3: Carbon Management

Motivation

The future dynamics of the carbon cycle will be determined by the combined result of the natural dynamics of the biogeosphere and the net carbon balance of anthropogenic activities. Past, present and future dynamics of the perturbed carbon cycle have been dealt in themes 1 and 2. Theme 3 will specifically focus on the science of managing the climate-human system as the points of intervention for humans to stabilise atmospheric CO_2 and associated climate change.

In addition, the capacity to generate worthwhile predictions or scenarios for the future has policy implications at international, national and regional levels. These are the direct consequences of several factors. First, human activity is one of the primary drivers of perturbations to the global carbon cycle, and decisions made by people introduce key uncertainties into projections of its future evolution. Second, human-induced changes in the global

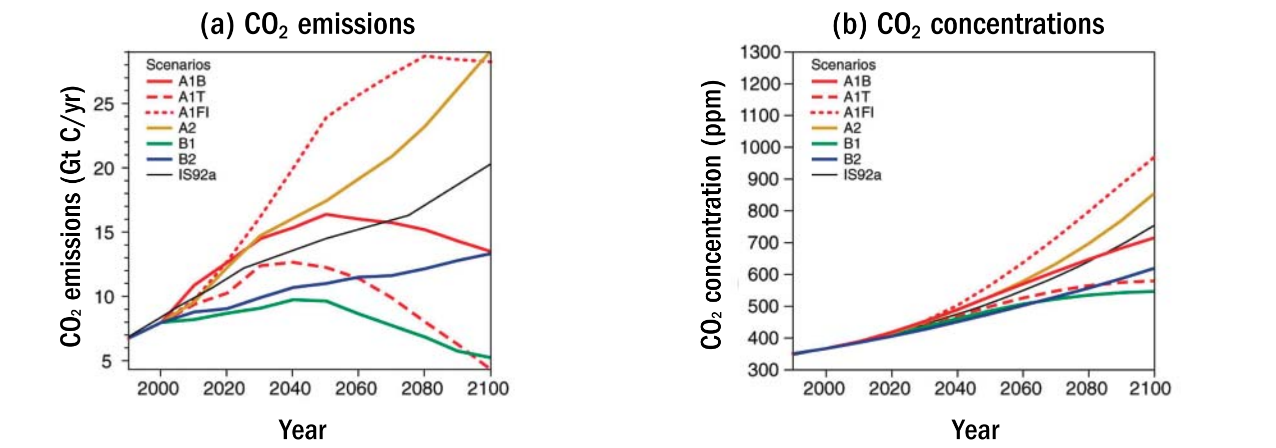


Figure 16

Projected atmospheric CO_2 (a) emissions and (b) concentrations from several general circulation model scenarios during the 21st century (IPCC 2000a).

carbon cycle have the potential to alter the global climate system, and hence affect water and food resources, environmental resilience, biodiversity, health and international political stability. The global carbon cycle has therefore become an important policy issue placed well beyond climate mitigation alone, and is now an important part of the wider agenda on development, sustainability and equity. A capacity to build the components of scenarios (e.g., policies, capacity of mitigation options) and perform robust analyses of future scenarios is a key interface between science and policy required for the success of CO_2 stabilisation goals of the UNFCCC (**Figure 16**).

Knowledge base

Plausible trajectories and the capacity to mitigate result from a number of analyses using integrative assessment models coupled to carbon-cycle models, analysis of current trends, and inductive reasoning. A summary of the existing knowledge base in this theme consists of a set of 'scenario elements' and estimates of technological development and innovation (IPCC 2000a,b; IPCC 2001a,b,c; Field and Raupach 2003):

1. Greenhouse gas concentrations will continue to increase for many decades, irrespective of global mitigation actions. Even with major emission abatement measures, a levelling-off of atmospheric CO_2 at twice the pre-industrial level would be a major achievement.
2. The world energy system delivered approximately 380 exajoules (EJ) (10^{18} joules) of primary energy in 2002 (BP Statistical Review of World Energy 2002), of which 81% was derived from fossil fuels.
3. There is no single technology or path that will take nations and regions to a low carbon emission future. Each nation will need to choose their own path given their socioeconomic, political and environmental circumstances.
4. A range of potential human responses are possible to the threat of undesirable climate change, most of which are likely to be used at a significant scale over the next century:
5. Continuous energy efficiency improvement, afforestation, low-carbon energy, and natural gas will play a central role in reducing carbon emissions during the first part of the 21st century. Innovative non-fossil fuel technology will be required to complete stabilisation.
6. Conservation and sequestration in forests could be as high as 60-87 PgC by 2050 and 44 PgC could be further sequestered in agricultural lands. This amount is equivalent to 10-20% of the projected fossil fuel emissions during that period.
7. Humans respond to threats to their welfare from undesirable climate change. They have begun to do so with the 1997 Kyoto Protocol (though the impact of the protocol on greenhouse gas concentrations will be slight in the first commitment period). The human response to the climate change threat will increase over the next century, although at an uncertain rate and under uncertain institutional and compliance levels.

Current research

Portfolio of carbon mitigation options

There is no one single technology or approach to mitigate carbon that will universally solve the climate problem. Instead, nations and regions need to find the right mix of options according to their sociocultural and environmental circumstances. An understanding of the multiple options available and their capacities for mitigation is driving a large body of research (Gupta et al 2001). Current research is focusing on five categories of mitigations (IPCC 2000b; IPCC 2001c; Field and Raupach 2003), detailed below.

Conservation and increased efficiency. A number of changes in technology, policy and human behaviour can reduce energy demands, either with benefits for economic productivity or, at most, small costs. Examples include more efficient appliances, transport (e.g., hybrid vehicles that electrically recover lost mechanical energy), better urban planning (e.g., better public transport), cogeneration (recovery and use of low-grade heat from electric power stations) or changes to diets that require less energy inputs (e.g., shifting diets towards vegetarian). The potential carbon gains from these options are large, in many cases from tens to hundreds of percent on a sectoral basis.

Non-fossil-fuel energies. These include hydropower, wind, solar, geothermal, tidepower and biofuels (the crops grown to produce biofuels take up at least as much carbon as is generated in carbon emissions from the use of these fuels). Up to 500 million hectares of land (around 3% of the global land area) could be made available for biofuel crop production by 2100, and could displace between 3 and 5 PgC during that time. Research on more advanced non-carbon technologies such as nuclear fission or fusion, spaced solar power, and geoengineering, is also underway, with the hope these technologies can play an important role in the future in climate mitigation.

Land-based options including disturbance reduction and biological sequestration. There is a large interest in these options because of the potential for additional environmental and development benefits, such as increased soil fertility and forestry activities (Yamagata and Alexandrov 2001). The potential carbon sequestration using reforestation, afforestation and land restoration (the land-based options accepted under the Kyoto Protocol) is in the order of 1 PgC yr^{-1} by 2010, and changes in forest management could sequester carbon at 0.175 PgC yr^{-1}. Reduction of net deforestation also has a large potential, because deforestation contributes about 20-25% of total anthropogenic emissions. However, although ending forest deforestation is a laudable goal, it has proved difficult or impossible to implement in many regions. Research is underway to explore tangible socioeconomic incentives and the ultimate drivers of deforestation (e.g., markets and policy) as points for intervention. Finally, mitigation options in the agricultural sector can avoid some of the 20% contribution to the total of anthropogenic greenhouse gases. The global potential for this option is estimated at 40-90 PgC.

Biological sequestration in oceans. The efficiency and duration of carbon storage by ocean fertilisation remain poorly defined and strongly dependent on the oceanic region and fertiliser used (e.g., iron, nitrogen, phosphorus). The maximum potential of iron fertilisation has been estimated as 1 PgC yr_1 by continuous fertilisation of all oceanic waters south of 30°S (Sarmiento and Orr 1991). However, the uncertainties and ancillary impacts are potentially enormous. This active research field requires substantial progress before this option is seriously considered by policy makers.

Engineered CO_2 disposal on land and in oceans. Research on deep ocean injection of pure liquid CO_2 is still at its infancy but deserves attention as we try to build a comprehensive portfolio of options. There is little understanding of the physical behaviour or biological and chemical consequences of deep ocean injection. Conversely, geological storage in sediments and rocks is much more advanced, and offers the potential for large CO_2 disposal in exhausted oil and gas wells, and in saline aquifers. This is a relatively clean solution provided there are not CO_2 escapes, dissolution of host rock, sterilisation of mineral resources or unforeseen effects on groundwater.

Technical versus achievable mitigation potential

The maximum mitigation that can be achieved by a strategy is its technical mitigation potential. It is based solely on biophysical estimates of the amount of carbon that may be sequestered or greenhouse gas emissions avoided, without regard to other environmental or human constraints. However, the achievable mitigation potential is less (often very much less) than the technical potential, because of a range of economic, environmental, and social drivers and constraints that lower the extent to which a given technology can be deployed and accepted by societies (**Figure 17**). For example, an analysis of a number of constraints on global implementation of carbon sequestration and energy cropping (i.e., increasing the biological sinks through tree planting) showed that only 10-20% of the technical potential of 2000-5000 $MtCyr^{-1}$ offset could be realistically achieved (Cannell 2003). A highly integrative new research field is currently emerging, to assess the achievable potential for deploying and implementing a number of mitigation options, and the immediate benefits to climate mitigation and sustainable development. Strategies for adaptation to climate change are similarly critical, and policy makers and social actors will need to weigh the pros and cons of the relative merits of mitigation and adaptation, including seeking situations that are win-win for the two types of policy.

Some of the constraints on technical potentials are price dependent, implying that a higher carbon price would increase the viability of the carbon management strategy. Some of the constraints are (IPCC 2001c; Raupach et al 2003):

Economic factors. Economic markets play an important role in governing access to resources and, used intelligently by governments, can provide important incentives to switch to lower carbon energy portfolios. Economic factors include:

- access to, and the nature of, markets for carbon relevant products
- the influence of pathways of industrialisation and urbanisation on existing and new carbon-relevant economic sectors
- the existence or absence of crisis-prone economic conditions
- the indebtedness of many countries, especially in the developing world.

Environmental requirements for other resources. The need for resources to supply essentials, such as food, timber and water, can reduce the estimated technical potential.

Environmental constraints: Mitigation activities can incur environmental costs such as waste disposal and ecological impacts.

Social factors. Differences in social factors between countries and between urban and rural locations strongly influence mitigation outcomes. On an individual level, class structure and lifestyles are often related to increase consumption and use of carbon-relevant commodities as cultural symbols (e.g., cars and travel). Lifestyle is also linked to poverty and lack of access to technical alternatives. On a societal level, values and attitudes determine the level of support for carbon-management strategies, through education and the self image of a society (e.g., frontier, promodernisation, proconservation).

Institutional factors. Institutions determine the structure of incentives influencing any management option in terms of taxes, credits, subsidies, sectoral strategies, property rights regimes and other formal components. They also influence incentives in terms of the policy climate or informal policies within which management strategies are designed and implemented. Examples of 'policy climate' include level of performance of institutions, the presence or absence of corruption, and the extent and nature of powerful vested interests. To illustrate the last point, significant constraints can arise within both public and private sectors that affect the speed at which technology is deployed and the choices of alternative systems. Owners of existing energy technologies can use their considerable

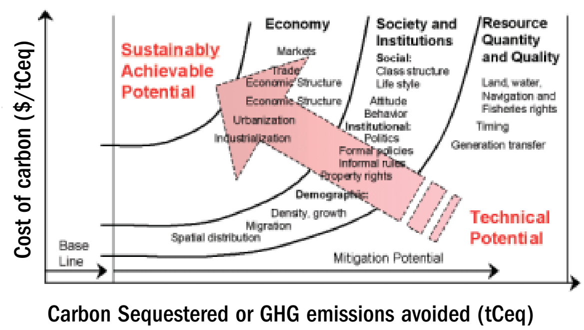


Figure 17

Effects of economic, environmental and social-institutional factors on the mitigation potential of a carbon management strategy. The technical capacity (upper horizontal line, independent of cost) is reduced by a combination of economic factors (markets, trade, economic structures, urbanization, industrialization); environmental factors (need for land, water and other resources, waste disposal, property rights); and institutional and social factors (class structure, politics and formal policies, informal rules, lifestyles, attitudes, behaviour). The end result is a sustainably achievable mitigation potential for the carbon management strategy being considered. This depends on the cost of carbon, which is a measure of the weight ascribed to carbon mitigation relative to other goals. The uptake proportion for the strategy is the ratio of the sustainably achievable potential to the technical potential. The figure also shows a baseline potential, representing the extent to which the carbon management strategy is deployed in a 'business as usual' scenario (after Raupach et al 2003).

financial and technological influence to block the development or deployment of alternative systems. Similarly, government regulators may use their powers to control the flow of investment in mitigation technology or its application in their country, to protect perceived national interests.

Institutional and timing aspects of technology transfer. Some features of technology transfer systems, like the patenting system, do not allow all countries and sectors to access the best available technology rapidly or even at all. The timing of technology transfer is an issue, as many technological paradigms need 50-70 years to be completely established.

Demography. The density, growth, migration patterns and distribution of the population can form another constraint, especially in countries with high levels of social segregation.

Consumption. The growth in, and form of, consumption, independent of changes in demography and economics, constrain technological choices.

Research needs to go even beyond these constraints because the actual set of technologies adopted by societies helps to transform institutions and remove economic constraints. At the same time, the constraints or lack of them determine research and development priorities and thus determine how the knowledge base for the potential set of technologies evolves over time. These two critical feedbacks need to be taken into account in developing future pathways for mitigation and adaptation, in addition to the above list of constraints. This is because what we have at present limits our choices for the future, and choices made in the past affect the possibilities for choices in the future. Thus, the full set of possibilities is not available to us and pathways for the future are limited.

Development of global emission scenarios

Given the unexpected nature of moving into the future, emission scenarios are descriptions of possible futures that can be analysed by today's policy makers. The analyses consider alternative trajectories departing from current trends and resulting in different models of societies; they also consider degrees of climate mitigation and development. The analyses are not a way to predict the future, but to explore the long-term consequences of taking (or not taking) specific actions and developing policies. Some of the most recent analyses have been done by Nakicenovic et al (1999) and the IPCC Special Report on Emission Scenarios (IPCC 2000a).

An important field of research is to explore the pathways and costs to closing the gap between the level of carbon emissions anticipated in a world that places no value on carbon (or other baseline scenarios of 'business as usual') and the level required to stabilise at a specific concentration (as intended by the FCCC). Even the 'business as usual' scenario IS92a - which assumes 75% power generation carbon free by the year 2100 and commercial biomass providing more energy than the combined global production of oil and gas in 1990 - do not achieve CO_2 stabilisation during this century (Edmonds et al 2003). Thus, any emission scenario to achieve atmospheric CO_2 stabilisation by the end of this century will require an enormous development of new technologies and policies.

Analyses of these scenarios with coupled socioeconomic and carbon models will allow the dimension and cost of the changes required and the best timing for their promotion, to be explored.

Scenarios are also critical tools for understanding the requirements of institutions (at various levels of social organisation) to implement large technological changes. Thus, scenarios will help to identify the prospect for designing, getting agreement on, and implementing a more effective climate regime that will allow for the stabilisation of atmospheric CO_2.

Areas of uncertainty and research priorities

Before attempting to steer the development of energy systems along one of many alternative paths, societies need to carefully consider the consequences to the environment, economy and society. Choosing one path over another involves making trade offs between efficiency, equity and sustainability. Clarifying these trade offs requires the development of scenarios in which combined technological, economic, institutional, environmental and social factors are analysed in detail.

In much of the world, transportation systems are dependent upon fossil fuel combustion, which directly connects the human need for transportation with changes in the carbon cycle. Transportation accounts for 25-30% of anthropogenic emissions of CO_2. Vehicle manufacture, construction of roads and cement production also add a significant fraction. Questions about redesign of transportation systems arise from three perspectives: technological, regional scale and complexity, and institutional. These perspectives need to be considered as a set of complex, dynamic relationships in which change in one component is likely to effect change in another.

