CARBON theme REPORT

IGOS
Integrated Global Observing Strategy

For the Monitoring of our Environment from Space and from Earth

2004

An international partnership for cooperation in Earth observations

Integrated Global Carbon Observation Theme

A Strategy to Realise a Coordinated System of Integrated Global Carbon Cycle Observations

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The Integrated Global Observing Strategy (IGOS) is a partnership of international organisations that are concerned with global environmental change issues. It links research, long-term monitoring and operational programmes, bringing together the producers of global observations and the users that require them, to identify products needed, gaps in observations and mechanisms to respond to needs in the science and policy communities. Its principal objectives are to integrate satellite, airborne and in-situ observation systems.

The IGOS partners are comprised of the Global Observing Systems (GOS), the International Organisations which sponsor the Global Observing Systems, the Committee on Earth Observation Satellites (CEOS), and International Global Change Science and Research programmes.

The IGOS Partners recognise that a comprehensive global earth observing system is best achieved through a step-wise process focused on practical results. The IGOS Themes allow for the definition and development of a global strategy for the observation of selected environmental issues that are of common interest to the IGOS Partners and to user groups. The current IGOS Themes include the Oceans, the Carbon cycle Geohazards, the Water cycle, Coastal areas with a Coral reef sub-theme, and Atmospheric chemistry.

The IGOS Carbon cycle theme (the IGCO - Integrated Global Carbon Observation theme) was initiated in 1999 by the International Geosphere-Biosphere Programme (IGBP), the Global Ocean Observing System (GOOS), the Global Terrestrial Observing System (GTOS), the Global Climate Observing System (GCOS), the National Aeronautics and Space Administration, USA, (NASA), the Centre National d'Etudes Spatiales, France (CNES), and the National Space Development Agency of Japan (NASDA) on behalf of the Committee for Earth Observation Satellites (CEOS), the United Nations Environment Programme (UNEP), the Food and Agriculture Organization of the United Nations (FAO) and the Global Atmosphere Watch programme of the World Meteorological Organization (WMO/GAW).

The proposal to develop the theme was approved by the IGOS Partners at their 6th Plenary in Rio de Janiero in November 2000 and a Theme Team was established under the chairmanship of Dr Philippe Ciais, LSCE, Unité mixte CEA-CNRS, France. With the support of a community of more than 400 people worldwide who contributed to this initiative, a draft report was submitted to the 10th IGOS Plenary in June 2003. Following an international peer review during July-September 2003, the present Theme report was approved for implementation by the IGOS Partnership in November 2003.

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Further information on IGOS can be obtained from: http://www.igospartners.org.
The Carbon cycle theme report is available from: http://www.igbp.kva.se
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The overall goal of the Integrated Global Carbon Observation (IGCO) Theme is to develop a flexible yet robust strategy for deploying global systematic observations of the carbon cycle over the next decade. This report sets forth a strategy to realise a coordinated system of integrated global carbon cycle observations. The 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 system integrates across the multi-faceted aspects of the three major domains of the carbon cycle: ocean, land, and atmosphere. Indeed, the most successful advances in understanding spring 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 carbon observing system requires:

- Consolidating data requirements, designing network configurations, and developing advanced algorithms for assimilating carbon observations, which will be the core of a future, sustained operational system;
- 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;
- Improving estimates of biomass based on national inventories and/or remote sensing observations;
- Developing 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; and
- Enhancing data harmonisation and intercomparability, archiving, and distribution to support model development and implementation.

This report provides a roadmap to realise the carbon observing system, which ultimately will be implemented both by research and operational agencies. The report identifies a core set of existing research-based observations upon which to build the system. It draws heavily from the Terrestrial Carbon Observing (TCO) strategy as well as documents that describe the Global Climate Observing System (GCOS), the Global Terrestrial Observing System (GTOS), and Global Ocean Observing System (GOOS). In addition, it describes the critical priorities and steps required to transfer the core set of research observations into an operational system.

The strategy for a carbon observing system is first a carbon crosscut of GCOS, GTOS, and GOOS and second an identification of new components not previously identified.

The coordinated system of integrated global carbon observations 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 optimised 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, with ca. 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 platforms of opportunity. Also, there needs to be an enhancement of the inter-calibration effort.*
- An optimised, 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 ca. 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 measurements, 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.*
- Georeferenced fossil fuel CO_2 emission maps including temporal variability and uncertainties;
  - *These observations are an important constraint input for atmospheric studies, and they are also central for the policy context.*

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 downscale the atmospheric CO_2 measurements into fluxes. Process- and data-driven carbon cycle flux models are required to scale-up point-wise *in situ* observations using remotely sensed variables.

Once the 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. The second set of observations focuses upon changes in the three key carbon pools:

- Forest aboveground biomass, which will be measured at 5-year intervals by *in situ* inventory methodologies and more frequently 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 the research community; they need to be systematised, carefully intercalibrated, and expanded over poorly sampled ocean gyres.*

Measuring changes in carbon stocks in these three pools is critical for carbon closure. It is a fundamental check upon the system, and essential for hindcast reanalysis of the carbon budget.

Processes. The third set of observations in the system are measurements related to important carbon cycle processes. Most of these will remain in the research domain, and thus will be coordinated within the framework of the international Global Carbon Project (GCP). Four process-related observations, however, are now appropriate for the operational domain and will become part of the core set of the carbon observing system:

- Fire distribution (hot spots) and burned area extent, to estimate the fluxes of carbon that are emitted during fires. Fire hot 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;
- A network of time series that measure sinking fluxes from sediment traps;
- Large scale systematic measurements of oxygen to determine changes in ocean stratification.
  - *These observations are currently made by the research community; they need to be systematised, harmonised, and expanded.*

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

Finally, this report describes the implementation timeline that is proposed for a coordinated system of integrated global carbon cycle observations.

The concentrations of CO_2 and CH_4 in the atmosphere are at the highest they have been in the past 25 million years. Current levels of CO_2 have increased by 30% from 280 ppm in pre-industrial times to more than 370 ppm today, and they continue to rise. Current levels of CH_4 of 2000 ppb are nearly triple the pre-industrial value of 700 ppb.

These changes are caused by human activities; the primary agents of change are fossil fuel combustion and modifications of global vegetation through land use and other agricultural changes (e.g., land conversion to agriculture including pasture expansion, biomass burning, and for methane, the increase in ruminants and rice cultivation). For the decade of the 1990s, an average of about 6.3 Pg C per year as CO_2 was released to the atmosphere from the burning of fossil fuels, and it is estimated that an average of 1.5-2.5 Pg C per year was emitted due to deforestation and land-use change during the same interval.[1]

The increasing CO_2 and CH_4 concentrations in the atmosphere raise concern regarding the heat balance of the global atmosphere. Specifically, the increasing concentrations of these gases will lead to an intensification of the Earth's natural greenhouse effect. This shift in the planetary heat balance will force the global climate system in ways which are not well understood, given the complex interactions and feedbacks involved, but there is a general consensus that global patterns of temperature and precipitation will change, though the magnitude, distribution and timing of these changes are far from certain. The results of general circulation models indicate that globally averaged surface temperatures could increase by as much as 1.5 to 6 degrees C by the end of this century.The increases in greenhouse gases in the atmosphere, as noted, are anthropogenically driven but partly compensated by absorption of CO_2 at the Earth's surface and by chemical reactions in the atmosphere, for example, by the oxidation of methane by the hydroxyl radical.

This report focuses on CO_2; it does provide, wherever necessary, links to CH_4. A specific strategy is being developed for CH_4 and other non-CO_2 carbon compounds (e.g., volatile organic compounds emitted by terrestrial vegetation) through the Integrated Global Atmospheric Chemistry Observation (IGACO) theme.[2]

On average only half of the CO_2 from anthropogenic emissions has remained until now in the atmosphere (Figure 1). Analyses of the decreasing $^{13}C/^{12}C$ and O_2/N_2 ratios in the atmosphere have shown that the land and oceans have sequestered the other half, in approximately equal proportions. However, the apportionment of carbon fluxes between ocean and land varies in time and space, and this variability is not well understood.

The primary mechanism for current land carbon uptake is most likely the recovery from historical land use in Europe and North America. There are several other terrestrial processes, such as enhanced plant growth due to the increase in atmospheric CO_2, whose effect is not yet well documented. For the ocean, the primary mechanism is ocean circulation coupled with the ocean solubility pump; the role of biota and changes in that role are less understood.

Further, the atmospheric growth rate of CO_2 exhibits large interannual fluctuations, on the order of the average long-term signal. The interannual variability signal cannot be explained by the variability in fossil fuel use. Rather it appears to reflect primarily changes in terrestrial ecosystems induced by changing large-scale weather and climate patterns.

Improved predictions of future CO_2 levels require better quantification and process-level understanding of the present state of the global carbon cycle, including both the natural components and anthropogenic contributions. The current state of the science, however, can neither account for the CO_2 average growth rate nor for the interannual variations with confidence. Such overall patterns of temporal dynamics in the carbon cycle are important, and our understanding of their primary drivers is limited.

At present, limitations in our current understanding also include an inability to locate well key sink or source regions. Independent information on spatial and temporal patterns of CO_2 sources and sinks is of extraordinary value for challenging process-based terrestrial and oceanic carbon cycle models, and thus for our ability to predict future CO_2 trajectories.

Quantifying present-day carbon sources and sinks and understanding the underlying carbon mechanisms are pre-requisites to informed policy decisions. This limitation is fundamental as nations seek to develop strategies to manage carbon emissions and to implement carbon sequestration activities.

The state of carbon science and its observational foundation must be sufficient to provide robust inferences on the distribution of carbon fluxes and the controlling processes. In part, this knowledge will be based upon existing or developing observational methodologies. For example, the terrestrial flux due to land-use change can be estimated from stock changes (e.g., forest to non-forest conversions); in other cases, remote observations of indicators of primary production (e.g.,

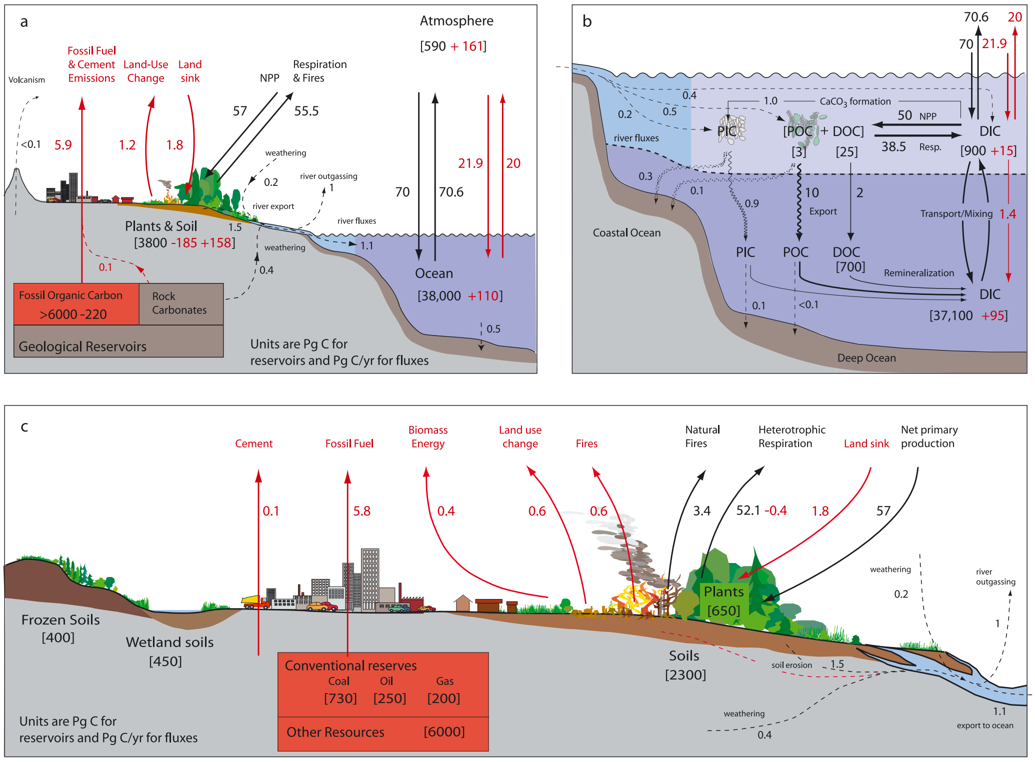

Figure 1. The Global Carbon Cycle: pools and fluxes controlling the rising atmospheric CO_2 concentration (from SCOPE 23, in press)

ocean colour) will guide process and/or phenomena based models. *In situ* observations will provide essential calibration and quantification information.

Measurements of the atmospheric concentration of carbon dioxide form an effective complement to verify measurements of carbon stock changes and process-level activity indicators. This is because the atmosphere is a rapid but incomplete mixer and integrator of spatially and temporally varying surface fluxes; therefore, observations of the distribution and temporal evolution of CO_2 *in the atmosphere* can provide a powerful gauge of surface fluxes. However, at present, the network of atmospheric *in situ* stations is too sparse to constrain well the pattern of sources and sinks; the density and coverage of the network should be increased to improve the flux estimates.

However, to achieve the needed observational density and coverage, new techniques are required. The most important of these is the satellite measurement of the distribution of global atmospheric CO_2, which is able to densely sample the global atmosphere in all latitudes and in all seasons. In addition, this space-based system would capture atmospheric CO_2 gradients directly over source/sink regions. These global observations provide the essential independent constraint on models of surface fluxes and the underlying processes.

This complement is the key to answering critical questions regarding spatial and temporal variability of carbon sources and sinks, and it forms the crucial capstone of the integrated observational strategy.

The ultimate target spatial resolution for global carbon dioxide surface fluxes is 10 km over land and 50 km over oceans with temporal resolution of a week. This can be attained through a coordinated system of integrated global carbon cycle observations (Section 4) and with significant improvements in data assimilation, atmospheric transport models, and *in situ* process models. The shorter-term objective of monthly fluxes with spatial resolution of 100 km over land and 500 km over the ocean should be possible within the decade (Section 5). Finer spatial resolution (10 km), however, might be attainable in some situations in the short-term for mechanistic studies and verification of compliance with policies.

In summary, a coordinated system of integrated global carbon observations would contribute to answering critical scientific and societal questions. Those questions include:

> What are the size, location, and processes controlling present-day terrestrial and marine carbon sources and sinks?

> What is the effectiveness of deliberate sequestration activities? What are the implications for the global carbon cycle of these activities?

> What will be the behaviour of carbon sources and sinks in the future under higher CO_2 and possibly altered patterns of climate, land vegetation, and ocean circulation?

The challenge of understanding and managing the carbon cycle can only be met through a coordinated set of international activities – research, observations, and assessment (Figure 2). All three are essential, tightly linked activities, which depend upon one another to achieve an overall understanding and knowledge base.

Research. There is an extensive array of individual and national carbon cycle research activities. At the international level the International Geosphere-Biosphere Programme (IGBP),[3] the International Human Dimensions Programme on Global Environmental Change (IHDP),[4] and the World Climate Research Programme (WCRP)[5] have recently joined forces to build an international framework for integrated research on the carbon cycle, the Global Carbon Project (GCP).[6] The GCP's three major themes are:

- **Patterns and Variability**: the current geographical and temporal distributions of the major stores and fluxes in the global carbon cycle.
- **Processes and Interactions**: the underlying mechanisms and feedbacks that control the dynamics of the carbon cycle, including its interactions with human activities.
- **Carbon Management**: points of intervention and windows of opportunity to steer the future evolution of the global carbon cycle.

The relationship between the Integrated Global Carbon Observing theme and the GCP is particularly important, with the GCP providing a framework for model development and intercomparison, advanced process studies, and research-based observations; and the Integrated Global Carbon Observing theme providing a strategy and implementation plan for systematic, long-term observations of carbon fluxes, pools, and processes.

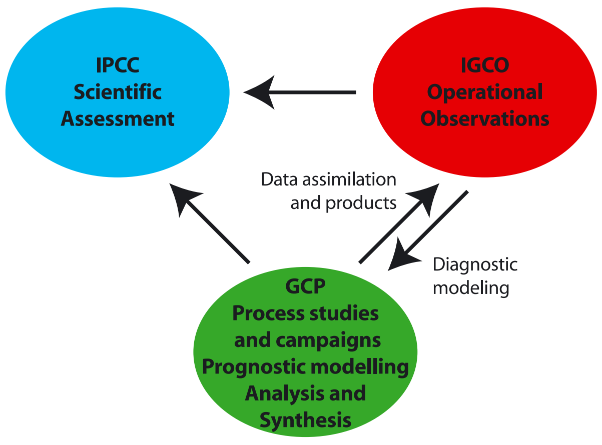

Figure 2. Links between operational observation (IGCO), research (Global Carbon Project, GCP) and assessment (IPCC)

Observations. Making available key global observations needed to improve understanding of the carbon cycle falls under the broad Integrated Global Observing Strategy (IGOS)[7] that seeks to unite the major satellite and surface-based systems for global environmental observations of the atmosphere, oceans, and land. The development and implementation of the IGOS is through a partnership, IGOS-P, among space agencies, as represented by the Committee on Earth Observation Satellites (CEOS),[8] the Global Observing Systems (the Global Ocean Observing System (GOOS),[9] the Global Terrestrial Observing System (GTOS),[10] and the Global Climate Observing System (GCOS),[11] as represented by both their programme offices and their sponsoring agencies, and the research community, as represented by two major international research programmes, IGBP and WCRP, and their sponsoring national funding agencies represented by the International Group of Funding Agencies (IGFA) and their common scientific sponsor, the International Council for Science (ICSU).

The Integrated Global Carbon Observation theme team has the task of formulating, within the IGOS context, a strategy for building a coordinated system of integrated global carbon cycle observations (henceforth called the 'carbon observing system' for short), encompassing the ocean, the land and the atmosphere, and including *in situ* as well as remotely-sensed observations. Key to this is the ability to integrate carbon observations from a wide variety of platforms and techniques within a coherent modelling framework based on data assimilation and model-data fusion methods. The Integrated Global Carbon Observation theme team is closely related to and benefits from the Terrestrial Carbon Observation (TCO) initiative, a component of GTOS, which has developed an extensive framework and implementation strategy for a comprehensive terrestrial and atmospheric carbon cycle observing system.

