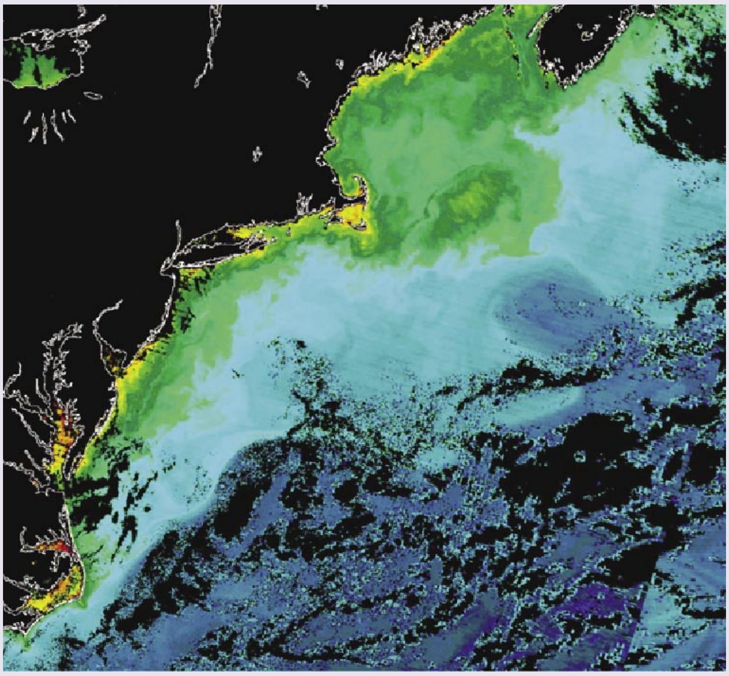
A Strategy for an

Integrated Global Carbon Observing System



Since ancient times humans have modified natural systems and thereby affected their local environment. However, since the beginning of the Industrial Revolution, human activity has begun to change the environment on larger and larger scales. The evidence is now overwhelming that human activity has significantly altered biogeochemical cycling at the regional, continental, and planetary scale.

- The carbon dioxide concentration in the atmosphere has increased by more than 30 percent since the beginning of the Industrial Revolution; methane has increased by 100%.
- The global annual flux of sulfur to the atmosphere has increased by more than 50%.
- More nitrogen is now fixed synthetically and applied as fertilizers in agriculture than is fixed naturally in all terrestrial ecosystems.
- More than half of all accessible freshwater is appropriated for human purposes.

The carbon cycle is a particularly important case. The concentration of atmospheric CO_2 has moved into a range unprecedented during the past twenty five million years. The pool of carbon in the atmosphere (in the form of CO_2) increased from about 590 to almost 780 Pg C (1 Pg C = 1×10^{15} g C = 1 billion metric tons C) during the 235 years between 1765 and 2000 as a result of fossil fuel burning and forest clearing. The annual rate of increase is almost 0.5% per year. There is a direct record (Figure 1) of this increase since 1958; moreover, ice core records show that the concentration of carbon dioxide was relatively constant over the last 1000 years up to the onset of increases in the 18th century. (Figure 2; **e.g., the ice-core records that connects the inferred atmospheric record of the last 1000 years with Keeling's atmospheric record**).

The increase of CO_2 in the atmosphere raises concern regarding the heat balance of the global atmosphere. Specifically, the increasing concentration of CO_2 in the atmosphere leads 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

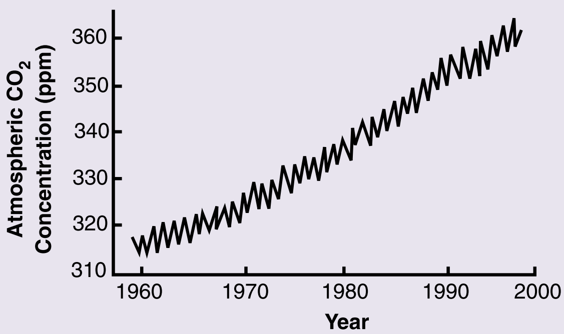


Fig. 1. Increase in atmospheric CO_2 concentration over the last 40 years as measured at the Mauna Loa, Hawaii, Observatory (adapted from Keeling and Whorf, Oak Ridge National Laboratory, USA, 2000).