Therefore, research on future scenarios or trajectories involves developing and testing 'scenario elements' such as those listed earlier, and then studying the interactions and feedbacks (including qualities and inconsistencies) between them. Providing reliable risk-assessment in the form of better decision-support tools for policy makers is key to these issues.

It is also important to realise, however, that the selected CO_2 stabilisation path and final target concentration will not be the result of a command and control process, given the large number of biophysical and socioeconomic constraints that will play out in ways difficult to predict (Vellinga and Herb 1999). Thus, there is a need to develop an adaptive system that can identify and take advantage of points of intervention and windows of opportunity as they appear, making the final CO_2 stabilisation pathway and target concentration an emergent property of the system.

Such uncertainties prompt the following research priorities for Theme 3: What are the likely dynamics of the carbon-climate-human system into the future and what points of intervention and windows of opportunity exist for human societies to manage this system?

1. *When and how will humans respond to changes in the carbon cycle?*
   - Design portfolios of mitigation options that are most feasible in different geographic, environmental, social and economic circumstances.
   - Explore the potential for unintended consequences of carbon mitigation options and assess the sustainably achievable potential once negative effects are taken into account.
   - Identify collateral benefits of mitigation options and their interactions with adaptation policies (e.g., win-win mitigation-adaptation options).
   - Study the relative merits of various policy options (e.g., emissions trading, carbon sequestration).
2. *How will natural dynamics of the carbon cycle and human activities feed back to influence future atmospheric* CO_2 *concentrations?*
   - Determine the potential range of pathways for CO_2 stabilisation given the predicted dynamics of the natural carbon cycle into the future.
   - Assess the carbon and climate consequences of adopting a portfolio of mitigations, and the resulting feedbacks of changes in human behaviour.
   - Explore the implications of non-technical factors (e.g., social and economic drivers of land use, property rights) on future directions of net terrestrial greenhouse gas emissions.
   - Explore alternative pathways of regional and urban development with reduced carbon signatures.
3. *What infrastructural factors need to be overcome to encourage alternatives to a fossil fuel-based economy?*
   - Study the effects of slow and rapid energy substitution, and how it influences energy intensity.
   - Identify the differences in energy use between industrialised and non-industrialised countries, and social, cultural, economic and technological conditions that account for differences in energy intensities.
   - Identify and quantify the technical, economic and social driving forces that direct the private energy sector towards the development of low carbon technologies and markets.
   - Identify what drives consumer needs and preferences in the field of energy and material use.
   - Explore how the need for mobility can be partly or completely decoupled from effects on the carbon cycle.
4. *What are the points of intervention and windows of opportunity for different countries and regions in the world?*
   - Identify biological (land and oceans) mitigation options with their time and space opportunities.
   - Identify energy systems-based mitigation options, including their time and space opportunities.
   - Explore the effects of human choices in the future development of available options.
5. *What is the role of institutions (at various levels of social organisation) in determining the nature and consequences of human responses to changes in the carbon-climate system?*
   - Determine the institutional, sociopsychological and technical arrangements that would influence the purchasing, investment and lifestyle towards significantly lower detrimental environmental effects.
   - Explore the institutions, monitoring mechanisms and compliance mechanisms needed to achieve effective stabilisation of greenhouse gas concentrations. Can the broad characteristics of their evolution be predicted?
   - Study the implications and the effectiveness of instruments proposed by UNFCCC and the Kyoto Protocol.
   - Explore the prospects for designing, getting agreement on, and implementing a more effective climate regime.
6. *What are (and will be) the different social, regional impacts of the changes in the climate-carbon system given the medium- to long-term impacts of climate change?*
   - Study how vulnerable social and economical sectors and regions will be to such changes.

3 Implementation Strategy

The implementation strategy is organised around the same three science themes of (1) patterns and variability, (2) processes and interactions, and (3) carbon management. Each theme is divided into three activities, which are the main research areas that the GCP will develop over the life of the project. Within each activity there are a number of tasks which are either discrete units of implementation or components of a step-wise approach to achieve an overall goal (Figure 18). In addition, there are project-wide efforts to develop timely synthesis of the global carbon cycle or parts of it, and specific products for communication and outreach for the multiple audiences of the GCP.

This section describes an initial set of activities from the larger portfolio that the GCP will develop over its projected life time of 10 years. The GCP website [www.globalcarbon-project.org] will be used to provide periodic updates of the implementation strategy and specific information on the development of the various activities.

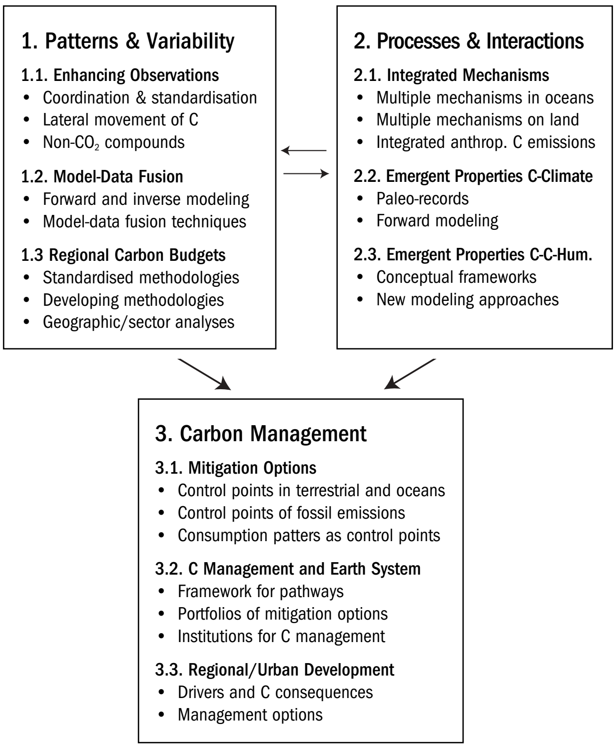


Figure 18

The Global Carbon Project implementation strategy.

The activities for the three themes will be implemented in parallel, requiring a major interdisciplinary and coordination effort among the various components to move towards successful integration of the global carbon-climate-human system. Although specific research communities will take the lead on a given activity, achieving the final goal of each activity will require a substantial input from, and coordination with, the communities taking the lead on other parts of the implementation strategy.

The research that is most disciplinary-based on the carbon cycle is already coordinated and implemented through a number of projects under the auspices of the GCP's sponsoring programmes (IGBP, IHDP, WCRP). Similarly, sub-global research efforts on the carbon cycle are implemented through many national/regional carbon programmes. The GCP will add value to this research by facilitating collaboration towards a higher-level integration, supporting the GCP's mandate of putting together the broader picture of the global carbon cycle.

Theme 1: Patterns and Variability

Activity 1.1: Enhancing observations of major carbon stocks and fluxes

Many regional and national carbon cycle programmes have the potential to complement and strengthen one another by establishing common protocols, sharing data, promoting rapid transfer of information on new applications and techniques, and leveraging resources in joint projects. However, at present these programmes largely rely on the efforts of individual investigators for coordination. Many countries are seeking to contribute to a coordinated international research effort, but information on existing national and regional plans is difficult to obtain. In addition, there is no global strategy that points to missing elements and overlaps, that could provide recommendations. In this environment, the GCP will make the following contributions in partnership with national and regional observational and experimental programmes to:

- Provide opportunities for coordinating research campaigns to enhance the value of measurements.

- Promote standardisation of techniques and methods to increase the comparability of results.
- Foster rapid transfer of results and methodologies among programmes.
- Include attention to non-CO_2 pathways for transporting carbon, in addition to atmospheric CO_2.
- Include observations of the human (anthropospheric) dimensions of the carbon cycle.
- Provide means of integrating across observations of the oceanic, terrestrial, atmospheric and anthropospheric aspects of the carbon cycle, through model-data fusion and related approaches (see also Activity 1.2).
- Provide recommendations for improved network design and coordination among national and regional carbon programmes.

To make these contributions, GCP will need to develop partnerships with multiple groups studying regions or individual components of the carbon cycle (see "Links to other projects and activities") with various degrees of formal agreement.

One important aspect of this activity will be to facilitate the standardisation of techniques and measurements in order to allow for intercomparisons and quality assessment/control. In many measurement and experimental programmes, for example, primary standards do not exist, or links to SI units are compromised by methods required to propagate the standard and/or make the measurement. Of particular concern is a widespread inability to merge data from laboratories/methods at optimum precision levels.

Task 1.1.1: Coordination and standardisation of stocks and flux measurements in the land, ocean, atmosphere, and anthroposphere

Ocean: A collaborative effort between the GCP and the SCOR-IOC Advisory Panel on Ocean CO_2 has been established: The International Ocean Carbon Coordination Project (IOCCP). This project will foster coordination of global-scale ocean carbon monitoring efforts, including reoccupation of WOCE sections by the CLIVAR programme, and surface pCO_2 and time series measurements made as part of the Solar Ocean-Lower Atmosphere Study (SOLAS), Integrated Marine Biogeochemistry and Ecosystem Research (IMBERT), Global Eulerian Observatories (GEO) pilot project, and ship of opportunity projects. Similar coordination will take place with air-sea fluxes and ocean-sediment measurements. The IOCCP is already collating and building upon the existing Web information to establish a model for coordinating activities including periodic workshops to facilitate international collaborations (http://www.ioccp.org; **Figure 19**). This will require active solicitation for updates on the latest national plans and international projects, and constant vigilance to find programmes that have possible conflicts or offer opportunities for better collaboration and more efficient use of limited resources.

Land: The GCP will promote standardisation of terrestrial measurements, calibration, and data treatment for a number of networks and global datasets compiled by individual nations such as, forest inventory data, flux towers (Fluxnet), land-use change (the Food and Agriculture Organization of the United Nations (FAO), UNFCCC), biomass burning (fire working group) and manipulative experiments. The GCP recognises the fact that this effort is well underway within a number of groups (e.g., GTOS), and will work with them to facilitate the continued success of this effort. The GCP will also provide an important link for the coordination of the terrestrial observations with the atmospheric and oceanic observation networks as appropriate.

Atmosphere: There are several global programmes to improve standardisation of atmospheric observations that the GCP will work with to foster quality assessment/quality control, and comparability and data quality. This includes GLOBALVIEW which harmonises measurements from over 100 sites run by 14 countries and the GLOBALHUBS strategy for atmospheric composition measurements that foster standardisation of methodologies and calibration, arising out of measurement expert meetings coordinated by the World Meterological Organization (WMO) and the International Atomic Energy Agency (IAEA). The GCP will also work with other groups dealing with measurements of O_2/N_2, atmospheric potential oxygen (APO), stable isotopes (GCTE-BASIN), water and heat, and others. Finally, the GCP will promote the development of measurements of CO_2 from space, their linkages to data assimilation approaches, and validation schemes.

Anthroposphere: There are a number of stocks and fluxes associated with human activity that need to be standardised and made compatible with critical users such as budget and atmospheric inverse calculations. These measurements include appropriate spatial and temporal coverage of fossil fuel emissions, emissions from land use activities including deforestation, landfills, agricultural practices, and many others. The GCP will work with the diverse groups working on specific sectors and ensure the coordination of national and regional efforts and the linkages to critical applications.

Task 1.1.2: Observations of lateral movement of carbon by fluvial transport, aeolian transport, and trade

Fluvial transport. The GCP will work on two priority research areas:

- Carbon sinks in freshwater bodies. Until recently it was believed that fluvial carbon was largely oxidised during transport and in coastal zones. However, there is now good evidence that some of this carbon is deposited in large water impoundments contributing to the contemporary carbon sink. The GCP will promote research that improves poorly constrained regional and global estimates of carbon transferred between land and water impoundments, and the sink strength of these water bodies.
- Coastal zones as carbon sources or sinks. There are still large uncertainties as to whether coastal zones act as sinks or sources. The GCP will promote research activities that collate existing and new datasets of carbon dynamics in these regions in order to (1) quantify horizontal carbon fluxes in different types of continental margins, (2) evaluate the importance of carbon deposition on the continental slope, and (3) produce an overall synthesis and assessment of carbon fluxes on and across continental margins.

(a)

(b)

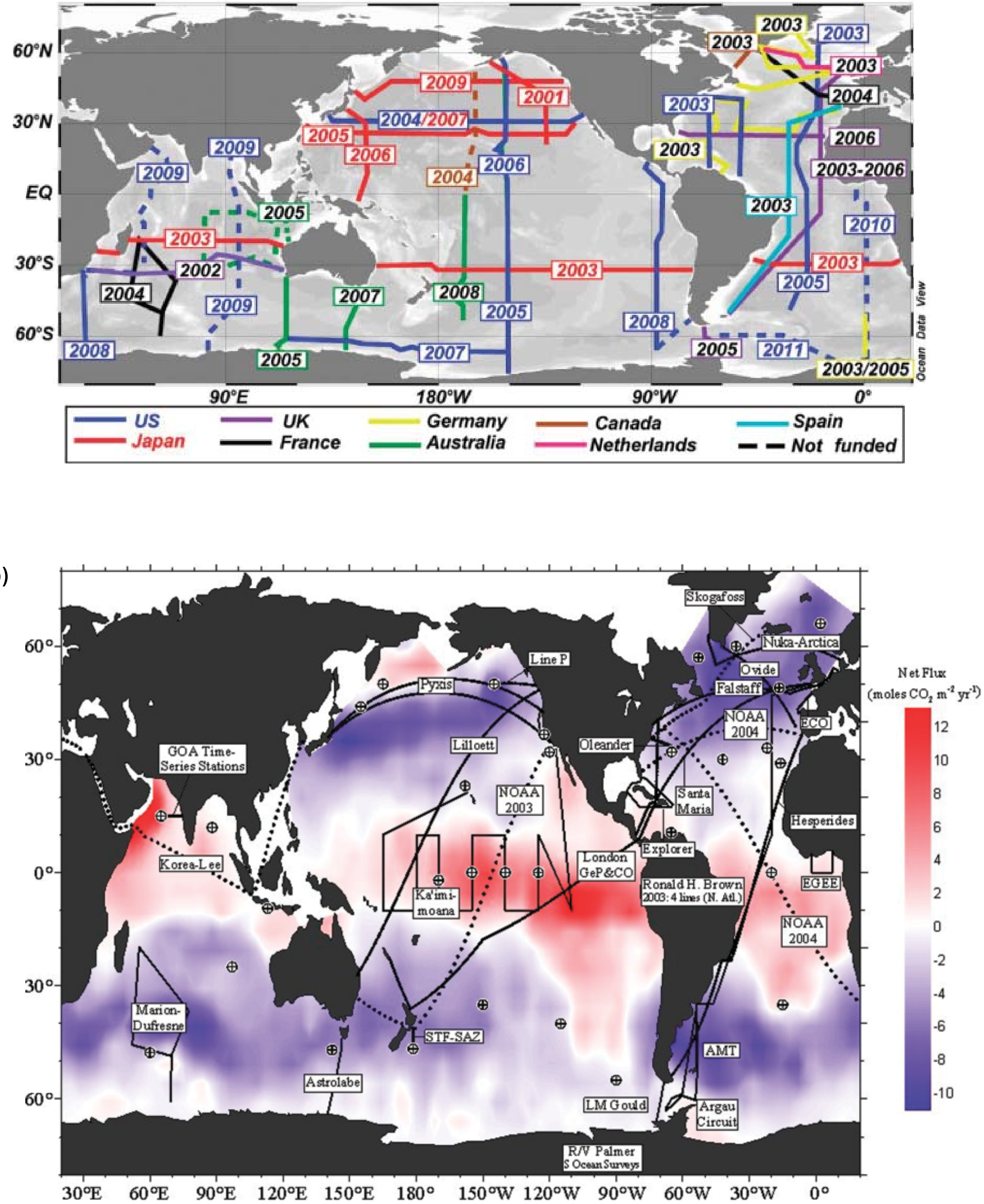


Figure 19

First results from the IOCCP (Task 1.1.1). (a) Global map of planned hydrographic sections with carbon system measurements (Solid lines indicate funded lines. Dashed lines indicate planned lines that are not fully funded at this time); (b) Global map of existing and planned near-surface pCO_2 measurements (Solid lines indicate existing lines. Dashed lines indicate planned lines that are not operational at this time. Labels indicate ship name or project title. White circles with crosses indicate preliminary estimates of planned and existing time-series stations with surface CO_2 measurements). The background map shows net annual CO_2 flux adapted from Takahashi et al 2002 (Sabine and Hood 2003).