The strategy for developing a carbon observing system rests similarly upon a strong base for ocean carbon observations, and benefits from the GOOS report N°118 that provides a strategy for a global ocean carbon observation system and its connectivity to the atmosphere.[12]

Furthermore, the ocean carbon survey will be linked with 10-year repetitive transects being planned in cooperation with CLIVAR (Climate Variability and Predictability, a project of the WCRP). There is also an initiative to develop a Global Time Series Observatory System pilot project, consisting of a limited set of mulit-disciplinary sites. Finally, there is an important technology challenge to develop observing systems for *in situ* carbon, such as an inexpensive carbon micro-sensor to be implemented on ARGO floats.

In addition to the existing global-scale but compartmentalised observation strategies, there are a number of important regional and national observation systems and strategies that will contribute valuable components to the strategy for developing a carbon observing system. At present, however, they still operate in a fragmentary fashion and their full potential can only be realised through the development of an internationally integrated observational strategy, as envisioned in Section 4. All of the building blocks are described in more detail in Section 5.

Finally, the strategy is strengthened through close collaboration with the Global Carbon Project on the development of model-data fusion methodologies.

Assessment. For the carbon cycle, the primary assessment activity occurs through the work of the Intergovernmental Panel on Climate Change (IPCC[13]). For example, the IPCC's Third Assessment Report (TAR) produced a comprehensive and well documented synthesis of our current understanding of carbon cycle dynamics. Special reports of the IPCC on Emission Scenarios, on Land Use, Land Use Change and Forestry activities, and Special Guidelines for sources and sinks reporting have also been produced to assess the scientific basis for carbon sequestration under the Kyoto Protocol. The IPCC has launched two additional assessment activities related to the carbon cycle: a special report on Carbon Dioxide Capture and Storage, due to be completed in 2005, and a collaborative effort with the research community to understand better the mechanisms that are leading to the current terrestrial carbon sink and the direct and indirect human influences on this sink.

The aim of this section is to outline briefly the coordinated system of integrated global carbon cycle observations as it is envisaged when it is operational, by 2015. Section 5 will provide more detail as to how this fully operational system can be built from a combination of existing components and the development of new components. Several aspects of the evolution to a fully operational system are important.

First, the transition from research observations to operational observations (monitoring) is a critical step for most components of the carbon observing system. Second, to meet its objectives, the system must integrate operational observations with models, and since model development and implementation is a primary responsibility of the Global Carbon Project, close collaboration between the GCP and the carbon observing system is essential. Finally, the carbon cycle is closely linked to other biogeochemical cycles, to the physical climate system, to terrestrial and marine ecosystems, and to a range of human activities. Thus, the spectrum of measurements of relevance to the carbon cycle is potentially vast. The strategy of the carbon observing system is to focus on a **core set of operational observations** that are centrally important for the carbon cycle itself.

4.1 SCOPE AND OBJECTIVES

The carbon observing system has two principal 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 first objective has both basic research and policy components, while the second is aimed at providing policymakers with direct and useable information in the context of international negotiations to regulate greenhouse gas emissions.

By combining reliable and well-calibrated measurements with realistic models of the marine and terrestrial carbon cycle one may infer, by means of inverse modelling and data assimilation, constraints on the fluxes of CO_2 between the Earth's surface and the atmosphere and thus address both objectives. This integration of models and data requires establishment of both data requirements and modelling-assimilation strategies.

4.1.1 Data Requirements for Integration

Well-founded data requirements are presented in detail in Section 9 and provide a rationale for new measurements, the development of new technologies and advanced algorithms, data harmonisation, archiving, and distribution. Until now, the majority of carbon observations have been tailored for research purposes, supported by research funding agencies and implemented mainly through national research programmes. This global-scale research effort will now be coordinated internationally by the Global Carbon Project. The challenge is to move towards a more focused, coherent system for monitoring carbon sources, sinks, and processes, built around a backbone of core operational observations to meet the objectives of the carbon observing system. Although research-generated observations will continue to be important, the most urgent priority is to implement, expand and enhance the core set of operational observations. A summary of the required observation system is given in the boxes in this section, classified into core and ancillary observations. A roadmap for achieving these observations is presented in Section 5.

4.1.2 Modelling Strategies for Integration.

Models validated by rigorous tests and supported by observations are a critical element for synthesising the spectrum of carbon observations, as already clearly recognised by the GCP, TCO, GCOS, GTOS, and GOOS.

Models can assimilate a wide range of routine observations, allow the use of imperfect or proxy measurements, help fill gaps in time or in regions of incomplete coverage, and provide a quantification of errors. A summary of model types and applications is given in Section 9. Models further enable us to invert observations into the desired carbon cycle quantities, such as surface sources and sinks or key driving parameters that may not be directly measurable or are unobservable at a particular scale. In addition, models can encompass the wide range of spatial and temporal scales needed to quantify carbon pools and fluxes; they thus provide an efficient means for optimising the design of cost-effective observational strategies.

The current challenge is to apply a multiple constraint approach using state of the art carbon models coupled to climate models, assimilating both *in situ* measurements and remotely sensed information. As an example, in the last decade the oceanography community (see GODAE)[14] is enhancing observational capability through a suite of global observing instruments in space, including altimetry, and through a network of approximately 3000 ARGO autonomous profilers to sample intermediate and deep waters. In parallel, data assimilation schemes have been developed, aiming towards an operational system in 2005 at global and regional scales. This kind of approach that provides both nowcasting (real-time analysis) and hindcasting (decadal reanalysis) must be envisioned for the carbon-climate system.

A major research focus of the Global Carbon Project is to carry this concept forward in order to understand and interpret the present behaviour of the carbon cycle, to simulate future CO_2 levels and, ultimately, to contribute to the projections of future climate change. The challenge is to realise the high quality, consistent, long-term data to support the models, while maintaining enough flexibility to respond to new observational challenges as understanding of carbon cycle dynamics evolves. Key issues for integrating systematic carbon observations in models are presented in Section 6.

4.2 THE COORDINATED SYSTEM OF INTEGRATED GLOBAL CARBON OBSERVATIONS

The coordinated system of integrated global carbon cycle observations needed to address the dual scientific and policy-relevant objectives stated above depends on both the research and operational agencies. It is designed primarily to monitor **fluxes** to the atmosphere, and within carbon reservoirs, and **pools** of carbon on a long-term basis. In addition, it will contribute to the observational base needed to understand the dynamic **processes** that control the carbon cycle. It focuses on long-term operational measurements, while aiming to build the partnerships needed to engage research-based observational networks and models appropriate for data assimilation.

4.2.1 Fluxes: Magnitudes and Distributions

The highest priority for the coordinated system of integrated global carbon cycle observations is to generate global, high resolution maps of the CO_2 fluxes between the Earth's surface and the atmosphere. The fundamental components of any carbon flux-measuring system must be *in situ* and space-based **atmospheric measurements** of the CO_2 distribution, as the atmosphere directly reflects the human perturbation of carbon cycle dynamics (primarily the combustion of fossil fuel and land-use change) and is a sensitive indicator of the exchange of carbon between the atmosphere and the oceans and land. Satellite measurements of atmospheric CO_2 distribution will be integrated with *in situ* **surface flux measurements** (e.g., ocean dissolved and marine boundary layer pCO_2, eddy covariance measurements of terrestrial ecosystem-atmosphere fluxes), scaled up using appropriate remote sensing data of surface properties with global coverage. The surface data will be assimilated within a modelling framework or used to calibrate or validate the remotely-sensed observations of atmospheric CO_2 distribution. The remotely sensed atmospheric observations that are foreseen will have a spatial resolution of 10 km or finer and near repeat interval of one week or less (for a typical polar orbit, this is obviously latitude dependent). The dedicated missions OCO (NASA) and GOSAT (JAXA), to be launched in 2007 and 2008 respectively, will be the first to provide such observations.

Box 1: Determining carbon fluxes between the atmosphere and the Earth's surface

Core Observations

- **Atmospheric column CO_2 concentration measured from satellites, with ground-based quality control (1 ppm)**
- **Atmospheric CO_2 concentration measured from *in situ* networks, including vertical profiles (0.1 ppm)**
- **Land-atmosphere CO_2 flux measured via eddy covariance flux networks covering all ecosystems / regions/ disturbance regimes**
- **Basin-scale observations of the air-sea flux: ocean ΔpCO_2 from ship-based measurements, drifters and time series as well as variables needed to calculate fluxes (e.g., SST, wind)**
- **Mapping of fossil fuel and bio-fuel CO_2 sources at high resolution (10 km) including temporal variability (3-hourly)**
- **Global, synoptic satellite observations of ocean and terrestrial surface to extrapolate point-wise *in situ* fluxes to larger regions (vegetation state and activity, ocean surface physical state and biological state)**

Non-CO_2 gases

- **Space observation of column atmospheric CH_4 (20 ppb)**

Models

- **Inverse atmospheric transport models to retrieve fluxes from atmospheric data.**
- **Models of ocean and terrestrial fluxes, both data-driven and process-driven, to assimilate space-borne and *in situ* data into global flux maps**

Combined together, *in situ* flux measurements, remote sensing data streams, including space-based atmospheric measurements of CO_2, and model analysis will deliver by 2015 global flux distribution at a spatial resolution of 10 km over land and 50 km over the oceans and a temporal sampling of about a week. The flux observation components of the system are given in Box 1.

For *in situ* measurements over land, high spatial and temporal resolution is required to account for the heterogeneity in land cover and to connect land management practices (e.g., farming, forestry) to the exchange of CO_2 with the atmosphere. **Eddy covariance** techniques now allow continuous monitoring of CO_2 fluxes over vegetation canopies. Terrestrial fluxes and their variability must be connected to weather patterns and biological processes. Temporal resolution of a week or so is sufficient to capture the variability in terrestrial fluxes driven by changing weather patterns (e.g., the effect of frost or drought on forests).

Over the oceans, CO_2 fluxes must be firmly related to physical and biological parameters (see Section 4.2.3) in order to map fluxes correctly. Observations of **surface pCO_2** at approximately monthly intervals over basin scales are required to make estimates of air-sea fluxes. The carbon observing system must also accommodate the significant variability of the fluxes in areas like the coastal margins and estuaries, where large gradients in water properties and productivity occur. This requires that the system must have the capability to support sampling at higher spatial and temporal resolutions, and to include ancillary observations that inform about underlying processes. The carbon observing system must also provide estimates of horizontal, sometimes called lateral, fluxes, even if these do not imply any net loss or gain to the atmosphere. **Lateral fluxes** include carbon transport by erosion, river transport, and wood and food product trade (see Section 5.3).

Finally, the carbon observing system must be able to detect improbable but potentially large carbon fluxes, such as CO_2 or CH_4 from destabilisation of permafrost areas or hydrates at the continental shelf margins. For the latter, collaboration with the proposed observing system for atmospheric chemistry (i.e., IGACO) is essential.

Models are required to extrapolate from local flux measurements to global flux maps (see Box 1). Two types of model are particularly important: (i) atmospheric transport models are required to invert atmospheric observations of CO_2 distribution into surface flux fields; and (ii) carbon cycle models are required to assimilate the wide range of *in situ* observations of fluxes and ancillary measurements.

It is important to recognise that none of the surface flux-measuring components of the carbon observing system currently exists in the operational state. *The biggest challenges* in building this component of the system over the next 15 years are therefore (i) to develop and deploy the technologies that enable remote sensing of column atmospheric CO_2 concentration from space, surface and aircraft and (ii) to expand and enhance both the current *in situ* flux measuring research networks and transform them into operational systems.

4.2.2 Pools: Magnitudes, Distributions and Changes

In addition to mapping surface-atmosphere fluxes, the carbon observing system will determine changes in the distribution and magnitudes of key carbon pools and their evolution over time (Box 2). Measuring changes in carbon pool sizes requires a temporal sampling period much longer than that required for fluxes. There is an inherent problem of small changes in large numbers. Indeed, given the heterogeneous nature of most carbon pools and the fact that anthropogenic perturbations are generally much smaller than the total carbon store, only changes over several years can normally be detected.

Over land, the carbon observing system will make repeat measurements (5-year intervals) of **above-ground biomass** in sample plots in all major forest biomes including both unmanaged and managed forests in the tropics, the temperate and boreal zones. Accounting for the fate of carbon in wood products is necessary to close the budget of biomass inventories. The strategy is to collaborate with national forest inventory programmes; the primary challenge is to harmonise the data from various countries, to adapt them for carbon cycle studies, and to report them in a transparent and verifiable manner to form an internally consistent global dataset for carbon accounting purposes and for scientific studies. Space-based measurements of biomass are also highly desirable; these depend critically on development and deployment of satellite lidars (e.g., Vegetation Canopy Lidar) and the appropriate radar systems (long wavelength radars and/or polarimetric interferometry).

Similarly, **soil carbon** survey programmes, developed in synergy with plant biomass inventories, will detect long-term changes (approximately every 10 years or so depending on local spatial variability) in carbon accumulation in soil horizons. However, given the huge heterogeneity of soil carbon distributions, numerous sampling sites around the world will be needed to detect significant changes in pool size.

Over the main ocean basins, measuring **the ocean dissolved carbon** pool approximately every 5 to 10 years will be sufficient to corroborate independently the air-sea flux mapping efforts. Determination of carbon pool sizes is of special interest for particular oceanic domains, such as the deep-water production areas in the North Atlantic and the Southern Ocean. Existing multi-tracer techniques will be refined to estimate correctly the invasion of the excess of atmospheric CO_2 into the ocean against the high background of natural dissolved inorganic carbon. The developing GEOTRACES[15] project would address well the *in situ* ocean carbon measurement requirements in a research context.

Finally, ancillary observations will be made of carbon storage in reservoirs and lakes and in carbon product pools (both wood products and food products including their processing and displacement in trade systems), storage due to charcoal formation, and storage in the deep sediments in the oceans. In particular, better measurements of the amount of carbon buried in coastal sediments will be obtained to improve estimates of the amount of carbon exported to the deep ocean via rivers.

An additional ancillary observation will be made of large permafrost soil carbon stores, up to 400 Pg C globally, which exist in Arctic regions and were deposited during the Pleistocene and Holocene. The Pleistocene stocks, made of relatively labile carbon compounds, could be degraded very rapidly if future regional warming initiates bacterial activity due to heating of the soil. Similarly, the shallow coastal seafloors of the Arctic Ocean contain important carbon stocks. Although it is uncertain if these huge stores are vulnerable to climate change, their monitoring (temperature; flux surveys) will be needed to detect any changes.

The pool measurements undertaken by the carbon observing system will enable key fluxes among sub-pools *internal* to each reservoir to be measured, in addition to the fluxes between the surface and the atmosphere. In particular, processes which transfer carbon from fast pools in contact with the atmosphere (e.g., the ocean mixed layer and leaves) to pools of longer turnover times (e.g., ocean intermediate waters, tree trunks, and terrestrial litter) need to be monitored closely.

Of the core measurements for carbon pools outlined above, only forest biomass inventories (and in some cases soil surveys) currently exist as operational systems, but not with the purpose to evaluate carbon storage. Rather, these numbers exist primarily for silvicultural and agricultural reasons. Consequently, these are generally nationally based, so the harmonisation of such existing data and the standardisation of methodologies is a central issue. Most other pool measurements exist only in research mode, and considerable further development is required before they can be included in hindcasting, re-analysis, or carbon budget studies in the context of an operational system.

Box 2: Monitoring carbon pools and pool changes

Core Observations

- **Forest biomass inventories over all forest biomes, both *in situ* and satellite data**
- **Soil carbon inventories.**
- **Basin-scale *in situ* inventories of dissolved and particulate organic and inorganic carbon in the ocean, with full column sampling of carbon system parameters**

Ancillary Observations

- **Carbon storage in the sediments of reservoirs and lakes;**
- **Carbon storage in anthropogenic pools, primarily wood products;**
- **Carbon storage in frozen Arctic soils, both terrestrial and shallow seafloor permafrost; and**
- **Sediment trap and sea-floor studies, with a special emphasis on coastal sediments.**

Models

- **Process-driven models of carbon dynamics in terrestrial and marine reservoirs**

4.2.3 Linking fluxes to processes by observations

One of the three major themes of the Global Carbon Project is to develop a better understanding of the processes that drive the dynamics of the carbon cycle. Improvement of process-based carbon cycle models is a key element in the GCP strategy. Because models are developed and tested on the basis of measurements of carbon cycle behaviour, process-relevant observations are an important part of the strategy. For example, observed flux patterns give vital information on underlying fundamental processes (e.g., air-sea gas exchange, primary productivity of the ocean and land, changes in ocean stratification and export of carbon from surface to deeper waters, photosynthesis, respiration, fossil fuel emissions, biomass burning).

Nearly all of the measurements used in model development lie in the research domain and will remain so for the foreseeable future. However, two observations are especially important, both to estimate fluxes and to inform about the underlying processes, and thus are recommended to become core observations in the operational domain. First, land-cover change is responsible for significant emissions of CO_2 every year, usually estimated to be in the range 1.5 - 2.5 Gt C y^{-1}. Routine observations of land-cover change, with global coverage at a resolution of at least 1 km., will constrain this important flux much better and will also provide insights as to the drivers of the observed changes. Second, ecological disturbances often lead to event-related, large emissions of CO_2 and other carbon compounds (Figure 3). Globally, the most important disturbance is fire, a source of 2 - 4 Gt C y^{-1}, partly offset by ecosystem regrowth after burning. Remote sensing technologies now allow the monitoring of fire distribution and extent of burned areas; such measurements are recommended to become core observations in the carbon observing system.