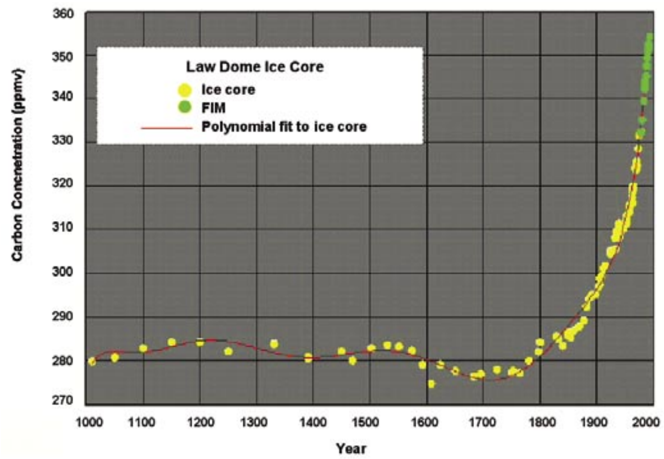


Fig. 2. Changes in atmospheric CO_2 concentration over the last 1000 years., as reconstructed from ice core studies reconstructed from ice core data that match the last 50 years of the keeling structure.

patterns of temperature and precipitation will change, though the magnitude, distribution and timing of these changes are far from certain.

Against this backdrop, it is essential for modern society to implement an Operational Observing System of the Carbon Cycle. This document, based on a more detailed report of the Integrated Global Carbon Observation theme of IGOS-P, outlines a strategy to realize this Observing System over the next decade.

The Observing System must achieve 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.**

New Text: The System will meet those objectives by quantifying and assessing routinely the global distribution of CO2 fluxes exchanged between the Earth's surface and the atmosphere, by measuring at regular intervals the changes of key carbon stocks, and by conducting targeted observations that help elucidate underlying biogeochemical processes. The Operational Global Carbon Observing System integrates across all multi-faceted aspects of the three major domains of the carbon cycle: ocean, land, and atmosphere. Indeed, the most successful advances in understanding will most likely spring from the combination of data and models for the different domains.

Implementing the Observing System requires:

- Establishing data requirements, designing network configurations, and developing advanced algorithms for operational carbon observations, which will be the core of a future, sustained operational system by 2015,
- Developing cost-effective, low maintenance, *in situ* sensors for atmospheric CO_2, ocean dissolved pCO_2, and terrestrial ecosystem fluxes,
- Developing and implementing technologies for remote sensing of CO_2 from space,
- 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 harmonization and intercomparability, archiving, and distribution to support model development and implementation

The final strategy document will present a vision of the Operational Global Carbon Observing System, which ultimately will be implemented both by research and operational agencies, and it provides a roadmap to realize the System. The full strategy will identify a core set of existing research-based observations upon which to build the System, and it describes the critical priorities and steps required to transfer the core set of research observations into an operational system.

The Operational Global Carbon Observing System should be built around complementary core groups of observations to address three themes: Fluxes, Pools, and Processes.