Aeolian transport. Aeolian transport of carbon is a minor component of the global carbon budget. However, major dust storm events can remove large amounts of carbon from regions, along with important nutrients such as iron and phosphorus, which in turn have an affect on carbon sources and sinks in the regions where they are deposited (e.g., oceans). The GCP in partnerships with erosion research networks will quantify the removal of carbon in regions prone to dust storms, and the source/sink implications of nutrient transport to freshwater bodies and coastal zones. A set of case studies will be selected.

Trade. Most fossil fuels are mined and much of the world's ecosystems are harvested, and in some cases very intensively. Carbon in the form of fossil fuel, lumber or food is transported laterally in domestic or international trade circuits, and CO_2 is lost to the atmosphere (e.g., fossil fuels or food) or accumulated (e.g., furniture) in places other than where the carbon was fixed. Although carbon sources and sinks due to trade have no global effect they contribute to the patterns and variability of sources and sinks at the regional level. The GCP will coordinate and synthesise datasets to be able to map the carbon fluxes due to trade in georeferenced data products using forestry and agricultural statistics.

Task 1.1.3: Observations of other relevant carbon compounds

The GCP will work on two priority research areas:

- Non-CO_2 gases also contribute substantially to the global warming and their shorter atmospheric residence times and increased warming potential make them strong target candidates for near-term warming mitigation. The GCP will synthesise available datasets and contribute to enhance the observational system in order to constrain regional and global budgets for a number of these gases with an emphasis on CH_4.
- Black carbon is a major product of biomass combustion and contributes to a long-term carbon sink due to its strong resistance to decomposition. The GCP will synthesise datasets and encourage new research to better understand the quantities and quality of black carbon production in a number of fire-prone regions in the world including savannas, temperate and boreal forests. Better constrained global estimates of black carbon residues will be produced.

Deliverables of Activity 1.1:

- An internet carbon portal with information on all major national, regional and global carbon programmes and projects [http://www.globalcarbonproject/carbonportal.htm].
- A web-based information tool that will provide up-to-date information on ocean observation activities, and targeted workshops to set agreements on practices and standards, and to provide recommendations for better coordination between programmes. The website will provide the basic information for the IOCCP of the GCP-CO_2 Panel [http://www.ioccp.org].
- A periodic set of recommendations to optimise resources for observations and identify the potential scientific benefits of a coordinated observation programme (based on gaps, duplications, and needs in carbon observations) in partnership with IGCO of IGOS-P.
- Guidelines for best observational practice and consistency requirements, developed in partnership with observational and regional/basin programmes.
- Standardised datasets, including oceanic, terrestrial, atmospheric and anthropospheric carbon observations, for constructing global carbon budgets and model validation, including promoting GLOBALHUBS for global intercalibration of CO_2 concentrations and isotopes.
- Compile and update existing global databases, including dissolved inorganic and organic carbon transport in riverine systems, and new estimates for sediment burial in reservoirs and coastal shelves.
- New estimates and methods for estimating the magnitudes and temporal trends of carbon transfers due to trade, including harmonisation of data on statistics of agriculture and forestry products.
- Compilation and synthesis of existing databases on anthropogenic driven compounds affecting sources and sinks (e.g., CH_4, black carbon).
- A number of validation products for major new data streams such as gross photosynthesis and surface temperatures from MODIS/Aqua and column CO_2 measured from space.

Links to other projects and activities:

This activity will require working in partnership with multiple national and regional programmes, and international projects already coordinating individual components of the carbon cycle. On carbon research, the GCP will work with IMBER, SOLAS, and CLIVAR. The IOC/SCOR CO_2 Panel will be a full partner in ocean coordination throughout the IOCCP activity. For lateral transport, the GCP will work with the Land-Ocean Interactions in the Coastal Zone (LOICZ), the JGOFS-LOICZ joint Continental Margins Task Team (CMTT), and IMBER. On land issues, the GCP will work with GCTE (e.g., BASIN, Erosion Network), Land-Use/Cover Change (LUCC), the new IGBP/IHDP Land project, Fluxnet, Industrial Transformation (IT) and others. Research on CO_2 from space will be in partnership with Global Energy and Water Cycle Experiment (GEWEX). A critical interface is being established with IGCO with regarding coordination, standardisation, and new operational observation requirements, with specific partnerships with GTOS (and the Terrestrial Carbon Observation strategy) and GOOS programmes. Cosponsorship is being established with Global Change Systems for Analysis, Research and Training (START) to engage less-developed countries. Cosponsorship of the South China Sea Regional Carbon Project also with the Southeast Asia Regional Committee of START (SARCS) is in progress. Links to all national and regional carbon cycle research programmes will be established (e.g., Australia, CarboEurope, North American Carbon Programme (NACP), China, Japan, Large-Scale Biosphere Atmosphere Experiment in Amazonia (LBA)).

Activity 1.2: Model development and model-data fusion

Model-data fusion is emerging as a primary tool for synthesising data and process information to predict space-time patterns and variability in the carbon cycle. Model-data fusion techniques also provide a powerful new toolkit for integrative analysis of process studies, especially from studies in which large number of processes and parameters are studied simultaneously. That is, the application of multiple constraints to our understanding. This activity centres on the development and implementation of methods for assimilating atmospheric, oceanic and terrestrial data into biophysical and biogeochemical models. A particular emphasis will be on the application of multiple constraints, from the simultaneous use of atmospheric, oceanic and terrestrial data and models, to the problem of determining patterns and variability in the carbon cycle.

Task 1.2.1: Improvement of forward and inverse models

This task will produce a new generation of improved models by using model-intercomparison and model-data intercomparisons, and by including new roles of anthropogenic disturbances such as land abandonment and subsequent succession, fire suppression, and nutrient fertilisation. Models will require prognostic capabilities with the appropriate observation and experimental datasets to calibrate them.

The task builds on a series of existing activities initiated under the umbrella of the IGBP Global Analysis Integration and Modelling Task Force (IGBP-GAIM). These include:

Atmospheric Trace Transport Model Intercomparison (TransCom). The goals of TransCom are to quantify and diagnose the uncertainty in inversion calculations of the global carbon budget that result from errors in simulated atmospheric transport, the choice of measured atmospheric carbon dioxide data used, and the inversion methodology employed. Analyses conducted in TransCom3 experiments allowed a rigorous assessment of the estimated source/sink distributions and their sensitivity with respect to the different transport models. Near-term future activities in TransCom3 will include comparison of transport when measurements are vertically integrated, the direct ingestion of atmospheric data into surface process models and the use of more advanced surface measurements, e.g. continuous and multi-species data. Other efforts will include incorporating non-CO_2 measurement constraints and so evolving towards a data-assimilation model approach described in Task 1.2.2.

Ocean Carbon-Cycle Model Intercomparison Project (OCMIP). The goals of the OCMIP activity are to improve the identification of global ocean CO_2 fluxes and understand differences between existing 3-dimensional global ocean carbon cycle models. The OCMIP activity will continue to run a number of model intercomparisons with up to 12 participant groups all using standard protocols of natural and anthropogenic CO_2 simulations. Subsets of the OCMIP-2 group will undertake new modelling studies including (1) the Northern Ocean Carbon Exchange Study (NOCES); (2) Constraining the air-sea exchange of natural and anthropogenic CO_2 by inverse modelling; and (3) Developing the Automated Model Ocean Diagnostic Facility (AutoMOD) for ocean model outputs.

The Ecosystem Model/Data Intercomparison (EMDI). The EMDI activity provides a formal opportunity for a wide range of terrestrial global carbon cycle models to be compared with observed and measured NPP. The primary questions addressed by this activity are to test simulated controls and model formulation on the water, carbon, and nutrient budgets with the observed NPP data providing the constraint for autotrophic fluxes and the integrity of scaled biophysical driving variables. EMDI will organise new model-data intercomparsions using new datasets that include a global litter database, additional interannual NPP observations, eddy-covariance flux intercomparisons, mean annual and interannual analyses for gridded data, and the MODIS NPP product.

Task 1.2.2: Development of model-data fusion techniques

Model-data fusion can be defined as the introduction of observations into a modelling framework, to provide (1) improved estimates of model parameters or state variables, (2) uncertainties on parameters and model output, and (3) the ability to reject a model. The term embraces a number of approaches, including inverse methods (atmospheric, oceanic, biogeochemical), data assimilation, parameter estimation, and multiple-constraint approaches. Such approaches have the potential to link process studies, observations and models, towards a global synthesis of the carbon cycle.

Major emphases in this task will be:

- Use of appropriately parameterised process models (many fully process-based models are over-parameterised for use in this way).
- Development of 'upscaling' methods integrating small-scale process information in the model-data fusion process.
- Development of improved methods for parameter estimation from complex datasets.
- Development of uncertainty analyses in the context of nonlinear inversions.
- Synthesis of carbon-cycle-relevant information from a wide range of observations to provide cross-checks for model consistency.
- Development of methods for use of data products for CO_2 column concentration measurement from new satellite sensors.
- Development of linkages with online data assimilation for weather forecasting, towards the inclusion of carbon cycle data in these assimilations.
- Development of network design methods, based on improving the cost-effectiveness of observation networks and process studies by appropriate sensitivity analyses.

Deliverables of Activity 1.2:

- Novel data-model fusion schemes using new applied mathematical approaches and data streams.
- Evaluation of current and planned observing systems and analytical approaches, within a formal framework of model-data fusion.
- A new generation of scientists from many different disciplines trained in model-data fusion techniques and observing systems issues. This effort will be supported by a number of research courses organised in different centres around the world. Each institute will consist of 2-4 weeks of talks and practical research training, and will address data assimilation tools and techniques in one of the three compartments of the global carbon cycle: atmosphere, oceans, and land. The last institute will deal with data assimilation at the scale of the Earth System.

- An integrated 4D data base for research and education applications with a web based interface.
- Tutorial materials and simulations for model-data fusion analyses.
- Publications including initial reviews on data assimilation approaches, data availability and uncertainty analyses, and network design for biogeochemistry cycle research.

Links to other projects and activities:

Critical partnerships with a number of operational observation programmes will be established, largely through coordination with IGCO (of IGOS-P), and with specific partnerships with GTOS (and its TCO strategy) and GOOS programmes. Because the diverse datasets involved in data assimilation, partnerships will need to be developed with many groups as appropriate including GAIM, GCTE, the new IGBP/IHDP Land project, LUCC, SOLAS, LOICZ, JGOFS, IMBER, and CLIVAR. A critical interface will be established with the JSC/CAS Working Group on Numerical Experimentation (WGNE) as the expert body on data assimilation in the atmospheric models. Partnerships with GEWEX will promote the understanding and development of global CO_2 measurements from space and surface parametarization projects such the Global Land/Atmosphere System Study (GLASS), and its Project for Intercomparison of Landsurface Parameterization Schemes (PILPS), and the GEWEX Modeling and Prediction Panel (GMPP). Efforts on global modelling will be done in closer coordination with GAIM. Partnerships will also be developed with a number of regional carbon projects developing model-data fusion schemes such as CarboEurope and NACP.

Activity 1.3: Comprehensive national, regional and sectoral carbon budgets

The GCP will actively promote the harmonisation of existing approaches to national, regional and basin scale carbon budgets to ensure comparability amongst regions having different social, economic and environmental conditions and histories. This activity will start with existing national, regional and sectoral approaches, to provide complete analyses of the carbon budget (stocks and fluxes) of a given region. Approaches will be modified as Activity 1.1 (Enhancing observations) and Activity 1.2 (Model-data fusion) mature. This activity also links to Activity 3.3 (Regional development) by documenting the human factors driving the changes in the carbon, and how they are spatially distributed among key sectors and regions of the world and so providing information on potential control points for carbon management. Activity 1.3 will:

- Compare regional budgets to gain insights on global patterns and variability.
- Use regional carbon balance estimates to constrain global estimates.
- Promote coordinated development of robust carbon budgeting systems for a number of space scales.

This latter focus will emphasise multiple constraint approaches (Activity 1.2) relevant to assessment and verification requirements for carbon accounting under the UNFCCC (greenhouse gas inventories) and its Kyoto Protocol, and as a contribution to the application of the new IPCC good practice guidance report for greenhouse gases inventories. The culmination of the activity brings together the results of the two previous activities in Theme 1 to provide a global perspective of the human-induced changes in the total carbon balance with appropriate spatial resolution.

Task 1.3.1: Development of standardized methodologies for estimating comprehensive carbon budgets (stocks, changes in stocks and fluxes) at regional and basin scales

National, regional/basin and sectoral carbon budgets have been developed for different reasons in various locations around the world over the last decade. Comparison of these analyses is limited because both the elements considered and the assumptions made differ substantially among budgets. Some terrestrial budgets include land-use change and fossil fuel emissions, while others focus only on natural ecosystems, ignoring direct human activities; some are based primarily on primary data (e.g., forest inventory) while others depend on process-scale model simulations.

This task will aim at reconciling the different analytical approaches and estimates to develop a set of common approaches to provide a comprehensive estimate of carbon stocks, carbon stock changes and carbon fluxes for a given region or basin that can be compared with another region or basin. Methods for integrating observational data for both stocks and stock changes (e.g., inventory data and atmospheric gradient analyses) and fluxes (e.g., from flux tower networks and ocean pCO_2 measurements) will be incorporated. Many regional and national carbon budgets, such as the country submissions to UNFCCC, are based on country statistics without explicit reference to georeferenced data. However, georeferenced data for land use and land cover, climate, ecosystem structure, site history and disturbances is needed to fully integrate direct observations to the new model approaches and to facilitate the verification requirements of international conventions.

Task 1.3.2: Developing methodologies for tracking and projecting temporal changes in regional and basin scale carbon budgets

This task is aimed at quantifying the space-time patterns of natural and human influences on the carbon cycle, and will extend and complement task 1.3.1 on methodologies for carbon budgets by:

- Explicitly adding a temporal component to regional carbon budgets.
- Examining the changing contribution of different sectors of human activity (e.g., energy, agriculture, forestry, fisheries, transport, industry, households, wastewater treatment) and of natural ecosystems to the regional carbon balance over time.
- Quantifying the human and natural factors affecting the carbon cycle and how this perturbation is spatially distributed among the main regions of the globe.

Documented changes over time in social, economic and environmental conditions will be incorporated to develop historical pathways. Various time scales (seasonal, interannual, decadal and longer term changes in the regional carbon budgets) will be explored to examine the importance of different factors. Identification of regions, sectors and critical data required to reduce uncertainties will be communicated to Activity 1.1 (Enhancing observations).

The results of these data-driven regional scale analyses may be used to test process-scale models and new model-data fusion methods developed under Activity 1.2 (Model-data fusion), as well as to provide additional input information for atmospheric inversion approaches.

Task 1.3.3 Geographic and sectoral analysis of human-induced changes in the carbon cycle

This activity will actively promote an international initiative to compare and analyse changes in regional carbon budgets, their human causes and their contribution to the global carbon cycle. It will begin with an identification of critical regions of the globe using existing integrated assessment models to determine where the existing social, economic and environmental conditions suggest likely high sensitivity to change in the recent past or immediate future. Analyses using the multisectoral approaches will be encouraged in these vulnerable regions to perform comprehensive regional assessments, to facilitate comparisons between the different regions, and to elucidate the critical human and natural factors governing changes in regional carbon budgets. Initially based on existing regional and sectoral budgets, later analyses will incorporate the data-model fusion and multiple-constraint procedures developed under Activity 1.2.