A large number of ancillary process-relevant measurements (Box 3) are important for the development of carbon cycle models. Some of these will remain as research observations and thus within the domain of the Global Carbon Project; others will be made as part of other observational systems, for example, meteorological observations of the physical climate system. Thus, it is important that the carbon observing system maintain a close collaboration with the GCP, with national research programmes, and develop partnerships with other observation systems (e.g., climate, biodiversity, atmospheric chemistry).

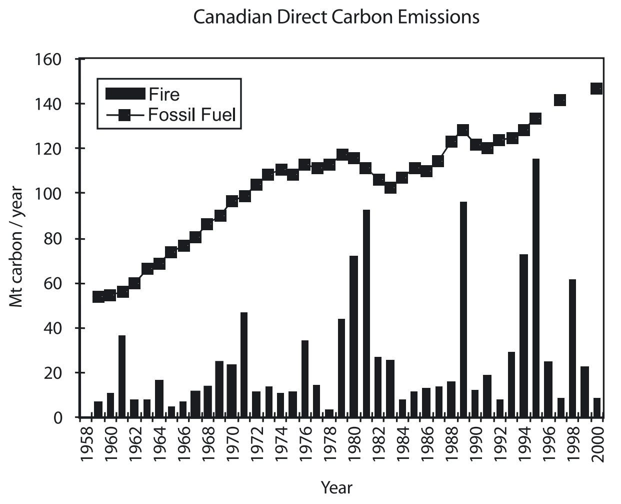

Figure 3. Comparison of fossil fuel CO_2 emissions and fire induced CO_2 emissions of Canada shows the importance of biomass burning in regional carbon budgets.

Box 3. Linking fluxes to major processes:

Core Observations

- **Global land-cover change (100 m) at intervals of 5 years from space**
- **Global ecosystem disturbances from space**
  - **Fire distribution (sub daily counts)**
  - **Burned areas (monthly products)**
  - **Other disturbances (harvest, insects, windstorms) at intervals of 1 year**
- **Vegetation state and activity from space**
  - **Leaf Area Index**
  - **Vegetation architecture and profile**
  - **Albedo, Fraction of Absorbed PAR and related biophysical parameters.**
  - **Parameters related to ecosystem condition, such as drought indexes**
  - **Gross and Net Primary Productivity**
- **Ocean colour (60% global on 3-5 days timeframe)**
- **Time series of eddy-covariance fluxes of CO_2, latent and sensible heat**
- **Time series of exported fluxes from sediment traps**
- **Large scale measurements of dissolved oxygen to determine changes in ocean stratification.**

Ancillary Observations

- **Co-sampling of parameters related to processes at eddy flux towers (e.g., soil moisture, nutrients, respiration terms, phenology)**
- **Co-sampling of parameters related to processes from ship-based measurements, drifters and time series (e.g., ecosystem variables, pigments, nutrients)**
- **Space observations related to processes driving CO_2 fluxes. For instance,**
  - **Climate and weather data, including precipitation**
  - **Soil moisture content**
  - **Radiation diffuse and direct components**
  - **Ocean circulation**
  - **Air-sea gas transfer (SST, SSS, winds)**
- ***In situ* observation related to processes**
  - **Soil characteristics**
  - **Phenology**
  - **Nutrient distributions (ocean and land)**
  - **Species composition of ecosystems**
- **Atmospheric tracers to separate ocean and terrestrial sources, fossil fuel and biomass burning (O_2:N_2; ^{13}C-CO_2; CO; aerosols).**

Non-CO_2 gases

- **Space observations of wetlands extent for CH_4**
- **Fire emissions of CH_4**
- **Non-CO_2 gas emissions by ecosystem (B-VOCs)**

Models

- **Process-driven carbon models to relate fluxes to processes**

Many of the ancillary measurements will be co-sampled with the operational flux measurements (e.g., as part of research programmes associated with the eddy-flux network or as part of shipboard measurements on research cruises). Several are now routinely measured from space-based platforms and are included in other observation systems; for example, measurement of ocean colour is included as a component of the Oceans Theme of IGOS-P.

The ancillary measurements also include observations needed to determine the net carbon balance of ecosystems, such as knowledge of emissions of non-CO_2 carbon gases such as CH_4, CO, and Volatile Organic Compounds (VOC).

The current system components are reviewed in Section 5.1 by Earth System domain (atmosphere, land, ocean), and Section 5.2 presents recommendations for expanded observational capabilities. For the atmosphere, there is a particular emphasis on a new space-based measurement instrument. This domain approach reflects the current organisation of most of the existing methodologies as well as the research and observational communities. However, the strategy for realising a coordinated system of global carbon observations will shift this existing domain-orientation to a structure based on flux, pool and process-related observations (Section 4).

5.1 IDENTIFY THE BUILDING BLOCKS

Building the carbon observing system outlined in Section 4 requires a pragmatic strategy based upon existing observation systems so far as possible. Identification of fundamental existing components have been carried out respectively by TCO for terrestrial and atmospheric measurements and by GOOS for ocean measurements (see Section 9). These systems and networks provide the building blocks from which a global system can be developed. However, at present they are mainly research tools and cannot be considered operational. These observations need significant enhancement, extension, and optimisation.

5.1.1 Existing Atmospheric Observations

The atmosphere is a fast but incomplete mixer and integrator of spatially and temporally varying surface fluxes, and so the distribution and temporal evolution of CO_2 in the atmosphere can be used to quantify surface fluxes, using numerical models of atmospheric transport. This process is known as inverse modelling. Relevant atmospheric observations also include carbon tracers and other tracers indirectly useful for carbon studies. Carbon tracers ^{13}C-CO_2, ^{18}O-CO_2 and O_2:N_2 deliver specific constraints to separate terrestrial from marine fluxes. Other tracers, such as the inert gases SF_6 and ^{222}Rn, or C_2Cl_4 and, are used to evaluate atmospheric transport parametrisations in models. Tracers related to combustion CO and black carbon, or surrogates of fossil fuel emissions such as $^{14}CO_2$, are used to constrain biomass burning and fossil fuel emissions. In addition, information on the dynamical structure of the atmosphere is necessary to interpret concentration measurements.

The existing components of atmospheric carbon observations are:

- Flask sampling networks including about 100 sites globally with weekly sampling frequency (Figure 4).[16] In most cases, multiple species are determined from flask air samples (e.g., ^{13}C-CO_2, ^{18}O-CO_2, O_2:N_2, CH_4, N_2O, SF_6, CO).
- Continuous stations of *in situ* CO_2 monitoring, including several marine atmosphere baseline stations (e.g., Mauna Loa), mountain stations, and more recently several tall towers in the interior of continents. About 10 of the *in situ* CO_2 stations out of a total of 20 around the globe have long records spanning over the past 20 years.
- Aircraft vertical profiles at about 10 sites around the globe (e.g., North America, Europe, Siberia, South Pacific) which deliver information on the vertical structure of tracers, related to source distributions of CO_2 and to atmospheric mixing (Figure 5).
- Calibration and inter-comparison activities. International exchange of standard samples is coordinated internationally by the Global Atmosphere

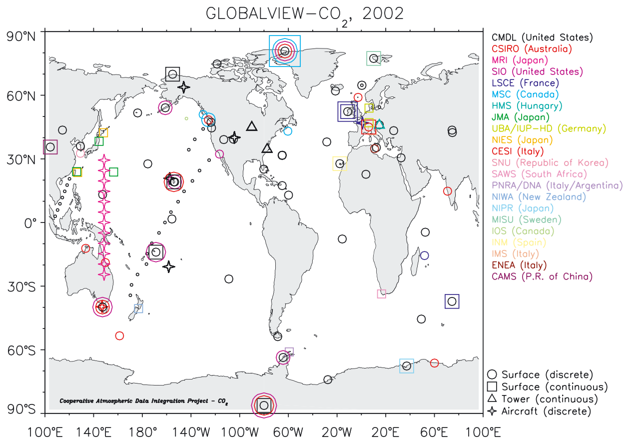

Figure 4. Map of the global air sampling network in 2002.

Figure 5. Airplane of AN-2 type used to sample vertical profiles of CO_2 in the lowest atmosphere over Central Siberia.

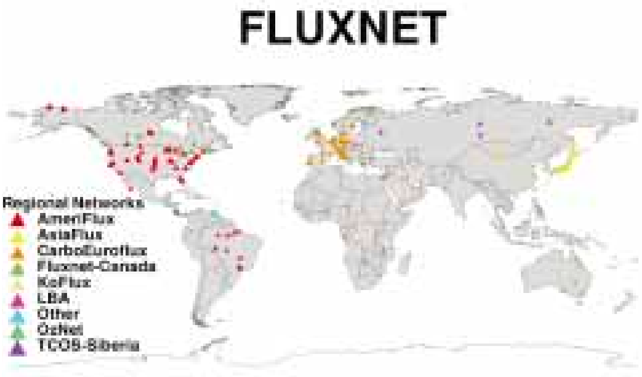

Figure 6. World-wide distribution of eddy covariance towers measuring CO_2, water vapour and energy fluxes. Ten years ago, only 5 such towers were operating.

Watch Programme of the WMO for CO_2 and by the International Atomic Energy Agency for isotopes. In parallel, there are several ongoing inter-comparison projects among the major air sampling networks (e.g., through common sampling at the same location). This is a very important activity and needs increased support.

5.1.2 Existing Terrestrial Observations

The current terrestrial carbon observation base is made up of *in situ* ecological measurements that are generally labour intensive and expensive (e.g., net primary productivity, biomass or soil carbon), flux measurements by the eddy-covariance technique, completed by atmospheric CO_2 concentration at continental locations (e.g. tall towers, aircraft), and remote sensing data and products.

In addition, there is partial information on nutrients, climate, soil moisture and radiation, and on some disturbances (e.g., global maps of burned areas and fire hotspots from satellite).

The existing components of today's terrestrial carbon observations are:

- Eddy covariance flux networks (about 100 towers, mainly over forests) (Figure 6).[17]
- Forest biomass inventories that exist for most developed countries include a very large number of sampling locations, but many forest biomes have little or no inventory data (Figure 7).[18]
- Soil surveys which exist at regional, national and global scale; however, their utility for carbon studies and particularly for estimates of change in carbon stocks is open to question.[19]

Figure 7. Large scale extensive forest inventories (top left) and forest harvesting to yield wood products.

- Networks and transects for ecological studies and phenological observations.
- Satellite remote sensing (land cover and land cover changes induced by land use practices (Figure 8), vegetation phenology and biophysical properties, fires, radiation).

Figure 9 shows the coverage of existing terrestrial carbon observations.

5.1.3 Existing Ocean Observations

The existing components of an ocean carbon cycle observing system are:

- Basin-scale surface observations of atmospheric and oceanic pCO_2 and related parameters on research ships and ships of opportunity (Figure 10). Regional datasets have been collected for the North Pacific, North Atlantic and equatorial Pacific. Global data products of monthly air-sea flux maps have been generated using the available pCO_2 data.[20]
- Large-scale ocean inventories from hydrographic survey cruises with full water column sampling of carbon system parameters (Figure 11). At present there are surveys generally on 5-10 years time scales (e.g., GEOSEC[21], Transient Tracers in the Ocean (TTO[22]), and two recently completed research projects of the IGBP and WCRP, respectively: Joint Global Ocean Flux Study (JGOFS[23]), and the World Ocean Circulation Experiment (WOCE[24])).
- Moored and shipboard time series measurements of the ocean carbon cycle components (Figure 12). In addition, some stations include sediment traps and sea-floor studies to investigate the transfer of carbon from the surface waters to deeper and longer-term storage compartments in the ocean. There are presently about 30 time series stations measuring carbon cycle variables.
- Satellite remote sensing of parameters related to carbon fluxes (e.g., surface winds, sea surface temperature, ocean colour) as well as key ancillary data such as altimetry.
- Coastal zone time series stations on the continental shelf measuring carbon system variables as part of national research programmes. Many of these are

Figure 8. Remote sensing of changes in land cover in Brazil (SPOT image)

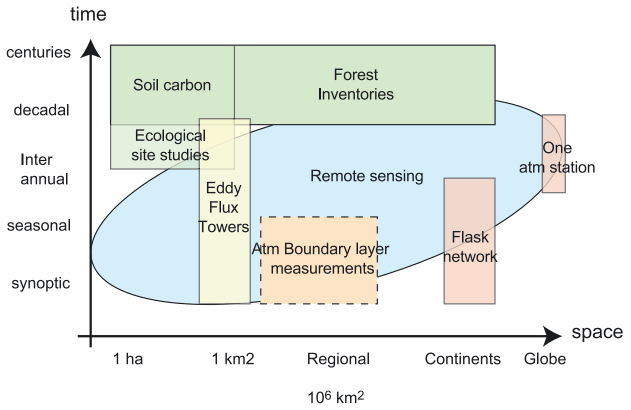

Figure 9. Spatial and temporal coverage of existing terrestrial carbon observations

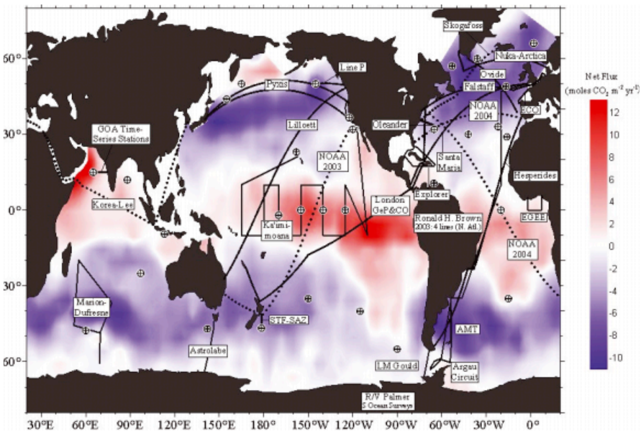

Figure 10. Map of ocean pCO_2 surveys on ships of opportunity, research vessels and moored points

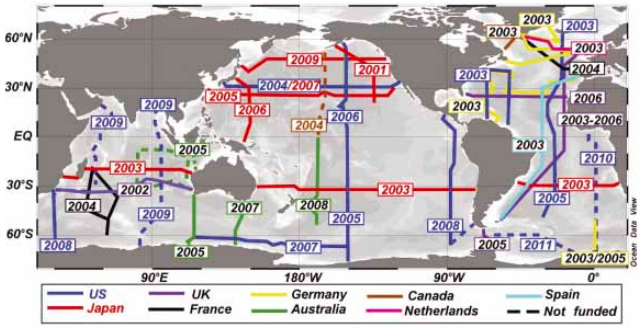

Figure 11. Map of existing coverage of ocean repeated inventories

part of LOICZ (Land-Ocean Interactions in the Coastal Zone) research project of the IGBP[25] but are not sufficiently supported at the international level in terms of an operational observation network.

Figure 13 shows the coverage of existing carbon observations.

5.2 THE MAJOR NEW ELEMENTS IN THE COORDINATED SYSTEM FOR INTEGRATED GLOBAL CARBON OBSERVATIONS

One central theme of the carbon observing system is the integration of satellite observations with key *in situ* measurements.

Satellite sensors measure scattered, reflected or emitted electromagnetic radiation that carries information about surface or atmospheric characteristics. Once calibrated, these measurements can be transformed into carbon cycle variables. Researchers in various programmes and countries have developed accurate and robust algorithms. Coordinated international activities have been undertaken with the sponsorship of organisations such as CEOS, IGBP, WCRP, IHDP, and DIVERSITAS as well as the national space agencies. While much progress has been achieved, this process needs to continue with vigour.

Figure 12 (Top) Roger Revelle research ship; (Bottom) Global network of ARGO floats and moored systems

In linking measurements to models, a choice exists as to whether future carbon cycle data models should assimilate carbon cycle variables or be fitted with radiative transfer codes to directly assimilate radiances measured by space-borne sensors. It appears that the latter approach could be better adapted as a means of retrieving fluxes from future satellite CO_2 observations, and could be extended to assimilation of ocean colour and vegetation reflectances.

The carbon observing system must:

- Support the development and testing of the required algorithms and their modification over time for new sensors. The overall aim should be to acquire and implement community consensus algorithms.
- Support the assimilation of satellite radiances (level 1 data products) using, if necessary, state-of-the-art numerical weather prediction models.

The list of satellite observations that would form the backbone of the carbon observing system is summarised in Section 9, and is based on a synthesis of the TCO and GOOS reports.[26]

The first subsection below highlights new satellite technologies for atmospheric CO_2, and the subsequent three sections describe the challenges in enhancing, extending, and optimising the existing research-based observing systems in each domain into operational components of the carbon observing system.

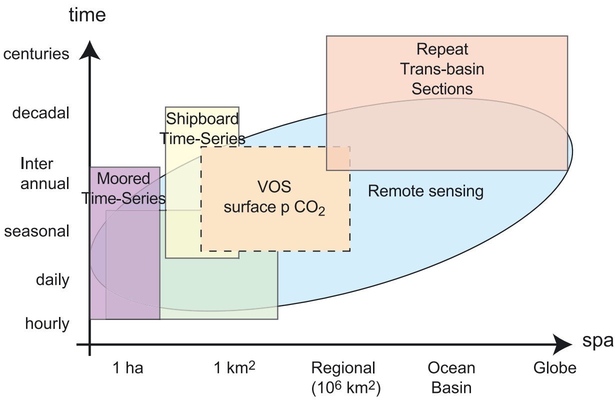

Figure 13. Spatial and temporal coverage of existing ocean carbon observations

5.2.1 Space-based Measurement of Atmospheric CO_2

Space-based high-precision measurements of the column-integrated CO_2 molecular density with global, frequent coverage would be of extraordinary and unique value in determining terrestrial and oceanic CO_2 fluxes. By linking the spatial distributions of CO_2 with atmospheric flux inversions, data assimilation techniques, and coupled atmospheric, terrestrial and ocean carbon modelling (Section 6), the scientific community will be able to determine sources and sinks of CO_2 at unprecedented space and time resolution. In addition, this measurement stream will have value in its independence from *in situ* measurements or "bottom-up" model-derived estimates of CO_2 flux.