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

- Satellite observation of column integrated atmospheric CO_2 distribution to precision of at least 0.5% with synoptic global coverage--all latitudes, all seasons;
- An optimized operational network of atmospheric in situ stations and flask sampling sites with an accuracy of at least 0.1 ppmv;
- An optimized, operational net-

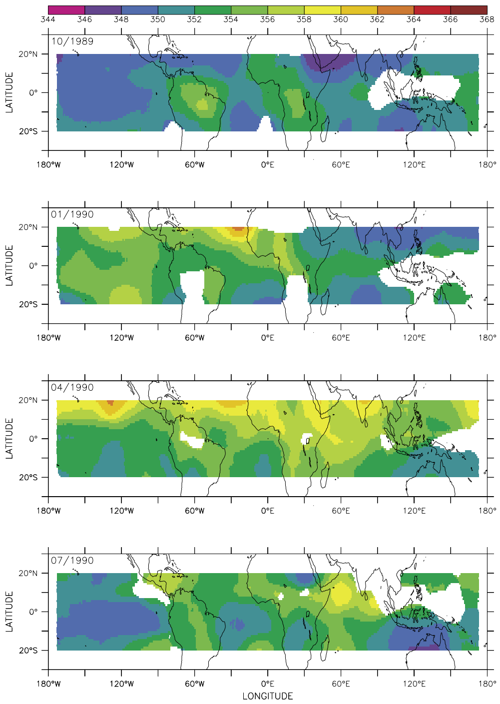


Fig. 3. Maps of upper tropospheric column integrated CO_2 retrieved from HIRS-2. Courtesy of A. Chedin.

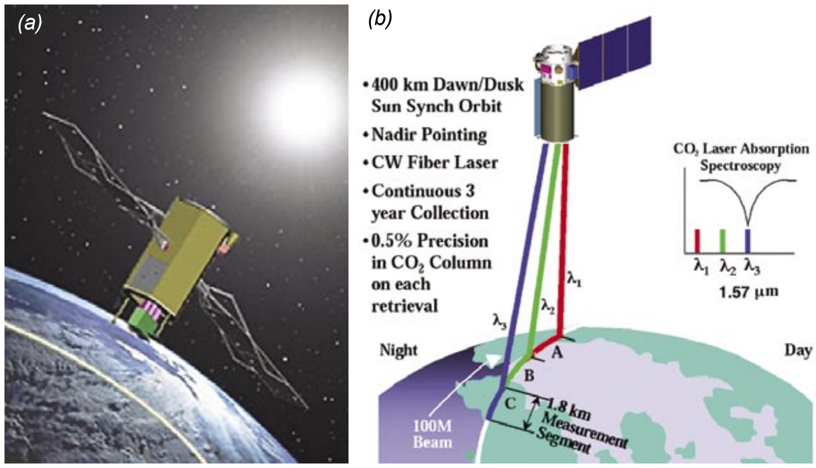


Fig. 4. a) Artist illustration of the JPL Orbiting Carbon Observatory under consideration by NASA. (b) Concept for a space based system for measuring the column integrated atmospheric CO_2 distribution at all latitudes and in all seasons.

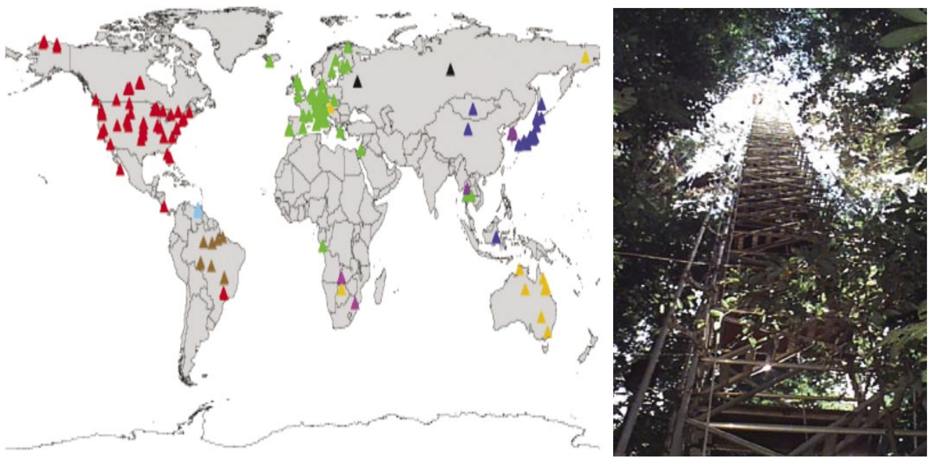
work of eddy covariance towers measuring on a continuous basis the fluxes of CO_2, energy and water vapour over land ecosystems;

- A global ocean pCO_2 measurement system using a coordinated combination of research vessels, ships of opportunity, and autonomous drifters;
- 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.
- Georeferenced measurements of the emission of CO_2 from fossil fuel combustion.