Deliverables of Activity 1.3:

- Full sectorial carbon budgets at the level of nations, regions, and globally.
- National and regional carbon budgets and an assessment of their use as bottom-up constraints in the global carbon budget.
- A review of existing national and regional approaches both on land and ocean carbon balances, and provide recommendations for improved analyses and methodologies.
- Improved carbon accounting systems with associated uncertainties analyses and verification techniques.
- Documented regional carbon balances and changes over time as case studies for use in Activity 3.3.
- Stronger interaction between national, regional, and global carbon programmes, with improved use, accessibility, and intercomparability of data and results from multiple projects and national programmes.
- An Internet Web Portal on carbon cycle resources, including information on national and regional carbon programmes, field campaigns and opportunities for collaboration and coordination, research agendas and highlights, presentations, and others.
- Improved understanding of the spatial and temporal patterns of contemporary carbon stocks and exchanges gained through coordinated research (including a set of special issues and books)

Links to other projects and activities:

Multiple national and regional carbon research projects. Ongoing IPCC-related activities including existing tasks: (1) 'Good practice guidance for land use, land-use change and forestry'; (2) 'Definitions and methodological options to inventory emissions from direct human-induced degradation of forests and other vegetation types' and, (3) 'Factoring out direct human-induced changes in carbon stocks and GHG emissions from those due to indirect human-induced and natural effects'. Activities of SBSTA and UNFCCC involving carbon sources and sinks, such as national communications on greenhouse gas inventories, and Kyoto Protocol reporting. GCTE, LUCC, the new IGBP/IHDP Land project, IT, IGCO and GTOS, START, JGOFS, CLIVAR, SOLAS, SCOR-IOC CO_2 Panel, IMBERT and LOICZ. Links to the International Energy Agency (IEA) Bioenergy Task 38 on Greenhouse Gas Balances of Biomass and Bioenergy Systems International Energy Agency Task.

Theme 2: Processes and Interactions

Activity 2.1: Mechanisms and feedbacks controlling carbon stocks and fluxes

This activity will promote new research and synthesis to increase our understanding of the controls on natural and human driven sources and sinks of carbon, and the spatially explicit complexities between causes and effects especially of human-driven mechanisms. Emphasis will also be placed on understanding the interactions among mechanisms and feedbacks among components of the coupled carbon-climate-human system. Such understanding is the foundation for (1) exploring control points that allow humans to modify the dynamics of the carbon cycle and (2) investigating future dynamics and stability of terrestrial and ocean sinks (Theme 3). They are both critical interplayers in the efforts to stabilise atmospheric CO_2 concentration.

Task 2.1.1: Integrated study of the multiple mechanisms determining ocean carbon dynamics

This task will promote research and synthesis to identify the multiple source and sink mechanisms, their relative importance, and their interactions responsible for current and future oceanic and freshwater net carbon fluxes. That is, how the processes of the carbon system work, individually and collectively. These processes include transport and mixing, biological carbon fixation and decomposition as well as their interaction. Particular emphasis will be given to:

- Determinants of oceanic productivity and euphotic zone community structure such as iron availability.
- Remineralisation processes in the upper ocean and in freshwater bodies.
- How climate variability and climate change affect the partitioning of carbon between the atmosphere-ocean system.
- Interactions between subsystems (for example, the impact of soil aridity on Fe transport to the open ocean).
- Understanding future dynamics of these mechanisms and interactions, and in particular their implications for possible ocean sink saturation.

The products will be distributions of sources and sink strengths, and assessments of the driving mechanisms and the potential feedbacks between them. This will permit the GCP to develop integrated regional carbon balances with attribution of quantities to each of the major mechanisms contributing to sources and sinks. The GCP will foster the development of these watershed and regional integrated carbon balances, through Theme 1.

Task 2.1.2: Integrated study of the multiple mechanisms determining terrestrial carbon dynamics

This task will promote research and synthesis to identify the multiple source and sink mechanisms, their relative importance, and their interactions responsible for current and future terrestrial net carbon fluxes. Special focus will be given to:

- Developing methods for attributing, quantifying and factoring out the mechanisms underlying the current terrestrial sink. Emphasis will be placed on indirect anthropogenic components of the terrestrial carbon sinks, such as CO_2 and N fertilisation, and regrowth from past human-induced disturbances as requested by the UNFCCC-Conference of the Parties (COP) meeting in Marrakech, 2001.
- Understanding the carbon sources and sinks due to land use change including management of forests, agricultural land, and rangelands.
- Understanding the stability of current sink mechanisms, and their likelihood of terrestrial sink saturation in the future.
- Surveying regional and sectoral carbon pools for susceptibility to future losses, with an emphasis on quantifying the risk, the potential magnitude, and the sensitivity to climate and other drivers.
- Climate change effects on heterotrophic respiration as a critical feedback to climate.

The task will produce maps of the locations and magnitude of the various sink mechanisms, together with spatially explicit assessments of the feedbacks between those mechanisms influencing terrestrial carbon sinks and sources. It will also produce integrated regional carbon balances with attribution of quantities to each of the major mechanisms contributing to current and future sources and sinks. The GCP will foster the development of these national and regional integrated carbon balances, through Theme 1.

Task 2.1.3: Integrated study of anthropogenic carbon emissions

This task will identify the individual drivers of patterns of productivity/consumption and land use change that give rise to anthropogenic emissions of greenhouses gases, and study the interactions, synergies and nonlinearities between different human drivers and carbon emissions. This will allow constructing globally representative case studies that can be aggregated and extrapolated to larger regions. The studies will include historic and recent tendencies of carbon change and its most relevant human drivers and their interconnectivity between regions (e.g., deforestation driven by increased beef demand in other parts of the world).

Deliverables of Activity 2.1:

- Better understanding of mechanisms and their interactions, suitable for (1) use in models, and (2) carbon mitigation options and identifying windows of opportunity for intervention.
- Spatially explicit attribution of ocean and terrestrial sink mechanisms, and their interactions, consistent with observed global carbon flux patterns (Theme 1);
- A state-of-the-art synthesis on the effects of CO_2 and nitrogen fertilisation and forest age structure on terrestrial carbon sinks. A consistent suite of tools available for attributing these mechanisms to observed terrestrial sinks, and engagement in the SBSTA request on this issue.
- Analysis of carbon pools susceptible to future loss and their possible impacts on the climate system (with activity 2.2).
- Synthesis on warming effects on heterotrophic respiration and recommendations for modelling improvement.
- Synthesis of human drivers that rise greenhouse gases emissions (i.e., drivers of productivity/consumption and land use change).

Links to other projects and activities:

The study of biophysical mechanisms will be strengthened and developed in collaboration with GCTE, the new IGBP/IHDP Land project, JGFOS, IMBER, SOLAS, LOICZ. The research agenda on human drivers of emissions will be closely developed with LUCC, IT, Institutional Dimensions of Global Environmental Change (IDGEC), IPCC Working Group II and III, and the Assessments of Impacts and Adaptations to Climate Change (AIACC). Close collaboration will be established with SBSTA-IPCC.

Activity 2.2: Emergent properties of the coupled carbon-climate system

Emergent properties are system behaviours that arise from interactions among the subsystems or components of a system. They may include the existence of multiple equilibrium states and instabilities, as found in box models of oceanic thermohaline circulation; quasiperiodic oscillations such as glacial-interglacial cycles in the carbon-climate system; sudden non-linear changes such as rapid climate change events; and even homeostatic processes as in James Lovelock's Daisyworld model. Similar behaviours are expected to become apparent when coupling human perturbations and responses in our modelling projections, and forcing models into future novel conditions brought about by global change.

This activity will focus firstly on developing a better understanding of the past variability in the carbon-climate system, especially the glacial-interglacial changes in CO_2. A critical organizing question in this activity will be: could human intervention in the carbon cycle delay or accelerate the next ice age? Although many mechanisms have been suggested to explain the glacial-interglacial cycles, there is no definitive understanding of this dominant mode of variability in the Earth system. The GCP will consider existing simple models of long-term variability in the carbon-climate system, in the context of the information-rich ice-core records. A key objective will be to determine how the paleoclimate record constrains internal model parameters, and thereby sets bounds on the behaviour of the "natural" carbon cycle in the future.

Secondly, this activity will investigate additional system properties that emerge when the perturbed carbon cycle is included as an interactive element in the Earth system, and in particularly, whether thresholds and instabilities could emerged from the coupling. Until recently, General Circulation Models of the climate system (GCMs) have neglected climate-carbon cycle feedbacks, instead assuming that ocean and land uptake will be insensitive to climate change. The first global climate model (GCM) experiments to include the carbon cycle as an interactive element suggest that such feedbacks could significantly accelerate increases of atmospheric concentrations of CO_2 and, as a result, intensify climate change in the 21st century. However, the associated uncertainties are large. In this part of the activity, simplified models of the carbon-climate system (developed in the context of the glacial cycles, see above) will be used to elucidate some of the key sensitivities to human drivers, providing a focus for detailed process studies. In addition, this task will also specifically explore the possible trajectories of the ocean and terrestrial uptake of anthropogenic CO_2 under global warming (and other global change forcings) with the mechanistic attribution gained in Activity 2.1 and model-data fusion advances made in this activity and Activity 1.2. Special attention will be paid at the possible saturation of the ocean and terrestrial carbon sinks.

Deliverables of Activity 2.2:

- Review on the development of coupled carbon-climate models, and foster further fostering of collaborative research between the climate and carbon scientific communities.
- Model intercomparisons and utilisation of available instrumental records and palaeo-data for model validation and development.
- Promote the development of appropriate data assimilation procedures for coupled models linked to activity 1.2.
- New constraints on climate-carbon cycle feedbacks from past climate and CO_2 records.
- More effective use and representation of process-based knowledge (e.g. on future carbon-climate feedbacks such as soil carbon dynamics, large-scale vegetation dynamics, and ocean circulation) into model development.
- A better understanding of possible surprises or abrupt changes that may arise in the carbon-climate-human system under new domains of human intervention.

Links to other projects and activities:

This activity will be developed in close association with the Coupled Carbon Cycle Climate Model Intercomparison Project (GAIM/WCRP-C4MIP), WCRP Working Group on Coupled Modelling (WGCM) and Past Global Changes (PAGES). Strong links to activity 1.2 and particularly on data assimilation, and Task 2.1 on mechanisms and impacts of vulnerabilities of the carbon cycle.

Activity 2.3: Emergent properties of the coupled carbon-climate-human system

The coupling of models of the physical, biochemical, and human components of the carbon cycle is in its infancy. This activity will help to initiate cross-disciplinary research in this area, by highlighting novel behaviours that emerge when all these subsystems are coupled together. It will therefore stimulate the development of more detailed predictive tools and conceptual frameworks ranging from General Circulation Models of the climate system coupled to carbon models (as the next step from Activity 2.2) to agent-based models. The activity will also provide a conceptual framework with which to interpret the results from these more complex models.

The construction of coupled carbon-climate-human models will be fostered from both directions: introducing physical and biogeochemical feedbacks into agent-based models of human actions, and at the same time introducing human interactions and responses into differential equation-based models of the climate-carbon system. This will be a significant challenge since models of the various subsystems have different basic structures. For instance, models of physical climate and biogeochemistry, are normally based on continuous differential equations, while models of human systems are often agent-based adaptive models. The activity will also use other simpler modelling tools and conceptual non-quantitative frameworks in order to explore the system behaviour under a number of scenarios of human perturbations. The resulting models will provide complementary views, and requiring consistency amongst these approaches above will yield additional constraints on each of them.

Some of the potential approaches above include (1) GCMs coupled to carbon models, (2) models of intermediate complexity, (3) integrative assessment models, (4) agent-based models, (5) environmental economics coupled to simple climate models, (6) dynamic-system and game-theory approaches, (7) optimality/control theory, (8) conceptual frameworks, and (9) interactive simulators to explore system behaviour.

Agent-based models are a specific promising area for investigating coupled systems because they can more directly represent adaptive or evolutionary behaviour of agents in a system, whether they are individual farmers, national or global institutions.

The GCP will (1) identify the current status of efforts to model those aspects of the human systems that most closely couple to the carbon system. Where serious deficiencies are noted, further development of such models will be encouraged; and (2) use these approaches improved models will be used to explore for new system behaviour of the perturbed climate-carbon-human system with an emphasis on feedback responses which may yield rapid changes and non-linearities.

Deliverables of Activity 2.3:

- A review book on current and promising new approaches to couple the climate-carbon-human system including dynamical systems, optimality/control theory, game theory, agent-based models, and others.
- A new generation of tools (including new models) and approaches to study the coupled climate-carbon-human system, including a contribution towards the development of Earth System models.
- Identification and characterisation of key interactions influencing the carbon-climate-human system, especially relating to management of the carbon cycle.
- A better understanding of possible surprises or abrupt changes that may arise in the carbon-climate-human system under new domains of human intervention.

Links to other projects and activities:

This activity will be developed in close association with C4MIP, WGCM and PAGES, and a number of IHDP initiatives using agent-based modelling including LUCC and IDGEC. It will also contribute to Theme 3 of the GCP.

Theme 3: Carbon Management

Theme 3 will help to complete the overall scientific vision of the GCP, by integrating observational knowledge (Theme 1) and process understanding (Theme 2) for effective management and assessment of the carbon-climate-human system. In this way, Theme 3 responds to the critical need expressed in the policy community and the various international and national processes related to climate change for scientific inputs regarding (1) the future evolution and dynamics of the carbon cycle and, (2) the opportunities for intervention. The evolution of this system through the 21st century will be the outcome of a three-way coupling among natural processes, anthropogenic drivers, and human responses.

Activity 3.1: Identification of points of intervention and assessment of mitigation options

This activity deals with (1) the identification and assessment of specific points of intervention by which the future evolution of the carbon cycle may be influenced, and (2) provides a critical assessment of the achievable mitigation potential of the various options once sustainable development concerns (i.e., triple bottom line) are considered.

In policy discussions mitigation is used to refer to efforts to regulate and ultimately to reduce emissions of greenhouse gases with the objective of avoiding significant anthropogenic changes in the carbon-climate system, thereby eliminating climate change as a policy problem. In other words, mitigation options represent points of intervention in the carbon cycle whereby humans can influence the future trajectory of atmospheric CO_2 (Task 3.1.1 and 3.1.2). Other points of intervention are related to consumption patterns which are key drivers of carbon emissions (Task 3.1.3). Points of intervention are control points in the carbon cycle which humans can influence directly.

Task 3.1.1: Points of intervention in terrestrial and ocean exchanges

Purposefully induced long-term storage of carbon on land and oceans provides a critical intervention point by which humans can modify the dynamics of the carbon cycle and, to some extent, influence the current upward trends of atmospheric CO_2 concentration. This includes:

- Reduction of carbon emissions from land disturbance (e.g., deforestation avoidance).
- Sequestration of carbon in terrestrial or oceanic biological sinks.
- Engineered disposal of CO_2 in geological and oceanic repositories.

In addition to the effects on greenhouse mitigation, large-scale carbon sequestration and disposal projects will have other cost and benefits to the environment, economy and sociocultural values. On one hand, there are large gaps between the technical mitigation potential of the various options and the mitigation that is realistically achievable once implementation constraints and concerns on sustainable development have been met. For instance, it is likely that reduced river flow and biodiversity due to large-scale monospecific forest plantations will limit the extent to which plantations can be used in semi-arid and arid regions. On the other hand, positive collateral effects might make it possible for mitigation options to be financially viable and more socially acceptable. For instance, large-scale reforestation may increase soil fertility and decrease soil salinisation which can bring additional interest from stakeholders and institutions on such projects. In the end, it is likely that ancillary costs and benefits will determine the viability of a given mitigation option to be implemented.

The GCP will conduct a series of analyses for a number of projects and mitigation options against environmental, social, and economic criteria (triple bottom line) which includes: (1) effectiveness in reaching climate goals; (2) technological feasibility; (3) economic viability; (4) social acceptability; (5) environmental performance against criteria other than climate benefits; and (6) equity. Effectiveness in reaching climate goals will not only focus on the quantities of carbon sequestered but also on stability, permeance, and verification of the new carbon stocks. Theses analyses will provide a more realistic and sustainably achievable mitigation potential in contrast to the technical (or theoretical) mitigation potential which have been provided in recent international assessments.