The atmospheric inversion approach exploits the atmospheric gradients in CO_2, which are strongest in the lower part of the atmosphere. In a very real sense, the flux retrieval accuracy is a function of precision and sample density of measured total column CO_2. The measurements need to be at the *0.3% (1 ppm) precision or better* for significant improvements in our knowledge of sources and sinks.

Two spectral domains are usable: the long-wave infrared and the short-wave infrared. Each has advantages and disadvantages.

Using existing measurements in the long-wave from the HIRS-2/AMSU instruments on the NOAA polar satellite series, which were not initially designed for CO_2 retrieval, very promising results have been obtained, producing four years of monthly retrievals at 15° spatial resolution of the CO_2 concentration over the tropics (20°N-20°S) that show good agreement with what is presently known from aircraft instruments (Figure 14).[27] Method-induced error of these retrievals is of the order of 3-4 ppm (around 1%). There is promise that additional advances will be achieved by exploiting new long-wave instruments that have been recently launched, such as the Atmospheric InfraRed Sounder (AIRS) - Advanced Microwave Sounding Unit (AMSU-A) package[28] or that will soon be launched, such as the IASI/AMSU[29] suite. The AIRS/AMSU and IASI/AMSU, as well as the planned CrIS[30] on NPOESS[31] have the advantage over HIRS-2/MSU of having a much higher spectral resolution, which allows isolation of a larger set of more specifically sensitive CO_2-channels from the interfering water vapour and temperature signals.[32] A precision on the order of 0.5% at a space-time scale of 100 km/weekly is envisaged. These instruments are not being launched with the measurement of atmospheric CO_2 concentration as their focus; however, their capabilities will improve our ability to monitor CO_2 and other trace gases from space.

The disadvantage is that the long-wave measurements tend to capture mostly the upper part of the troposphere, where the signal of surface sources and sinks is of smaller magnitude (except in the tropics) and hence the gradient is weak.

Using the short-wave infrared signal has the advantage of penetrating the atmosphere down to the ground. Retrieval of CO_2 from SCIAMACHY[33] on ENVISAT[34] is underway (Figure 15), using both sun-glint and nadir measurements (the latter over land) of the instrument

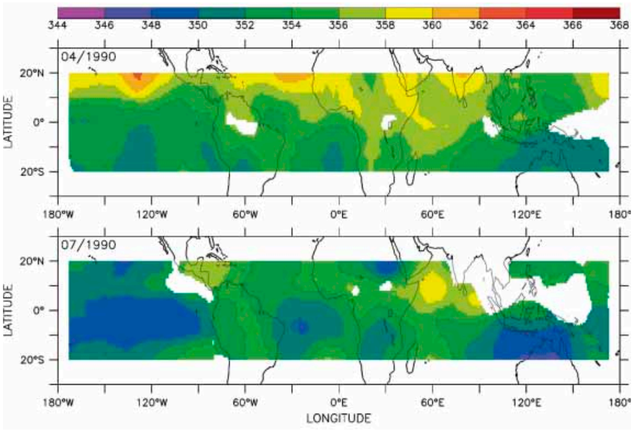

Figure 14. CO_2 monthly mean concentration maps as retrieved from NOAA-10, at the resolution of 15°x15° (1°x1° moving average), for four months corresponding to the minimum (October), maximum (April), or to intermediate values (January and July) of the northern hemisphere CO_2 seasonal cycle. Courtesy of A. Chédin.

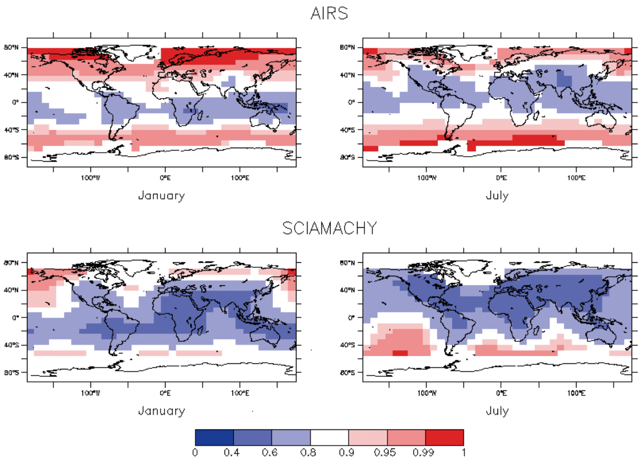

Figure 15. (Top) Modelled uncertainty reduction on surface fluxes as delivered by space-borne CO_2 measurements on AIRS in LWIR and (Bottom) SCIAMACHY in the SWIR spectral domain. Courtesy of S. Houwelling.

but atmospheric diffusers such as clouds and aerosol particles are an important source of contamination, and, given the 50 km field of view of SCIAMACHY, may yield to high data rejection.

Nevertheless, given the lead time for developing the required sensor technology, better use of existing sensors should be pursued concurrently.[35]

On the 2007 horizon, the Orbiting Carbon Observatory (OCO - NASA; Figure 16)[36] will use measurements of reflected sunlight in the short-wave infrared to provide global, high-precision measurements of the column-integrated CO_2 mixing ratio. For the two year OCO mission, the measurement objective is daytime column integral measurements of CO_2 with a precision of 0.3% (1 ppm). This precision is needed to characterise CO_2 sources and sinks. The Orbital Carbon Observatory will carry three high-resolution spectrometers, one for O_2 and two for CO_2 (1.6 and 2.06 μm respectively). It will be the first mission dedicated to atmospheric CO_2 measurement and will likely serve as a pathfinder for future long-term CO_2 monitoring missions.

The Greenhouse gas Observing Satellite (GOSAT - JAXA; Figure 16)[37] is also being planned for launch around 2007, with aims to observe CO_2 global distribution, using either long-wave infrared or short-wave infrared signals.

Reaching the ambitious goals set for OCO and GOSAT will require a better characterisation of spectroscopic coefficients as well as effects of pressure, water, dust, tropopause location, and other atmospheric constituents. In that respect, the use and development of ground-based solar observatories for CO_2 is urged to characterise the ultimate accuracy of the near IR absorption technique. Such a ground-based column CO_2 network will also provide a unique control for any space-based CO_2 mission. Complementary surface or airborne lidar, used for photochemistry, should be improved to remotely capture CO_2 vertical structure and give insight on estimated CO_2 column bias.

These passive CO_2-focused instruments are the logical next step and build upon the results from AIRS/AMSU and other spectrometers and interferometers. They, however, share some of the drawbacks. Passive instruments may not sufficiently resolve the lower part of the atmosphere, and there is an inherent inability to sample low-light regions. This could inject a bias into the inferred fluxes since there will be a systemic sampling of photosynthetically active temporal and regional conditions (e.g., day versus night, lack of high latitude samples in the late fall to early spring).

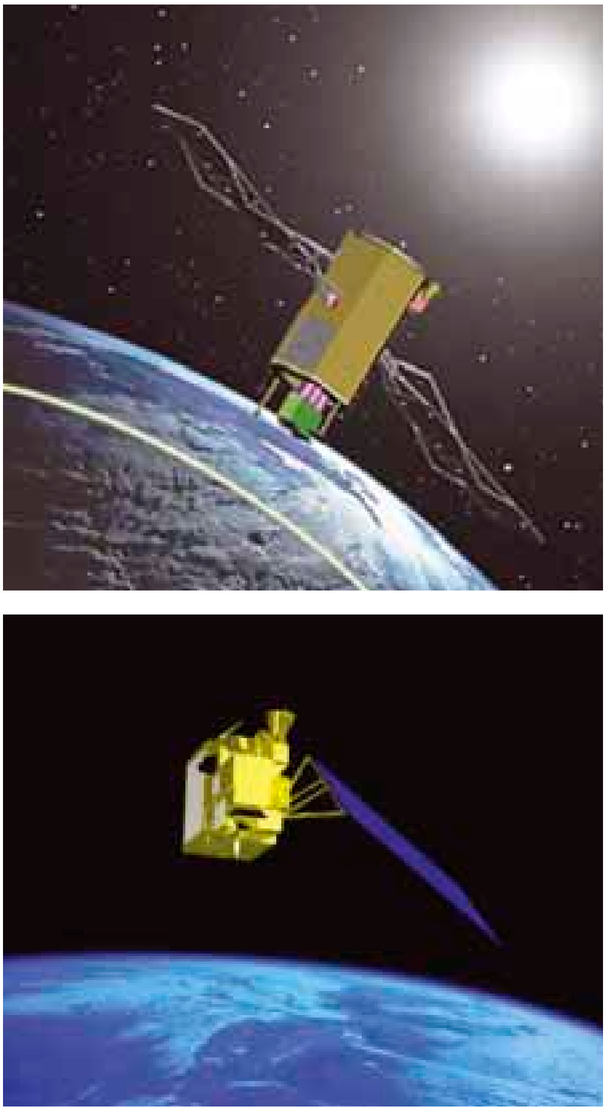

Figure 16. Artist illustration of (top) the OCO spacecraft (to be lauched in 2007) orbiting the Earth in the nadir sounding mode, and (bottom) the GOSAT spacecraft, to be launched in 2008.

The appropriate next step after OCO and GOSAT is an active mission that focuses upon the measurement of column CO_2 without diurnal, seasonal, latitudinal, or surface restrictions. This mission could be accomplished with the measurement technique based upon Laser Absorption Spectroscopy (LAS),[38] which is a powerful tool for high-precision trace gas spectroscopy. LAS provides measurements of CO_2 via measurements of received power at wavelengths on and off an absorption line.

LAS differs from DIfferential Absorption LIDAR (DIAL) in that DIAL operates in a pulsed mode, which is not required for column measurement.[a] This criti-

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[a] Determining the atmospheric profile globally of carbon dioxide would be of significant value, but it also presents a very high technological hurdle and would require a very significant investment. Having a cloud altimeter on board would be useful and may represent an appropriate compromise between achieving a profile versus simply the total column.

cal distinction enables exploitation of investment by the commercial telecom industry, which has produced highly reliable laser products that fortuitously operate through a set of clean, well-isolated CO_2 absorption lines.

In parallel to algorithm development and new space-borne sensors, validation and calibration of space-based CO_2 measurements by enhanced *in situ* observations must also be built into the carbon observing system. Aircraft or balloon vertical soundings must be carried out up to the stratosphere for systematic comparison with remotely-sensed column CO_2 from space, in synergy with network of ground-based upward-looking remote sensing CO_2 stations. Efforts should be made to coordinate international satellite observation projects being planned in the US, Japan, Europe and other countries.

5.2.2 Challenges in Enhancing, Extending and Optimising the *in situ* Atmospheric Observing System

The first challenge in realizing the *in situ* atmospheric component of the carbon observing system is to build and stabilise site networks that are denser and more spatially representative of the variability in fluxes. Especially urgent are:

> Expansion of networks over the interior of continents (e.g., Africa, Siberia, Amazon) where the variability of sources and atmospheric transport imposes the need for a much higher sampling density than currently achieved. This expansion may require a range of platforms, including mountain stations, tall towers, tethered balloons, and high frequency aircraft measurements (possibly on commercial aircraft flights).
> Development of multiple chemical-species analysis in flask air samples, including high-precision analysis of tracers (e.g., O_2/N_2, Ar/N_2).
> Improvement of atmospheric tracer transport models and inverse methods towards higher spatial resolution as well as towards better use of prior information on the geographic patterns of the fluxes (e.g., fossil fuel emissions).
> Development of robust remotely-operated continuous analysers, with an acceptable trade-off between logistical independence and precision.
> Development of column CO_2 optical sensors in preparation for future satellite CO_2 observations.
> Continuation of intercomparison and calibration activities under the WMO-GAW programme.

A second challenge is to implement these atmospheric observations synergistically with observations on the surface and subsurface, both on land and in the ocean (e.g., on top of eddy covariance towers and onboard ships of opportunity), and to include ancillary observation of ecosystem condition. Atmospheric measurements need to be integrated with surface data into a single, internally consistent, coherent strategy. For instance, tall towers for atmospheric observations should best be located within denser regional networks of eddy flux measurements, ecological studies, and remote sensing information.

5.2.3 Challenges in Enhancing, Extending and Optimising the Terrestrial Observing System

The core observations required in the terrestrial domain of the carbon observing system will be built by expanding and enhancing existing components rather than by introducing new components.

The core observations identified in Section 4 must be transferred to the operational domain over the coming decade. These are (i) the eddy covariance flux networks, (ii) forest biomass inventories, (iii) soil carbon surveys, and (iv) remote sensing of land-cover change and of fire frequency and extent.

Eddy Covariance Flux Network. It is of great importance to ensure the continuity of existing measurements of eddy covariance ecosystem fluxes for at least 10 years at each site (e.g., Figure 17); to expand the network in under-sampled regions and ecosystems undergoing disturbances, develop real time data transfer, and to enhance data quality insurance procedures. Also, calibrated CO_2 concentration measurements should be added on top of suitable flux towers to complement atmospheric networks.

Forest Biomass Inventories. Forest biomass inventories are important for monitoring changes in the above-ground terrestrial carbon pool size. At present, however, these inventories are primarily designed to quantify the volume of merchantable wood in a given region with high accuracy (standard error of 1% at the national level). This quantity relates in a predictable manner to carbon stored in tree biomass. Allometric equations relating biomass to diameter, height and tree age factors are needed to convert these volume estimates into whole tree carbon content. Using constant conversion/expansion factors, as is usually done, results in large errors, since both wood density and expansion factors vary considerably with age and between species. Further, conversion of volume increment obtained from repeated inventories into carbon

Figure 17. Eddy covariance tower in Manaus, Brazil, measuring fluxes of CO_2, water vapour and energy.

sequestration needs an extra set of expansion factors that take into account differences in turnover rates of different plant organs.

Much work has yet to be done to create continuous, standardised, geo-referenced forest biomass and soil carbon inventories. It is critical to harmonise the widely varying methodologies for inventory and analysis, in order to synthesise carbon estimates based on national forest inventories. In addition, a major observational challenge is to establish allometric functions converting above-ground biomass to total biomass. Further work is also needed to expand the coverage over non-commercial forests and woodlands, over tropical forests, and to develop satellite technology (Radar and LIDAR) for remote sensing of biomass.

Synthetic Aperture Radar (SAR) data are expected to contribute to estimating biomass. However, high resolution observation of forest by SAR has been fragmented in terms of temporal and spatial sense, and conditions of observation (incident angle, etc.) are different from one satellite to another. There is a need to build systematic, repetitive, spatially homogeneous and well coordinated global observation strategies for forest mapping by high resolution SAR.

The use of LIDAR for vegetation biomass via height determination holds great promise,[39] but to date, it has been difficult to achieve.[40] This difficulty, while real, must not discourage the efforts to achieve this important measurement.

Soil Carbon Surveys. The soil carbon pool is more than twice the size of both the atmospheric and the above-ground terrestrial carbon pools, and it is extremely sensitive to management practices. In order to characterise this pool, data are needed for both the organic layer and the mineral soil. Carbon concentrations on their own are not sufficient, since the total carbon pool is determined also by bulk density and profile depth. In addition, to understand the vulnerability of soils, it is necessary to distinguish between sub-pools of fast and slow turnover, which are linked to biological, chemical and physical mechanisms of immobilisation.

In many countries separate soil surveys are carried out that allow quantification of carbon stocks in the soil. While most of these surveys suffer from the poor quality of their soil bulk density and stone content estimates, they represent the only source of information currently available. The challenge to the carbon observing system is to ensure that the current *in situ* soil inventories are standardised, fully exploited, and significantly extended. In addition, the system must develop new soil carbon measurement techniques; it must have the flexibility to absorb new model-based approaches for estimating soil carbon, and it must provide the biophysical parameters needed by models.

Land-use Change and Fire. Two observations associated with processes critical for the terrestrial part of the carbon cycle - land-use change and disturbance - have been included as core observations in the carbon observing system. The challenge here is to employ in an operational mode satellite systems to monitor land cover changes (5-year time interval, 1 km spatial resolution), fire hot spots (daily resolution), and burned areas (monthly resolution). The land-cover change observations should also emphasise forest/non-forest transitions at higher spatial resolution (25 m).

The carbon observing system should include, as ancillary observations, improved satellite systems with adequate ground-truthing (e.g., at flux tower sites) to provide global coverage of continents on synoptic time scales (1-7 days) for biophysical quantities (LAI, FPAR, and related information such as radiation and soil moisture), in order to estimate photosynthetic activity.

Another major challenge for the carbon observing system is to scale up point measurements and construct a bottom-up continental scale estimate of the terrestrial carbon budget with higher resolution information about regional patterns within continents, over seasonal to interannual time scales. This will be achieved by increasing the density of the *in situ* measurements listed in Section 5.1.2 and by increasing the frequency of associated atmospheric sampling, combined with satellite observations.

5.2.4 Challenges in Enhancing, Extending and Optimising the *in situ* Oceanic Observing System

Some of the ocean carbon observations, such as the pCO_2 surveys, could be transferred from research mode to operational mode in the near future, with significant efforts for enhancing data inter-comparability and reducing instrument maintenance and costs (Figure 18). At present questions about the data quality from an operational system and about the release of data in real-time are slowing the conversion to operational mode. The primary longer-term challenge for developing a global-scale operational ocean observation network is the lack of accurate, robust, cost-efficient, autonomous instruments for surface and subsurface sampling of principle carbonate system components. Conducting sustained observations from dedicated research ships is an essential part of an ocean carbon research programme, but it is labour intensive and expensive. A large-scale operational ocean observation system must be largely built on autonomous instruments. Although several prototype instruments are available, much more research and development is needed to advance the technology to the state of being operational.

A second major challenge for the quantification of global air-sea fluxes is the development of robust algorithms for estimating air-sea gas exchange from easily measured parameters. It is becoming increasingly clear that gas exchange parameterisations based solely on wind speed are not sufficient to constrain the flux to within 20-30%. Additional research is needed to develop algorithms using additional or different parameters (e.g., sea surface roughness) that are more accurate. Once these algorithms have been derived, the necessary parameters need to be incorporated into the observational programme so that more accurate flux maps can be developed.