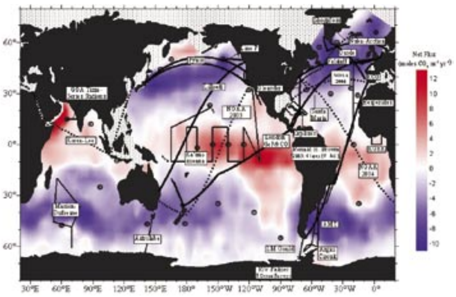
The approach for using these observations to quantify the distribution and variability of CO_2 fluxes between the Earth's surface and the atmosphere requires reconciliation of both down-scaling and up-scaling estimates. Atmospheric transport models are required to downscale the atmospheric CO_2 measurements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

Once the Operational Global 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

Fig. 5. World-wide distribution of eddy covariance towers measuring CO_2, water vapour and energy fluxes. Only five such towers were operating 10 years ago. The photo shows an eddy covariance tower near Manaus, Brazil.



(a)



(b)

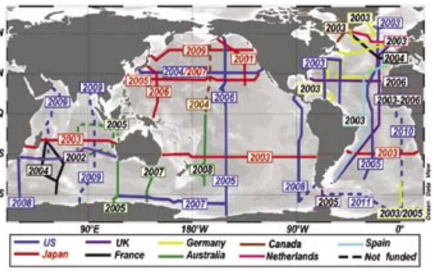


Fig. 6. (a) map of existing coverage of ocean repeated inventories; (b) map of ocean pCO$_2$ surveys on Ships of Opportunity, moored points. The photo shows a typical Ship of Opportunity operating in the North Atlantic Ocean.

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.
- Inventories of dissolved carbon in the main ocean basins, measured at 10-year intervals, to estimate the sequestration of anthropogenic CO_2 into surface waters.

Measuring changes in carbon stocks in these three pools is critical for carbon closure. It is a fundamental check upon the system.

Processes. The third set of observations in the System is measurements related to important carbon cycle processes. Most of these will remain in the research domain; however, two process-related observations are appropriate for the operational domain and will become part of the core set of the System:

- Fire distribution (hotspots) and burned area extent, to estimate the fluxes of carbon that are emitted during fires.
- Land-cover change, to estimate the fluxes of carbon associated with forest clearing and reversion of agricultural lands to natural ecosystems.

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.

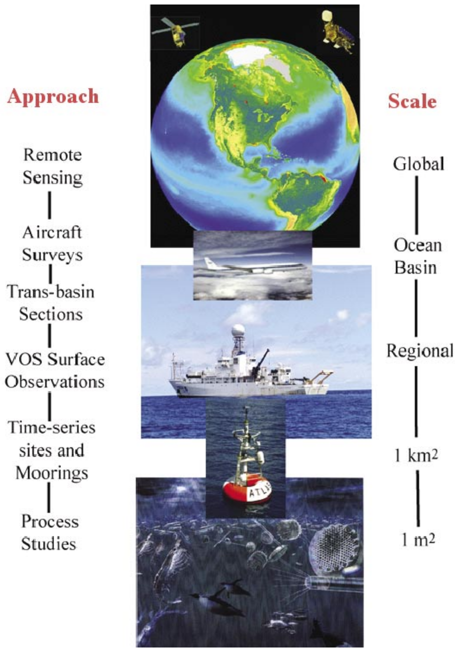


Fig. 7. Integration across scales for ocean carbon observations.

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