The analyses will be developed for:

- Large-scale sequestration projects as case studies in which the triple-bottom-line analyses will be considered as part of the feasibility and efficiency assessment of the projects.
- Some globally important regions (e.g., South-East Asia).
- Globally.

Task 3.1.2: Points of intervention in fossil fuel emissions

There is a range of options for altering both the carbon intensity of energy production as well as the energy intensity of economic output. These include, for example, non-fossil-fuel energy generation options such as renewables, nuclear (fission) and fusion; as well as options for increasing energy use efficiency (for example through cogeneration and distribution systems in the standing energy sector, and hybrid and non-fossil-fuelled vehicles in the transport sector). In addition, engineered carbon sequestration is also considered in this section, that is removing carbon from fossil fuels either before, during or after combustion. As in Task 3.1.1, assessment of mitigation options needs to consider environmental, social and economic criteria (triple-bottom-line).

The GCP will develop a similar series of analyses as in task 3.1.1 for a number of projects and mitigation options in order to better assess the sustainably achievable mitigation potential when all the ancillary costs and benefits are taken into account. These analyses, in addition to consider the triple-bottom-line criteria, will need to include an analysis of the potential speed and extent of technological change, as one of the key variables of energy-economic models. The analyses will be done using:

- Large scale projects as case studies.
- Global analyses of the achievable potential for specific mitigation options.

Task 3.1.3: Consumption patterns as points of intervention

Consumption patterns are the root drivers of fossil fuel emissions, as well as other environmental pollution problems. At the same time, consumption patterns arise due to more fundamental pressures of human wants, needs, values and preferences, which can be eventually translated into marketplace activity and production behaviour. Environmental pollution has typically been addressed through intervention on the production side, with reasonable success. On the other hand efforts to change behaviour and bring about societal transformations have been often unsuccessful. In the case of fossil fuel emissions, it is likely that substantial response might require fundamental changes in consumption patterns.

The GCP will undertake a number of case studies on the evolution of consumption patterns, and production - consumption systems. This will provide insights into ways by which more sustainable consumption patterns might be fostered, in particular, whether and how changes in these patterns would, in turn, influence the entire production system, with attendant environmental and carbon consequences.

Deliverables of Activity 3.1:

- A set of analyses published in peer reviewed papers on the realistic and sustainably achievable carbon mitigation potential for a number of options. The analyses will be organised by major categories of mitigation options: (1) terrestrial biological sequestration and disturbance reduction; (2) biological sequestration in the oceans; (3) engineered CO_2 disposal on land and oceans; (4) non-fossil fuel energy sources; and (5) energy conservation and efficiency. The analyses will be globally in scope but specific nations and regions will be targeted as per their regional and global importance.
- A set of analyses and recommendations on potential points of intervention at the level of consumptions patterns.

Links to other projects and activities:

National and international energy programmes; IPCC; IDGEC and IT; GCTE, LUCC, new IGBP/IHDP Land project, SOLAS, IMBER, Integrative Assessment Community, IEA and Global Environmental Change and Food Systems (GECAFS).

Activity 3.2: Carbon management in the context of the whole Earth system

The overall success of any given carbon mitigation or portfolio of options will depend on a number of issues including the effectiveness in climate mitigation, the balance of negative and positive collateral effects, and on the human processes which aid or act against implementation of biophysically appropriate measures. All the issues have a strong spatial and temporal scale which will require the development of unique mixes of mitigation options for a given region and the development of the institutional capacity to take advantage of windows for implementation. This activity will also contribute to the development of monitoring and research necessary to assess how the whole Earth system is responding to human activities.

This activity will develop a formal framework to assess the best mitigation options in a full system analyses framework (Task 3.2.1), design dynamic portfolios of carbon mitigation options for specific regions (Task 3.2.2), and provide an analyses, design and assessment of appropriate institutions for carbon management to improve the portfolio effectiveness (Task 3.2.3).

Task 3.2.1: Framework for designing integrated mitigation pathways

The task will develop a formal framework/s for analysing CO_2 stabilisation pathways within the full range of carbon-climate-human interactions. This will include the effects of synergisms and antagonisms between carbon mitigation, adaptation, and other sustainable development objectives. Adaptation and mitigation strategies for climate change need to be considered in a comprehensive and integrated manner. This is not only because many mitigation strategies (e.g., improved agricultural practices, forest management or cleaner energy) are likely to provide benefits in coping with the impacts of climate change, but also because of the linkage between adaptation and developmental activities. As a result, it is important to evaluate adaptation and mitigation options jointly, with particular attention to issues such as ancillary costs and benefits in the light of sustainable development. Such evaluation might lead to the identification of trade offs as well as possible win-win or no-regrets strategies. This approach will allow examining the implications of these activities for a range of other ecosystem functions and services such as provision and conservation of biodiversity, soil fertility, food and fibre, non-timber forest products, climate regulation, and flood and storm protection. These services and functions are critical, and are also intimately tied to local communities and sustainable livelihood issues.

A conceptual framework will be developed with specific tools and approaches (e.g., computer simulation tools) that can directly support carbon management in general, and more specific to design and assess mitigation portfolios in task 3.2.2. These will include methodologies for assessment and evaluation of trade offs, policy options, and responses of the entire Earth system including indirect effects on current sinks and sources. Approaches for stakeholder involvement in policy formulation, trade off decision making, as well as tools for envisioning the consequences of alternative policies and development pathways must also be considered. A good example is Integrated Assessment which has rapidly emerged as an approach of choice for addressing complex, multidisciplinary issues to produce policy-relevant insights. The creation of methods and tools will include:

- Integrated assessment models and approaches, including simulation tools.
- Scenario building and scenario-based reasoning.

- Transitions management, adaptive management and learning by doing.
- Participatory approaches.

For those research areas which are already active on their own right the GCP will seek to contribute a carbon perspective to these efforts, for example, Integrated Assessment Models that would have a carbon cycle component.

Task 3.2.2: Designing dynamic portfolios of mitigation options

Stabilising atmospheric greenhouse gases will require major changes in energy systems, management of forests and agriculture, and other human activities. No single technology or approach can achieve this goal. Instead, a portfolio of mitigation options will be required to successfully achieve stabilisation in the larger context of development, sustainability, and equity. Regions and countries will need to design specific portfolios of mitigation options in accordance to their environmental, socioeconomic, and institutional circumstances. It is unlikely that two regions or countries in the world will design identical portfolios although general similar patterns may emerge for regions and countries with more similar realities. In fact, the portfolios will not be static and good for all times, but will be dynamic and evolving more like a pathway.

This activity will use the framework and tools developed in task 3.2.1 and build upon the results on achievable mitigation capacity in Activity 3.1 to design the 'best' mix of mitigation options for a number of contrasting and globally relevant regions. Designing the mix requires to define and maximise benefits, utility and well being, at the same time it minimises a generalised cost including environmental ones. It will also need to consider the right incentives (and barriers) for mitigation and using windows of opportunity as they emerge. Finally, it will be important to have a long-term vision which ensures results beyond the immediate needs (e.g., first commitment period for Kyoto Protocol signatory nations).

A preliminary list of regions for this analyses includes selected countries in the Asia Pacific region (China, Japan, Philippines, Thailand), Africa (Senegal), Europe (Germany, Spain), and Americas (United States, Mexico, Argentina).

Task 3.2.3: Designing carbon management institutions

The effectiveness and success of any carbon management strategy depends on a complex set of technological, organisational and institutional factors, at a variety of levels - local, subnational, national and international. Valuable insights can be obtained by evaluating different institutional structures and designs that have been formulated and implemented in the past for managing environmental and related resources. This will require identification of metrics, assessment tools and evaluation paradigms. The analyses will provide insights into what works and what does not, and will also enable adoption of learning-by-doing strategies. This task will include the analysis of institutional, organisational and technological options and strategies. At the international level, it will include how far regimes are changing policy, shifting behaviour, and inclining nation states towards compliance with international agreements. In these analyses, there will be an assessment of the relative merits of various policy options (e.g., emissions trading, carbon sequestration).

A set of case studies will be selected and analysed in light of what can be learned for carbon management. The case studies will include the successful Montreal Protocol, acid rain, and an analysis of the evolution of the Kyoto Protocol up to now.

Deliverables of Activity 3.2:

- A formal framework for assessing portfolios of mitigation options including the development of a computer simulation tool to test policy consequences in the carbon-climate-human system.
- Portfolios of carbon mitigation options for selected countries and regions. A preliminary list: Asia Pacific region (China, Japan, Philippines, Thailand), Africa (Senegal), Europe (Germany, Spain), and North-South America (United States, Mexico, Argentina).
- An analysis of the relative merits of various policies options (e.g., emission trading, carbon sequestration) and the potential benefits of combining the portfolios of mitigation and adaptation options.
- A number of papers with lessons learned for carbon management from the analyses of past international environmental agreements.
- A set of detailed studies of the effectiveness of the Kyoto mechanisms - emissions trading, joint implementation, the clean development mechanism, carbon sequestration options - together with a systematic comparison between these mechanisms and alternative approaches to reducing overall emissions of greenhouse gases.
- Recommendations on new institutional design to minimise the gap between the required mitigation to reach a given stabilisation scenario and the achievable mitigation potential with current institutional arrangements.

Links to other projects and activities:

IDGEC, GCTE, LUCC, new IGBP/IHDP Land project, and START. SCOR, IOC, CO_2 Panel and IMBER for ocean carbon sequestration. IPCC-Working Group II (Impacts, Adaptation and Vulnerability) and Working Group III (Mitigation), UNFCCC SBSTA, and the UNFCCC Secretariat. Asia-Pacific Network for Global Change Research (APN), Inter-American Institute for Global Change Research (IAI), European Network for Research in Global Change (ENRICH) and GECAFS.

Activity 3.3: Carbon consequences of regional development pathways

Pathways of regional development are sequences of interrelated changes in social, economic and political systems. They vary from place to place and over time, in ways that are likely to have different net consequences for carbon stocks and fluxes, which in turn may constrain or in other ways feed back upon development processes.

Urbanisation and physical planning are key processes for integrating carbon management into development. Although cities and surroundings only occupy a small part of the earth's surface they play large and growing role in driving changes to the carbon cycle. The way cities are designed and managed over the next several decades will have a large influence on the future of the carbon cycle. On the one hand, well-designed cities provide many technical opportunities to reduce per-capita carbon emissions. On the other hand, cultural and life-style changes associated with urbanisation, tend to increase levels of consumption, fossil fuel use, water use and waste production.

Although one could imagine carbon management becoming a significant part of development planning, it is highly likely that this will need to consider trade offs with not only economic and social development goals, but also with the capacity to maintain other ecosystem goods and services upon which livelihoods of the poor and the wealthy depend on either directly or through long chains of transformation, substitution and transfers. For this reason we propose a study with an emphasis on carbon, in many ways a 'carbon's eye view of development', which however, at the same time makes a substantial effort to understand interactions, with in particular, biodiversity conservation, and the supply, demand and provision of fresh water and of food from agriculture, aquaculture and fisheries.

It is recognised that many actions taken by corporations, governments and individuals might be made for reasons other than carbon management but may still have very important carbon cycle consequences. For example, concerns with air quality in urban and industrial areas, or travel times in over-congested and extended megacities. A key part of this project will therefore be to explore creatively how local, regional and global goals, or private and public goals, can be aligned.

The GCP will undertake a major comparative analysis of a network of contributing regional case studies. Regions are thought to be large enough to include a range of landscape types (urban, industrial, agricultural, forest) and thus may be subnational, national, or rarely, multinational. A special emphasis will be placed on recruiting case study regions including major cities, because of the predicted importance of urbanisation for carbon emissions and sequestration.

The focus of this activity is on understanding how key social, ecological and biophysical processes unfold and interact during regional development. The motivation for seeking this understanding is to apply to the development of scenarios and policy analysis.

The key questions the Activity will address are:

1. What are the consequences of different pathways of regional development on carbon stocks and fluxes?
2. What are critical processes and interactions in development that result in pathways with widely differing carbon consequences?
3. What are the most important trade offs and synergies between changes in carbon stocks and fluxes, with other ecosystem services, especially the provision of food, water, clean air, and the maintenance of biodiversity?

The first step in this activity will be to:

- Establish an international network of regional case studies which would allow structured and coordinated comparisons of the carbon consequences of different development pathways.
- Identify small key set of variables (or clusters of processes and sequences) that need to be measured and understood to be able to address the research questions from a comparative perspective.
- Recruit an initial set of 6-12 regional case studies from around the world which agree to conduct joint analyses based on minimum datasets and shared protocols. This should include a high proportion of sites with cities so that urbanisation issues can be addressed.

The analyses of the case studies will encompass two tasks:

Task 3.3.1: Drivers of development and its carbon consequences

- Identify the main structures and processes that help explain why different regional development pathways have different consequences for carbon stocks and flows.
- Identify the main differences between case studies with potential to affect carbon stocks and flows.
- Use a variety of methods, including models and sensitivity analyses, statistical decomposition, and in-depth review of historical processes (e.g., related to energy use and policy) to identify both proximate and underlying causes of differences.

Task 3.3.2: Carbon management options and future scenarios

- Explore options for how carbon management could be integrated into development and suggest ways this could be tested through scenario and policy analysis.
- Identify the main trade offs and synergies between 'carbon management' goals and various services, especially those important for human well being, from historical experiences in the case studies.

Deliverables of Activity 3.3:

- START and the GCP will organise a number of research/summer institutes on the topic, being the first one schedule for July 2003 in Boulder, Colorado (USA) on the topic 'Urbanisation, emissions, and the global carbon cycle'.
- A well coordinated set of regional case studies from around the world, many encompassing major cities, and set in a diverse economic and political contexts, (1) including full carbon budgets (by sector and over time if possible), (2) analysis of factors driving the carbon balances, and (3) data to parameterise, formulate and test coupled carbon-climate-human models.
- Book or special issue of a journal documenting the case study analyses and synthesis.
- Development-oriented policy papers on theme of integrating carbon management in regional development: where and when is it worthwhile?

Links to other projects and activities:

This activity will build on past work of IT, the new activity on Urban Ecosystems and Biogeochemistry in GCTE (and the new IGBP/IHDP Land project) and the crosscutting activity on Urbanisation in IHDP, and other programmes such as START, IDGEC, IGAC-cities. Regional partnerships will be established with APN, IAI, and ENRICH, and the ESSP Integrated Regional Studies and GECAFS. Activity 3.3 will contribute to Activity 1.3 (Regional carbon budgets) and 3.2 (Carbon management).

Synthesis and communication

The GCP will deliver high-level syntheses of information on the carbon cycle, including patterns and variability (Theme 1), processes and interactions (Theme 2), and carbon management (Theme 3). Although a large portion of the synthesis will be aimed to the research and assessment communities, specific written products and web-based resources will be developed for policy makers, high education communities, and general public. Specific products for multidisciplinary audiences will be also developed in order to foster a common understanding and language.

High-level synthesis. The main objective will be to deliver the state-of-the-art synthesis on the integrated view of the carbon-climate-human system and specific components of it. This will be done by organising synthesis workshops or commission synthesis to individuals or groups of scientists with a rapid turn-over time publication in order to provide quick feedback to research directions. Collaborative synthesis projects will be developed with the Scientific Committee on Problems of the Environment (SCOPE).

Issues in carbon cycle research. This task will produce synthesis and discussion papers dealing with unresolved issues in the global carbon cycle such as biospheric respiration responses to increasing temperature, or emerging tools to study the coupled carbon-climate-human system. The focus is not only to synthesise the latest understanding on a specific issue, but also to provide information on the development and use of new research tools and approaches.

Communication products. Given the importance of some of the findings resulting from the three implementation themes and synthesis activities, products will be developed to suite audiences other than the highly specialised research communities, such as policy makers, governments, high education, and general public. Such products will include brochures, posters, computer presentations developed with the involvement of communication experts and scientific writers. Two other specific products will be developed to increase communication and dissemination of research results: (1) a project website, and (2) an Internet carbon portal that will provide a number of resources on the carbon cycle relevant to research, policy and education.