To meet this challenge, there is a need to develop satellite systems with adequate ground-truthing incorporated on ships and buoys to obtain higher ocean coverage of Sea-Surface Salinity (SSS), Sea-Surface Temperature (SST), Sea-Surface Height (SSH), wind speed, and ocean colour (60% global, over a 3-5 day timeframe). These measurements will serve to extrapolate surface pCO_2 measurements across full basins. Although many of the individual components of such a system exist, a new emphasis is required to build a coordinated system from these pieces.

Figure 18. Ship of Opportunity used to make routine pCO_2 measurements across the North Atlantic Ocean.

Third, measurements are needed to allow the attribution of the air-sea fluxes and export from the surface to deeper waters to the controlling processes. To meet this process-understanding challenge requires the development of a network of time series that measure sinking fluxes from sediment traps along with nutrients and dissolved oxygen. In addition, there is a need for large scale measurements of oxygen to determine changes in ocean stratification. Finally, we must continue the decadal basin-scale carbon and nutrient profile/inventories, which are fundamental to cross-checking model calculations and unraveling ocean processes. The planned GEOSEC II is appropriate to this need.

5.3 FILLING GAPS IN CURRENT CARBON OBSERVATION

Other gaps in knowledge hinder the development of a comprehensive observation system for the carbon cycle. While these gaps may be in areas of quantitatively smaller carbon fluxes, they are nonetheless important. For instance, lack of quantitative knowledge about these fluxes could bias the pattern of carbon fluxes and associated processes determined by assimilation procedures. Each subsection concludes with recommendations on observational elements which should be included in the overall strategy, either as ancillary observations or as data to be obtained from other observation systems (e.g., climate, atmospheric chemistry).

5.3.1 Transport through Rivers, Estuaries, and Coastal Seas

Part of the carbon fixed on land is transported to the oceans by rivers, about 1% globally, much more in some regions. Although this transport of carbon is well known in principle, it is poorly quantified. The fraction of carbon that takes this pathway varies with the type of soil and vegetation, the season and the hydrological cycle; it is also significantly modified by land management, reservoirs, and land-use practices in watersheds and river basins.

River carbon is found in both organic and inorganic forms, and it can produce substantial CO_2 and CH_4 fluxes to the atmosphere. Once in the ocean, river carbon is integrated into oceanic carbon cycle processes. Its residence time in the ocean depends on its chemico-physical form and on how far it is transported before it is exhaled back to the atmosphere or buried in sediments. It is now recognised that estuaries play a key role in outgassing substantial amounts of river carbon before it reaches the coastal waters. Transport away from the coasts varies with topography and the local oceanic currents and ranges from a few kilometres to thousands of kilometres, and from a few hours to few hundred years.

In addition to river carbon, the specific topography of the coastal ocean leads to enhanced vertical ocean mixing and marine productivity, both of which affect the air-sea flux of carbon in ways that are highly heterogeneous and poorly quantified. Satellite data of ocean colour show that marine biomass is 10 to 100 times larger along the coasts than in the open ocean (Figure 19). Such information for the air-sea flux of carbon in the coastal zones cannot yet be retrieved. River transport of nutrients (N, P, Si) into ocean waters can also have a substantial impact on the coastal ocean carbon cycle. Eutrophication has been recognised for years but its effect on the marine carbon cycle is still poorly understood.

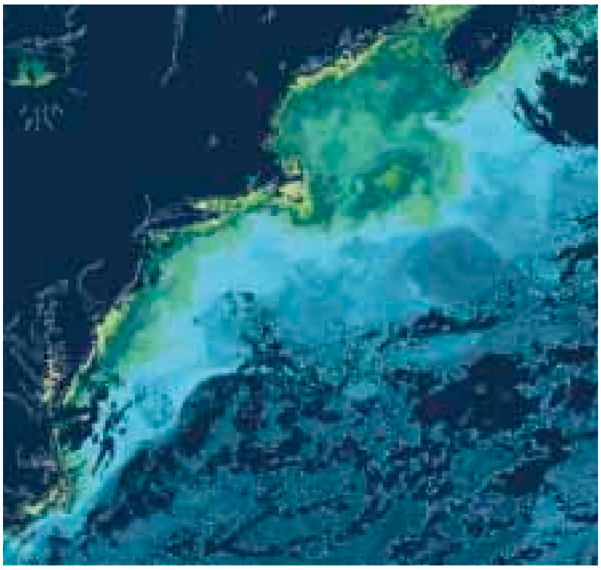

Figure 19. Ocean colour pattern off the east coast of the United States in spring (MODIS image).

It is important to compile, update, and make available existing global databases of riverine dissolved carbon and nutrient transports. In parallel, a high priority is to develop gridded erosion models to spatially allocate the source of the riverine dissolved and particulate organic carbon, and to account for sediment burial in reservoirs and coastal shelves. Quantification of erosion losses into sediments and onto terrestrial landscape positions also needs to be carried out. Similarly, quantification of the transport of carbon off the continental shelves into the open ocean needs to be determined. The IGBP-LOICZ project is undertaking a global-scale survey of biogeochemical budgets, including carbon emission and sequestration, based on a standardised methodology. A critical next step in the development of the coastal zone component of the carbon observing system is to determine whether the LOICZ budgeting projects should be moved from the research to the operational mode.

5.3.2 Transport of Wood and Food Products via Trade Circuits

Harvest, trade and utilisation of food and wood products transports large amounts of carbon away from the ecosystems that produced them. The carbon is respired back to the atmosphere everywhere humans process and use it. The amount of carbon harvested from croplands and forests is roughly 2-3 Gt C y^{-1} globally, an amount which partly goes into international trade circuits.

Lateral transports of wood and food products have not been well quantified to date. The decay of harvested wood products in pools of different longevities further bypasses the natural return to the atmosphere by respiration and disturbances, but it is not yet clear if it acts to accelerate or to slow down the turnover of carbon fixed by forests. Globally, carbon displacement by products/trade is important but on a regional basis or landscape basis, it may be an even more significant component of the terrestrial carbon balance. The magnitude of this transport varies with the type of transfer and geographic region. Within the context of the carbon observing system, standardised methodologies are required to process agricultural and forestry data[41] to obtain credible estimates of the magnitude and temporal trends of lateral anthropogenic transfers, including imports and exports of products and packing material. Such methods should aim at producing gridded estimates of the carbon fluxes involved in the processing, trade, and consumption of wood and food products.

5.3.3 Non-CO_2 Components of Ecosystem Respiration

The fluxes of non-CO_2 carbon gases such as CO, CH_4 and VOCs from terrestrial ecosystems, sometimes called "non-CO_2 respiration", must be quantified in order to fully close the carbon budget for an ecosystem, given that atmospheric methods (eddy-covariance flux towers, atmospheric inversions) in general measure CO_2 fluxes only. In some cases, a significant fraction of CO_2 withdrawn from the atmosphere is released back to the atmosphere in the form of non-CO_2 gases (up to 30% in some ecosystems), creating a local imbalance in the CO_2 budget. Globally, the oxidation of these compounds amounts to a production of 1.3 Gt C y^{-1} in the atmosphere. Non-CO_2 compounds produced by terrestrial (and marine) ecosystems may be of sufficiently short lifetime to be quickly transformed into CO_2 before they reach an atmospheric background station, but this is not the case for CO and CH_4, which have mean atmospheric lifetimes of many years. Eddy covariance techniques measuring CO_2 simply miss these fluxes.

The emission, transport and chemical destruction of non-CO_2 carbon compounds is of primary interest to the Integrated Global Atmospheric Chemistry Observation (IGACO) theme. In practice at the scale of eddy flux towers, it is most efficient to measure simultaneously the emissions of CO_2 and of non-CO_2 carbon gases, either directly with micrometeorological methods or indirectly by models driven by ecological process and meteorological data. At the global scale of atmospheric inversions, state-of-the-art atmospheric chemistry transport models are required to compute the atmospheric production of CO_2 from its chemical precursors and to account for this process in the inverse retrieval of fluxes. Thus, close collaboration between the carbon observing system and IGACO is essential.

An important challenge to the atmospheric chemistry observing system is to develop satellite observation techniques to deliver methane-related products: in particular, the spatial and temporal distribution of wetlands globally and global soil moisture measurements.

5.3.4 Nutrient Fluxes to Ecosystems

There is increasing recognition of the key role of nutrients (both stores and fluxes) in constraining both terrestrial and marine carbon fluxes and their future evolution. As data is acquired on core carbon cycle variables, parallel data on nutrients, particularly N, P, Si and Fe, will be urgently needed and is important for the Global Carbon Project to develop better process-level understanding of carbon cycle dynamics. This ancillary data will include production rates (wind and water erosion, fertilisation, fixation), changes in soil stores, export to atmosphere and subsequent deposition on land and oceans. There are substantial anthropogenic nitrogen and phosphorus loadings to groundwater and river systems through leaching from agricultural fertiliser. On the other hand, silicate may be retained in freshwater systems due to building of dams and large water reservoirs (silicate is needed by diatoms, which account for a substantial part of oceanic biological export production of carbon). Anthropogenic atmospheric nitrogen (NH_4^+) deposition to the coastal seas can be of equal importance quantitatively as the direct input through rivers.

5.3.5 Geo-referenced Fossil Fuel Emissions

To understand the perturbed global carbon cycle, it is important to improve the observation of the location and timing of fossil fuel emissions. Present data on fossil fuel emissions are typically obtained from energy production statistics and aggregated on an annual basis at the scale of individual countries;[42] little information is presently available of the detailed space and time patterns of fossil CO_2 emissions. In the developing world, fossil fuel emissions are becoming an increasingly important fraction of total carbon emissions, but emissions of CO_2 associated with more traditional fuel types (e.g., with biomass fuel) are poorly mapped.

The carbon observing system must measure fossil emissions in the major industrialised areas of the world at the appropriate spatial and temporal scales to be utilised in atmospheric transport models and inversion studies. A realistic requirement is a spatial scale on the order of 10 km or better and temporal resolution that accounts realistically for fossil fuel CO_2 release patterns, such as daily traffic peaks or the enhanced emission from power plants during cold weather episodes or heat waves. Similar efforts to map biomass fuel emissions should be undertaken.

5.4 IMPROVING DATA PRODUCTS AND DELIVERY TO USERS

The ultimate goal of the carbon observing system is to generate data products that are of value for the user communities. Raw observations are rarely adequate on their own. To create usable products, *in situ* measurements from a variety of sources need to be integrated with remote-sensing observations within a modelling framework. To achieve this, a major challenge is to collect, process and harmonise *in situ* data from diverse sources. At present problems with *in situ* data include, among others, inconsistent parameter definitions, incomplete data, differing spatial and temporal scales and sampling bias in measurements.

One issue is the question of data availability when there is an intersection with national policy, in particular for 200 miles coastal zone, forestry, and fossil-CO_2 emissions. Other issues include the delivery of *in situ* measurements to models. Some *in situ* measurements are infrequent or require laboratory processing or tedious field work, and would thus only enter into an assimilation procedure once every year or so, perhaps to improve the retrospective analysis of carbon fluxes and pools. Some other *in situ* observations on the other hand, such as pCO_2 on ships of opportunity, terrestrial ecosystem fluxes, or atmospheric concentrations, can be transferred in real time to data centres and delivered to an operational procedure to now-cast carbon fluxes, much in the same way as current meteorological observations produce weather now-casts.

6.1 INTEGRATING ACROSS SCALES

Today, carbon observation networks have sparse data coverage, but they have reached a sufficient stage of maturity so that regional estimates of fluxes and other carbon quantities can be set as a feasible objective. Science communities are well established for themes such as eddy covariance flux towers, atmospheric networks, or ocean pCO_2 mapping.

Organised, globally oriented networks exist for flux towers, atmospheric concentrations, soil and biomass surveys, ecological studies, and ocean pCO_2, but these different methods all operate at different spatial and temporal scales. Uncertainties in either their upscaling or downscaling prevent us from delivering quantitative global understanding of carbon sources and sinks at the regional scale. To reduce uncertainties in an objective manner, we need strong integration across scales (Figures 20, 21), based on modelling schemes for model-data fusion or data assimilation, which can include observation of different characteristics. In the ocean, the intermediate and deep oceans have to be included as these reservoirs are flushed fairly quickly - 1000 - 2000 years - on a geological time scale. The entire marine system must be considered for any kind of overall budgeting.

Data integration should proceed from the merging, synthesis, and eventual the fusion of carbon observations within process oriented carbon models. It will

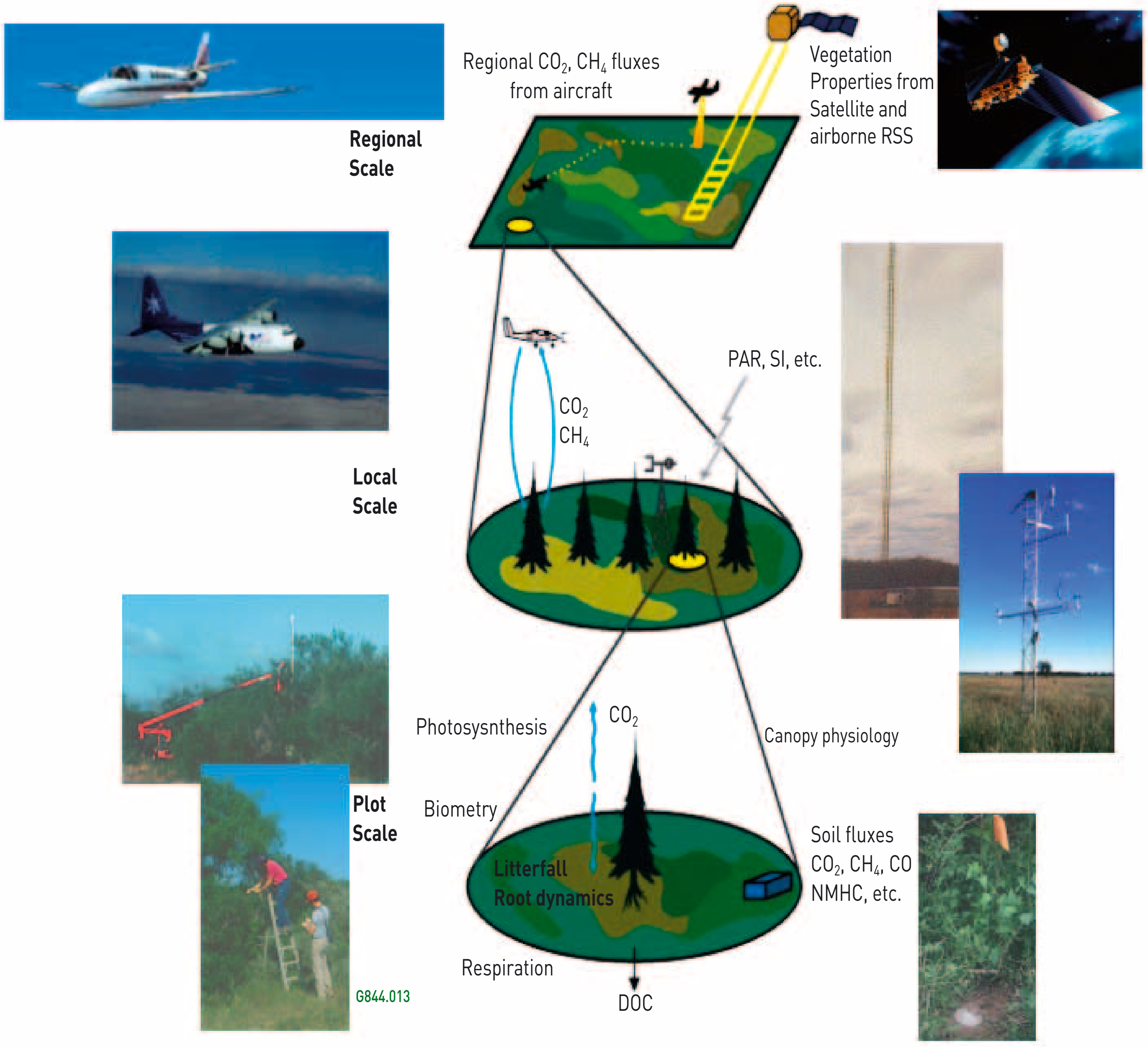

Figure 20. Example of integration across scales from local to regional in up-scaling terrestrial observations.

require comprehensive advanced carbon cycle data assimilation models, which are expected to analyse large amounts of data and diagnose on a routine basis carbon quantities and to provide error diagnostics. Given the strong carbon-climate interactions, it is most likely that numerical weather prediction models, fitted with specific terrestrial modules to compute carbon cycling, will provide the best framework to assimilate terrestrial and atmospheric measurements. Similarly, operational oceanography models that work at higher resolution than current ocean carbon models should be appropriately computing the biogeochemical state of the ocean and the relevant nutrients and carbon fluxes. Ultimately, a global assimilation in full ocean-atmosphere-land carbon-climate is required jointly for physical and biogeochemical variables. This approach will both improve hindcasts and forecasts of weather, climate, and the carbon cycle.

Remote sensing products ultimately will deliver several orders of magnitude more information than *in situ* measurements. However, including all types of data within a single assimilation procedure may create the risk that the optimal solution would be excessively dependent on potential biases of remote sensing products and/or the possible biases introduced by the likely heterogeneous distribution of *in situ* observations. In order to avoid this situation, *in situ* data may be kept aside as precious sources of independent quality assessment in the carbon cycle data assimilation system. It should also be recognised that a variety of different biogeochemical models based on distinct hypothesis should be used in parallel, rather than one single model.