Deliverables:

- A collection of synthesis, special journal editions and books on high level and topical information of the carbon cycle, including state-of-the-art understanding and methodological issues. The first effort will be on the Rapid Assessment Project on the Carbon Cycle (SCOPE-GCP) in 2003 which will produce a state-of-the-art synthesis of the entire carbon cycle including carbon-climate and human interactions. This synthesis will be repeated every 4 years. Similar efforts will follow on terrestrial carbon sinks and global oxidation pathways.
- A collection of brochures, posters, and web-based materials to communicate research findings to a variety of audiences including multidisciplinary research communities, policy makers, assessment, higher education and general public.
- A website for the GCP [http://www.globalcarbonproject.org] and an Internet carbon portal [http://www.globalcarbonproject.org/carbonportal.htm] with multiple carbon resources.

Initial Timetable (2003)

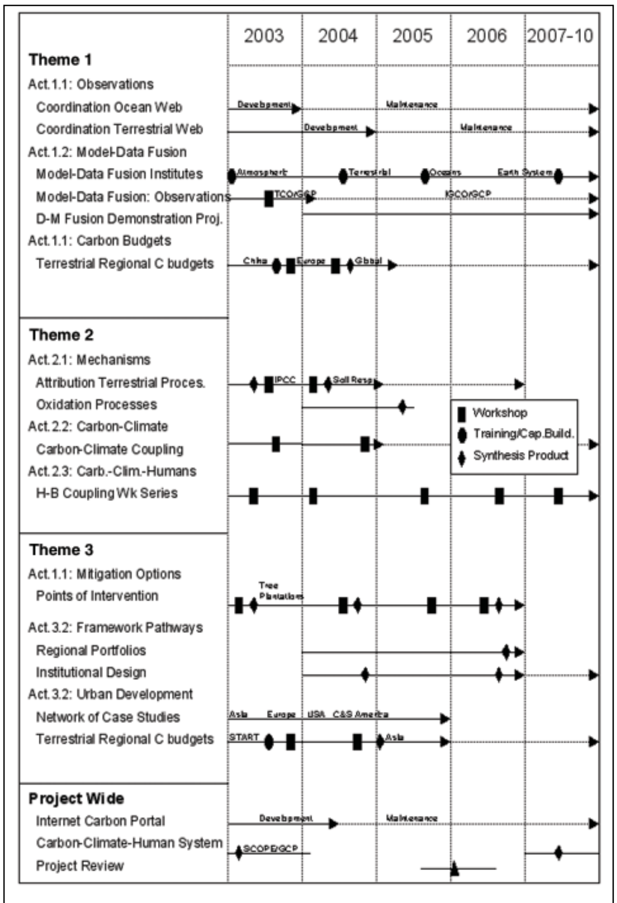


Figure 20

Global Carbon Project planned workshops, capacity building activities, and products for the next 4 years as part of the 10-year implementation strategy.

Capacity building

The GCP will organize a number of capacity building activities associated with the main research themes. This will promote the development of a new generation of young and senior scientists on highly interdisciplinary topics of the carbon-climate-human system. A good example of this activity is the already underway 'summer institutes on data assimilation' which will be a major contribution to capacity building in this new field (see Activity 1.2).

The GCP will work in close coordination with START as the programme partner sponsored by IGBP, IHDP, WCRP, and DIVERSITAS. From this partnership, a major 'research institute' is planned for 2003 on

'Urbanisation, emissions, and the global carbon cycle' (see Activity 3.3). Other linkages will be established with IAI, APN, and ENRICH, and other regional programmes to foster research on the carbon-climate-human system in less developed regions where little carbon research is currently taking place.

Timetable

The GCP has developed an initial timetable of activities and deliverables based upon the most pressing priorities and a number of already on going activities (**Figure 20**). Most of the specific activities (e.g., workshops, capacity building courses, commissioned synthesis) are presented in the various sections of the implementation strategy and **Figure 20** summarises them all. Subsequent versions of the timetable and the entire plan will be posted in the GCP website. A major mid-term project review will take place in 2005.

Management structure and execution

The work of the GCP is guided by a SSC made up of scientists covering the main research areas of the GCP science framework and implementation. The SSC also consider recommendations on implementation activities made by their sponsor programmes and projects within. The SSC is appointed for a two-year term with possible extensions up to six years. It is co-chaired by three scientists who were initially appointed by each of the sponsor programmes (IGBP, IHDP and WCRP). The executive director/s coordinate the execution strategy and implementation of the GCP. Below is the list of the SSC-2003.

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The GCP is supported by the International Project Office (IPO) in Canberra, Australia. A second IPO will be established in 2003 in Tsukuba, Japan. The GCP has also a number of affiliated offices with a variable degree of formal arrangements. This includes the SCOR-IOC Advisory Panel on Ocean CO_2 with the headquarters in Paris, France, and the CarboEurope office in Jena, Germany (shared with the Concerted Action on Greenhouses Gases office based in Viterbo, Italy). Other affiliated offices have been proposed in the United States and China. In addition, the GCP will work with the START regional offices to liaise with research programmes and scientific communities from other parts of the world.

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How to get involved:

The GCP falls under the umbrella of non-governmental organizations devoted to environmental research. It operates thanks to hundreds of scientists who volunteer their time and efforts to contribute to the development and execution of the implementation strategy.

Proposals for involvement and activity development (e.g., workshops, synthesis) that support the implementation strategy are welcome. Please, contact Pep Canadell at [pep.canadell@csiro.au] or any of the SSC members.

4 Acknowledgements

The editors want to thank the hundreds of scientist over the world who have contributed directly or indirectly to the development of this document by participating at the scoping meetings, providing written contributions, reviewing previous versions and providing scientific leadership to identify the most pressing issues in carbon cycle research (see *Contributors). Special thanks are given to Berrien Moore and Will Steffen for orchestrating the initial steps to make the Global Carbon Project a reality.

The Netherlands Organization for Scientific Research (NOW) provided the initial, generous grant that built the sound financial basis for the GCP planning process to begin and grow. Funding for the various scoping workshops that took place during the period 1999-2003 came from the European Commission DGXII, the National Aeronautics Space Agency (NASA) in the United States, the National Institute for Environmental Sciences (NIES) in Japan, the National Science Foundation (NSF) in the United States, the Scientific Commission of Problems of the Environment (SCOPE), and the three sponsor programmes of the GCP: the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), and the World Climate Research Programme (WCRP). NSF through a grant to GAIM supported the involvement of Kathy Hibbard during the first stages of the project.

The Australian Greenhouse Office (AGO) and Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), through their support to the GCP International Project Office based in Canberra, made possible the involvement of Michael Raupach, Rowena Foster and Josep Canadell, who coordinated the development and editing of this document.

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6 Appendixes

Appendix A:

A Selection of Relevant Initiatives and Networks

A.1. The GCP sponsor programmes and their carbon activities

The three global change programmes that cosponsor the GCP are the IGBP, IHDP and WCRP. To date, there is a wealth of ongoing and proposed activities within, and shared between, the three programmes in carbon cycle research. The collaboration already initiated by the three programmes provides a strong platform for links to national and regional activities as well as to future projects in the GCP.

International Geosphere-Biosphere Programme (IGBP)

[http://www.igbp.kva.se]

The IGBP has a long-standing suite of carbon-research activities, ranging from iron fertilisation experiments in the ocean, experimental studies of terrestrial ecosystem response to warming and elevated CO_2, budget approaches to coastal-zone carbon fluxes and comparisons of a wide range of models related to the carbon cycle.

Global Analysis, Integration and Modeling (GAIM)

[http://gaim.unh.edu]

- Ocean Carbon Model Intercomparison (OCMIP)
- Ecosystem Model/Data Intercomparison (EMDI)
- Atmospheric Tracer Transport Model Intercomparison Project (TransCom)
- Global Net Primary Productivity Model Intercomparison
- Trace Gas and Aerosol Cycles in the Earth System (Traces)
- Earth System Models of Intermediate Complexity (EMICs)
- Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP) (co-sponsored by WCRP)
- Coupled Carbon Model Linkage Project (CCMLP)

Global Change and Terrestrial Ecosystems (GCTE)

[http://www.gcte.org]

- Effects of elevated CO_2 on terrestrial ecosystems
- Effects of warming on terrestrial ecosystems
- Biosphere-Atmosphere Stable Isotope Network (BASIN)
- Soil Organic Matter Network (SOMNET)
- Disturbances and biogeochemistry
- Dynamic Global Vegetation Model (DGVM) development
- Fluxnet

Land Use/Cover Change (LUCC) (cosponsored by IHDP)

[http://www.geo.ucl.ac.be/LUCC]

- Land-use and Climate Change Impacts on Carbon Fluxes (LUCCI)
- Carbon sequestration supply from and clean development mechanism rules for tropical forest carbon sinks: a case study of Costa Rican LUCC

Land project (cosponsored by IHDP)

- Terrestrial coupled biogeochemistry
- Disturbances and carbon emissions
- Coupled human-biogeochemical terrestrial system

Note: This is the new project from the fusion of GCTE and LUCC which will start in 2004.

Global Ocean Ecosystem Dynamics (GLOBEC) (cosponsored by SCOR and IOC)

[http://www.pml.ac.uk/globec/main.htm]

- Food web dynamics in the ocean

Joint Global Ocean Flux Study (JGOFS)

[http://ads.smr.uib.no/jgofs/jgofs.htm]

- Global surveys: air-sea flux of CO_2
- Continental margins
- Time-series stations
- Basin cruises

Note: JGOFS will finish at the end of 2003 and the new IGBP/SCOR IMBER project will be initiated in 2004.

Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) (cosponsored by SCOR).

It will be initiated in 2004.

- Deep ocean transport and storage of carbon

Interactive Land Ecosystem-Atmosphere Processes (ILEAPS)

The new project on land-atmosphere interactions which will address the mechanisms underlying these land-atmosphere interactions. The project will be initiated in early 2004.

Land Ocean Interactions in the Coastal Zone (LOICZ)

[http://www.nioz.nl/loicz/]

- The effects of changes in external forcing or boundary conditions on coastal fluxes
- Coastal biogeomorphology and global change; the fate of carbon in coastal and shelf waters
- Carbon fluxes and trace gas emissions: carbon transport down rivers to the coastal zone
- Economic and social impacts of global change in coastal systems: coastal system sustainability and resource management issues

Past Global Changes (PAGES)

[http://www.pages.unibe.ch/]

- PAGES and Climate Variability and Predictability (CLIVAR) - The carbon-climate system investigated through ice cores and deep sea sediments
- International Marine Past Global Change Study (IMAGES)
- Past ecosystems processes and human-environment interactions

Surface Ocean-Lower Atmosphere Study (SOLAS) (cosponsored by SCOR, Commission on Atmospheric Chemistry and Global Pollution (CACGP) and WCRP)

[http://www.solas-int.org]

- Biogeochemical interactions and feedbacks between ocean and atmosphere
- Exchange processes at the air-sea interface and the role of transport and transformation in the atmospheric and oceanic boundary layers
- Air-sea flux of CO_2 and other long-lived radiatively active gases

International Human Dimensions Programme (IHDP)

[http://www.ihdp.org/]

IHDP has initiated a wide range of carbon-related activities through each of its four core science projects: IDGEC, IT, LUCC and Global Environmental Change and Human Security (GECHS). These include a flagship project on the institutional dimensions of carbon management (investigating institutional issues associated with controlling greenhouse gas emissions); research on industrial transformation and the decarbonisation of energy systems; research on transformation of land-use systems and the behaviour of the terrestrial component of the global carbon cycle (and our responses to those changes); and the implications for human security of changes in carbon-cycle dynamics. For more information, please check the IHDP Global Carbon Research document found on the GCP website.

Institutional Dimensions of Global Environmental Change (IDGEC)

[http://fiesta.bren.ucsb.edu/~idgec]

- The Political Economy of Tropical and Boreal Forests (PEF)
- Carbon Management Research Activity (CMRA)
- Performance of Exclusive Economic Zones (PEEZ)

Industrial Transformation (IT)

[http://www.vu.nl/ivm/research/ihdp-it/]

- Energy and material flows
- Cities/transportation
- Governance and transformation processes

The IT project has written a document listing specific IT-related research questions relevant to the GCP. This document can be viewed at the GCP website

Land-use and Land-cover Change (a cosponsored project with IGBP)

[http://www.geo.ucl.ac.be/]

- Land-use and Climate Change Impacts on Carbon Fluxes (LUCCI)
- Carbon sequestration supply from and clean development mechanism rules for tropical forest carbon sinks: a case study of Costa Rican LUCC

World Climate Research Programme (WCRP)

[http://www.wmo.ch/web/wcrp/wcrp-home.html]

The WCRP provides the modelling tools for climate variability and change essential towards understanding internannual to intercentury variability in the carbon cycle, the strong control of oceanic and atmospheric circulation over carbon transport and storage, as well as links between the carbon and hydrological cycles. A brief list of major activities sponsored by WCRP are listed below.

Global Energy and Water Cycle Experiment (GEWEX)

[http://www.gewex.org]

- Global Land/Atmosphere System Study (GLASS), and particularly its Project for Intercomparison of Landsurface Parameterization Schemes (PILPS C-1)
- GEWEX Modeling and Prediction Panel (GMPP) to develop and improve cloud and land-surface parameterization schemes and their integration into GCMs
- Data projects
- Global CO_2 measurements from space

Climate Variability and Predictability (CLIVAR)

[http://www.clivar.org/]

- Repeated transoceanic sections at decadal time scales of ocean physical properties and carbon system variables
- Working Group on Seasonal to Interannual Prediction (WGSIP)

Working Group on Coupled Modelling (WGCM)

[http://www.wmo.ch/web/wcrp/wgcm.htm]

- Development of fully interactive, comprehensive Earth system models including a realistic representation of the carbon cycle

Working Group on Numerical Experimentation (WGNE - Co-sponsored by WCRP JSC and WMO Commission for Atmospheric Sciences, CAS)

[http://www.wmo.ch/web/wcrp/wgne.htm]

- Model intercomparisons to improve the characterization of CO_2 processes in GCMs
- Data assimilation approaches

Arctic Climate System Study and Climate and Cryosphere Project (ACSYS/CliC)

[http://www.npolar.no/acsys/]

- Influences of changes in the cryosphere on the global carbon cycle
- Greenhouse gases emissions from permafrost
- Sink strength of the Artic Ocean

A.2. A selection of national and regional programmes

National-level carbon research programmes are the fundamental blocks of research and scientific communities to develop a global strategy. Through activities to enhance comparability, leverage resources, rapid transfer of methodologies and acknowledge, the GCP hopes to further enhance the capabilities of the national and regional programmes at the same time it provides scientific leadership to bring together all the components of what is a single global carbon cycle. In this section, three examples of national and regional programmes are described. For information on other national programmes, check the GCP website.

The Australian Carbon Cycle Programme

[http://www.greenhouse.gov.au/science/index.html], [http://www.greenhouse.crc.org.au]

The Australian Carbon Cycle Programme includes activities of CSIRO (Biosphere Working Group, BWG) and the Cooperative Research Centre for Greenhouse Accounting (CRCGA). Its foci are:

- Process interactions between the biosphere and the atmosphere, particularly the role of the biosphere in the cycles of biogenic greenhouse gases (carbon dioxide, methane, nitrous oxide) in the Australasian region.
- Feedbacks between terrestrial, ocean and the atmospheric systems in the Australasian region, and their implications for regional climate change and variability.
- Development and application of multiple-constraint approaches to determine regional sources and sinks of greenhouse gases and to improve coupled ocean-atmosphere-terrestrial climate models.

CarboEurope

[http://www.bgc-jena.mpg.de/public/carboeur/]

CarboEurope is a cluster of projects to understand and quantify the carbon balance of Europe, funded by European Commission DG Research - 5th Framework Programme (to be continued under 6th FP). The objectives of the CarboEurope cluster are to advance the understanding of carbon fixation mechanisms and to quantify the magnitude of the carbon sources/sinks for a range of European terrestrial ecosystems and how these may be constrained by climate variability, availability of nutrients, changing rates of nitrogen deposition and interaction with management regimes. Research focusing on European ecosystem is complemented by investigations of the sink strength of Siberian and Amazon forests. Relevant specific topics are:

- To provide a multidisciplinary, fully integrated framework to verify across scales, from ecosystems to regional and continental areas, the space and temporal behaviour of carbon sources and sinks and to assess their socioeconomic drivers and consequences.
- To make use of state-of-the-art technologies for carbon accounting and modelling.
- To adopt a consistent carbon accounting strategy across scales.

China Carbon Flux Programme

A multi-agency effort including the National Science Foundation of China (NSFC), State Science and Technology Committee (SSTC), and the Chinese Academy of Sciences (CAS) has established a carbon programme with five foci:

- Carbon flux and storage of typical terrestrial and marginal sea ecosystems in China, including forest, cropland, grassland, lake and marginal sea ecosystems.
- Biogeochemical processes of carbon flux and storage of terrestrial and marginal sea ecosystems in China and biological acclamation.
- Historical processes of terrestrial carbon cycling in China and land use change.
- Modelling carbon cycling of terrestrial and marginal sea ecosystems.
- Comprehensive research on carbon budgeting and carbon mitigation/sequestration.

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Japan Integrated Research on Carbon Management

Sponsored by the Global Environment Research Fund of the Ministry of the Environment, Japan, the project will elucidate carbon dynamics between the atmosphere and terrestrial ecosystems in Asia in order to ultimately minimize the rate of increase in CO_2 concentration. The programme encompasses four themes:

- Analyses of the carbon balance in terrestrial ecosystem using bottom-up approaches based on micrometeorological and ecological methods.
- Analysis of meso-scale terrestrial carbon balance using top-down approach based on atmospheric monitoring.
- Assessment of carbon balance dynamics and evaluation of methodologies for carbon budget management in terrestrial ecosystems.
- Promotion of integrated research and information sharing.

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The Large Scale Biosphere Atmosphere Experiment in Amazonia (LBA)

[http://lba.cptec.inpe.br/lba/indexi.html]

As part of the LBA, and number of countries including Brazil, US, and several European countries are coordinating research on the carbon cycle in Amazonia. The main four areas of research are:

- Biogeochemical interactions and feedbacks between the Amazon forest and atmosphere climatic forcing that regulates carbon cycling in tropical forests.
- Carbon fluxes from deforestation and human dimension drivers.

- Effects of climate change on tropical ecosystems.
- Evasion of CO_2 from flooded forests.
- Effect of aerosols on the radiation balance and carbon cycling.

The United States Carbon Cycle Science Programme (USGCRP)

[http://www.carboncyclescience.gov]

The United States Global Change Research Programme has established a Carbon Cycle Science Programme. The new Programme provides critical unbiased scientific information on the fate of carbon in the environment and how cycling of carbon might change and be changed in the future. This includes providing the scientific foundation for management of carbon in the environment. Research will be coordinated and integrated to identify and quantify regional to global-scale sources and sinks for carbon dioxide and other greenhouse gases and to understand how these sources and sinks will function in the future, providing essential information for future predictions of the state of the Earth system.

A.3. A Selection of other International Initiatives

In addition to the national and regional programmes, several additional international initiatives and programmes are attempting to address a suite of issues related to the global carbon cycle, and climate change and variability:

Carbon Variability Studies by Ships of Opportunity (CAVASSOO)

[http://lgmacweb.env.uea.ac.uk/e072/]

The aim of CAVASSOO is to provide reliable estimates of the uptake of CO_2 by the North Atlantic, and how this varies from season to season and year to year. These will in turn assist in constraining estimates of European and North American terrestrial (vegetation) sinks, using atmospheric inverse modelling techniques.

Global Quality Control for Long-Lived Trace Gas Measurements (GLOBALHUBS)

The aim of GLOBALHUBS is to improve interlaboratory comparability for measurement of long-lived atmospheric trace gas species, resulting in improved derivation of source/sink fluxes from spatial and temporal atmospheric composition changes.

Integrated Global Observing Strategy Partnership (IGOS-P)

[http://ioc.unesco.org/igospartners/igoshome.htm]
The IGOS-P is a partnership that develops common, integrated strategies to be implemented and coordinated by the Global Observing Systems:

- Global Ocean Observing System (GOOS) [http://ioc.unesco.org/goos/]
- Global Terrestrial Observing System (GTOS) [http://www.fao.org/gtos/index.html]
- Global Climate Observing System (GCOS) [http://www.wmo.ch/web/gcos/gcoshome.html]

The Intergovernmental Panel on Climate Change (IPCC)

[http://www.ipcc.ch/]

Recognizing the problem of potential global climate change, the World Meteorological Organization (WMO) and the United Nations Environment Programme established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The role of the IPCC is to assess the scientific, technical and socioeconomic information relevant for the understanding of the risk of human-induced climate change. It does not carry out research nor does it monitor climate related data or other relevant parameters. It bases its assessment mainly on peer reviewed and published scientific/technical literature.

The Millennium Ecosystem Assessment (MA)

[http://www.millenniumassessment.org/en/index.htm]

The Millennium Ecosystem Assessment is an international assessment activity charged with examining the processes supporting life on Earth, including the world's grasslands, forests, rivers and lakes, farmlands and oceans, with respect to the capacity of an ecosystem to provide goods and services important for human development. The goal of the four-year programme is to improve the management of the world's natural and managed ecosystems by helping to meet the needs of decision-makers (in governments and the private sector) and the public for peer-reviewed, policy-relevant scientific information on the condition of ecosystems, consequences of ecosystem change, and options for response. In addition, the MA will build human and institutional capacities to provide information.

Northern Eurasian Earth Science Partnership Initiative (NEESPI)

[http://neespi.gsfc.nasa.gov/]

The goal of NEESPI is to establish a large-scale, interdisciplinary programme of funded research aimed at developing a better understanding of the interactions between the ecosystem, atmosphere, and human dynamics in northern Eurasia in support of international science programmes. NEESPI partners include NASA and other United States agencies, the Russian Academy of Sciences and Russian and international institutions, GOFC, IGBP and other international programmes. NEESPI's approach to carbon research combines regional in situ data, remote sensing observations and measurements, and models, including terrestrial carbon, socioeconomic, landscape, and integrated models. Current carbon-related projects include:

- Modeling carbon dynamics and their economic implications in two forested regions: pacific northwestern United States and northwestern Russia.
- Modeling Siberian forest land-cover change and carbon under changing economic paradigms
- Determining the contribution of emissions from boreal forest fires to interannual variations in atmospheric CO_2 at high northern latitudes.
- Determining the contribution of emissions from boreal forest fires to interannual variations in atmospheric CO_2 at high northern latitudes.
- Modeling and monitoring effects of area burned and fire severity on carbon cycling, emissions, and forest health and sustainability in Central Siberia.
- Combined satellite mapping of Siberian landscapes.

- Changes in terrestrial carbon storage in Russia as a result of recent disturbances and land-use change.

The Scientific Committee on Oceanic Research (SCOR)

[http://www.jhu.edu/~scor]

In addition to cosponsoring JGOFS, SOLAS, and the Ocean Biogeochemistry and Ecosystems project with IGBP and the Ocean Carbon Dioxide Advisory Panel with IOC, the Scientific Committee on Oceanic Research (SCOR) has several working groups on related carbon cycle research:

- Carbon Dioxide in the Atlantic Ocean (CARINA)

[http://www.ioc.unesco.org/iocweb/co2panel/]. CARINA is a project linked to the IOC/SCOR panel that aims to inventory and publish CO_2 data in the North Atlantic Ocean.

- Biogeochemistry of iron in seawater.
- The role of marine phytoplankton in global climate regulation
- New methodologies on:
  - surveying plankton
  - estimating downward carbon flux from the surface ocean

The Scientific Committee on Oceanic Research (SCOR) - Intergovernmental Oceanographic Commission (IOC) Panel on Ocean CO_2

[http://ioc.unesco.org/iocweb/co2panel/]

The Scientific Committee on Oceanic Research and the Intergovernmental Oceanographic Commission of UNESCO established the Advisory Panel on Ocean CO_2 in 2000 to catalyse, coordinate and communicate ocean carbon activities of common interest to the international community. Programme areas currently include:

- Coordination of observations (with the GCP via IOCCP).
- Advocacy for standards and reference materials.
- Information exchange and measurement technology.
- Development and maintenance of information on carbon sequestration in the oceans.

Appendix B:

Integrated Global Carbon Observing Strategy (IGCO)

A Strategy to Build a Coordinated Operational Observing System of the Carbon Cycle and its Future Trends

P Ciais, B Moore, W Steffen, M Hood, S Quegan, J Cihlar, M Raupach, I Rasool, S Doney, C Heinze, C Sabine, K Hibbard, D Schulze, M Heimann, A Chédin, P Monfray, A Watson, C LeQuéré, P Tans, H Dolman, R Valentini, O Arino, J Townshend, G Seufert, C Field, I Chu, C Goodale, A Nobre, G Inoue, D Crisp, D Baldocchi, J Tschirley, S Denning, W Cramer, R Francey

Executive summary

The overall goal of the Integrated Global Carbon Observing theme (IGCO) is to develop a flexible yet robust strategy for deploying global systematic observations of the carbon cycle over the next decade. This report builds upon the foundation set by the IGCO strategy and sets forth an operational global carbon observing system. This system has two main objectives:

- To provide the long-term observations required to improve understanding of the present state and future behaviour of the global carbon cycle, particularly the factors that control the global atmospheric CO_2 level
- To monitor and assess the effectiveness of carbon sequestration and/or emission reduction activities on global atmospheric CO_2 levels, including attribution of sources and sinks by region and sector.

The system will meet those objectives by routinely quantifying and assessing the global distribution of CO_2 fluxes exchanged between the Earth's surface and the atmosphere, and by measuring at regular intervals the changes of key carbon stocks, along with observations that help elucidate underlying biogeochemical processes. The global carbon observing system integrates across all multifaceted aspects of the three major domains of the carbon cycle: ocean, land, and atmosphere; Indeed, the most successful advances in understanding springs from the combination of data and models for the different domains, wherein results from one domain place valuable constraints on the workings of the other two.

Implementing the observing system requires:

- Establishing data requirements, designing network configurations, and developing advanced algorithms for operational carbon observations, which will be the core of a future, sustained operational system by 2015.
- Developing cost-effective, low maintenance, in situ sensors for atmospheric CO_2, ocean dissolved pCO_2, and terrestrial ecosystem fluxes.
- Developing and implementing technologies for remote sensing of CO_2 from space.
- Developing, in collaboration with the research community, operational carbon cycle models, validated through rigorous tests and driven by systematic observations that can deliver routine diagnostics of the state of the carbon cycle.
- Enhancing data harmonisation, archiving, and distribution to support model development and implementation.

This report presents a vision of the global carbon observing system, which ultimately will be implemented both by research and operational agencies, and it provides a roadmap to realize the system. The report identifies a core set of existing research-based observations upon which to build the system, drawing from the terrestrial carbon observing strategy and global ocean observing system. In addition, it describes the critical priorities and steps required to transfer the core set of research observations into an operational system.
The global carbon observing system should be built around complementary core groups of observations to address three themes: fluxes, pools, and processes.

Fluxes. The first set of observations enables quantification of the distribution and variability of CO_2 fluxes between the Earth's surface and the atmosphere. It contains:

- Satellite observation of column integrated atmospheric CO_2 distribution to an accuracy of at least 1 ppm with synoptic global coverage - all latitudes, all seasons.
  - These observations do not exist yet and must be given a very high priority.
- An optimized operational network of atmospheric in situ stations and flask sampling sites with an accuracy of at least 0.1 ppm.
  - These observations, at present, are achieved in research mode, comprise 100 stations worldwide. They must be increased in horizontal and vertical coverage to include continental interiors and poorly sampled regions. This requires development of cost-effective sensors and the systematic use of opportunity platforms.
- An optimized, operational network of eddy covariance towers measuring on a continuous basis the fluxes of CO_2, energy and water vapour over land ecosystems.
  - These observations are currently made from a research network comprising 100 towers. The network must be secured for the long term, and expanded over ecosystem types, successional stages, and land-use intensities.
- A global ocean pCO_2 measurement system using a coordinated combination of research vessels, ships of opportunity, and autonomous drifters.
  - These observations represent at present about 100 cruises. The central challenge to developing a global-scale operational ocean carbon observation network is the lack of accurate, robust, cost-effective, autonomous sensors for ocean pCO_2.
- A combination of satellite observations, backed up by a long term continuity of sensors, delivering global observations of parameters required to estimate surface-atmosphere CO_2 fluxes where direct in situ measurements are scarce.
  - These crucial satellite observations are: land cover status, disturbance extent and intensity, parameters related to vegetation activity, ocean colour, and ancillary atmospheric and oceanic variables controlling the fluxes.

The approach for using these observations to quantify the distribution and variability of CO_2 fluxes between the Earth's surface and the atmosphere requires reconciliation of both down-scaling and up-scaling estimates. Atmospheric transport models are required to down-scale the atmospheric CO_2 measurements into fluxes. Carbon cycle flux models are required to scale-up point-wise in situ observations using remotely sensed variables.

Once the operational carbon observing system is in place model-data fusion techniques will routinely assimilate the above listed data streams of carbon measurements to produce consistent and accurate estimates of global CO_2 flux fields with typical resolution of 10 km over land and 50 km over oceans with weekly frequency.

Pools. Global carbon observing system will monitor changes in three key carbon pools:

- Forest aboveground biomass, which will be measured at 5-year intervals by in situ inventory methodologies and more frequently corroborated by remote sensing techniques.
- Soil carbon content will be measured at 10-year intervals primarily by in situ inventory methodologies.
    - These observations are already collected on a systematic basis for assessing the commercial value of forests and the quality of soils, respectively. They need, however, to be expanded over non-managed forests, adapted for carbon cycle studies, and be made available on a georeferenced basis.
- Inventories of dissolved carbon in the main ocean basins, measured at 5 to 10-year intervals, to estimate the sequestration of anthropogenic CO_2 into surface waters.
    - These observations are currently made by research community; they need to be systematized, carefully intercalibrated expanded over poorly sampled ocean gyres, and, most importantly, they need to be made.

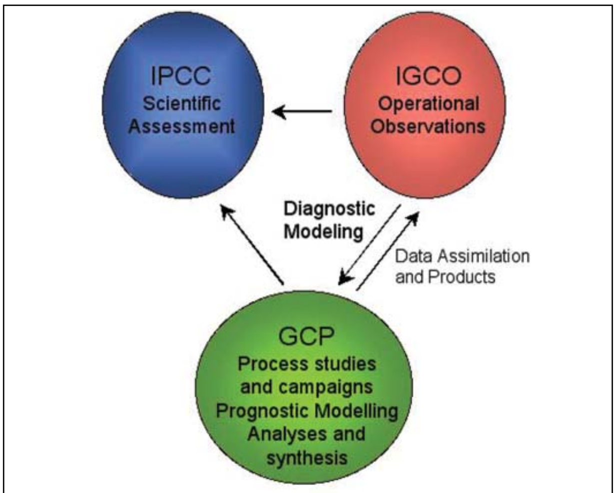

Figure 21

Links between operational observation (Integrated Global Carbon Observation, IGCO), research planning (Global Carbon Project, GCP) and assessment (IPCC, Intergovernmental Panel on Climate Change) (Ciais et al 2003).

measurements related to important carbon cycle processes. Most of these will remain in the research domain, to be coordinated within the framework of the Global Carbon Project (**Figure 21**). Two process-related observations, however, are more appropriate for the operational domain and will become part of the core set of the system:

- Fire distribution (spots) and burned area extent, to estimate the fluxes of carbon that are emitted during disturbances such as fire. Fire spots will be measured on (sub) daily time steps, with fire extent at monthly intervals.
- Land-cover change, to estimate the fluxes of carbon associated with forest clearing and reversion of agricultural lands to natural ecosystems. The sampling interval will be 5 years with a spatial resolution of 1 km.

The observation efforts will be combined with an end-to-end data analysis system to deliver high quality products that will be freely accessible to the scientific and policy communities around the world.