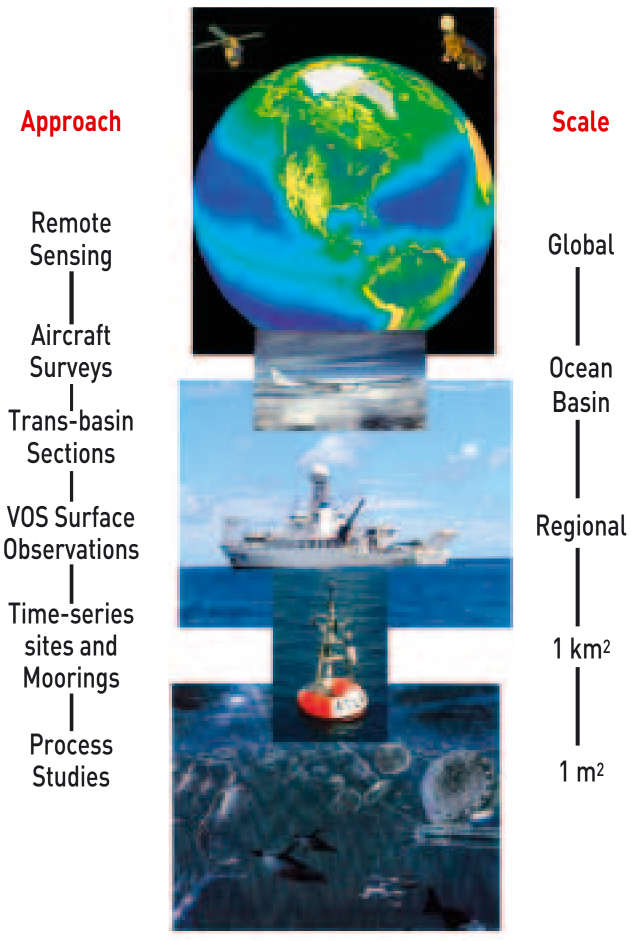

Figure 21. Integration across scales for ocean carbon observations.

The relevant scale at which it is desirable to quantify fluxes from a global perspective is typically 10-50 km with weekly resolution. Over land, climate and weather patterns acting on carbon fluxes at 10 km scales can be analysed from numerical weather analysis with input data from carbon cycle models. Over the ocean, at the scale of 50 km, meso-scale eddies can be resolved in operational oceanography models. Carbon processes partly operate differently at even smaller scales, depending on topography, ecosystem distributions, and anthropogenic land use patterns. However, on timescales of up to a few years they show a remarkable degree of coherency over larger scales, due to the predominantly similar temporal response to climate and weather.

6.2 TOWARDS A MULTIPLE CONSTRAINT ASSIMILATION OF CARBON CYCLE OBSERVATIONS

Process modelling of the carbon cycle has advanced significantly. Ocean biogeochemical models have been developed and are increasingly being tested[43] and developed using oceanographic process data, time series measurements, and satellite observations including altimetry, sea surface temperature, and ocean colour observations. Land surface-physical climate models are at an advanced stage of development and are being coupled to land carbon-nitrogen models for vegetation and soils. Longer-term controls over the carbon cycle such as natural disturbance and land use are being added to models as global land cover and land-cover change data improve. Several experiments have been done using coupled carbon-climate models.

In this context, multiple-constraint data assimilation[44] techniques are of particular importance in exploiting observations to improve our understanding of the global carbon cycle and concurrently our ability to express this understanding in both diagnostic and prognostic models (See also the Tables 9.4 and 9.5 in Section 9 of this report). The essence of the approach is to use the multiple kinds of measurements to constrain model parameters to optimal values, and then to infer complete space-time distributions of carbon stores and fluxes (or other sought variables). The inference is done by using the model to predict the observed variables at locations where measurements are available, and then finding the set of parameter choices that minimises the overall departure between model predictions and measurements.

The multiple-constraint data assimilation approach is related to, but differs from, current atmospheric inverse methods in which surface source-sink distributions at large scales are determined from measured concentration distributions alone. Key differences include: (1) atmospheric inversions are restricted to concentration measurements, whereas, multiple constraints can accommodate data of any kind predictable by the generic model; (2) atmospheric inversions infer sources and sinks directly from concentration measurements, without the need to infer an intermediate set of parameters; (3) the inverse problem generally exploits linear expressions of atmospheric transport and mixing; whereas in multiple constraint, the problem formally allows nonlinear forward expressions; and (4) the multiple constraint approach offers the possibility of accessing multiple sources of constraining data with vastly different spatial, temporal, and process resolutions, thus producing more constrained predictions.

A multiple constraint approach is potentially falsifiable by confronting the model with a diverse range of data sources. Failure to accommodate all data streams simultaneously with a common parameter set constitutes a means of model falsification, thus preserving the scientific integrity of the approach. In a similar vein, the data assimilation, multiple constraint approach 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 return 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, allowing preliminary tests of experimental designs.

Fortunately, data assimilation schemes for a number of specific processes have been developed. Ocean carbon data have been used in assimilation schemes to estimate oceanic carbon fluxes. There are initial efforts to assimilate CO_2 flux observations into terrestrial process models, and approaches are emerging as to how to assimilate multiple process observations simultaneously. However, the state-of-the-art is still relatively young, and significant progress is needed in order to exploit fully the data from an integrated global carbon observing system.

There are several further challenges (see also Section 6.3), including the need for high dimensional, efficient methods. Other challenges are found in the current state of carbon modelling. For instance, in order to assimilate and integrate a wide range of different observations, the models must include state variables and parameters related to the observations. At present, carbon cycle models do not include the full range of processes required to link to the array of emerging observations. A high priority of the Global Carbon Project is to develop the models required for multiple constraint approaches.

There is currently no unified model (and likewise no single family of observations), which would enable us to execute successful carbon data assimilation. Given the diversity of scales, it is possible that a suite or a hierarchy of models nested one within each other may be needed to capture properly the variability inherent in some observations[45] (Figure 22). However, the overarching goal of obtaining a global picture of the carbon cycle should be kept in mind, which favours the choice of models that are sufficiently generic in their parameterisations and input variable requirements, and yet based on state-of-the-art mechanistic understanding (see Section 9). We summarise below some of these scientific challenges specific to the assimilation of carbon observations:

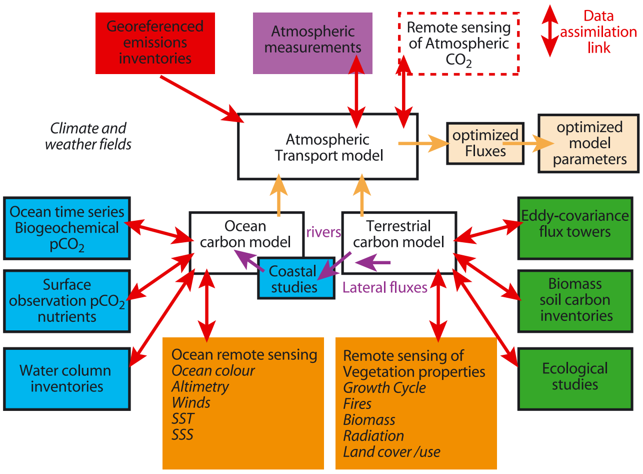

Figure 22. Illustrative information flow in a global carbon cycle data assimilation system.

- Develop the ability to accommodate vast amounts of disparate satellite observations. To best do so, biogeochemical models need to be fitted with radiative transfer modules in order to enable them to simulate state variables (e.g., reflectances), which are as close as possible to what the sensors can actually measure. A carbon assimilation system must therefore be dimensioned to digest massive amounts of satellite data, both in terms of variational requirements (given nonlinearities in the models) and in terms of data processing and storage.
- Account for the uneven distribution of *in situ* measurements. Some regions of the world, where intensive sampling programs are put in place, are expected to have much better observational coverage than others. Global carbon data integration should thus address the issue of bridging the gap between data rich and data poor areas that should eventually be linked to the atmospheric growth rate and to our ability to mitigate it. At present, we live in a data-poor world for carbon cycle *in situ* observations, and most of the observations are operated on a research basis. But we see the onset of the development of denser networks with regional emphasis over, for instance, North America, Europe, Japan, Siberia, and the Amazon. It is thus key to the success of a carbon cycle data assimilation system to plan at an early stage improved data calibration, harmonisation, and quality insurance procedures which will ensure that *in situ* observations produced by different networks are fully compatible with each other.
- Account for the coupling of weather and climate with carbon cycling. Over land, optimising photosynthesis will likely alter the latent and sensible heat fluxes, which in turn feed back on the boundary layer transport of atmospheric CO_2. It is thus inevitable that the most realistic manner to assimilate carbon observations is to insert carbon cycling models within numerical weather prediction models, and beyond in coupled ocean-atmosphere-land climate and Earth System models. This will become crucial when remote sensing of the atmospheric CO_2 concentration becomes operational, because concentration, temperature, and humidity profiles are intimately linked in the atmospheric radiative transfer.
- Develop the ability to retrospectively analyse the available observations at regular intervals (roughly every season). Carbon data assimilation is different in that respect from meteorology where the atmospheric state keeps no memory beyond a few days. In the global carbon cycle, several processes are expressed on longer time scales.

6.3 PRINCIPLE REQUIREMENTS FOR ASSIMILATING CARBON CYCLE OBSERVATIONS

The recent *Carbon Data Assimilation Report*[46] (See Box 4) noted several research gaps, challenges, and opportunities including:

- Developing component and coupled carbon cycle models (generally from existing carbon process models) that address the requirements and objectives of an assimilation system for state, flux, or parameter estimation;
- Developing observational operators to link models and observables in assimilation systems;
- Developing more efficient adjoint operators for well-validated transport models with cost functions computed from potential satellite observations; coupling these adjoint operators into an efficient optimisation algorithm; and developing algorithms for generating efficiently parts of the error covariance matrix.
- Evaluating better measurement bias from instrumental, algorithmic or sampling error. Assimilation models that will integrate multiple data types will be more vulnerable to bias than inverse models that

Box 4: Excerpt from Carbon Data Assimilation Report [46]

"Observations have not been assembled to study the carbon cycle as an integrated whole. Observing and understanding a single reservoir (land, atmosphere, or oceans) does not translate to a concordant understanding of multiple reservoirs interacting within the coupled system. In order to understand the patterns and variability of sources and sinks of carbon dioxide, it is necessary to integrate together data about the land, atmosphere, oceans, and fossil fuels. Analyzing the carbon system as a whole requires unprecedented integration of information, far exceeding today's modeling and data analysis techniques.

Data assimilation is a family of techniques for improving estimates of geophysical quantities combining models and observations. Although best known as a tool in weather forecasting, data assimilation is also used in analysis of complex data sets, and in estimation of parameters in models. Data assimilation is particularly valuable in bringing disparate observations to bear on a common problem to achieve the best analysis, consistent with all the available information. Data assimilation techniques can play a major role in carbon cycle science, producing robust & consistent estimates of contemporary sources and sinks by integrating atmospheric, terrestrial and oceanic data together into a common analysis framework. The goal of the data assimilation program is to characterize the variability of CO_2 sources and sinks, aid in confirming the mechanisms causing sources and sinks, and, ultimately, increase the credibility of prediction of the carbon system."

have largely relied on data from surface concentration networks. The space/time variations in biases from different measurements must be defined well before use in assimilation systems.

- Advancing land and ocean process-driven and data-driven models (Table 9.5). As noted, the global carbon cycle is regulated by long-term processes (e.g., deep ocean circulation, disturbance and recovery of land vegetation) varying over periods much longer than those of most observational records. Assimilation techniques for the carbon cycle must be developed to account for this "background" in order to provide mechanistic understanding of the present-day variability of fluxes and storage.
- Understanding basic atmospheric mixing processes, especially PBL (Planetary Boundary Layer) mixing and unresolved convection, which have a major impact on CO_2 distributions and must be understood to estimate surface fluxes from atmospheric observations. Additional analysis, collaboration with physical meteorologists and possibly new field studies are required to improve models of these processes for coupled surface-atmosphere assimilation systems.
- Geographically resolving fossil fuel emissions, which have generally been defined in carbon cycle studies from data sets with low spatial and temporal resolution. Techniques using atmospheric tracers of fossil fuel combustion and improved socio-economic data are needed to understand fossil emissions in new higher resolution assimilation schemes. These techniques can also help to quantify biomass-burning fluxes. The observational need regarding fossil fuels has been noted in Section 5.3.5 of this report.

6 THE INTEGRATION CHALLENGE

The establishment of a systematic observation system for the global carbon cycle is a complex undertaking, primarily because the complexity of the carbon cycle intersects with political and economic structures (e.g., energy systems) that have been established at international as well as national levels. An effective and efficient framework for global carbon cycle observation must rely on several components, most of which have multiple clients and are sponsored for different reasons. It is therefore essential that the design and implementation of the observing system as well as those of international and national carbon research programmes are clearly linked with each other and to the policymaking community charged with meeting the carbon/climate challenge.

New and stable institutional arrangements are needed in order to establish and maintain these linkages so that a reliable system of observations on the global carbon cycle can be built. A strong and effective partnership with the Global Carbon Project is particularly important to link research and operational observations; to ensure that data produced by the carbon observing system is fully integrated into model development, analysis and synthesis; and to develop effective protocols for information management.

A particular institutional challenge for the carbon observing system is to ensure that the component observing systems are coordinated, internally consistent and complementary with respect to space, time and methodological protocol. For instance, there is a need for coordination between the eddy covariance flux tower and atmospheric flask sampling networks. By improving the calibration of atmospheric CO_2 measurements at the top of eddy covariance flux towers, these data can be used in atmospheric inversions. Similarly, improving the accuracy of CO_2 concentration measurements onboard ships of opportunity measuring ΔpCO_2 will help atmospheric methods to improve air-sea flux estimates.

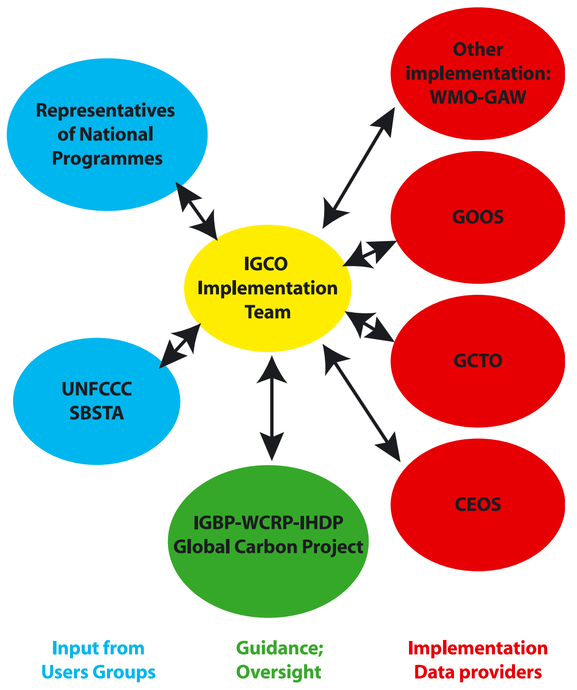

Figure 23. Institutional links and implementation of a coordinated system of global carbon observations

A large challenge to ocean carbon measurement is to coordinate major initiatives involving ship-based, satellite-based, and land-based observation efforts. These are often large-scale, expensive endeavours undertaken with national or regional-based funding. There are numerous opportunities for benefiting from economies of scale arising from international planning and coordination in this realm. For example, in terms of ship-based observations of pCO_2, the CO_2 Panel of the Intergovernmental Oceanographic Commission (IOC[47]) and Scientific Committee on Oceanic Research (SCOR[48]) is collaborating with the Global Carbon Project to ensure the most effective re-occupation of the WOCE hydrograph sections over the coming years.

Thus, it is clear that the carbon observing system must emphasise coordination and collaboration with existing activities where these are positioned to generate the needed input or output products; use the best available scientific expertise in the generation of new products intended to fill gaps; and rely on the IGCO Implementation Team to monitor the implementation process.

Figure 23 presents a proposed framework for guiding the carbon observing system. This institutional structure is designed to meet the challenges outlined above by formation of an IGCO Implementation Team that will be guided by input from its primary user groups and simultaneously interact strongly with the data providers. A key linkage is between the IGCO Implementation Team, CEOS, and the global observing systems (GXOS) that include *in situ* measuring components. Each of these organisations will be responsible for a component(s) of the carbon observing system, but the system will not be effective without coordination between the components. Thus, an important task of the IGCO Implementation Team is to monitor the integration of component activities.

Equally important is the interaction of the IGCO Implementation Team with the user groups. The policymakers are represented at two levels - representatives of the national level policy community and at the level of the UN Framework Convention on Climate Change through their Subsidiary Body on Scientific and Technological Advice (SBSTA). Given the tight coupling between operational observation, research observation and the scientific research itself, the carbon observing system must have a close working relationship with the Global Carbon Project. This can best be achieved through significant cross-membership of the IGCO Implementation Team and the GCP Scientific Steering Committee; joint activities and workshops; and co-publication of major reports and papers that have both observation and research aspects.

There are two additional organisational challenges towards building the carbon observing system from national and regional components: (i) continuity of observations and (ii) research and technology development in support of the observing system.

A major issue confronting the carbon observing system is to ensure the continuity of the core measurements, at a minimum. Satellite observations are coordinated within CEOS, a partner of IGOS; however, atmospheric *in situ* observations (e.g., trace gas concentrations) are linked via the World Meterological Organization (WMO)[49]to national agencies. Ocean observations are coordinated through the Global Ocean Observing System (GOOS)[50] in collaboration with national agencies under the auspices of the Intergovernmental Oceanographic Commission (IOC)[51] of UNESCO. For terrestrial ecosystems, the links between the national funding and implementation agencies and the international community are currently weak. Internationally, the Global Terrestrial Observing System (GTOS)[52] and its sponsors (particularly the Food and Agriculture Organization (FAO),[53] the United Nations Environment Programme (UNEP),[54] and WMO) have national points of contact, but even at the national level, the observation programmes and their funding are not typically coordinated centrally.

There is a unique opportunity provided by the recent Earth Observation Summit[55], held in July 2003 in Washington DC, to gain commitments for continuity and expansion in core carbon observations from a broad range of organisations, each operating in its own particular institutional setting. In this context, the follow-on summits in Japan and Europe are particularly important.

Improvements beyond an initial observing system described herein require vigorous support for research development in several areas. The most important of these are: (i) improved and new instrumentation for *in situ* and satellite observations of atmospheric CO_2; (ii) network enhancement and design optimisation studies, in turn requiring the capability to evaluate trade-offs in performance based on various hypothetical improvements in the observations; and (iii) development of models and algorithms that are able to more effectively invert or assimilate raw observations to produce global carbon flux fields. Finally, and most importantly, observations (particularly space-based) must be *readily available* to the broad, international scientific community.

Requirements for a Coordinated System of Integrated Global Carbon Observations by 2011

- The global atmospheric CO_2 network should be in place, both on land and oceans, including aircraft profiles, for a continuous *in situ* CO_2 analysis with an accuracy of 0.2 ppmv and with a typical spatial resolution of 5° by 5° grid over land and 10° by 10° grid over the oceans.
- The eddy covariance tower network has been expanded with new towers and inter-calibrated. It operates for complex and disturbed ecosystems, and across gradients of succession, stand age, and land-use intensity.
- Global soil carbon content is updated every 10 years on a 1° by 1° grid. Forest biomass changes are updated every 5 years and the data from various national institutions are available on a geo-referenced basis.
- On ocean surface basin-scale, an operational system of extensive *in situ* sampling of surface pCO_2 levels has been implemented.
- Basin-scale *in situ* measurements of dissolved and particulate organic and inorganic carbon in the ocean, with full column sampling of carbon system parameters, are being made.
- Land satellite products are evaluated and are ready to be used in process-based terrestrial ecosystems models.
- Ocean satellite products are evaluated and ready to be assimilated in operational oceanography models fitted with carbon cycle capabilities.
- New satellites are now in place for measuring column density of CO_2 and other carbon compounds.
- The modelling community is ready to ingest these data in the models to determine precisely the sources and sinks of carbon and the future evolution of carbon related compounds in the atmosphere.

The roadmap towards those objectives is described below:

Phase 1: Preparation (2003-2006)

Institutional Actions

- Approval of IGCO Theme Report by IGOS-P.
- Improved coordination among existing international programmes and components, particularly GCP and IGCO.
- Beginning convergence of current regional studies through joint workshops (e.g., CARBOEUROPE, NACP...) to a coordinated programme within the framework of the Global Carbon Project.
- Involvement of operational satellite agencies such as NOAA, EUMETSAT in these workshops/studies from the very beginning.

Synthesis of Existing Data

- Organise workshops to define requirements and initiate collection of geo-referenced information dealing with:
  - – Georeferenced fossil fuel CO_2 emission maps,
  - – Lateral movement of C by fluvial transport,
  - – Lateral movement of C by trade of wood and food products, and
  - – Non-CO_2 gas emissions (e.g., CH_4, CO, VOCs) and their contribution to regional budgets in coordination with IGACO Theme Team.

Algorithms and Model Developments

- Establish a strategic plan for a global CO_2 satellite observation system combining existing OCO mission, and future Japanese (GOSAT) and European projects.
- Conduct re-analysis of the NOAA-TOVS HiRs data following pioneer work by Chédin and co-workers (Tables 9.1 and 9.4).
- Expand efforts to retrieve CO_2 distribution from existing satellites, such as AIRS, SCIAMACHY, IASI and TES (Tables 9.1 and 9.4).
- Develop algorithms to map from land observing satellites (e.g., Landsat, SPOT, ALOS, NPOESS) the global distribution and temporal variability of: forest-no-forest information; global land use; biomass information; seasonal cycle of vegetation and fires; and wetland cover (Tables 9.1 and 9.3).
- Develop prototype carbon cycle data assimilation models (Table 9.5).

In Situ Networks Development

- Increase atmospheric measurement networks, building upon regional initiatives (CARBOEUROPE, NACP, Siberian projects, LBA). An increase of 50% of the number of available measurements is a feasible target (Table 9.4).
- Increase terrestrial ecosystem networks, in particular flux towers and soil/biomass carbon surveys especially in the tropics. An increase of 50% of the number of available measurements is a feasible target (Table 9.3).
- Increase coverage of air-sea flux measurements and ocean interior surveys such as the planned

GEOSECS II; US and EU programmes in the Atlantic, Japanese and US in the North Pacific; and the various planned surveys in the Southern Ocean (Table 9.2).

- Develop measurements of atmospheric CO_2 on eddy covariance towers (Table 9.4).

Methodological Developments – Network Design Studies

- Define a methodology so that global soil carbon content can be updated every 10 years on a 1° by 1° grid (Table 9.3).
- Define a methodology, including enhanced geo-referenced data availability, so that forest biomass inventories can be updated every 5 years as components of the observing system. (Table 9.3).
- Design a global network of ecological, bio-optical, and biogeochemical observations, as the basis for calibrating, validating, and adding value to remotely sensed ocean colour data. Products will be the developed through the Ocean Biology Project initiated by CEOS and presently coordinated by the International Ocean Colour Co-ordinating Group (IOCCG). (Tables 9.1 and 9.2).
- Evaluate the current capabilities to derive the air-sea gas transfer velocity distribution from satellite observed surface roughness (scatterometer and altimeter). Process-level work needed particularly for high and low wind speed, and bubble dominated environments. (Table 9.1).
- Initiate technology development in the area of Lidars for operational satellites, which may provide a complete profile of atmospheric CO_2 and other carbon molecules. (Table 9.1).

Phase 2: Demonstration (2006-2010)

Institutional Actions

Assessment of the status of global carbon observations and revision of data requirements for:

- Satellite-derived atmospheric CO_2 measurements, and their impact in obtaining better flux output products;
- Gradual improvements of input satellite data products for land and ocean (point and gridded) and of models;
- Gradual improvement of point and gridded data products of lateral carbon flows and emissions of fossil fuel CO_2;
- Improvment of global *in situ* networks;
- Production of new inventory data flux estimates;
- Development of data assimilation methods of carbon cycle observations;
- Development of biomass and soil carbon surveys to obtain full coverage of forest ecosystems, particularly in the tropics.

In Situ Networks Development

- Deployment of CO_2 *in situ* measurements on several passenger aircraft;
- Use of *in situ* network and aircraft campaigns for validation of new satellite data of atmospheric CO_2 columns and possibly vertical profiles obtained particularly from OCO AIRS, SCIAMACHY and IASI;
- Pursuit of methods and sensor development for eddy covariance flux measurements;
- Development of biomass and soil carbon surveys to obtain full coverage of forest ecosystems, particularly in the tropics:
- Deployment of new sensors for ocean carbonate system and nutrient observations.

Methodological Developments – Network Design Studies

- Comparison and systematic evaluation of carbon cycle data assimilation models;
- End-to-end check on the data system so that it fulfills the need of the international modelling community.

Table 9.1 Space observations related to the Integrated Global Carbon Observations

<table>
<tr><th>Component of Surface-Atmosphere Carbon Flux</th><th>Global Observation Required</th><th colspan="4">Existing, Approved, or Proposed Instruments / Missions</th></tr>
<tr><th></th><th></th><th>Historic</th><th>Current and Near-term</th><th>Through 2010</th><th>Future</th></tr>
<tr><td>Surface fluxes inverted from atmospheric CO_2 measurements</td><td>Atmospheric CO_2 variability</td><td>HIRS-2</td><td>LWIR: AIRS, IASI
SWIR: SCIAMACHY</td><td>OCO
GOSAT</td><td>Active CO_2 sensors</td></tr>
<tr><td rowspan="2">Attribution of surface fluxes to combustion processes</td><td>Atmospheric CO variability</td><td></td><td>MOPITT SCIAMACHY</td><td>TES</td><td></td></tr>
<tr><td>Atmospheric BC aerosols variability</td><td>TOMS
POLDER-I</td><td></td><td>CALIPSO
POLDER-II
APS</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="5">Land-atmosphere CO_2 flux and terrestrial carbon processes</td><td rowspan="5">Land cover type
Land cover change
Burned areas</td><td colspan="2">AVHRR</td><td></td><td></td></tr>
<tr><td colspan="2">LandSat1-7</td><td></td><td></td></tr>
<tr><td colspan="3">SPOT1-5</td><td></td></tr>
<tr><td rowspan="2">AVNIR</td><td rowspan="2">MODIS
GLI
ASTER
MERIS
AVNIR-2</td><td>LDCM</td><td></td></tr>
<tr><td>NPOES
VIIRS
Prep. Prog.</td><td>NPOES
VIIRS</td></tr>
<tr><td rowspan="7"></td><td rowspan="7">Biophysical products:
LAI, FAPAR, Albedo...
Vegetation Productivity</td><td colspan="2">AVHRR</td><td></td><td></td></tr>
<tr><td colspan="2">Landsat 1-7</td><td></td><td></td></tr>
<tr><td rowspan="5"></td><td>MERIS
MODIS
SeaWIFS</td><td>LDCM
ALOS
ASTER</td><td></td></tr>
<tr><td colspan="2">SPOT-4-5 (Vegetation/HRG)</td><td></td></tr>
<tr><td rowspan="3"></td><td>METOP-1-2-3...</td><td></td></tr>
<tr><td>MSG/SEVIRI</td><td></td></tr>
<tr><td>NPOES
VIIRS
Prep. Prog.</td><td>NPOES
VIIRS</td></tr>
<tr><td></td><td>Vegetation architecture or profile</td><td></td><td>MISR</td><td></td><td></td></tr>
<tr><td rowspan="3"></td><td rowspan="3">Fire hotspots</td><td rowspan="3"></td><td>TRMM
MODIS
GLI
ASTER</td><td></td><td></td></tr>
<tr><td colspan="2">AATSR</td><td rowspan="2">NPOES
VIIRS</td></tr>
<tr><td colspan="2">ATSR</td></tr>
<tr><td rowspan="4"></td><td rowspan="4">Biomass and regrowth</td><td colspan="2">AVHRR</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="2">SPOT
JERS-1</td></tr>
<tr><td colspan="2">ERS-1, ERS-2</td></tr>
<tr><td></td><td>ASAR
RADARSAT</td><td>ALOS</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Climate variables driving land-atmosphere fluxes</td><td>Soil moisture regime (surface and deep)</td><td>SSM I</td><td>ASAR</td><td>SMOS</td><td>NPOES
CMIS</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">Precipitation</td><td rowspan="2"></td><td rowspan="2">TRMM</td><td></td><td></td></tr>
<tr><td colspan="2">GPM, Follow–on missions, geosynchronous</td></tr>
<tr><td rowspan="4"></td><td rowspan="4">Cloud cover</td><td rowspan="4">AVHRR</td><td rowspan="4">MODIS
CERES</td><td>CloudSat</td><td></td></tr>
<tr><td>NPOES Prep Prog.</td><td>NPOES</td></tr>
<tr><td colspan="2">METOP-1-2-3</td></tr>
<tr><td colspan="2">MSG</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Other Contributing Remote Sensors	Potential New Missions	Spatial Sampling Frequency	Temporal Sampling Frequency
IIP (FPI and LIDAR)	Active CO_2 measurements using Laser techniques	1-50 km	Daily *
		25 km	Daily *
NPOES CrIs		1-50 km	Daily *
AVIRIS AIRSAR	Synergistic multispectral optical + multifrequency polarimetric radar	30 m and 250-1.000 m	weekly
AIRSAR	Synergistic multispectral optical, radar missions Hyperspectral Mission e.g. SPECTRA	25-1000 m	weekly
NPOES CrIs			
AIRSAR LVIS SLICER	VCL Wide-swath LIDAR + interferometric radar	25 - 250 m	Annually
			Daily
	VCL, Wide-swath LIDAR + low-frequency polarimetric radar	50 – 100 m	Annually
AIRSAR LVIS SLICER			
AIRSAR, IIP (UHF / VHF radar)	Higher-resolution radiometers, lower-frequency radars	5-50 km	3-day for surface, 10-day for depth
DPR TRMM		5 km	Daily
	Follow–on missions, geosynchronous	1 km	Daily

<table>
<tr><th rowspan="2">Component of Surface – Atmosphere Carbon flux</th><th rowspan="2">Global Observation Required</th><th colspan="4">Existing, Approved, or Proposed Instruments / Missions</th></tr>
<tr><th>Historic</th><th>Present and Near – term</th><th>Through 2010</th><th>future</th></tr>
<tr><td>Land–atmosphere CH_4 flux</td><td>Atmospheric CH_4 variability</td><td>IMG</td><td>MOPITT
AIRS
SCIAMACHY</td><td>TES</td><td></td></tr>
<tr><td></td><td>Biomass burning CH_4 emissions</td><td>See fire spots and burned areas</td><td></td><td></td><td></td></tr>
<tr><td rowspan="4"></td><td rowspan="4">Wetland extent</td><td colspan="2">AVHRR</td><td></td><td rowspan="3"></td></tr>
<tr><td colspan="2">LandSat 1-7</td><td></td></tr>
<tr><td colspan="3">SPOT1-5</td></tr>
<tr><td>SIR-C
ERS-1
JERS-1</td><td>ERS-2
ASAR</td><td>ALOS, LDCM</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="5">Air–Sea CO_2 flux</td><td colspan="2">ERS1-2</td><td></td><td></td><td></td></tr>
<tr><td>Wind speed</td><td>ERS – 1-2</td><td>QUICKSCAT
ASAR
MERIS
AMSR-E
WindSat
SeaWinds
AMSR</td><td>ESA's Atmospheric Dynamic Explorer</td><td></td></tr>
<tr><td rowspan="3">Sea surface temperature</td><td colspan="2">AVHRR</td><td></td><td>SBERS</td></tr>
<tr><td rowspan="2"></td><td>ATSR
AATSR</td><td>VIIRS NPOES Prep. Prog.</td><td>VIIRS NPOES</td></tr>
<tr><td></td><td>METOP 1-2-3</td><td></td></tr>
<tr><td rowspan="2">Ocean biogeochemistry</td><td rowspan="2">Chlorophyll
Ocean colour
Ocean productivity</td><td rowspan="2">CZCS
POLDER-I</td><td rowspan="2">SeaWIFS
MODIS
POLDER-II
ADEOSII GLI
MERIS</td><td>SGLI</td><td></td></tr>
<tr><td>VIIRS NPOES PrepProg.</td><td>VIIRS NPOES</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Ocean circulation</td><td>Circulation & hydrography</td><td>TOPEX
ERS-1</td><td>JASON–1
ENVISAT/ALTIMETER
ERS-2</td><td>JASON–2</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

* longer temporal averaging may be needed to get desired precision

Other Contributing Remote Sensors	Potential New Missions	Spatial Sampling Frequency	Temporal Sampling Frequency
		25 – 100 km	TBD
AIRSAR	Low-frequency polarimetric radar	25 m or less, and – 1 km	weekly
	ALPHASCAT Wind Lidar	25 km	Daily
		1 Km	Daily
NPOES CrIS			
SIMBIOS A / C particulate LIDAR		1 km	Daily
		300 km	10 day

Table 9.2 Observation requirements for in situ ocean measurements (source GOOS)

Ocean carbon cycle	Basin-scale Surface Observations	Large scale inventories
Parameter requirements (continuity)	Global surface mapping of: ΔpCO_2 Carbonate system Nutrients Fluorescence, Optical properties Tracers, hydrography parameters	Vertical profiles of: Carbonate system Nutrients, Tracers Biogeochemical species (iron, DOC and POC) Hydrography parameters
Sampling requirements (expansion with current parameters)	Cover all ocean gyres to map seasonal, annual, inter-annual fluxes Platforms: Oceanographic research vessels, VOS, and SOOP vessels	for each basin on a 5-10 year revisit time to track the penetration of anthropogenic CO_2, Platforms: shipboard surveys; coordinated sampling of above parameters
New parameters requirements	Collect atmospheric data along the VOS lines (prec. 0.1 ppm) to better resolve regional budgets	Add new time-series stations in key remote locations (high latitude water formation regions, ocean margins). Measurements of dissolved oxygen to determine changes in ocean stratification.
New sensors, techniques	Develop spatially and temporally extensive in situ sampling of surface pCO_2 Develop co-sampling of other ecosystem and biogeochemical data to place pCO_2 data in proper context	Develop autonomous carbonate system sensors that could be deployed on profiling floats

Biogeochemical Time Series	Ocean Remote Sensing	Coastal Observations
Time series of: ΔpCO_2 Sediment traps Trace metals Ocean optical properties Plankton species and abundance through the Continuous Plankton Recorder Programme (CPR)	Global maps of: Chlorophyll, ocean colour, ocean productivity global fields with sampling frequency enabling collocation with in situ data (see Table 9.1) Possibly major plankton species	
Continuous time series stations Frequent survey by ships for CPR		Ensure continued support for developing a common network of coastal observing system elements
Develop a network of quasi-autonomous ecological, bio-optical, and biogeochemical time series Development of automated techniques for measuring biogeochem. properties Development of a network of time series to measure sinking fluxes from sediment traps along with nutrients and dissolved O_2	Develop satellite system to obtain higher ocean coverage (60% global, over a 3-5 day timeframe) Develop systematic in-situ measurements to support satellite ocean colour (incorporated into VOS+time series)	Establish a long-term observing network for coastal zones and ocean margins (use pilot studies for optimal design)

Table 9.3. Observation requirements for terrestrial component (source TCO)

Terrestrial carbon cycle	Land cover and land use	Biomass	Seasonal growth cycle	Fires / disturbances
Continuity challenges	Continuity of calibrated, fine resolution optical data from both fixed-view (eg., Landsat) and pointable (eg., SPOT) sensors Continuity of calibrated, moderate resolution global satellite observations Systematic reprocessing of satellite data to prepare time-stamped or time series data	Ensure ongoing availability of canopy structure measurements Improve availability and harmonisation of inventories More efficient use of national inventories (e.g. improved expansion factors...) Ensure systematic observation of forest by SAT (eg, ALOS)	Ensuring continuity of moderate resolution optical sensor measurements: same as for land cover Ensuring agency commitments to generating global LAI products beyond the MODIS/TERRA period. Ensuring continuity of moderate resolution optical sensor measurements	Continuity of calibrated moderate resolution satellite data; Burned areas (res <200 m needed). Fires hotspots (res ≈ 1000 m) Information on historical changes in fire regimes (long term satellite data + ground surveys)
Knowledge challenges	Obtain global land use information by means of satellite data at various spatial scales Develop methods for deriving global land use information by means of satellite at various spatial scales, in linkge with the effect on carbon fluxes	Expand inventories to tropical forests, non-commercial forests, woodlands Develop new soil carbon measurement techniques, and sampling strategies Update the 1:5 million soil map of the world (underway) Develop satellite technology for remote sensing of biomass (eg.,SAR and Lidar)	Use of new satellite techniques (lidar, multi-angle optical) to detect frost-free season duration at high latitudes Use of new satellite sensing techniques (multi-angle optical, lidar) to be further investigated for improving LAI accuracy at high LAI values and information on the distribution of sunlight within canopy	Develop methods to quantify partial disturbances in forests (insect damage, selective harvesting) Information on plume composition from satellite Information on injection height New methods to map areas burned by 'ground fires'

Land Cover information					
Water					
Snow and ice					
Barren or sparsely vegetated					
Built-up					
Croplands					
Forest	Leaf type	Needle	Broadleaf	Mixed	
	Leaf longevity	Evergreen	Deciduous	Mixed	
	Canopy cover	10 – 25 %	25 – 40 %	40 – 60 %	60 – 100 %
	Canopy height	0 – 1 m	1 – 2 m	> 2 m	
		(low shrub)	(tall shrub)	(trees)	
Forest special theme: flooded forest					
Spatial resolution: 1 km (coarse) and 25 m (fine)					
Update cycle 5 years (coarse and fine)					

Solar radiation	Eddy-covariance flux towers	Methane / soil moisture and surface wetness	Canopy biochemistry
Ensuring the development and production of daily to monthly SW products.	Continuity to maintain existing measurement programs for at least 10 years at a site Expand the current network in underrepresented regions, and ecosystems undergoing disturbances Improving international coordination (on-line data transfer, data quality assurance)		
Develop daily PAR products from geostationary and polar orbiting sensors. Spatial resolution near ~10 km and direct estimation for the PAR spectral region (0.4 - 0.7 µm).	Poof of "virtual tall towers" concept accurate CO_2 concentration measured at flux towers (< 1 ppm) Standardise methodologies among the regional networks (joint ecological measurement, use of high resolution remote sensing, gap filling)	Map the global distribution and temporal variability of wetland cover types Develop satellite observation techniques and modelling tools to estimate methane fluxes from wetlands (include. water table depth) Develop satellite-based capability to monitor global soil moisture	Experimental programs to determine the operational feasibility of producing robust estimates of canopy biochemical properties. (C and N content of pools)

Table 9.3 (continued) Satellite data requirements for terrestrial observing system component

Land Cover Change information	Coarse	Fine
Resolution	1 km initially 250 m as soon as possible	25 m
Cycle	Annual wall – to – wall	5 year wall – to – wall; 20% - 30 % annual
Classes	No change	No change
	Forest ➔ non - forest	Forest ➔ non - forest
	Non -forest ➔ forest	Non - forest ➔ forest
Special products	Burned forest	Forest fragmentation
		Forest change occurrence

Fire information	Spatial resolution	Revisit cycle	Temporal cycle	Source(s) of data
Fire monitoring	250 – 1 km	12 h	12 h	Coarse resolution optical (thermal)
Mapping burned area	25 m - 1 km	Annual	3 months	Coarse and fine resolution optical with SAR backup
Modelling	250 m – 1 km	Annual	6 months	Coarse resolution optical plus land cover plus biomass, emission factors, etc.

Biophysical information	Accuracy needed	Spatial resolution	Temporal cycle	Source(s) of data
LAI m^2 / m^2	± 0.2 – 1.0	1 km	7 days	Coarse resolution optical
PAR W / m^2	± 2 – 5 %	1 km	30 min – 1 day	Coarse resolution optical
FPAR Dimensionless	± 5 – 10 %	1 km	7 days	Coarse resolution optical
Above ground biomass G / m^2	± 10 – 25%	1 km	5 years	Inferred from land cover until spaceborne measurements are available
NPP $g C / m^2 / yr$	± 20 – 30 %	1 km	1 year	Above products plus ground and spaceborne meteorological data

Table 9.4. Observation requirements for atmospheric measurements and inversion modelling

Atmospheric components	In situ Measurements	Transport models and Inversions	Satellite CO_2 Measurements
Parameter requirements (continuity)	CO_2 measured continuously at in situ stations Other greenhouse gases (e.g., CH_4, N_2O) at in situ stations and in flask sampling programmes Carbon cycle related tracers in weekly flask samples: O_2/N_2, ^{13}C in CO_2, 180 in CO_2 Analogue tracers of fossil fuel CO_2: ^{14}C in CO_2, SF_6, CO, C_2Cl_4 Transport tracers: ^{222}Rn, CFCs, SF_6…	Availability of existing atmospheric data through data centers (e.g. WMO) Generation of homogeneous atmospheric data products for modellers (e.g. GLOBALVIEW-CO_2) A priori information on the spatial and temporal patterns of terrestrial and oceanic fluxes, if possible with an error-structure Information on atmospheric structure and transport (e.g. From NWP centers) allowing the development of improved transport models	Algorithm development to retrieve column integrated CO_2 and CH_4 abundances from existing sensors in Long Wave Infrared (AIRS, TOVS) and Short Wave Infrared domains (SCIAMACHY)
Sampling requirements (expansion with current parameters)	Ensure commitment of the present flask sampling programs. Add new sites for flask sampling based on network optimisation studies, especially in the interior of continents Add in situ CO_2 vertical profiles with high enough sampling frequency to characterise the mean gradients between the boundary layer and the free troposphere Increase the number of continuous stations (e.g. tall towers) inside the continents, particularly in the tropics – coordinated with vertical profiles Develop sampling of CO_2 onboard commercial passenger aircraft (2 programmes currently existing) Coordinate expansion of atmospheric programmes with shipboard measurements of air-sea fluxes and ecosystem fluxes (underway in Europe, North America, Siberia) Frequent calibration of laboratories to the primary WMO standards Frequent intercomparison programmes for CO_2, and other species	Increased resolution in space and time for the surface fluxes to be optimised Use of higher resolution Atmospheric Transport Models	Algorithm developments on quantifying the error structure for CO_2 retrieval from space (diffusers, spectroscopy studies, diurnal cycle…)
New parameters / products requirements	Develop analysis of new tracers (eg Ar/N_2) Develop new sampling platforms for high frequency in situ CO_2 measurements: tethered balloons, unmanned aircraft Development of robust remotely-operated continuous CO_2 and O_2 analysers, with an acceptable trade-off between logistical independence and precision.	High resolution maps of fossil fuel emission (up to hourly, 10 km) and bio-fuels emissions High resolution maps of fire emissions (fires, injection heights, emission factors, delayed emissions following disturbance) Develop high resolution transport models in conjunction with land surface schemes	Develop specific infrared CO_2 monitoring mission: NASA-OCO and possibly NASDA-GOSAT (precision 1 ppm) - Develop assimilation framework in numerical weather prediction models to assimilate satellite radiances - Research on active sensors to retrieve CO_2 vertical structure (ESA ongoing study: FACTS)

Table 9.5 Range of models for assimilating carbon cycle observations

Ocean models	*Applications*	Terrestrial and Anthropogenic models	*Applications*
Data-driven models Examples: Diagnostic models of ΔpCO_2 Ocean productivity models driven by satellite observations...	Generate continuous carbon and biogeochemical fields that incorporate available data Interpolate and extrapolate pointwise observations to basins Separate anthropogenic and natural components Fusion of satellite observations Estimate bio-geochemical rates Estimate of current sources and sinks Initial / Boundary conditions for prognostic models Design of optimal observation networks.	**Data-driven terrestrial biosphere models** Examples Light Use Efficiency models driven by satellite fields Neural network upscaling of eddy-covariance data **Data-driven emission models**	Generate continuous fields of GPP, NPP, NEP Simulate short term variability of Net Ecosystem Exchange Fusion of satellite observations Upscaling of eddy flux observations Input flux patterns to atmospheric transport models Generate time varying maps of biofuels, fossil emissions of CO_2 and tracers
Process-driven models Examples: Global ocean carbon models Coupled ocean-atmosphere models with carbon cycling	Sensitivity of fluxes to controlling processes Study of interactions between processes Study of interactions between carbon cycle and climate on interannual and longer time scales	**Process-driven terrestrial biosphere models** Examples: Carbon, Energy, water process-based models Energy, water, carbon, nutrients process-based models Energy, water, carbon, nutrients models with disturbances and ecosystem dynamics **Process-driven emission models**	Sensitivity of fluxes to controlling processes Study of interactions between processes Study of interactions between carbon cycle and climate Long integrations to examine carbon pools and rates, and NEP Impact of nutrient addition and limitation Impact of land use and land management and disturbances on carbon pools and long term sequestration Generate algorithms that allow interactive calculation of emissions with climate and other drivers
Regional ocean models Basin-to-global models Coastal / Regional models	Study of small scales effects on large scale quantities Coastal dynamics and CO_2 flux studies	**Forestry models** **Agricultural models** **Riverine Transport models** **Soil erosion models**	Calculate biomass dynamic evolution in managed forests in response to management action. Calculate yield of crop under different stress, and practice Calculate non CO_2 gas emissions (N_2O and CH_4)

Atmospheric models	*Applications*
Global off-line transport models resolution >100–50 km **Global on-line transport in climate models** resolution >100–50 km **Weather prediction models with atmospheric transport** resolution >100–50 km	Inversions of CO_2 sources and sinks Inversions of parameters controlling the fluxes (in conjunction with ocean and terrestrial flux models) Inverse and forward simulations of atmospheric CO_2. Coupling with ocean and terrestrial flux models Retrieval of atmospheric CO_2 distribution from space-borne sensors
Regional off-line transport model resolution 50 – 1 km **Regional on-line transport in climate model** resolution 50 – 1 km	Inverse and forward simulations for inverting regional fluxes Interpretation of intensive campaign data Representation error in coarser scale models Generate high resolution climate and weather fields to drive flux models Inversion of model parameters controlling regional fluxes Coupling between climate variability and carbon fluxes
Turbulent transport models Examples Large eddy simulators Turbulent canopy transfer models	Canopy scale processes

[1] Climate Change 2001: Synthesis Report: Third Assessment Report of the Intergovernmental Panel on Climate Change, in Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A., eds.: Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press, 881 pp.

[2] http://ioc.unesco.org/igospartners/IGOSP7/Report/p7igaco.doc.

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

[4] http://www.ihdp.uni-bonn.de/

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

[6] http://www.globalcarbonproject.org/

[7] http://ioc.unesco.org/igospartners/igoshome.htm

[8] http://www.ceos.org/

[9] http://ioc.unesco.org/goos/

[10] http://www.fao.org/GTOS/

[11] http://www.wmo.ch/web/gcos/

[12] http://ioc.unesco.org/goos/docs/doclist.htm

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

[14] http://www.bom.gov.au/bmrc/ocean/GODAE/

[15] ftp://ftp.ldeo.columbia.edu/pub/boba

[16] CMDL Flask Network (GLOBALVIEW-CO_2 2000, Cooperative Atmospheric Data Integration Project - Carbon Dioxide: Boulder, Colorado, NOAA-CMDL)

[17] http://www-cger.nies.go.jp/~moni/flux/asia_flux/index.html, http://www.isa.utl.pt/def/gemf/carboeuroflux.htm, http://public.ornl.gov/ameriflux/Participants/Sites/Map/index.cfm, http://www.fluxnet-canada.ca/welcome.html, http://www.clw.csiro.au/research/waterway/interactions/ozflux/, http://www-eosdis.ornl.gov/FLUXNET/

[18] As an exception see http://www.geog.leeds.ac.uk/projects/rainfor/

[19] http://www-eosdis.ornl.gov/SOILS/igbp-surfaces.html and http://www.fao.org/ag/agl/agll/dsmw.HTM

[20] http://ioc.unesco.org/ioccp

[21] http://ingrid.ldeo.columbia.edu/SOURCES/.GEOSECS/

[22] http://cdiac.esd.ornl.gov/oceans/ndp_004/ndp004.html

[23] http://www.uib.no/jgofs/jgofs.html

[24] http://www.soc.soton.ac.uk/OTHERS/woceipo/index.html

[25] http://wwwold.nioz.nl/loicz/

[26] http://www.fao.org/gtos/TCO.html (TCO) and http://ioc.unesco.org/goos/ (GOOS)

[27] Chédin et al. Journal of Geophysical Research, 108 D18, 2003

[28] Which is flying on board the NASA/Aqua satellite that was launched in May 2002.

[29] The Inrared Atmospheric Sounder Interferometer (IASI) will fly with AMSU on board the EUMETSAT/MetOp that is scheduled for launch in 2005.

[30] Which will fly which will fly on the NOAA-NASA's NPOESS Preparatory Program (NPP) Mission as well on the NPOESS meteorological satellite.

[31] http://www.ipo.noaa.gov/

[32] For instance, AIRS measures 2378 frequencies at high spectral resolution and covers most of the infrared spectrum while HIRS-2 measures 19 infrared frequencies.

[33] http://envisat.esa.int/instruments/sciamachy/

[34] http://envisat.esa.int/

[35] In particular, the 25-year archive of the HIRS-2 should be used to produce a CO_2 record at a space-time scale of 10° /monthly and with a target precision of 1%.

[36] http://oco.jpl.nasa.gov/

[37] http://www.jaxa.jp/missions/projects/sat/eos/gosat/index_e.html

[38] May, R.D. and Webster, C.R. 1990. "Balloon-borne Laser Spectrometer Measurements of NO_2 with Gas Absorption Sensitivities Below 10-5", Appl. Opt. 29, 5042-5044. C.R. Webster, C.R. and May, R.D. 1991. Aircraft Laser Infrared Absorption Spectrometer (ALIAS) for Polar Ozone Studies", Infrared Technology XVII, 1540, 187-194. Webster, C.R. and May, R.D. 1992. "In-Situ Stratospheric Measurements of CH_4, 13CH_4, N2O, and OC18O Using the BLISS Tunable Diode Laser Spectrometer", Geophys. Res. Letters 19, 45-48. Michelson, H.A. et al. 1999. "Intercomparison of ATMOS, SAGE II, and ER-2 observations in the Arctic vortex and extra-vortex air masses during spring 1993", Geophys. Res. Letters, 26, 291-294. Zahniser, M. S. et al. 1995. "Measurement of trace gas fluxes using tunable diode laser spectroscopy." Phil. Trans. R. Soc. Lond. A, 351, 371-382. Nelson, D.D. et al. 1996. "Recent Improvements in Atmospheric Trace Gas Monitoring Using Mid-infrared Tunable Diode Lasers." SPIE Proceedings, Vol. 2834, 148-159.

[39] http://www.geog.umd.edu/vcl/

[40] http://essp.gsfc.nasa.gov/vcl/

[41] http://www.fao.org/

[42] http://cdiac.esd.ornl.gov/by_new/bysubjec.html#trace and http://arch.rivm.nl/env/int/coredata/edgar/index.html

[43] http://www.ipsl.jussieu.fr/OCMIP/; http://eos-webster.sr.unh.edu/data_guides/ccmlp_dg.jsp; http://eos-webster.sr.unh.edu/data_guides/vemap_trans_dg.jsp; http://transcom.colostate.edu/

[44] A data assimilation system consists of three parts 1) A description of the system, usually in terms of the values of spatial fields (e.g., of temperature, biomass, salinity...). The collection of all these describes the "state" of the system. 2) A numerical "forecast or forward model that describes the evolution of the state from one time to the next. 3) A set of so-called observational operators that relate aspects of the state to observed quantities. These may be very simple if the state variable is observed directly but may also involve a substantial numerical model.

[45] For instance the CO_2 atmospheric concentration at a tall tower can be interpreted using a suite of nested models from the globe down to proximate source areas.

[46] http://www.cdas.ucar.edu/oct02_workshop.pdf

[47] http://ioc.unesco.org/ioccp

[48] http://www.jhu.edu/~scor/index.htm

[49] http://www.wmo.ch/wmo50

[50] http://www.ioc.unesco.org/goos

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

[52] http://www.fao.org/gtos

[53] http://www.fao.org

[54] http://www.unep.org

[55] http://www.earthobservationsummit.gov/

The IGOS Partners

CEOS
Committee on Earth Observation Satellites
http://www.ceos.org

FAO
Food and Agriculture Organization of the United Nations
http://www.fao.org

GCOS
Global Climate Observing System
http://www.wmo.ch/web/gcos/gcoshome.html

GOOS
Global Ocean Observing System
http://ioc.unesco.org/goos/

GOS/GAW
Global Observing System/
Global Atmosphere Watch of WMO
http://www.wmo.ch

GTOS
Global Terrestrial Observing System
http://www.fao.org/gtos/

ICSU
International Council for Science
http://www.icsu.org

IGBP
International Geosphere-Biosphere Programme
http://www.igbp.kva.se/

IGFA
International Group of Funding Agencies
for Global Change Research
http://www.igfagcr.org

IOC-UNESCO
Intergovernmental Oceanographic
Commission of UNESCO
http://ioc.unesco.org/iocweb/

UNEP
United Nations Environment Programme
http://www.unep.org

UNESCO
United Nations Educational,
Scientific and Cultural Organization
http://www.unesco.org

WCRP
World Climate Research Programme
http://www.wmo.ch/web/wcrp/wcrp-home.html

WMO
World Meteorological Organization
http://www.wmo.ch

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