Appendix C:

Providers and users of carbon observations

C.1. Examples of existing providers of carbon observations

Type (in situ, satellite)	Sponsor*	Data/products provided	Coverage in space and time	Reference
In situ terrestrial				
FLUXNET	Countries/IGBP/WCRP	Ecosystem data and fluxes; micromet. data	All continents (except Antarctica)	http://www-eosdis.ornl.gov/FLUXNET/
ILTER	Countries/	Ecosystem data	21 countries	http://www.ilternet.edu/
GT-Net	Countries/GTOS	Ecosystem data	84 countries, numerous networks	http://www.fao.org/gtos/gt-net.html
SOMNET	Countries/IGBP	Soil data	~70 sites, 6 continents	http://www.rothamsted.bbsrc.ac.uk/aen/somnet/index.htm
In situ oceanic				
GOOS	Countries/IOC	See Appendix B	Global or regional	http://ioc.unesco.org/goos/
CDIAC Oceans	JGOFS, CLIVAR, GLODADP, CARINA	CO_2 measurements	Global	http://cdiac.esd.ornl.gov/oceans/home.html
PICIS PICNIC	PICIS	CO_2 measurements	North Pacific ocean	http://picnic.pices.jp
CARINA	CARINA	Carbon data	Atlantic ocean	http://www.ifm.uni-kiel.de/fb/fb2/research/carina
IOCCP	IOC - WMO - UNEP - ICSU	Observation system information and coordination	Global, regional, national	http://www.ioccp.org
CLIVAR	WCRP	Repeat hydrographic surveys of carbonate system, hydrography, traces, metereological observations, vessel-mounted ADCP.	Global, basin scales , 5-10 year repeats; 30-50 km spacing along sections with more dense sampling on the continental shelf. Full water column.	http://www.sprint.clivar.org/ http://www.ioccp.org
Carbon SOOP	Coordinated by: IOCCP	Underway measurements of pCO_2, ocean colour, metereological variables, CO_2, ^{13}C, ^{14}C, ^{18}O related variables	Regional (basin-scale), continuous along tracks, monthly to seasonal.	http://www.ifremer.fr/ird/soopip/instr.html http://www.ioccp.org
Global Ocean Time Series Observatory System	OOPC - CLIVAR - POGO; carbon information compiled by IOCCP	pCO_2, carbonate system, ocean color variables, ancillary physical, meteorological, chemical and biological measurements	Fixed-point moorings or revisited stations in strategic locations; high-frequency to interannual	http://www.oceantimeseries.org

* Both the direct sponsor (usually a national agency) and the international umbrella organisation are listed

C.1. Examples of existing providers of carbon observations

Type (in situ, satellite)	Sponsor*	Data/products provided	Coverage in space and time	Reference
In situ oceanic (cont.)				
International Ocean Colour Coordinating Group	IOCCG, SCOR	Basin-scale surface biomass productivity; phytoplankton natural fluorescence	Global spatial coverage, 4-8 km resolution; coastal regions, 0.5 - 2 km resolution; daily to weekly	http://www.ioccg.org/
In situ atmospheric				
GLOBALVIEW- CO_2	Countries/WMO	Trace gas concentrations	Global; ~weekly	http://www.cmdl.noaa.gov/ccgg/globalview/index.html
Multiple				
Carbon Dioxide Information Analysis Center	U.S. DOE	Data repository for ocean carbon data and informatio from global, regional, and national research programmes.	Global, regional, and national.	http://cdiac.ornl.gov/oceans/home.html
Satellite				
Fine resolution	NASA/CEOS	Images, land-cover	Global	http://ivanova.gsfc.nasa.gov/daac/
	CNES/CEOS	Images, land-cover	Global	http://www.spot.com/
	NASDA/CEOS	Images	Global	http://www.eoc.nasda.go.jp
	CSA/CEOS	Images	Global	http://www.spot.com/
Medium to coarse resolution	NASA/CEOS	Images, land-cover and change; LAI; fires; CH_4, solar radiation; NPP	Global	http://ivanova.gsfc.nasa.gov/daac/ http://www.gewex.com/srb.html
	NOAA/CEOS	Solar radiation, images	Global	http://www.osdpd.noaa.gov/
	NASDA/CNES/CEOS	OCT, POLDER	Global	http://www.eoc.nasda.go.jp
	ESA/JRC (WFW)/EC	Fires	Global	http://www.gvm.sai.jrc.it/
	CNES/SNSB/OSTC/ SAI/EC	Images; land-cover and change; fires; ecosystem productivity;	Global	http://www.vgt.vito.be/

* Both the direct sponsor (usually a national agency) and the international umbrella organisation are listed

C.2. Examples of Carbon Information Users

Programme	Sponsor	Data used/needed	Coverage in space, time	More information
Global/International				
IPCC	UN FCCC	Ecosystem productivity	Global; past, present	http://www.ipcc.ch/
Global Environmental Research Programmes	Countries or regions	All variables	Global; past, present	http://www.igbp.kva.se/ http://www.ihdp.org/ http://www.wmo.ch/web/wcrp/wcrp/wcrp-home.html
IOC	UNESCO	Ocean Variables	Global, regional All time scales	http://ioc.unesco.org
IGBP (several core projects)	Countries or regions	All variables	Global; past, present	http://www.igbp.kva.se/
Forest resources assessment	FAO	Land-cover and changes, biomass, fires, productivity	Global; every ~5 years	
Global Environmental Outlook	UNEP	All variables	Global; present; every 2 years	http://www1.unep.org/unep/eia/geo/reports.htm
NGOs (WRI, WCMC, others)	Various public and private	Land-cover and changes, biomass, fires, productivity	Global, regional; present	http://www.wri.org/ http://www.wcmc.org.uk/
Convention on Biological Diversity	Countries	Land-cover and changes, biomass, fires, productivity	National to global; past, present	http://www.biodiv.org/
Convention to Combat Desertification	Countries	All variables	National; present	http://www.unccd.de/
National				
Carbon accounting	Countries, e.g.: Australia US, Norway	All variables	Present; national; project - based	http://www.greenhouse.gov.au/ncas/ http://www.eia.doe.gov/oiaf/1605/ggrpt/
Resource planning (vegetation, forest)	Countries, e.g.: Australia Africa, Canada	All variables	Present; national or sub-national	http://www.nlwra.gov.au/ http://metart.fao.org/default.htm
Resource management: fire – related	Countries, e.g. Africa, Indonesia, various others	Fires; land-cover and change; biomass	Present; national	http://www.iffm.or.id/ http://www.ruf.uni-freiburg.de/fireglobe/
Resource management: crops, water	Countries (Africa,..)	Land-cover and change, biomass, productivity	Present; national	

C.3. Status of Satellite Missions for Global Carbon Cycle Observations *

Agency	Mission***	Carbon cycle sensors	Category**
CAST			
CNES	SPOT-3,- 4	HRV	1
CNES, EU	SPOT-4, SPOT –5	HRG, VEGETATION	
CSA	Radarsat -1, -2	SAR	1
DARA	***		
ESA	ENVISAT-1	ASAR, MERIS, AATSR, SCIAMACHY	1
ESA	ERS-2	ATSR, AMI	1
ESA, CNES	SMOS ***	MIRAS	1
EUMETSAT	METOP –1, -2, - 3	AVHRR /3, IASI, ASCAT	1
EUMETSAT	MSG	SEVIRI	1
INPE	MECB SSR-1, -2	OBA	Planned
ISRO	IRS -1C, -1D	LISS-III, PAN, WIFS	
ISRO	IRS- P2, -P5, -P6	LISS-II (-IV), WiFS, HR-PAN, AWiFS	
ISRO	IRS- P3, -P4	MOS, WiFS, MSMR	
NASA	EOS Aqua	CERES, MODIS, AMSR-E	
AIRS	1		
NASA	EOS Aura	HIRLDS, TES	1
NASA	EOS Terra	ASTER, CERES, MISR, MODIS, MOPITT	1
NASA	ESSP/VCL	MBLA	
NASA	ICESat	GLAS	1
NASA			
QuikScat	SeaWinds	1	
NASA		OCO	1
ORBIMAGE (NASA data buy)	SeaStar***	SeaWiFS	1
NASA	NMP/EO-1	ALI, Hyperion	4
NASA, NASDA	TRMM	CERES, VIRS	
NASDA	ALOS	ALOS/PRISM, AVNIR-2, PALSAR, PRISM	1
NASDA, CNES	GCOM – B1, - B2 ***	GLI, POLDER, IMG	2
NASDA, CNES, NASA	ADEOS-II	GLI, POLDER-2	1
NASDA, NASA	GCOM – A1, - A2 ***	SAGE-III, ILAS-II??	2
NOAA	Landsat	ETM	1
NOAA	NPOESS	VIIRS, CrIS/ATMS, CMIS, OMPS, CERES	
NOAA	TIROS-N	AVHRR, TOVS	
NOAA	GOES I,J,K,L,;M		1
NOAA	GOES - N,O,P,Q		1
NOAA	GOES SEI		
NOAA, NASA	NPOESS Preparatory Project (NPP)***	VIIRS, CrIS/ATMS	3

* Note: the table includes only missions directly supporting carbon observations and products; other missions may provide supporting information

** Category: **1** = confirmation and timing of missions already planned **2** = proposed missions using known technology **3** = transitioning of research instruments/missions into operational **4** = development of new technologies, products or missions **5** = data and information systems

*** Not in the WMO/CEOS database

7 Abbreviations & Acronyms

ACSYS	Arctic Climate System Study
AGO	Australian Greenhouse Office
AIACC	Assessments of Impacts and Adaptations to Climate Change
AIRS	Atmospheric Infrared Sounder
AMSU	Advanced Microwave Sounding Unit (NOAA-15)
APN	Asia-Pacific Network for Global Change Research
APO	Atmospheric potential oxygen
AutoMOD	Automated Model Ocean Diagnostic Facility
AVHRR	Advanced Very High Resolution Radiometer
BAHC	Biospheric Aspects of the Hydrological Cycle
BASIN	Biosphere-Atmosphere Stable Isotope Network
BATS	Bermuda Atlantic Time-series Study
BWG	Biosphere Working Group
C4MIP	Coupled Carbon Cycle Climate Model Intercomparison Project
CACGP	Commission on Atmospheric Chemistry and Global Pollution
CARBOSAT	ESA space mission dedicated to monitoring of the carbon cycle
CARINA	Carbon Dioxide in the Atlantic Ocean
CAS	Commission for Atmospheric Sciences
CAVASSOO	Carbon Variability Studies by Ships of Opportunity
CCMLP	Coupled Carbon Model Linkage Project
CLIVAR	Climate Variability and Predictability Project
CMRA	Carbon Management Research Activity
CMTT	Continental Margins Task Team
COP	Conference of the Parties
CRCGA	Cooperative Research Center for Greenhouse Accounting
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CZCS	Coastal Zone Color Scanner Data
DGVM	Dynamic Global Vegetation Model
DIC	Dissolved Inorganic Carbon
EMDI	Ecosystem Model-Data Intercomparison
EMIC	Earth System Model of Intermediate Complexity
ENRICH	European Network for Research in Global Change (EU)
ENSO	El Niño Southern Oscillation
ENVISAT	ESA satellite
EOS	Earth Observing Satellite
ESA	European Space Agency
ESSP	Earth System Science Partnership
EU	European Union
FACE	Free Air CO_2 Enrichment
FAO	Food and Agriculture Organization of the United Nations
GAIM	Global Analysis, Integration and Modelling
GCM	Global Climate Model
GCOS	Global Climate Observing System
GCP	Global Carbon Project
GCTE	Global Change and Terrestrial Ecosystems
GECAFS	Global Environmental Change and Food Systems
GECHS	Global Environmental Change and Human Security
GEO	Global Eulerian Observatories

GEWEX	Global Energy and Water Cycle Experiment
GLASS	Global Land/Atmosphere System Study
GLOBEC	Global Ocean Ecosystem Dynamics
GLOBALHUBS	Global Quality Control for Long-Lived Trace Gas Measurements
GLODAP	Global Ocean Data Analyses Project
GMPP	GEWEX Modeling and Prediction Panel
GOFC	Global Observations of Forest Cover
GOOS	Global Ocean Observing System
GPP	Gross Primary Production
GTOS	Global Terrestrial Observing System
HOT	Hawaii Ocean Time-series program
IAI	Inter-American Institute for Global Change Research
IAEA	International Atomic Energy Agency
IASI	Infrared Atmosphere Sounder Interferometer
ICSU	International Council of Science Unions
IDGEC	Institutional Dimensions of Global Environmental Change
IEA	International Energy Agency
IGBP	International Geosphere-Biosphere Programme
IGCO	Integrated Global Carbon Observation
IGOS-P	Integrated Global Observation Strategy Partnership
IHDP	International Human Dimensions Programme on Global Environmental Change
ILEAPS	Interactive Land Ecosystem-Atmosphere Processes
IMAGE	Integrated Model to Assess the Greenhouse Effect
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IOC	Intergovernmental Oceanographic Commission
IOCCP	International Ocean Carbon Coordination Project
IPCC	Intergovernmental Panel on Climate Change
IT	Industrial Transformation
ILTER	International Long-term Ecological Research
JGOFS	Joint Global Ocean Flux Study
JSC	Joint Scientific Committee
LBA	Large-Scale Biosphere Atmosphere Experiment in Amazonia
Land project	Fusion of GCTE and LUCC under development by IGBP and IHDP
LOICZ	Land-Ocean Interactions in the Coastal Zone
LUCC	Land Use/Cover Change
LUCCI	Land-Use and Climate Change Impacts on Carbon Fluxes
MA	Millennium Ecosystem Assessment
METOP	Meteorological Operational Polar Satellite
MODIS	Moderate Resolution Imaging Spectroradiometer
NACP	North American Carbon Programme
NASA	National Aeronautics Space Agency
NCAR	National Center for Atmospheric Research
NEESPI	Northern Eurasian Earth Science Partnership Initiative
NOAA	National Oceanic and Atmospheric Administration
NOCES	Northern Ocean Carbon Exchange Study
NPP	Net Primary Production
NSCAT	NASA Scatterometer
OCO	Orbiting Carbon Observatory
OCMIP	Ocean Carbon-Cycle Model Intercomparison Project
OCTS	Ocean Color and Temperature Scanner
PAGES	Past Global Changes
PEEZ	Performance of Exclusive Economic Zones
PEF	Political Economy of Tropical and Boreal Forests
PEP	Pole Equator Pole Transects
PICES	The North Pacific Marine Science Organization
PILPS	Project for Intercomparison of Landsurface Parameterization Schemes
POLDER	Polarization and Directionality in the Earth Reflectances
POC	Particulate Organic Carbon
ppm	Parts per million
ppmv	Parts per million by volume
SARCS	Southeast Asia Regional Committee of START
SBSTA	Subsidiary Body for Scientific and Technological Advice
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography

SCOPE	Scientific Committee on Problems of the Environment
SCOR	Scientific Committee on Oceanic Research
SeaWiFs	Sea-viewing Wide Field-of-view Sensor
SOIREE	Southern Ocean Iron Release Experiment
SOLAS	Surface Ocean-Lower Atmosphere Study
SOMNET	Soil Organic Matter Network
SOOP	Ships Of Opportunity
SSC	Scientific Steering Committee
SST	Sea Surface Temperature
START	Global Change Systems for Analysis, Research and Training
SVAT	Soil Vegetation Atmospheric Transfer Scheme
TCO	Terrestrial Carbon Observation
TIROS-N	Television Infrared Observational satellite-Next
TOPEX	US-French orbital mission to track sea-level height with radar altimeters
TOVS	TIROS Operational Vertical Sounder
Traces	Trace Gas and Aerosol Cycles in the Earth System
TransCom	Atmospheric Tracer Transport Model Intercomparison Project
UNFCCC	United Nations Framework Convention on Climate Change
USGCRP	United States Carbon Cycle Science Programme
WCRP	World Climate Research Programme
WGCM	Working Group on Coupled Modelling
WGSIP	Working Group on Seasonal to Interannual Prediction
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment