GEO
CARBON STRATEGY
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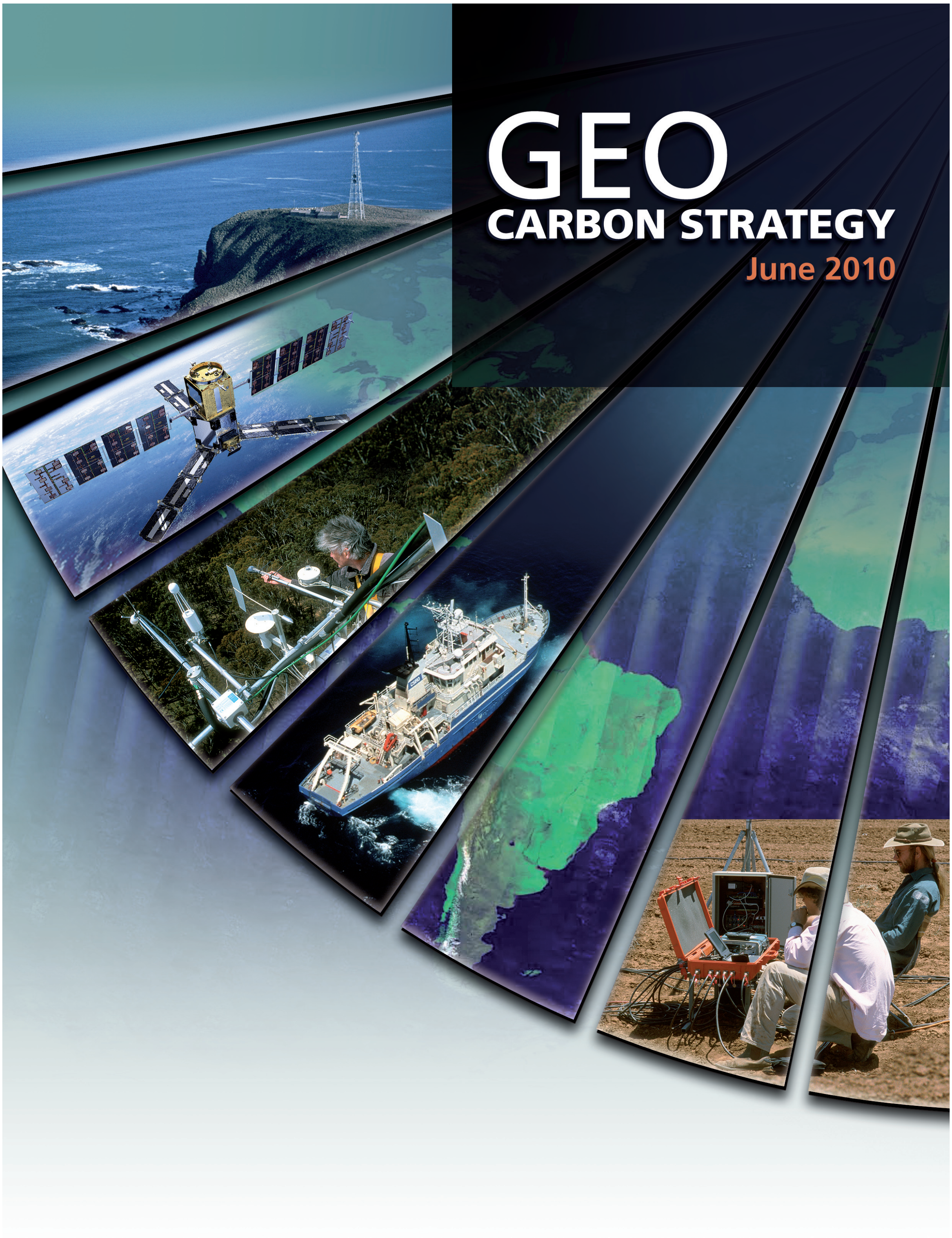

GROUP ON EARTH OBSERVATIONS

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GEO Carbon Strategy

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Preface

Recognizing the growing need for improved Earth observations, over 130 governments and leading international organizations are collaborating through the Group on Earth Observations (GEO) to establish a Global Earth Observation System of Systems (GEOSS) by the year 2015. They are contributing their respective Earth monitoring systems to GEOSS and interlinking these systems so that they work together better. They are developing common technical standards to make it possible to pool information, and they are promoting the free sharing and dissemination of Earth observations and data. This expanding coalition of countries and organizations has already transformed the ability of governments to manage natural resources and promote the safety and well-being of their citizens.

GEO plans to produce globally harmonized data sets on global, national and local scales, using common algorithms, variables and units; as well as, to develop an integrated model that stitches all carbon observations together. The IGOS-P, through their leadership and implementation plans have now been fully integrated into GEO and are the foundation for the Communities of Practice. The new GEO Carbon Community of Practice will implement a plan for an Integrated Carbon Observation program.

GEO through its Members and Participating Organizations, has begun work to implement a global carbon observation and analysis system addressing the three components of the carbon cycle (atmosphere, land and ocean) to provide high quality information on carbon dioxide (CO_2) and methane (CH_4) concentrations, and emission variations. By combining observations, reanalysis and product development we will be able to develop tools for carbon tracking and carbon storage evaluation, including improved global networks of atmospheric CO_2 observations, air-surface exchange flux networks, as well as surface ocean CO_2 and related marine biochemistry observations.

GEO Members and Participating Organizations: Australia, Canada, France, Japan, Netherlands, Norway, UK, Italy, USA (NASA,NOAA,USGS,USDA), Carbon Community of Practice (formerly IGOS-P), Committee on Earth Observation Satellites (CEOS), European Space Agency (ESA), Food and Agriculture Organization (FAO) Global Climate Observing System (GCOS), Global Terrestrial Observing System (GTOS), World Meteorological Organization (WMO), the World Climate Research Program (WCRP) and The William J. Clinton Foundation are supporting the development of an integrated global carbon observation system. GEO encourages the development of high-resolution global and regional data-assimilation and modeling systems to enhance the utility of the spatial and temporal resolution of those observations and provide relevant regional-scale information.

Through GEO, coordinated Earth Observations can provide the capability and capacity to support the monitoring, reporting, and verification (MRV) information required by future regulatory frameworks for the inclusion of forests in post-Kyoto climate agreements. This would ensure assessment of permanence, additionality and leakage to support Forest Carbon Tracking. This builds upon existing and planned GEO efforts in forest monitoring, associated modeling and use of these tools for timely provision of observations required for their routine use world-wide. In close collaboration with national governments, space agencies, and relevant technical experts, GEO will demonstrate this capability through the establishment of robust methodologies, satellite acquisition plans and a series of regional pilot studies, which will provide a template for a consistent and reliable global carbon monitoring system.

Activities include: (i) establishment of several regional reference test-sites; (ii) consolidation of observational requirements and associated products; (iii) coordination of observations, including their long-term continuity; (iv) coordinated assessment of tools and methodologies at these sites, (v) coordination of the production of reference data sets,and (vi) improved access to observations, data sets, tools and expertise.

One other major activity is to foster the use of space-based greenhouse gas (GHG) observations and consolidate data requirements for the next-generation GHG monitoring missions. By establishing close cooperation with CEOS and the GEO Carbon Community of Practice plans will be implemented for the end-to-end utilization of space-based GHG data, particularly those of Japan's GOSAT mission and NASA's replacement OCO mission, and other GHG-observation missions being prepared in Europe.

The global carbon cycle determines the amount of carbon dioxide and methane that accumulates in the atmosphere, increasing the Earth's greenhouse effect. It is therefore a key component of the global climate system. The carbon cycle also responds to climate change, and understanding the ability of the carbon cycle to continue to act as a partial sink of fossil fuel emissions into the future will be a vital factor in determining the "allowable" fossil fuel emissions, while keeping concentration below certain levels.

Current uncertainties on the space-time distribution of CO_2 and CH_4 fluxes are very large. For well informed policy action aiming to curve down the future increase of CO_2 and CH_4, these uncertainties must be reduced, by establishing an Integrated Global Carbon Observing system (IGCO). The main goal of this report is to describe the building blocks and coordinated implementation of such an Integrated Global Carbon Observing system.

It is anticipated that this document will become a live document, subject to frequent updates and available online. As actions are completed, the following steps will become clear, necessitating new actions and new directions. IGCO will be a service provider to the practitioners of the carbon community, facilitating the flow of information and the coordinated implementation of new observations.

Executive summary

Understanding the global carbon cycle, and predicting its evolution under future climate scenarios is one of the biggest challenges facing science today; there are huge societal implications. The uncertainty in the natural sinks of the carbon cycle is a major contributor to the uncertainty in climate predictions. The feedbacks between climate change and the carbon reservoirs are not well known or understood. The spatial and temporal distribution of natural sinks over land and oceans remains elusive, which precludes better quantification of their underlying mechanisms and drivers. In addition to natural sinks, anthropogenic emissions from fossil fuel burning and land use change need to be known at regional level and with better accuracy. These uncertainties must be reduced to underpin well-informed, evidence-based policy action.

A key reason for our lack of understanding of the global carbon cycle is the dearth of global observations. An increased, improved and coordinated observing system for observing the carbon cycle is a prerequisite to gaining that understanding.

This report sets out a number of key actions that build on a strategy to expand the current observations into a fully integrated observation system measuring the essential parameters and variables. Some actions are already being carried out, while others still need to be addressed and implemented.

Completing an Integrated Global Carbon Observing system (IGCO) within the Group on Earth Observation (GEO) and the Global Climate Observing System (GCOS) will involve thousands of scientists, technicians, agency representatives and policy makers. One key element of an Integrated Global Carbon Observing system is the provision of communication points to facilitate the flow of information from the data providers to the data users. These communication points will also acts as nodes for summarizing and disseminating the current state-of-the-art information.

The main recommendations are to:

i) increase the density of in situ networks, in particular for stations and aircraft atmospheric observations, ocean pCO2 observing systems using Voluntary Observing Ships, and eddy covariance terrestrial ecosystem flux measurement networks.

ii) develop space measurements of global CO_2 and CH_4 distributions, to fill the gap after GOSAT and SCIAMACHY;

iii) develop spatial scaling techniques for pCO_2 and land flux observations for application to wider regions, using satellite information;

iv) undertake a decadal full basin survey of ocean carbon state, together with regular inventories of forest biomass and soil carbon pools;

v) improve access to a continuous supply of mid-resolution Earth observing satellitedata (i.e., LAI, FAPAR, disturbance, land cover change), to monitor areas of forest;

vi) develop space measurements of vegetation 3-dimensional structure to improve estimates of global terrestrial aboveground biomass and carbon stocks and continue the observational data streams started with JERS-1, ALOS PALSAR, and ICESat;

vii) develop new space missions and satellite products to improve estimation of carbon capture and export in the ocean;

viii) improve access to geospatial and temporal fossil fuel emission information, including spatial-data infrastructure;

ix) assemble geospatial information about use of wood and food products, and continuously monitored dissolved and particulate carbon, if possible with age information, for relevant rivers;

x) implement a data architecture that facilitates the combination of different data-streams;

xi) establish an International Carbon Office to operate a program to produce annually updated regional and global carbon budgets.

1.Human perturbation of the carbon cycle: the current state

The concentrations of CO_2 and CH_4 in the atmosphere are higher now than at any time in the past 20 million years. Current levels of CO_2 have increased by nearly 40% from pre-industrial levels of about 280 ppm to more than 386 ppm today, and they continue to rise at about 2 ppm per year. Current levels of CH_4 of over 1800 ppb are two-and-a-half times the pre-industrial value of 700 ppb. After a decade of stability, CH_4 has recently begun rising again.

The main causes of the observed increase in CO_2 are fossil fuel combustion and alteration of global vegetation through deforestation, land-use changes and agricultural management. The amount of CO_2 released each year through fossil fuel burning alone, continues to increase exponentially. In 2008, 8.7 Pg C were emitted. An estimated 0.5-2.5 Pg C per year were also emitted from deforestation and land-use change during that year. Emissions rose sharply between 2000 and 2008 reflecting increasing per capita emissions, with emerging economies contributing the largest share of the increase; coal burning was the main source of the increased emission (Fig. 1).

Almost half of the total anthropogenic CO_2 emission accumulates in the atmosphere. The rest is absorbed by sinks in the ocean and in terrestrial ecosystems. These natural sinks thus provide a discount of around 50% on the potential greenhouse effect caused by increasing CO_2 emission. The ocean takes up some 2.3 Pg C per year and soils and vegetation 3.0 Pg. The global magnitude of these sinks is uncertain, their patterns in time and space even more so.

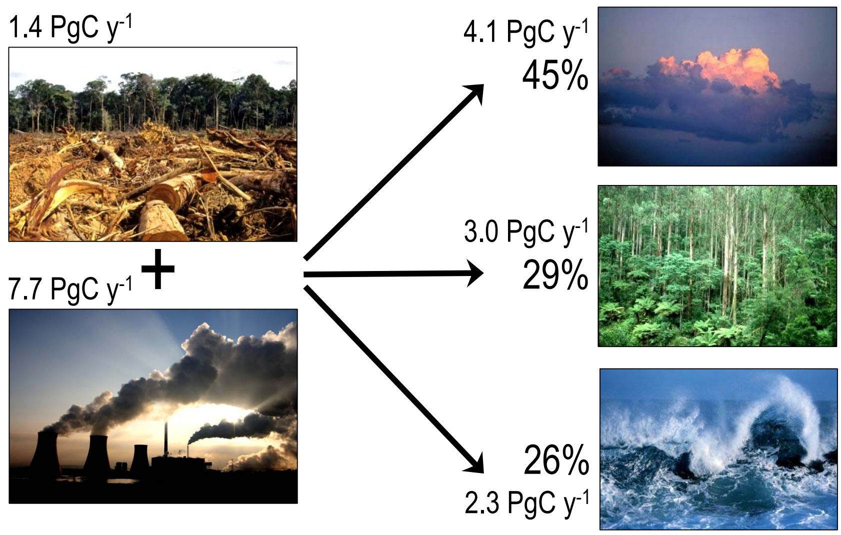

Figure 1. The anthropogenic perturbation to the global carbon budget and its fate during the period 2000-2008 (Global Carbon Project, 2010)

Natural CO_2 sink strengths vary with weather and climate. The large global climate perturbations driven by events such as El Niño or volcanic eruptions exert a strong influence on the exchange of CO_2. Regional climate anomalies such as the recent droughts in Amazonia, North America and Western Europe (2005, 2002 and 2003 respectively) can turn the land biosphere carbon sink into a temporary carbon source. Methane is another potent GHG. Its emissions include man-made sources reflecting the use of fossil fuel, waste decomposition in landfills, livestock production and rice cultivation, as well as natural sources such as wetlands, termites and wildfire. After being stable for the past decade, CH_4 concentration started to increase again early in 2007. This pattern is as yet unexplained, illustrating our limited understanding of CH_4 source and sink processes. Methane sources are sensitive to both socioeconomic drivers and climate variations.

The spatial distribution of CH_4 fluxes is highly uncertain. The atmospheric chemistry of CH_4 is quite unlike that of CO_2. Hydroxyl radicals (OH) remove CH_4 from the atmosphere on a time scale of eight years, a process that is also sensitive to climate change, through chemical reactions in the atmosphere. Therefore a small change in CH_4 sources or in the chemical sink can tip the CH_4 budget out of balance.

2.Rationale for an Integrated Global Carbon Observing System

Increasing CO_2 and CH_4 concentrations in the atmosphere modify the balance of the radiative budget of the Earth. Specifically, the growing atmospheric burden of these gases leads to an intensification of the Earth's natural greenhouse effect. This causes a shift in the planetary heat balance and forces the global climate system to change in ways that are not well understood, not least because of the complex interactions and feedbacks involved. Underscoring the urgency of this issue, the IPCC 4th Assessment Report (IPCC-AR4; Solomon et al., 2007) concluded that climate change is "unequivocal", that human emissions of GHGs are "very likely" causing this change, and that CO_2 is the "most important anthropogenic greenhouse gas".

Measurements have shown that since 1990, the Kyoto Protocol base year for reducing GHG emissions, radiative forcing of these long-lived agents had actually increased by 26% by 2008, rather than decreasing by 5% as had been the target for signatory countries. Increasing CO_2 alone was responsible for 80% of this increase and has been responsible for over 85% of the increase in radiative forcing during the past decade. The IPCC-AR4 further concluded that a doubling of CO_2 from pre-industrial levels of 280 ppm, anticipated in all scenarios to occur by "mid-century", will lead to an average global increase of temperature of between 2.0 and 4.5 ºC.

CO_2 is thus the most critically important GHG. Yet, there is huge uncertainty associated with the behavior of future natural CO_2 sources and sinks, as well as of future anthropogenic emissions and the effectiveness of mitigation efforts. This lack of knowledge creates the need to monitor CO_2 with a substantially improved observing, analysis and forecast system.

In the long run, information from this system will narrow down future uncertainties, providing observational evidence of the current state of the carbon cycle perturbation. Some of the variables that need to be observed have been classified as essential climate variables by the Global Climate Observing System (GCOS) and are observed through advanced sets of observation networks. The important opportunity now is for GEO to foster better integration of in situ and satellite observations with model-output under the GEOSS framework. This will significantly improve the quality of the Integrated Global Carbon Observing system (IGCO).

2.1.Policy-Relevant Information

The carbon cycle has significant relevance to climate change mitigation and adaptation in three ways:

i) Implementing effective GHG management strategies to safeguard climate requires a full knowledge of the natural carbon cycle. Today, only about half of the CO_2 emitted from fossil fuels remains in the atmosphere, but we do not know if or by how much this fraction is changing, nor do we understand the forces driving global and regional changes to land and ocean carbon uptake and release. Individual nations may implement emission controls but a comprehensive strategy of emission offsets and natural sink conservation must be designed to effectively curve down the increase of CO_2 (and CH_4) concentrations in the future and verify that in an independent transparent manner.

ii) It is possible that continued GHG emissions will take us past what is referred to as "tipping points". Tipping points describe positive feedbacks mechanisms in the Earth system whereby increased climate forcing leads, for example, to an increase in natural CO_2 emissions from the biosphere, in a spiral of increasing global warming. The impacts of these thresholds, whether in the Arctic, tropics, or elsewhere, are difficult to specify, much less to quantify.

iii) Uptake of anthropogenic CO_2 by the Earth system causes changes to ecosystems, both beneficial and deleterious. One of these is the fertilization effect, through which plants grow faster in a richer CO_2 environment and thus perhaps sequester a larger fraction of the CO_2 emitted by human action. Another is acidification of the oceans caused by the uptake of CO_2 by seawater, with substantial consequences on marine ecosystems. Therefore climate mitigation measures that target atmospheric CO_2 concentrations will also have collateral benefits such as combating ocean acidification.

It is critical that we quantify and understand the current and potential impacts of the anthropogenic perturbations on the carbon cycle, both globally and regionally. Selecting the appropriate mitigation options depends upon this understanding, as do possibilities for sequestration. Although managing carbon emissions will require the involvement of industry, financial markets, and governments at all levels, the ready availability of the best possible, accurate and open information will be critical to the success of these endeavors.

2.2. Emerging Measurement Needs

Because of the urgency and potential severity of climate change, it is likely that society will strengthen efforts to substantially reduce CO_2 and other GHG emissions. Unlike other large-scale emission reduction efforts such as the 1987 Montreal protocol against ozone-depleting substances, these will likely involve many economic sectors of society and will vary by nation, region, and approach. Large-scale non-carbon emission reductions in the past have all required on-going verification to ensure that the desired outcomes are achieved. These include measurements of pH in lakes and rain for sulfur emission reduction; measurements of ozone and ozone-depleting gases for stratospheric ozone recovery; and measurements of ozone, other reactive gases, and particulate matter for regional air quality improvement. The scale, complexity and variability of the carbon cycle, along with the involvement of other GHG, the global nature of the problem, and the number and variety of emitters and offset options as well as the presence of natural sources and sinks, make independent verification of the effectiveness of GHG management strategies a daunting task.

The ability of nations to implement policies that limit atmospheric CO_2 and other GHG concentrations will depend on their ability to monitor progress and determine what is, and what is not working. Uncertainties in existing observations and analyses need to be reduced substantially to support effective national-level policies and international reporting on climate change mitigation.

To date, efforts to monitor and report CO_2 and other GHG emissions have been based mostly on limited land-use observations, self-reported data on energy use, and extrapolated point-source emission measurements. Such data are known to have many uncertainties that limit their ability to support GHG management strategies. This presents a challenge to implementing the range of GHG policies that are being discussed in many countries. These policies include supporting treaty negotiations, verifying treaty obligations, certifying tradable permits, offsetting GHG emissions, and providing more accurate inventories of emissions and offsets. UN-level negotiations on the inclusion of land use activities in developing countries, for instance, have been held back for many reasons, including key technical challenges such as access to regular and sufficient-quality satellite data and associated analysis tools for national-level forest-cover and annual change mapping at sub-hectare resolution.

Thus to develop effective GHG management strategies, there is an urgent need for a globally integrated observation and analysis system to track changes in atmospheric GHGs and provide routine estimates (with confidence limits) of net atmosphere-surface exchange at regional or sub-regional scales. The complexity and variability of the natural carbon cycle combined with the effects of climate change on natural systems only make the challenge greater. Beyond the essential knowledge of fluxes, information is also needed about drivers of fluxes in each region. In addition, quantification of carbon pools and their changes in response to human intervention and climate is key for making accurate future projections.

Systematic global observations are also essential to improve our knowledge of the carbon-cycle feedbacks between the ocean and land components. National and sovereign circumstances will naturally dictate the complexity and type of national monitoring, reporting and verification (MRV) systems, which individual countries might agree to establish for reporting emissions to the UNFCCC. GEO has an important role in coordinating global observation and facilitating unencumbered access by all countries to relevant data, tools and methodologies.

3.Vision and Elements of IGCO

The Integrated Global Carbon Observing System is designed to support two major products used by policy makers in implementing carbon policy:

i) The establishment of a robust and transparent carbon tracking system

ii) The establishment of accurate carbon budgets at different scales.

Both tools will help in estimating the effectiveness of the measures undertaken to control emissions and manage the carbon cycle, and underpin this with new understanding of carbon cycling in the Earth system and climate feedbacks.

The vision of an Integrated Global Carbon Observing System is built around two complementary groups of observations representing the main carbon reservoirs (pools) in each of the Earth system elements (Fig. 2) and exchanges (fluxes) between these reservoirs. Hence, the system should include observations of the carbon content in each of the elements and the corresponding exchanges between these elements. These observations are made in parallel to the development of new geo-informational tools, products and models.

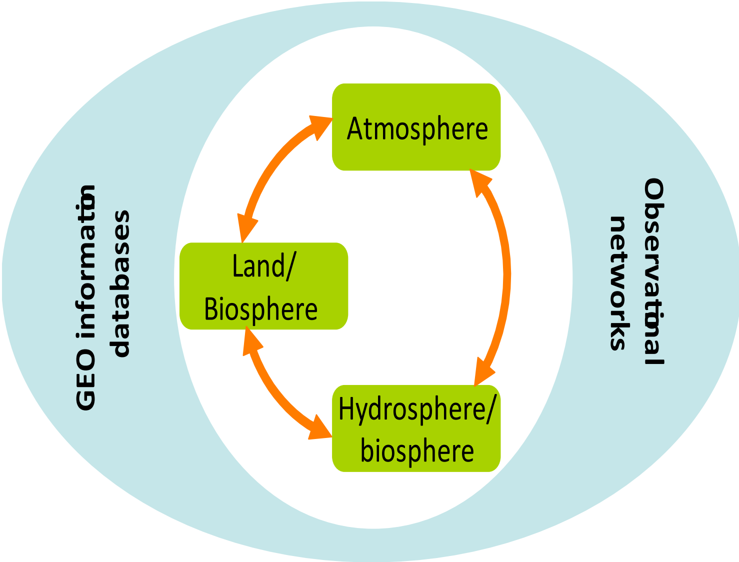

Figure 2. The Global Carbon Cycle and Elements of the Integrated Global Carbon Observing System

Carbon Reservoirs. *This group of observations enables quantification of the current carbon stocks, as required to assess their vulnerability or stability over time scales of 10 years or more.*

CO_2 and CH_4 Exchange. *This group of observations enables quantification of the regional distribution and temporal variability of CO_2 and CH_4 fluxes around the globe and among different elements of the Earth system.*

Integrative data sets. *This group of observations consists of geo-information tools, databases and models integrating global products of carbon pools and fluxes.*

3.1.A scientifically ground-breaking, policy-relevant IGCO

An integrated global carbon observation and analysis system will need to differentiate the large natural source and sink processes from the smaller anthropogenic exchanges. It should also monitor the short and long-term compliance of specific climate mitigation measures at global and national-level scales. It will need to identify the types and the source of emissions, e.g. distinguish fossil fuel and non-fossil-fuel sources, and it should be able to track agricultural and forest sinks by detecting relatively small departures from reference levels. Developing and operating such a system will require a coordinated effort, spanning several partner organizations to support instrument development, data and model validation, sustained observations, quality assessment and control, data assimilation, database management, carbon-cycle modeling, fossil-fuel inventories, large-scale computing resources, decision-support analyses, and systems engineering.

The spatial resolution needed for global maps of CO_2 and CH_4 surface fluxes depends on their final use. For global studies with inversion models, the ultimate target spatial resolution, is typically 10 km over land and 50 km over the ocean, with temporal resolution of a week or less (Fig. 3). 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 process models of land and ocean carbon cycling. The short term objective of monthly fluxes with spatial resolution of 100 km over land and 500 km over the ocean may be possible within the next decade (Section 5). However, finer spatial resolutions (sub-hectare to 10 km) are needed for national-level land-use monitoring, reporting situations in the short term for mechanistic studies and verification of compliance with policies, and for detailed mechanistic and validation studies.

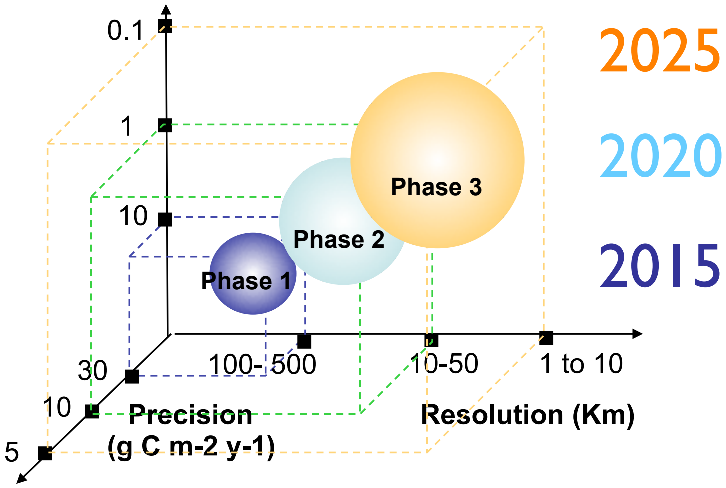

Figure 3. Future evolution of requirements toward finer resolution and precision capabilities for producing global maps of CO_2 and CH_4 surface fluxes.

3.2. The core observational elements

The core elements to observe the reservoirs and exchange fluxes of the Integrated Global Carbon Observing system are:

3.2.1. Atmospheric domain

i) Surface-based in situ stations and aircraft observations of high precision CO_2 and CH_4 concentrations across a global network of at least 1000 surface stations, covering all tropical and boreal ecosystems as well as vulnerable ocean regions.

ii) Complementary in-situ observation of isotopes of CO_2, CH_4 and N_2O, and O_2/N_2 ratio to evaluate land and ocean sink ratio, and the locations of these sinks.

iii) Synoptic global satellite observations of column-integrated and vertical distribution of atmospheric CO_2 and CH_4. Sufficient accuracy will be obtained to assess fluxes from satellite data by making auxiliary observations of aerosols and clouds or development of other disturbance free methods. Instrument calibrations will be traceable to a primary standard and frequently calibrated using ground-based observations.

3.2.2. Ocean domain

i) A global ocean CO_2 flux measurement network measuring the surface CO_2 partial pressure difference between atmosphere and seawater (pCO_2) with a coordinated combination of research vessels, ships of opportunity, and autonomous drifting buoys.

ii) Complementary pCO_2 observations in coastal oceans, requiring a variety of platforms (fixed stations, frequent ship transects).

iii) Dissolved carbon content of the ocean with global coverage, measured typically at 10-year intervals, to estimate the input of anthropogenic CO_2 into surface waters.

3.2.3. Terrestrial domain

i) In situ observations of ecosystem fluxes made by the eddy-covariance technique, with observations of CO_2, water vapor and heat fluxes at representative locations, including a range of successional stages and land-use practices and intensities. Over wetlands and rice paddies, CH_4 eddy-covariance flux observations should also be made. A global network of about 500 flux measurement stations is envisioned.

ii) Inventories of the spatial and global distribution of forest and woodland biomass, measured in situ at a minimum of five-yearly intervals, and annually by high-resolution remote sensing techniques. Key control indices such as nitrogen content, and leaf area index will also be measured.

iii) Inventories of the spatial and global distribution of litter and soil organic carbon content in the upper meter of soil, measured in situ typically at ten-year intervals, again including nutrient content, and measures of decomposability.

iv) In situ and remote-sensing observations of the spatial distribution of permafrost, peatland and wetland organic carbon pools down to bedrock, measured typically at ten-year intervals, but at higher frequency in fast changing areas. Monitoring of the abrupt loss from these pools, due to events such as peatland fire or collapse of permafrost land.

v) Carbon harvested as crops and wood products, as well as peat and biomass harvested and used for energy production.

vi) Changes in the carbon content of water reservoirs, lakes and freshwater sediment pools.

3.2.4.Satellite observations

A combination of satellite observations, backed up by long-term continuity of measurements, delivering global observations of the essential ancillary variables required to estimate surface-atmosphere CO_2 fluxes by modeling. These essential ancillary variables are:

i) Ocean color and marine ecosystem composition.

ii) Ocean physical state, e.g. from altimetry

iii) land cover, land use and land-use change.

iv) Wetland area.

v) Fires and other ecosystem disturbances.

vi) Land ecosystem biophysical variables.

vii) Permafrost area and its dynamics.

viii) Satellite information relevant to fossil fuel emissions.

3.2.5.Integrative data sets

i) Global geospatial information on fossil fuel emissions of CO_2 and CH_4 and their temporal variability, including sectorial information and uncertainties.

ii) Global geospatial information on CO_2 and CH_4 emissions from biomass burning.

iii) Geospatial information on CH_4 emissions from landfill, and CO_2 emissions from food and wood production.

iv) Climate and weather variables at the various scales necessary to model atmospheric transport accurately, and ocean and terrestrial CO_2 and CH_4 fluxes and their variability at the relevant scales for assimilation into the atmospheric models used in inversion modeling.

3.2.6.Data archive

A comprehensive data archive containing the quality-checked observations and data syntheses.

3.2.7.A synthesis and assessment system

An international carbon office, building upon a network of experts in different countries, providing regular and fast-track synthesis of the global carbon budget, of regional details in CO_2 fluxes and their drivers, and of the global CH_4 source and sink distributions.

In summary, a multi-scale, coordinated system of integrated global carbon observations would contribute to answering critical scientific and societal questions, including:

- What are the size, location, and processes controlling present-day terrestrial and marine carbon sources and sinks?
- What is the effectiveness of deliberate carbon sequestration activities? What are the implications of these activities for the global carbon cycle?
- How effective are regional and national GHG management and policy interventions? How can they be improved and where?
- How will carbon sources and sinks behave in the future under higher CO_2 and altered patterns of climate, land vegetation, and ocean circulation?
- How soon will feedbacks that enhance global warming come into play and what carbon-cycle management tools are likely to be effective in combating or preventing them?

4.Towards an Integrated Global Carbon Observing System

4.1.Current and Evolving Carbon Cycle Observations

Over the past ten years, the carbon cycle observing system has developed through various programs and projects. Spatial coverage has been extended through the establishment of new in situ monitoring stations and transects, and through the launching of space-based remote sensing platforms. An overall picture of how these ingredients complement each other was provided by the Carbon Theme Team report produced by IGOS-P in 2004.

Implementation was largely through ad hoc research programs, rather than being designed with an operational system in mind. The integration of the observations, both within and across disciplines and with models has moved forward significantly. Various harmonized and integrated data products from the GLOBALVIEW, GLOBCOLOR, GLOBCOVER, SOCAT and Fluxnet program have improved quality and accessibility to data. Modeling projects such as CarbonTracker, TransCom, GEMS/MACC, GEOLAND-2, CARBONES and CCDAS have begun to integrate data across platforms and atmospheric, oceanic and land reservoirs.

The spatial and temporal scale coverage of the current observation system is depicted in Fig. 4. In other cases, satellite observations of indicators of primary production (e.g., ocean color; Fraction Absorbed Photosynthetically Active Radiation, FAPAR) will guide process-based models. Time-series measurements of dissolved inorganic carbon in the deep ocean allow tracking of the ocean sink and surface ocean measurements can aid in evaluating the influence of interannual variability in oceanic fluxes, such as that caused by El Niño events.

4.2.Atmospheric domain

4.2.1.In situ surface station networks

Measurements of atmospheric concentrations of CO_2 and CH_4 form an effective complement to observations of fluxes and pools at the ocean and land surface to verify measurements of carbon stock changes and process-level variables. Although the atmosphere is

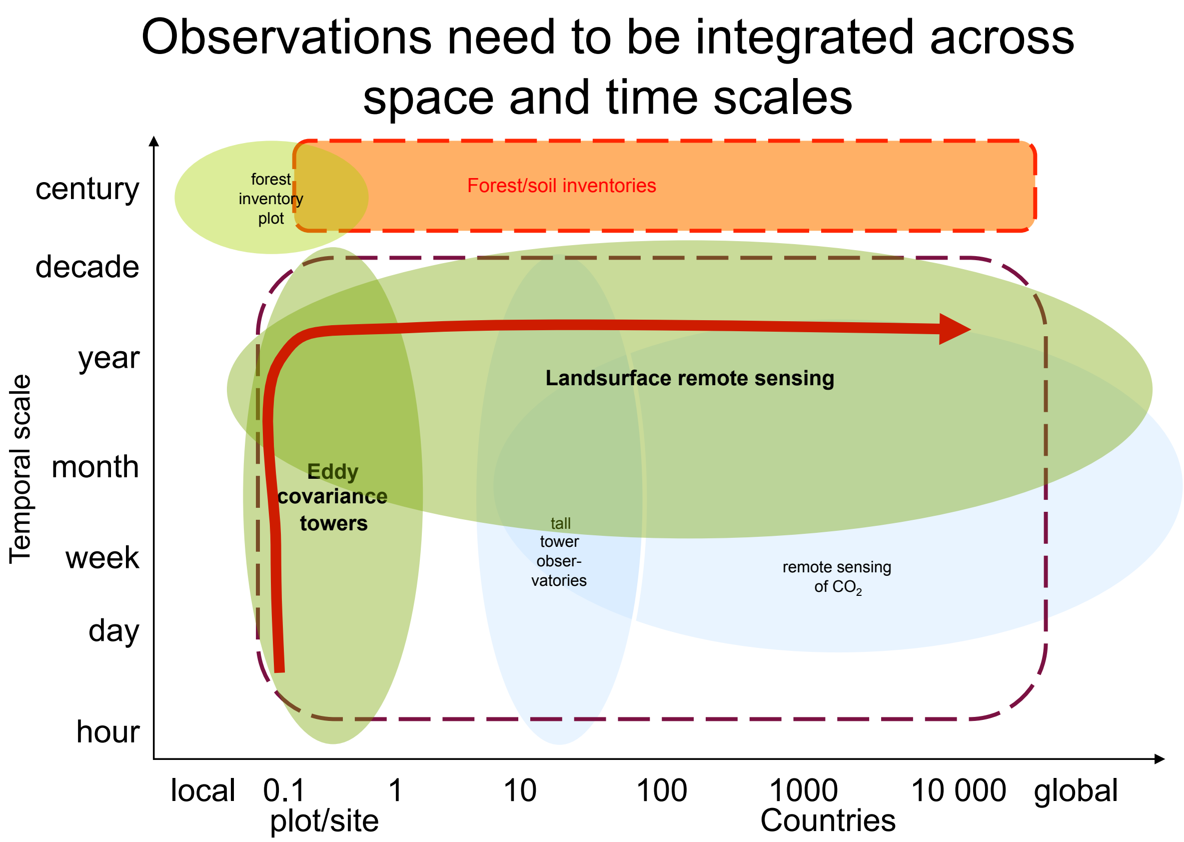

Figure 4. Observation need to be integrated across time and space scales. Example of the range of observations from a terrestrial fluxes perspective. x-axis is in km.

well mixed the small signals of spatially and temporally varying surface fluxes persist for several days in the observed patterns of CO_2 concentration in the atmosphere. Observations of CO_2 concentration can be used to quantify surface fluxes using so called "atmospheric inversion" models. Inversion is a powerful technique, which has already proved capable of providing global-scale, and in some instances, continental-scale information on fluxes. However, the very sparse network of atmospheric in situ stations cannot constrain the patterns of sources and sinks at the policy-relevant, single-country scale. The density and coverage of the atmospheric network thus needs to be increased substantially to derive national or even regional flux estimates. Measurement of tracers such as carbon isotopes can provide further constraints to disentangle the impact of anthropogenic, terrestrial and oceanic contributions.

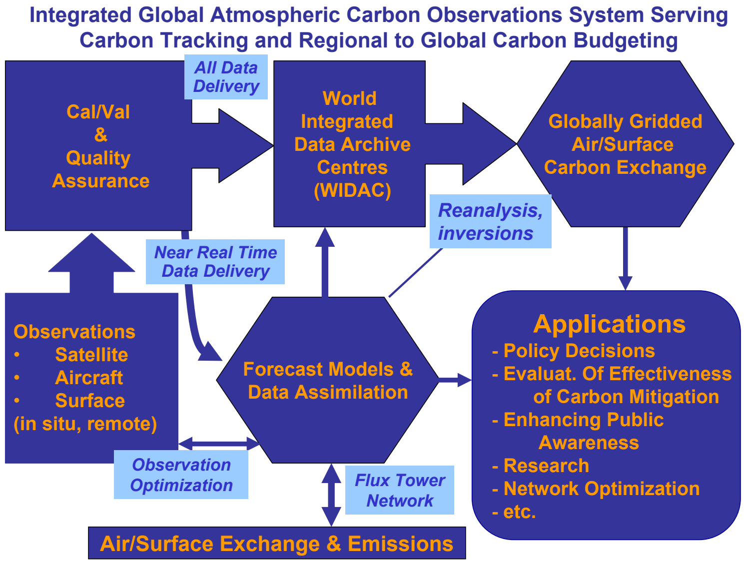

Figure 5. IGACO GHG strategy being implemented by WMO-GAW as the atmospheric component of IGCO.

4.2.1. WMO-GAW coordination role

The WMO GAW program (http://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html) offers a unique integrated approach to coordinating atmospheric carbon cycle observations and research (Fig. 5). It is a unique international framework of a multitude of national monitoring organizations, and is recognized by the Global Climate Observing System in its implementation plan to the UNFCCC. WMO GAW implements the recommendations of the Integrated Global Atmospheric Chemistry Observations strategy (IGACO WMO TD No 159; ESA SP182) report on Atmospheric Chemistry to IGOS-P that was subsequently adopted by GEO.

The GAW program coordinates the activity of the observational network contributed by the partner national monitoring organizations, and includes a Central Calibration Laboratory maintaining primary standards for CO_2, CH_4 and N_2O, and the WMO World Reference Scale for GHG recognized by the Bureau of International Weights and Measures (Bureau International des Poids et Mesures, BIPM). It includes World and Regional Calibration Centers maintained by WMO partners, performs station audits, develops standard operational procedures and measurement guidelines and manages a rolling review process for the data quality objectives and measurement requirements through biennial WMO/IAEA Expert Workshops. Quality controlled measurement data are submitted, archived and disseminated by the World Data Center for Greenhouses Gases (WDCGG). This set of data is used to create global products and assessments.

The atmospheric surface in situ and aircraft network is shown in Fig. 6. It consists of flask air sampling measurements, continuous measurements at fixed stations, and observations from mobile platforms (ships and aircraft). It has changed little in spatial extent since the large expansion seen in the 1980s and 1990s.

However several new elements have improved the frequency and quality of the observations. For example, technological developments (e.g. cavity ring-down spectroscopy) have provided more accurate instrument calibration for GHG analyzers. Tall towers equipped with continuous analyzers have increased in number, especially in the framework of dense regional networks such as NACP (http://www.nacarbon.org/nacp/) in North America and ICOS in Europe (http://www.icos-infrastructure.eu/). The development of accurate CO_2 sensors, equipment capable of automatic operation at remote sites, has made this possible, along with the outfitting of several commercial airliners to carry continuous gas analyzers, providing regular profiles and upper tropospheric transects across various routes. These CO_2 observations are operated as part of a research project (CONTRAIL, CARIBIC). The interplay of these measurements throughout the atmosphere is depicted in Fig. 7.

As reported by the last assessment of the WDCGG [WMO WDCGG Data Summary, No. 33, GAW DATA, Volume IV-Greenhouse Gases and Other Atmospheric Gases, Published by Japan Meteorological Agency in co-operation with World Meteorological Organization, March 2009] 193 submissions of data are available for CO_2 and 177 for CH_4. One of the key data products available for the atmospheric domain is the annual WMO Greenhouse Gas Bulletin which summarizes the current state of GHG measurements and reports the changes in atmospheric GHG contents (available at http://www.wmo.int/pages/prog/arep/gaw/ghg/GHGbulletin.html). Other products are available at the sites of various partner organizations, e.g., http://www.esrl.noaa.gov/gmd/dv/, http://www.carbontracker.eu/, and https://ramces.lsce.ipsl.fr/.

4.2.2.Satellites

Satellite observation of CO_2 and CH_4 concentrations are key to improving the spatial coverage of the sparse in situ networks, particularly where there are large gaps in coverage. A reanalysis of the infrared bands from the NASA AIRS instrument has produced estimates of mid-troposphere column integral CO_2.Infrared observations for both CO_2 and CH_4 are also available from the Tropospheric Emission Spectrometer (TES) and the Infrared Atmospheric Sounding Interferometer (IASI). Although observations by these instruments contain very little direct information on surface sources and sinks they are complementary with other types of GHG measurements, with the potential to provide vertical information on GHGs and help to improve transport models and inversions.

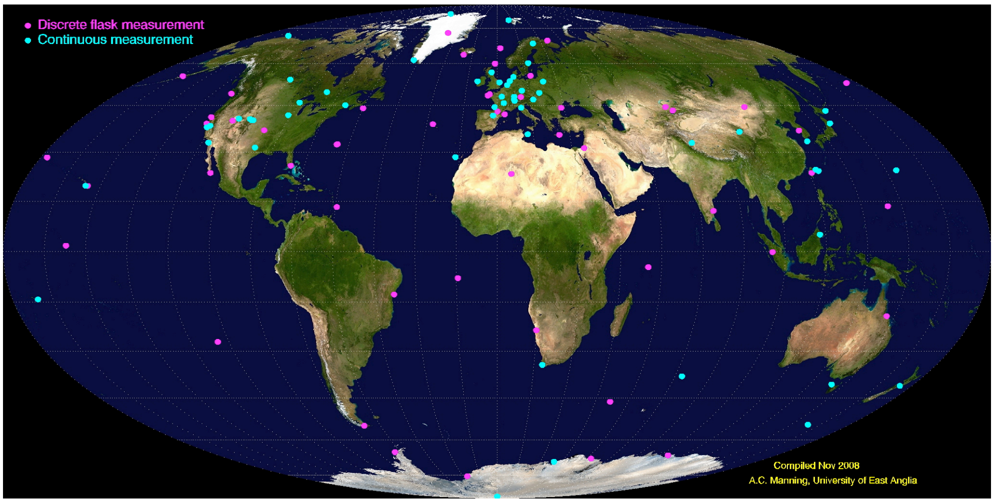

Figure 6. Map of the current atmospheric surface network. This network represents the cooperative efforts of various national programs, coordinated worldwide by the Global Atmosphere Watch program of the WMO. Data are reported to the World Data Center on Greenhouse Gases (http://gaw.kishou.go.jp/wdcgg/). Continuous measurement sites contain more information to constrain nearby fluxes than discrete flask sampling.

The SCIAMACHY instrument on the European environmental satellite (ENVISAT, launched in 2002) is the first to provide CO_2 and CH_4 measurements sensitive to all altitude levels, including the atmospheric boundary layer. This capability comes from its nadir observations in the near-infrared/shortwave-infrared spectral range. The precision for CO_2 is a few parts per million. The precision for CH_4 is around 1%. SCIAMACHY data are being used for initial inverse modeling of CH_4 fluxes, but require complementary information from ground-based in-situ networks.

GOSAT from JAXA and OCO from NASA are the first satellites dedicated for GHG observation from space. They have similar goals of measuring CO_2 and CH_4 column integrals at better than 1% precision, liked to current spatial and temporal integration scales. This precision would be sufficient to improve the surface flux estimates compared with that obtained from using the surface in situ network alone,

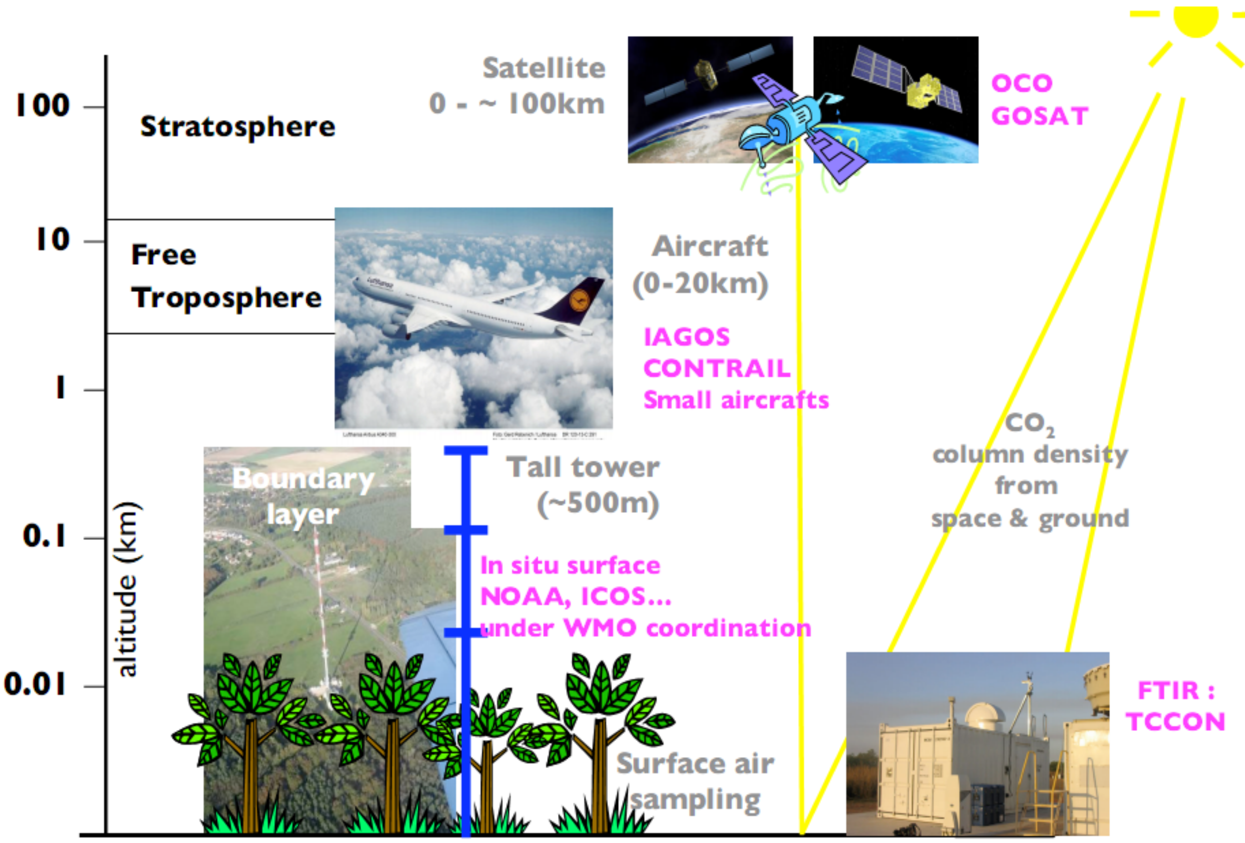

Figure 7. Example of vertical continuity needed for atmospheric GHG observations between surface networks and satellites. It is of paramount importance that these data remain calibrated on the same scale to be used by atmospheric inversions.

especially over continental regions poorly covered by the surface network (Tropics, Siberia).

While GOSAT attained orbit and has begun sending data, the OCO launch failed. However, OCO 2 is now being planned and the experience gained through the construction, testing and calibration of the original will be useful in designing the second version. In addition, EUMETSAT and ESA are planning to include solar absorption channels for the detection of CH_4 and potentially CO_2 in the Sentinel 5 UVNS sensor that will be flown on the European post-METOP system from 2020 onwards. Further phase-0 studies are underway for a micro-satellite MICROCARB at CNES, CARBONSAT at DLR and for a LIDAR observing CH_4 called MERLIN, as a joint German / French initiative between CNES and DLR.

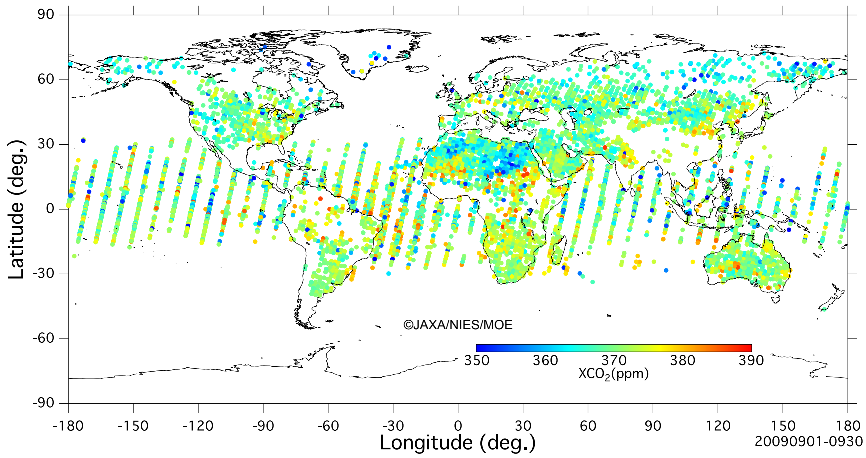

Figure 8. XCO2 column averaged dry air mole fraction from GOSAT. Data Sep.1 to Sep.30.

Data and retrieval algorithms from GOSAT are currently being tested and early retrievals look promising (Fig. 8). Improvements to the treatment of the aerosol and/or cloud disturbances are in progress, including the retrieval of surface pressure from an O_2 absorption band. Further data integration activities are required to take full advantage of this new data product, i.e. validation with surface-based total column observations from the TCCON network (Fig. 9) and comparison with data measured from aircraft.

In the longer term data from active (LIDAR) sensors could improve upon the passive sensor capability used so far, and might be able to provide better spatial and temporal coverage, in particular coverage of mid- and high latitude regions in wintertime.

New analytical approaches such as the development of quantum-cascade lasers, and deployment of ground-based (i.e. upward looking, total-column) remote sensing systems should enhance both the coverage and frequency of high quality GHG from space observations,

These improvements in observational capacity need to be complemented by improvements in our capability to model high spatial resolution atmospheric transport. At the high resolution that will be required for verification purposes the uncertainty in our transport models is currently too large and needs to be reduced to make the best use of the new high resolution carbon data.

4.3.Ocean Domain

To compute correct air-sea CO_2 fluxes and carbon inventories in the ocean both ocean surface data sets and three-dimensional deep section data are required.

4.3.1.Ocean surface measurements

High quality ocean surface CO_2 partial pressure measurements (pCO_2) must be made, together with atmospheric pCO_2 measurements at the same location. The air-sea CO_2 fluxes can then be computed. Two paired measurements of ocean carbon variables are needed: total dissolved inorganic carbon and alkalinity, and these measurements have to be made at relatively short time intervals, as the surface ocean pCO_2 varies with the seasonal cycle and the associated temperature, salinity, circulation, and biological production changes. Over the last decade, the ocean domain has seen a dramatic increase in the quality and quantity of observations coming from hydrographic cruises, ships of opportunity and moored buoys. The International Ocean Carbon Coordination Project (IOCCP, http://ioc3.unesco.org/ioccp/Index.html) has been leading the coordination of the ocean observations and produces regular updates of maps of the observing system. Actions following workshops on hydrography, pCO_2 and O_2 observations continue to improve the ocean observing system.

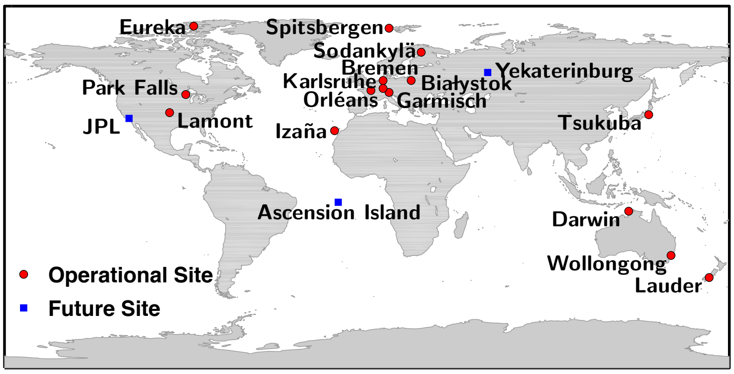

Figure 9. TCCON station locations, 2009.

Satellite measurements of ocean color, wind stress, temperature, and further physical as well as chemical/biological variables are needed, especially in areas where only few in situ measurements are available to produce a better constrained distribution of ocean carbon state variables

The surface data from all of these platforms have been combined into large data products. Previous global climatologies, e.g. by Takahashi et al. (2009), gave a spatially detailed but time-averaged view of fluxes. But in a major synthesis effort, the Surface Ocean CO_2 Atlas (SOCAT) project, these are now in the process of evolving towards time-resolved data products, which reveal decadal and shorter trends. Recent efforts have shown that, for regions such as the northern hemisphere oceans, which are well covered by shipping routes, it is possible to constrain the net annual uptake flux to an accuracy of order 20%, with good seasonal and spatial resolution. The Carbo-Ocean project for the North Atlantic achieved this by combining data from a surface observing network with remotely sensed observations and re-analysis products. Fig. 10 shows the current global observing system.

4.3.2.Deep ocean surveys

Three-dimensional ocean carbon data classically consist of total dissolved inorganic carbon measurements together with alkalinity measurements from the same cast. Highest measurement accuracy is needed as changes in

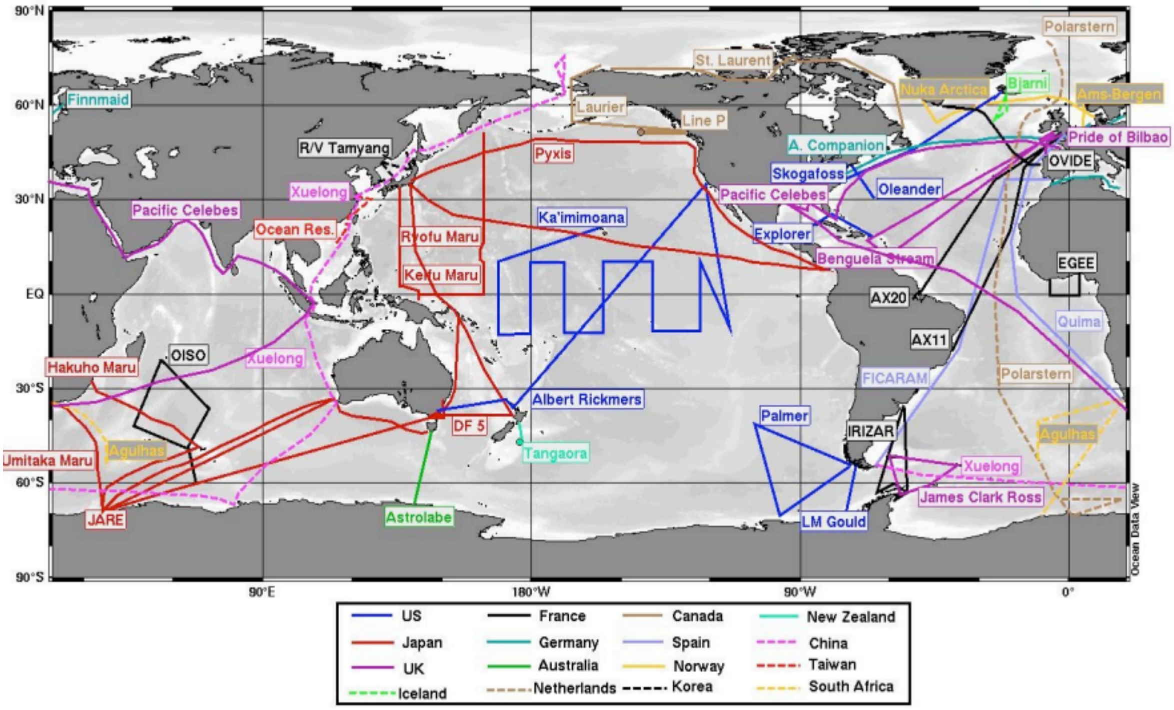

Figure 10. Route of ships (research vessels, ships of opportunity) observing pCO_2

ocean carbon inventories due to natural fluctuations and anthropogenic CO_2 uptake are small against large background values. The anthropogenic contribution to oceanic carbon, can be isolated using carbon isotope data, as well as marine oxygen measurements in concert with atmospheric O_2/N_2 measurements. Satellite measurements of ocean color, wind stress, temperature, and further physical as well as chemical/biological variables are needed, especially in areas where only few in situ measurements are available to produce a better constrained distribution of ocean carbon variables

4.4. Terrestrial domain

4.4.1. Eddy-covariance flux networks

The heterogeneous nature of the land surface, and the difficulties in modeling the behavior of biological processes make in situ observations of terrestrial fluxes and reservoirs a major challenge. The Fluxnet project is a collaboration of regional flux networks, intended to combine data for global synthesis. There has been a large expansion in the number of eddy covariance towers from around 100 in 2000 to almost 600 in 2009. The network has expanded to every continent (except Antarctica; Fig. 11). The main Fluxnet regional networks are: Ameriflux, Asiaflux, ICOS-CarboEurope, CarboAfrica, LBA (Amazonia) and OzFlux (Oceania). In terms of temperature and rainfall, the range of climates covered is almost complete; cold-and-dry climates, and wet-and-warm climates are exceptions.

The Fluxnet global network provides an important data set covering many different ecosystem types, climates and disturbance classes. Most of the measured variables are crucially relevant to the carbon cycle: fluxes of carbon, water and energy; meteorological data; ancillary data at each sites (e.g. LAI, biomass, soil carbon, soil moisture, etc.). Data availability has improved dramatically with the release of the Fluxnet Synthesis Data product in 2006, when a global scale synthesis activity was started (http://www.fluxdata.org, see Fig. 11). This synthesis requires the standardization of all data from the different regional networks.

The Fluxnet observations, that are by essence made at local scale, are being combined at intensive observation sites with land use and land cover information, satellite imagery, and complementary biometric and soil measurements in order to develop better retrievals of land-atmosphere fluxes, given landscape heterogeneities.

Fluxnet observations are also being combined with ancillary information such as global satellite measurements of surface biophysical parameters, soil properties and climate data, using new data mining, pattern recognition and machine learning algorithms, to produce maps of CO_2, water and energy exchange fluxes, including re-analysis of the past 20 years (Fig. 12). These techniques are yielding promising results, in identifying the drivers and limitations of photosynthesis, evapotranspiration and net CO_2 flux using.

Figure 11. The Fluxnet observational network based on La Thuille data set. Red dots are sites with incomplete data records. Land cover codes are green: trees; yellow circle: grass; yellow square: crop; inverted orange triangle: shrub; blue wetlands.

4.4.2. Forest and soil extensive inventories

Many countries have national forest inventories that span decades and contain data from a large number of sampling locations, but many forest biomes elsewhere, and in particular those in developing countries, have little or no inventory data. Moreover, very few developing countries have national forest inventories at repeated points in time. Countries with existing forest biomass inventories typically use these as the basis of their forest resource reporting to the UNFCCC, and in some cases, the in situ forest inventory information is scaled to national accounts using remote sensing information on forest cover and type (Fig. 13). However, many of these surveys were originally developed for assessing forest resources and for agricultural purposes (not for carbon measurement) at the national and sub-national levels. Very few developing countries operate “border-to-border” national forest monitoring systems, making it a difficult task to coordinate and aggregate inventory data internationally, or to better integrate them with remote sensing information and ecosystem and carbon models for predictive purposes.

To improve the data from forest inventories as a basis for monitoring carbon, additional sampling is needed for carbon in soils, dead wood and woody debris. Areas recently disturbed by events such as hurricanes and large wildfires need additional sampling to assess impacts. If reports are required for areas smaller than states, such as groups of counties or specific national forests, remote sensing augmented with an intensified sampling density will be required.

Various databases have been developed to provide allometric equations, wood density and biomass expansion factors for the various forest ecosystems of the world (http://afoludata.jrc.ec.europa.eu, http://www.carboafrica.net/index_en.asp).

Currently, methods to estimate carbon stocks in temperate forests are well established and accurate; although the methods for tropical forests are limited. The allometric equations that have been developed for tropical forests do not cover the various tree sizes and the range of tree species is very limited, covering small geographical areas. Using constant conversion/expansion factors, as is usually done, results in large errors, since both wood density and expansion factors vary considerably with age, species and geographical location.

The Food and Agriculture Organization of United Nations (FAO) through the Global Forest Resources Assessment 2010 (FRA 2010), is undertaking a remote sensing survey (RSS) of forest which covers 1 percent of the global land surface, compatible with many national forest inventory programs. Satellite data will complement the national data, producing global and regional tree cover maps, and showing where changes in forest cover are occurring. The survey incorporates auxiliary information including local knowledge and results from existing and past field inventories.

Progress towards an integrated system has also been made as a result of the Global Terrestrial Observation System (GTOS) that sup-

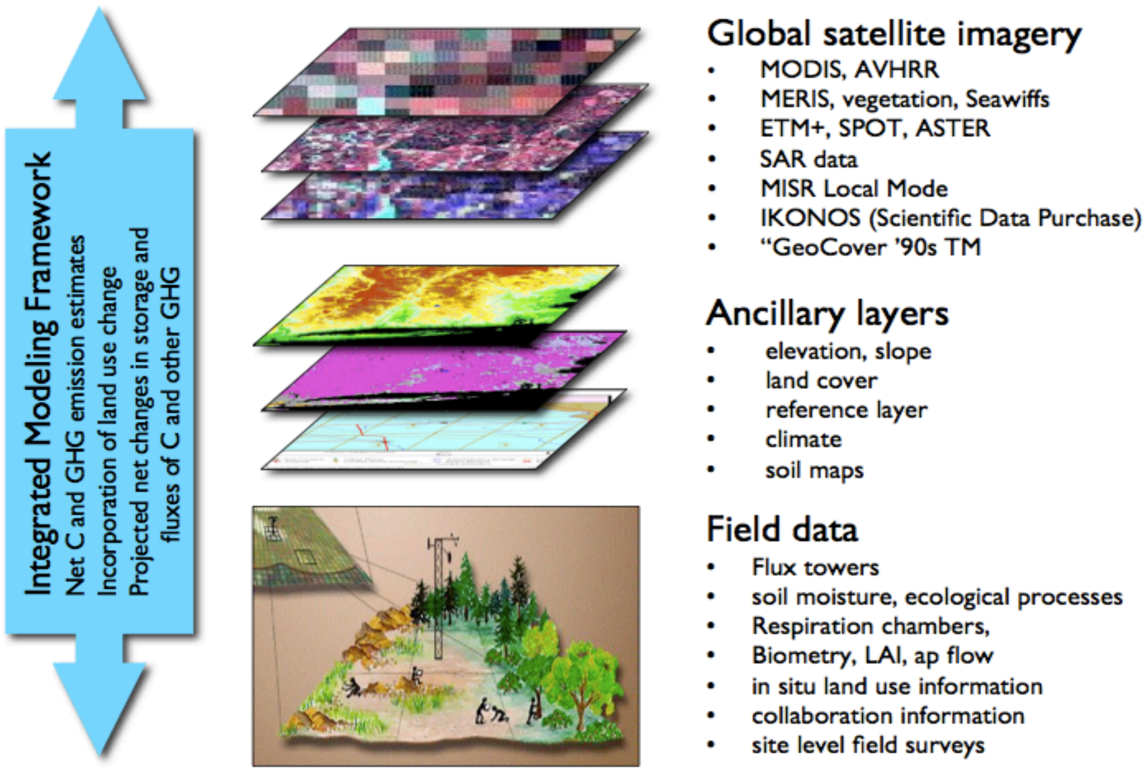

Figure 12. Diagram showing how ground-based flux data can be upscaled from local to regional scales.

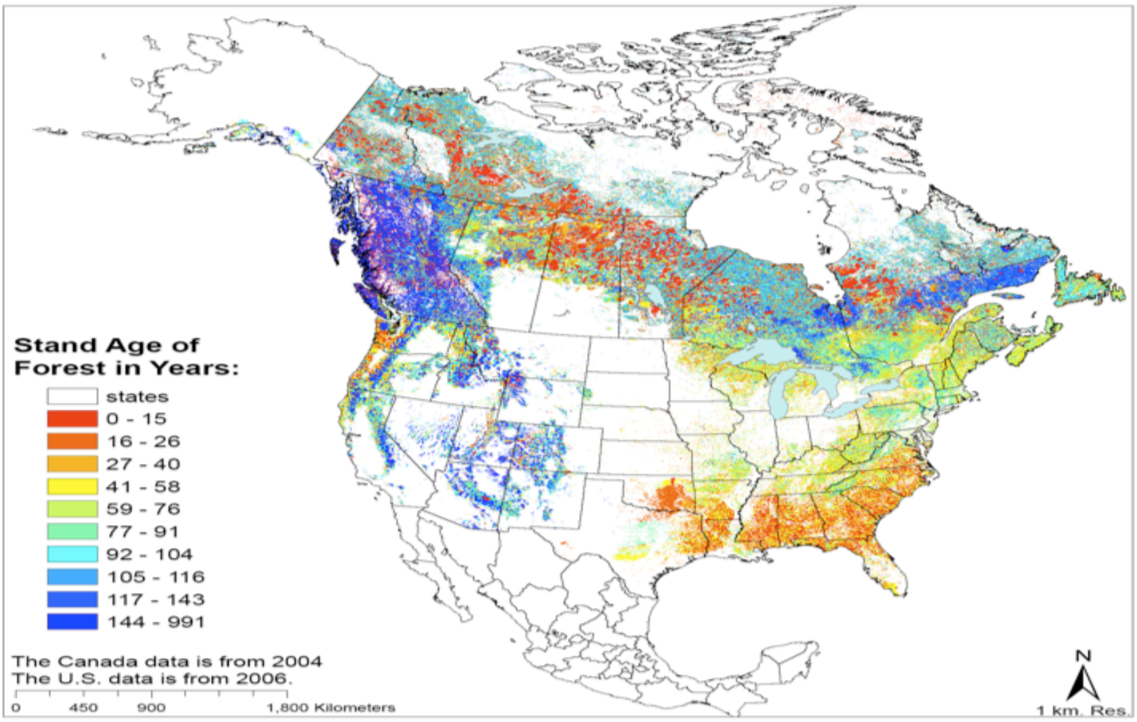

Figure 13. Map of stand age structure of US and Canada forests (data US Forest Service).

ports the development of standards for each of the essential climate variables (ECVs) in the terrestrial domain, including biomass and leaf area (soil carbon will be included soon) (http://www.fao.org/GTOS/doc/ECVs/T12/GTOS-ECV-biomass-v08.pdf).

Finally, the recently established United Nations collaborative program on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD), is a joint international project between UNEP, UNDP, FAO and nine developing countries. REDD supports the countries in developing national monitoring, reporting and verifying systems. It allows the development of national forest inventories that integrate permanent and temporary sample plots in unmanaged and managed forest with a combination of multi-spectral optical and radar satellite imagery. Nevertheless, there is still a high degree of inconsistency and uncertainty in the quality of national inventories with regard to definitions, standards, type of data collected, and quality.

4.4.3.Soil carbon

Various national soil surveys are carried out and these allow the quantification of carbon stocks in soils. The best inventories sample countries on a grid of a few km, with a revisit time of 10 years. After 1-2 revisit times, these inventories allow the detection of regional changes driven by trends in climate or land use change. While most of these surveys suffer from the poor quality of data, they represent the only source of information currently available. At global scale, various efforts have been developed to harmonize the different soil classifications in already existing soil data, and to establish a world soil map (FAO-IIASA). While the various efforts to improve the precision of the maps and the associated carbon data continue, new soil profiles are continuously collected and the data are harmonized using pedotransfer functions. However, in many parts of the world the resolution of the soil maps is still very coarse and the number of soil profiles limited. Institutions such as the ISRIC are collecting data on soil properties in order to provide international databases (http://www.isric.org/).

Unfortunately much work has yet to be done to create continuous, standardized, geo-referenced forest biomass and soil carbon inventories. It is critical to harmonize the widely varying methodologies for inventory and analysis, in order to synthesize carbon estimates. Methods to measure carbon stocks do not have to be identical, they can be adapted to the local, logistic and economic context but must provide data that respect standards to produce comparable, transparent, accurate, and consistent carbon stock data. Particularly in carbon rich soils such as those in permafrost and peatland areas, uncertainties are currently still very large.

4.5.Fossil fuel emissions

Understanding the behavior of the current global carbon cycle requires an accurate understanding of the perturbation that results from burning fossil fuel. We need to measure not only the global, annual total of emissions from fossil fuels, but also to quantify the distribution of this flux at the same temporal and spatial scales as the other processes we are working to understand. This implies the objective of characterizing emissions at the scales of days (even including the diurnal variation, e.g. of ground transportation) and 1 km over the land, including geo-referenced information on large point sources such as power plants and industrial sites.

Data on the use of fossil fuels is generally acquired from questionnaires to fuel producers, traders, and users. The data are typically collected by some government agency. Because of the importance of energy in the global economy and because most fossil fuels are traded in formal markets; there is a wealth of data on the production, trade, and consumption of fossil fuels.

International compilations of energy data are maintained by the United Nations Statistics Office (UNSO) and by the International Energy Agency (IEA). The UNSO maintains data for all countries and the IEA maintains data for some 140 countries that play a significant role in the production, trade, or consumption of petroleum or petroleum products. These two agencies cooperate in the distribution of their questionnaires and share the energy data retrieved. Data on global energy production and use are also collected by organizations such as the US Department of Energy and the British Petroleum Company. These primary data sets are at the scales of countries and years, although both the UNSO and IEA do retain some monthly data. Many developed countries have at least a portion of their energy data at a monthly scale and in some cases the data are collected for major political subdivisions of the countries, e.g. for states or provinces (US Department of Energy).

4.6. Remote sensing of land and ocean surfaces

Remote sensing of land and ocean surface characteristics has proven extremely valuable. For land, we have the long time-series of AVHRR-derived NDVI since the 1980s, and the higher resolution optical (infrared and visible) products from MODIS, Landsat and SPOT. New derived products such as the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) are also derived from remote sensing data. FAPAR is an important parameter in the models (e.g. light-use efficiency models) that estimate terrestrial carbon fluxes over a range of temporal and spatial resolutions. Spatially explicit description of FAPAR, is one of the GCOS Essential Climate Variables, since it informs about the relative strength and location of terrestrial carbon pools and fluxes (http://www.fao.org/GTOS/doc/ECVs/T10/GTOS-ECV-T10-fapar-v06.pdf).

PAR is monitored as part of the standard protocol at ecological research sites (e.g. Fluxnet). In the AmeriFlux network, sensors are calibrated to Quality Assurance laboratory standards, but few other sites generate reliable measurements of FAPAR that can be meaningfully used for the validation of satellite products. Community efforts are underway to document the accuracy of available space-derived data sets; while ground-based networks, coordinated by CEOS Working Group on Calibration and Validation (CEOS-WGCV), perform measurements relevant to these validation exercises.

Space agencies and other institutional providers generate global maps of leaf area index (LAI) at various spatial resolutions for daily to monthly periods, using mainly optical space-borne sensors. In this case, the values depend on allometric relationships developed from ground measurements or modeled values simulated global vegetation classes, such as the 12 or so proposed by the IGBP. Global estimates of LAI are generally made at 1 km resolution, which, when compared to local observations tend not to be very accurate for local vegetation types. Several efforts to derive more accurate LAI estimates from remote sensing data are underway. These are most commonly based on empirical relationships derived from ground-based measurements, for instance at validation sites spanning a range of land cover types. Such validation initiatives are now performed in the framework of ground-based networks, including both national research groups and international entities, such as the Land Product Validation (LPV) Sub-group of the CEOS-WGCV. Current validation efforts concentrate mainly on expanding the number of validation sites, and on improving the reliability and accuracy of the ground-based estimates by defining state of the art protocols addressing the very different spatial dimensions of in situ and remote sensing measurements.

For active fire mapping, the ESA World Fire Atlas (WFA) provides the longest available continuous global record of active fires, while MODIS is the best currently polar orbiting sensor for this phenomenon. Other polar orbiting (AVHRR, TRMM) and geostationary satellites (e.g. MSG and GOES) extend these observations to better characterize the diurnal cycle of active fire. The WFA has recently been upgraded using a new nighttime algorithm and extended back to 1991. For fire radiative energy, SEVIRI and MODIS are the only currently operating sensors with demonstrated capability to make measurements to the required specifications.

The Global Fire Emission Database (GFED) is an integrated product, combining MODIS, ATSR, and VIRS satellite products of fire activity with the CASA terrestrial biosphere model to estimate CO_2, CO, CH_4 and a suite of other trace gases and particulates from 1997 to the present. The spatial and temporal pattern of fires is relatively well understood but uncertainties in global fire emission estimates remain substantial. Other products exist as well (FLAMBE, GLOBCARB).

Satellite observations from space using Synthetic Aperture Radar (SAR) are also beginning to provide “all-weather” land-surface information, in particular over cloud-affected regions in the tropics and high-latitudes, where optical satellite data are sparse. JAXA developed a systematic acquisition strategy for the ALOS L-band Synthetic Aperture Radar (PALSAR) for generation of global coverage of wall-to-wall SAR data for tracking land-use change. ALOS PALSAR builds on the JERS-1 L-band SAR technology and acquisition strategy (used for tropical and boreal forest monitoring during its lifetime), and should provide the first systematic global observations for generating forest-change and derived biomass maps. Several research programs are underway to implement the use of SAR, as well as air and space-borne LIDAR, to derive robust global estimates of vegetation aboveground biomass. Satellite missions such as BIOMASS (currently in phase-A at ESA) and the DESDynI project of NASA are being designed for this purpose.

Remote sensing techniques integrating space-borne imaging and airborne LIDAR (CLASLITE, http://claslite.ciw.edu/; Asner et al., 2005) have demonstrated strong capability for tracking and quantifying biomass and structural changes in forest undergoing deforestation at the national and county scale.

Achieving the necessary density of observations will require innovations in both deployment strategies for existing methods, and new and improved measurement techniques. Satellite observations of land cover, disturbance extent and intensity, parameters related to vegetation activity, ocean photosynthesis (ocean color), parameters related to anthropogenic activity such as land-cover changes, light activity as seen from space, and critical atmospheric and oceanic variables controlling the fluxes all need to be ensured to derive high resolution maps of carbon fluxes. The emerging capability to measure GHG directly from space needs to be enhanced, validated, and coordinated with existing measurements.

For ocean, we have two long time-series of satellite data that have strongly contributed to a better estimation of carbon fluxes. The AVHRR-derived sea-surface temperature (SST) since the early 1980s and the SEAWIFS-derived Chlorophyll-a concentration (Chl-a, a proxy of the phytoplankton concentration in surface waters) available since the late 1990s. These sensors have changed our understanding of the temporal variability and spatial distribution of the ocean dynamic and of the marine biology and has led to important improvements in ocean modeling during the last decades. Several other recent sensors such as MODIS and MERIS have contributed to strengthened this ocean observing system.

Nevertheless, estimating pCO_2 from satellite measurements still remains a challenge because the carbon content in this fluid envelop depends not only on the surface temperature and phytoplankton biomass that can be monitored, but also on the mixed layer depth and the water-mass history. Recent attempts that combine satellite data and model simulation have demonstrated the potential of this approach (Telszewski et al., 2009). The development of operational ocean circulation models associated with more and more accurate satellite products will probably lead to an acceleration of the use of these approaches to assess the marine pCO_2 and to produce routinely ocean CO_2 fluxes. The IOCCP strongly supports these activities at the international level.

These methods will likely benefit from the forthcoming sea-surface salinity (SSS) measurement that should be allowed using the SMOS sensor which should be launched before the end of 2010. In some specific regions affected by the discharge of large rivers, for example the equatorial Atlantic that is affected by the Amazon river, the thermodynamic processes that control pCO_2 depend not only on the SST but also on the SSS.

Regarding the biological part of the ocean carbon cycle, several new satellite products are expected to emerge in the next years. The detection of the Phytoplankton Functional Types (PFT) is one of the most promising. Several algorithms have been developed during the last five years and they will likely become robust enough to be used by space agencies in the next five years, as shown by the interest of the IOCCG for this topic. This information is crucial to assess the biological carbon pump because phytoplankton species have very different roles in carbon capture and export. It is also crucial in the meantime that space agencies work on the development of hyper-spectral sensors that would allow more refined analysis of the water-reflectance and thus of the phytoplankton composition.

All these new measurements and methods will allow more precise estimates of carbon fluxes in the open ocean, but their equivalent for the coastal ocean is still to be conceived. The coastal ocean is important, yet is particularly challenging to observe from space. The reasons range from the diurnal cycle of the biology to the complex water optical properties. Future geostationary missions dedicated to the observation of the coastal ocean are likely to hold the key to solving this problem.

5.Future Requirements

The current carbon observation systems provide a reliable picture of the trends and distributions of GHG in the global atmosphere only as a whole. They also provide the current framework for understanding carbon fluxes between the atmosphere, ocean, and terrestrial biosphere. These observation systems are diverse and loosely coordinated, but have to some extent served the purpose of informing decision making over the past few decades.

However, the driving science and policy questions for the 21st century require a globally coherent observation system-of-systems that can provide relevant regional-scale information, can be traceable to primary standards, and is interoperable with other Earth Observation systems. To achieve these goals **requires augmenting the observation and analysis systems in all domains**. The fundamental observational gaps are related to the impacts of climate change on the carbon cycle, and to verifying and reporting reliably on land use and fossil fuel emission management strategies. The system should be able to inform policy at regional, national, and international levels and should be consistent in space and time, with sufficient accuracy to detect regional trends within the variability of each sub-region. Below we outline such a system.

5.1.Atmospheric domain

5.1.1. Surface station network

The existing set of in situ CO_2 and CH_4 bservations (see Section 4.2.1) from surface stations and aircraft has substantial gaps in Africa, South America, northern Eurasia, and Southeast Asia, as well as over large areas of the Southern Hemisphere oceans. The global atmospheric network is composed of many national sampling networks coordinated by WMO GAW, but until now, the analytical measurements have largely been made under research programs from just a few countries: e.g. NOAA/ESRL USA; CSIRO Australia; NIES Japan, LSCE France; MPI Germany. There are also many existing aircraft and tower sites (e.g. NOAA NACP sites; ICOS CarboEurope sites; and NIES Siberian sites operated as part of a Japan-Russia program) where high quality measurements are being made, but for which the data are not readily available to users.

Importantly, much of the current surface network remains based on the collection of discrete air samples over ~5 minute periods on a weekly or less frequent basis, seriously limiting the temporal coverage. As a result, substantial efforts are needed in:

i) **Expanding the number of atmospheric in situ stations in under-observed regions.**

ii) **Increasing the number of quasi-continuous in situ measurements at existing sites.** The GAW program supporting regional integrated observation systems such as ICOS in Europe can offer an established international mechanism to fill these gaps.

iii) **Application of new multi-component gas analyzers such as deployed in the TCCON network** (Fig. 9) to expand measurement from the boundary layer to the entire air column, complementary to forthcoming satellite GHG measurements

In addition to the spatial and temporal gaps in the observation network, there are also substantial gaps in supporting trace gas species beyond CO_2 (and sometimes CH_4), like the O_2/N_2 ratio, the stable and radio (^{14}C) isotopomers of CO_2 and CH_4, and anthropogenic halocarbon and hydrocarbon species. These species offer the advantage of being mechanistically linked to certain carbon cycle flux components (e.g. terrestrial exchange with O_2/N_2 and $\delta^{13}CO_2$, and fossil fuel emissions with $^{14}CO_2$ and halocarbons). By introducing measurements of these tracers, it is possible to identify the contributions of different sectors and different regions toward emission reductions. In situ sensors for O_2/N_2 exist, although they are not commercially available; commercial instruments for $\delta^{13}CO_2$ are available, but not yet at the precision required for background monitoring. As a group, these species require discrete air samples to be collected in situ and then analyzed in a laboratory, emphasizing the need for continued and expanded air sample collection around the globe.

The lack of infrastructure creates a challenge in instituting new sites over continents where the major gaps exist. Unlike in the marine boundary layer and mountain observatories above the tree-line, where the surface CO_2 networks originated, air sampling above vegetation requires either aircraft or the use of tall towers — preferably reaching into the daytime boundary layer. This requirement is to avoid undue influence of local vegetation signals and obtain regionally (~10^5 – 10^6 km^2) representative measurements.

Further, the development of Cavity Ring Down spectroscopy offers the potential to have instruments that require less use of reference gases than the previous generation of sensors, reducing the complexity and cost of installation. Instruments like these are also easier to deploy aboard commercial aircraft.

5.1.2.Aircraft observations

Programs in which instruments are carried on board commercial aircraft such as CONTRAIL on Japan Airline flights, CARIBIC on Lufthansa flights, and IAGOS on several airline companies programs should be expanded globally. While it is mainly during aircraft ascent and landing that the measurements are useful for deriving surface fluxes of carbon, the cruising altitude (> 10 km a.s.l.) measurements provide information critical to large scale transport of CO_2 and CH_4, as well as remote sensing validation.

5.1.3.Future ground-based networks

To achieve the necessary future regional flux diagnostics, needs continental coverage by a surface network of stations, complemented by vertical profiles. These stations will need to be spaced typically 200-300 km apart. Over the oceans, a network of continuously operated stations, rather that flask discrete sampling, will be needed, albeit with a lower station density than over land.

With some 1000 surface continuous-measurement stations to be spread more or less evenly across all continents, this requires a co-ordinated global effort. In the next five years, priority must be given to achieving the construction of high density networks in North America (NACP) and in Europe (ICOS) and to develop networks of similar or higher density over Australia, China, India, Japan, Brazil, Russia, where strong observation and science capabilities exist. In the following 5-10 years, coverage of ocean regions, Africa and other continental regions must be tackled by an international effort led by WMO-GAW with the ambition of doubling the number of new stations every 3 years until the required density is achieved.

5.1.4.Satellite observation of GHG concentration

Satellite observations will be needed to create an effective carbon observing system. Future satellite observations have a critical need for parallel long-term aircraft and surface-based remote sensing observations to first establish the bias in the spatial and temporal patterns observed from satellites, and then to correct them. Satellites are currently our only means to obtain global coverage, but improvements in accuracy are needed.

With the advent of the technical means to provide new monitoring and measurement of GHGs from space, CEOS has identified the coordination and application of these measurements as a top priority for the coming years. To foster the use of space-based CO_2 and CH_4 observations and consolidate data requirements for the next generation GHG monitoring missions from space, a strategy for easy access to GHG satellite observations should be developed. A coordinated planning effort towards the next generation of a constellation of GHG satellite observations is also required.

Space-based high-precision (1 ppm) measurements of the column-integrated CO_2 molecular density with frequent global coverage are highly valuable in determining terrestrial and oceanic CO_2 fluxes, provided they are linked to a reference scale. By linking the spatial distributions of CO_2 with atmospheric flux inversions, data assimilation techniques, and coupled atmospheric, terrestrial and ocean carbon modeling, 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. The flux retrieval accuracy is a function of the precision and sample density of measured total column CO_2. The measurements of the total column integrated CO_2 molecular density down to the Earth’s surface need to be at 0.3% (1 ppm) precision or better for significant improvements in our knowledge of sources and sinks. Existing instruments such as AIRS/AMSU, IASI/AMSU , TES and CrIS are able to monitor CO_2

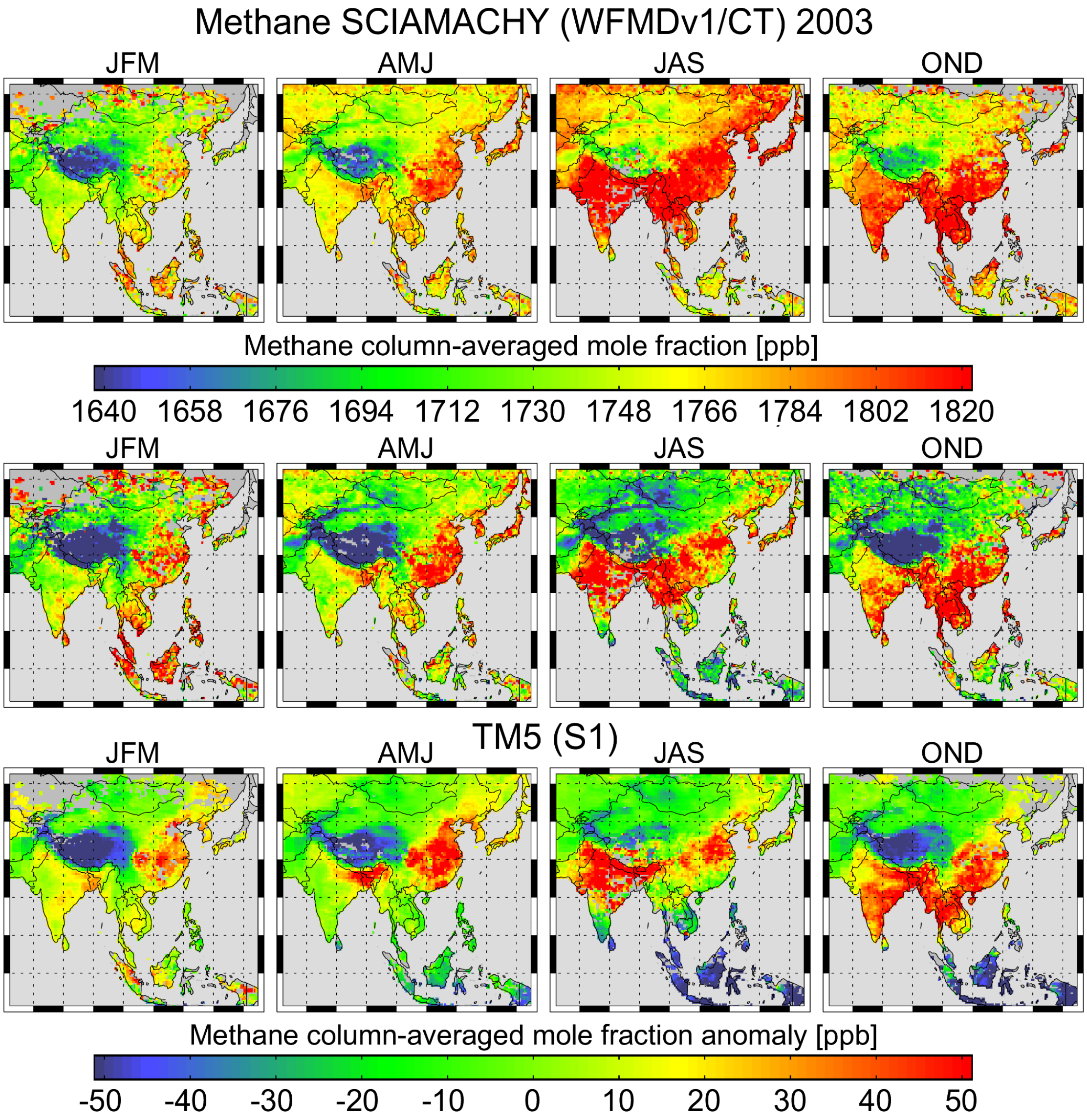

Figure 14. Top: SCIAMACHY XCH4 during 2003 over China and India. Middle: idem but as anomaly, i.e., with average subtracted. Bottom: corresponding TM5 model simulation (Schneising et al., 2009).

and other trace gases from space. They have high spectral resolution, which allows isolation of a large set of specifically sensitive CO_2-channels from the interfering water vapor and temperature signals from the free troposphere and above, but exclude the lower troposphere. The Canadian Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) makes limb measurements of upper tropospheric and stratospheric CH_4 with high vertical resolution and similar capability for CO_2 is being developed. Currently, a precision of about 0.5% at a space-time scale of 100 km/weekly is achieved for the middle-tropospheric CO_2 column abundances. However these characteristics do not allow for the inversion of surface sources and sinks.

Using the shortwave infrared signal, as done by SCIAMACHY, OCO and GOSAT, has the advantage of penetrating the atmosphere down to the ground. The SCIAMACHY sensor has been flying since 2002 on ESA's ENVISAT mission and has been successful in producing CH_4, CO and the first CO_2 column-integrated retrievals over land, with an accuracy for CO_2 of a few ppm and for CH_4 around 1% relative accuracy. This accuracy is sufficient to improve quantification of regional-scale methane surface fluxes. Fig. 14 shows a comparison of the SCIAMACHY XCH4 with TM5 model simulations performed at EC-JRC, Ispra.

The Orbiting Carbon Observatory (OCO - NASA) was designed to use measurements of reflected sunlight in the short-wave infrared to provide global, high precision measurements of the column-integrated CO_2 mixing ratio with a precision of 0.3% (1 ppm). The observatory carried three high-resolution spectrometers, one for O_2 (0.765 μm) and two for CO_2 (1.6 and 2.06 μm). OCO was expected to serve as a pathfinder for future long-term CO_2 monitoring missions, but unfortunately OCO failed to achieve orbit. A follow-on mission is being planned.

The Greenhouse Gases Observing Satellite (GOSAT) is the world's first purpose-built satellite to observe the concentration of CO_2 and CH_4 from space. The main purpose of the GOSAT project is to produce more accurate estimates of the flux of GHG on a subcontinental basis (several 1000 km resolution). A GOSAT follow-on mission study is now underway, and it is essential that this should take into consideration the needs of the GEO Carbon tasks.

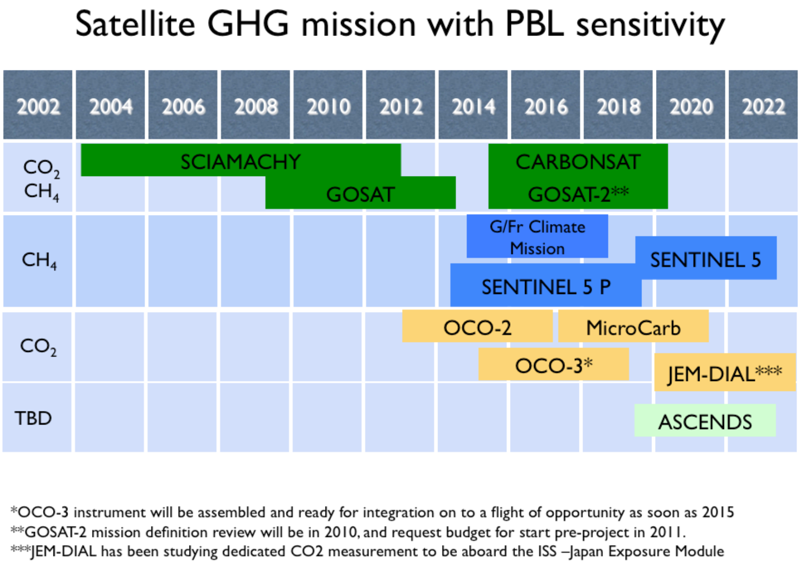

Figure 15. Current status of planned GHG measurements from space that include the planetary boundary layer (PBL).

To fulfill the GCOS requirements on the GHG Essential Climate Variables CO_2 and CH_4 the **next generation of GHG satellite measurements needs to provide high accuracy measurements with high spatial resolution (1-2 km) to minimize cloud contamination**. A 1-3 day repeat-frequency is needed to get good monthly mean GHG fields. Such coverage will help to effectively monitor emissions from strong local source areas for example industrialized urban areas or power plants.

In the long term this requirement could be achieved by an international GHG-satellite constellation equipped with both passive sensors (for GHG imaging and monitoring the natural and anthropogenic hot spots) and active sensors (to deliver very precise but spatially sparse GHG data).

The active sensor mission could be accomplished using the Laser Absorption Spectroscopy (LAS) technique, which is a powerful tool for high-precision trace gas spectroscopy. LAS provides measurements of CO_{22} from of received power at wavelengths on and off an absorption line. LAS and DIAL, operating in a pulsed mode, which is not required for column measurement, have been proposed as the next generation GHG instruments. ASCENDS, A-SCOPE, and other LIDAR instruments have been studied by ESA, NASA, JAXA and several other agencies, but it has to be recognized that technology barriers must still be overcome before such a mission can be achieved.

Passive sensor missions needs to be developed as soon as possible to continue the SCIAMACHY and GOSAT GHG time series on CO_2 and CH_4 and needs to include the lessons learned from the SCIAMACHY, OCO and GOSAT projects.

The highest short term priority for the international community is to continue the time series of space-based planetary boundary-layer CO_2 and CH_4 measurements over the next decades with incrementally improved passive sensors, ideally in a GHG-satellite constellation within the international system of operational meteorological satellites.

Within this overall priority, over the next 5 years, the urgent need is for the continuation of SCIAMACHY and GOSAT, the launch of OCO-2 and the development of subsequent improved passive GHG observation capabilities from space precursors of constellations (e.g. MICROCARB, CARBONSAT) as well as pilot-studies for active sensors (e.g. MERLIN) and CH_4 observations and consolidate data requirements for the next generation GHG monitoring missions from space. A strategy for easy access to GHG satellite observations should be developed. A coordinated planning effort towards the next generation of a constellation of GHG satellite observations is also required.

5.2. Ocean domain:

The most urgent need is to develop and implement a network of routine observations to monitor ocean carbon. This requires new automated measurement techniques to be developed, and the integration of existing ocean carbon observations into an homogenized network. Sustained observing systems for carbon variables are essential in quantifying the global carbon cycle and a necessary backbone for the further research that must proceed in parallel.

5.2.1. Surface pCO_2

Despite an increasingly dense observational network, whole regions or basins are still not adequately sampled for surface CO_2. Basin-wide and global sea surface pCO_2 and air-sea flux maps are often estimated using a variety of interpolation methods including algorithms relating sea surface pCO_2 to satellite-derived parameters and re-analysis products. Neural network approaches are also used. The density of surface measurements of pCO_2 (surface ocean, atmosphere, temperature and salinity) from commercial ships ((Volunteer Observing Ships or VOS lines) has improved over the last few years.

Building on this success, the highest, most urgent priority is for **the extension and sustained maintenance of these surface ocean pCO2 observing systems using VOS lines**. The respective shipboard atmospheric CO_2 measurements should be further developed and exploited. To determine the regional air-sea flux of CO_2 to within ± 0.2 Pg C yr^{-1} requires evenly spaced and regular sampling in the northern North Atlantic of 5 to 9 crossings per year every 1500 km, in the temperate North Atlantic 6 samples per year every 1500 km, in the temperate North Pacific 9 samples per year every 200 to 600 km, in the equatorial Pacific 15 samples per year every 200 km, and in the polar South Pacific every 300 km in summer to every 800 km in winter. Recent modeling approaches to optimize sampling scales showed that in the Southern Ocean, the CO_2 air-sea flux can be determined to within ± 0.1 Pg C yr^{-1} with regular 3-monthly sampling at a spatial resolution of 3 degrees meridionally and 30 degrees zonally.

It is recommended that **all research vessels and support ships going to Antarctica are equipped with high accuracy automated CO_2 measurement systems**. Use of unmanned buoys in the Southern Ocean for measuring pCO_2 and deriving air-sea CO_2 fluxes is in principle a success, but more autonomous drifting-buoy systems are needed to provide a reasonable data coverage for systematic up-scaling of basin-wide fluxes.

5.2.2. Hydrography

Ship-based hydrography is the only method for obtaining high quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological variables over the full water column, and in areas of the ocean inaccessible to other platforms. Global hydrographic surveys have been carried out every decade since the 1980s through research programs such as GEOSECS, WOCE / JGOFS, and CLIVAR.

Two types of survey are required to meet scientific objectives:

i) **Decadal surveys, requiring full basin synopticity** over a less than 3 year period beginning in 2012,

ii) **A sub-set of the decadal survey lines sampled at higher frequency (repeated every 2-3 years)**.

Elements of coordination and implementation based upon a more pro-active oversight structure to maintain a repeat hydrography program firmly linked to national, regional and international research programs. These include:

i) **The development of a sustained international coordination body for integrated and interdisciplinary repeat hydrography** that is independent of any single time-limited research program (for example, following the model of Argo sites);

ii) **A single, international information and communications forum to facilitate field program planning**, to set experimental standards and methods, and to underpin data sharing and synthesis activities, including data management activities.

5.2.3. Time series

Only few ocean-carbon time series exist. They have provided a considerable amount of very useful data, but better regional coverage is badly needed. Eulerian time series are a prerequisite for long-term climate observations of the ocean carbon cycle and for creating better process understanding (the latter leading to improved process parameterizations in prognostic models and respective forecast skill improvements). So far only a very few attempts at using automated deep-sea winches have been made (e.g. Porcupine abyssal plain). However, these may significantly contribute to an additional radiative forcing due to the high specific greenhouse potential of this gas.

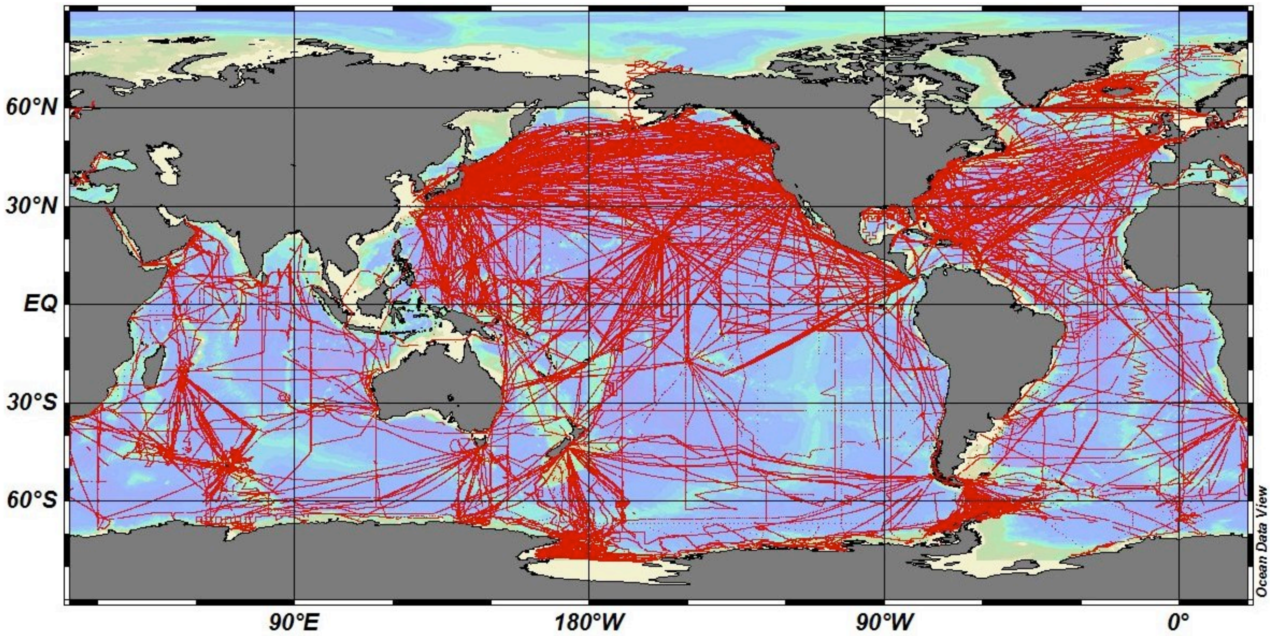

Figure 16. Data coverage and gaps in the geographical coverage of ocean pCO_2 observations 2000-2007 (from LDEO database)

are needed in order to detect changes in ocean storage of CO_2 and $CaCO_3$ lysocline level changes in view of decreasing pH (ocean acidification). Ideally Eulerian time series would be constructed of arrays which cover a wider area (dependent on the variability in the area of interest) in order to avoid aliasing due to slowly moving fronts (i.e. slow mean changes of the biogeochemical ocean state have to be detected against a background of frequency variability). New technology is needed to provide carbon sensors that can be deployed on moorings.

5.2.4.Oxygen sampling from autonomous platforms

Oxygen observations, especially those on the Argo drifting buoys, will help considerably in discerning between natural and biologically induced air-sea carbon fluxes and inorganic buffering of anthropogenic CO_2 in the oceans. A dense O_2 network also will also help to assess the slow widespread decline of oceanic dissolved oxygen levels. Such observations become crucial around continental margins, where anthropogenic nutrient input and a potentially slower ocean overturning during global warming may lead to more low oxygen areas. These domains will also be prone to emitting N_2O, which

5.2.5.Ocean color

Ocean color data have successfully been used in constraining coupled physical-ecosystem models. However, improved ground-truth measurements of ocean color data are required to link them to chlorophyll or primary production data. Ocean color data should also be used for estimating biological export production, this being essential for any net air-sea CO_2 fluxes associated with biogenic carbon cycling. It is a challenge to merge remotely sensed data with direct flux data from sediment traps. Sediment trap data have considerable systematic errors, but are extremely useful in resolving seasonally varying fluxes of particulate carbon through the water column. Deployment at more shallow depths in conjunction with measurements of dissolved quantities and large scale surface ocean color may allow scientists to derive a more precise quantification of changes in the biological carbon pumps (organic carbon, calcium carbonate).

5.2.6.Integration

Marine ecosystems and the biological carbon pumps in the ocean are strongly coupled to nutrient cycling (element cycles of nitrogen, phosphorus, silicon, micronutrients such as Fe, Zn, etc.), the pH of seawater and changes in oceanic circulation. We need observations to reveal how marine nutrient cycles change as a consequence of human activities and climate change. This includes the change in CH_4 and N_2O due to altered stratification and biological production. The associated coupled biogeochemical cycles have to be understood using a common approach. Changes in the oxygen budget provide crucial information about the mode of changes in the carbon cycle (biospheric versus physical/chemical cycling). High precision measurements of carbon, oxygen, and nutrients are needed as a tool to help in detecting and diagnosing large scale changes in oceanic overturning, which cannot easily be measured by physical techniques. The requirement is thus for an integrated international interdisciplinary program of ship-based hydrography, time-series moorings, floats and gliders with carbon system, pH and oxygen sensors, and ecological and chemical surveys to determine the large-scale changes in the properties of ocean water and the associated biological responses to ocean acidification. Many of the open-ocean research requirements of the ocean-acidification community could be met by careful coordination with the future research of the ocean carbon and biological communities, and by adding additional sensors and moorings where needed. For coastal environments, a large network of new hydrographic and ecological surveys, moorings and floats is required to provide integrated coastal observations.

Presently, many countries are engaged in ocean carbon research and monitoring activities, creating a need for international coordination. Such a coordinated international effort must be closely linked with other international carbon research programs, such as the CLIVAR/CO2 Repeat Hydrography Program. There are already well established links to the IGBP core projects SOLAS, IMBER, and LOICZ, but links to the trace metal core project, GEOTRACES, have to be improved. Achieving this will require steady funding, but the total amount is small relative to the scientific return.

5.3. Terrestrial domain

Moving from a research to an operational mode for integrated terrestrial observations, requires both coordinating and rationalizing ongoing operational programs (such as forest and agricultural inventories and monitoring) to produce high-quality carbon-stock data and flux estimates. Eddy covariance flux sites offer subannual spatially integrated estimates of net carbon uptake or NEP, representing one to a few kilometers, but these intensive measurements are made at fewer locations than inventories. To gain global coverage with some 500 sites, each site must be carefully selected against a predefined set of objectives supported by quantitative analyses. Developing a coordinated international strategy to locate such sites, and ensure consistent measurements of stocks, fluxes and key control parameters is a challenge that must be met. Because of the scale of biospheric processes, any global estimate will be informed by site-specific data, extrapolated using spatially explicit remote sensing observations and models. Below, we describe the various types of measurements that must be made, ideally within a coordinated and integrated strategy aimed at improving interoperability of the various data sets used.

5.3.1. Eddy covariance and process controls over fluxes

An observational network of in situ flux observations is an essential component of IGCO. It should be emphasized that they do not replace but rather enhance and complete the value of an integrated observation and carbon tracking system. Harmonization of the measurement protocols and resulting data sets is critical to ensuring the usefulness of Fluxnet data. The main requirements are:

i) **Improved access to data from the entire Fluxnet network** including fluxes of water vapor, heat and ancillary ecosystem measurements made at these sites. It is important to note that the long term sustainability of the Fluxnet sites is a critical issue, with many sites currently run only for short periods with limited funding.

ii) **Improved coverage by FLUXNET over representative land use states, including disturbed ecosystems**.

iii) **A rationalization of the network to distinguish core and supporting sites.** Importantly, such a network of core sites should function as a reference network for satellite validation and calibration. Inventory measurements and flux observations must be co-located at flux sites so that the spatially extensive inventory and intensive but sparse flux data can be used synergistically.

iv) **Development of spatial scaling techniques for application over the wider, het-**

erogeneous landscapes around but outside the flux tower footprints. For example, flux site biological measurements (e.g. NPP, LAI, coarse woody debris) can also be made at predetermined locations across a landscape for model calibration and spatial scaling.

v) **Effective use of remote sensing information for spatially extrapolating such local data to the wider region.** Site selection can be based on stratification by major biomes within ecoregions, with a cluster of sites at each location, one of which is the core long-term site and the others capture variation due to disturbance and management in that biome, as described in the AmeriFlux Strategic Plan (http://public.ornl.gov/ameriflux/).

5.3.2.Forest and soil inventories

Efforts to create continuous, standardized, geo-referenced forest biomass inventories will require harmonization of the widely varying methodologies for data collection and analysis. Field surveys remain essential to monitor both forest and soil carbon stocks, because neither the satellite imagery nor the flux measurements can give reliable information about the carbon stocks. However, the costs of field measurements are high and monitoring carbon stocks at national, regional or continental scales requires the use of satellite images and mathematical models for spatial and temporal extrapolation. Repeated measurements of carbon stocks in time improve the calibration of models, the estimation of the evolution of carbon stocks and quantification of the influence of factors such as climate change or land use change. Since the turnover of carbon in forest biomass is quicker than in the soil, it is preferable to repeat measurements every 5 years for trees, while allowing 10 years for the soil compartment.

The standard methodology for biomass values should include:

i) **Probability-based sampling across regions** (e.g. systematic grid design);

ii) **Minimum, maximum, mean, median, standard deviation, estimation protocol, number of points included** (e.g. variable radius subplots in forests adjusted to maximum coefficient of variation <20%);

iii) **Biomass by stemwood, root, foliage, and branch components**; coarse and fine woody debris, litter mass to derive dead mass pools and heterotrophic respiration.

iv) **Better allometric functions designed to estimate carbon content rather than forest timber yield**. These functions must relate carbon content to stem diameter and height for a range of vegetation types, climate zones, and fertility classes (e.g. yield classes based on age-height relations). Allometric functions are also needed in a similar range of conditions to convert aboveground biomass to total biomass.

Regional or national biomass conversion and expansion factors (BCEF) and biomass/carbon conversion factors are also needed. Conversion factors for computing carbon from biomass of foliage, root, and wood components are needed in a global library. Individual studies have measured carbon content of these pools, but this is not broadly measured and compiled in one database. Some networks are compiling these data (e.g., AmeriFlux, http://public.ornl.gov/ameriflux/).

5.3.3.Forest carbon tracking

In 2008 GEO recognized the need for improved international coordination and access to wall-to-wall, medium resolution satellite data, as well as adequate tools, standards and methodologies, to assist countries in the establishment of national forest and carbon monitoring systems. The “Forest and Carbon Tracking” task was set up to demonstrate that coordinated Earth Observation, informed by in situ measurements, and properly linked to forest ecosystem models, can provide the basis for reliable information services of suitable consistency, accuracy and continuity to support effective post-Kyoto sovereign national forest MRV systems.

The following elements are seen as key on the path towards the establishment of such comprehensive and operationally robust forest and carbon monitoring systems:

i) **improved access to a continuous supply of mid-resolution satellite data, to annually monitor areas of forest**, deforestation and forest degradation, as well as afforestation and reforestation;

ii) regular and in situ validated land use mapping information to determine post deforestation land use;

iii) **in situ forest biomass and structure measurements** for model calibration, validation and verification;

iv) **ecosystem carbon models parameterized for local conditions, to estimate the present state and predict future carbon stocks** and GHG emissions from trees, forest floor litter and soils;

v) **spatial-data infrastructure, GIS and web-delivery systems to transfer data, hold and present maps, and to produce reports** according to prescribed UNFCCC accounting and reporting rules;

vi) **continuous programs to improve ecosystem model, inventories and remote sensing integration**, as well as more direct estimates of forest biomass and forest degradation though the use of new optical technologies (e.g. hyperspectral) or SAR (multi-wavelength X-, C-, and L-band);

vii) **web reporting of results** and accuracy assessment, including remote sensing data products (e.g. aboveground biomass), and model input parameters and output (e.g. net carbon uptake, carbon stocks) with version documentation.

5.3.4. Leaf Area Index

Validation of satellite-derived products such as Leaf Area Index (LAI) and FAPAR is generally still poor. Validation campaigns should be initiated over selected sites, distributed globally to sample a large number of terrestrial surface types. These networks must ensure the standardization of measurements, their optimal spatial distribution, and the benchmarking of the acquisition protocols. Optimal distribution and benchmarking must capitalize on current 3D radiation transfer modeling capabilities.

The conversion of field measurements to effective values is an essential step when trying to estimate LAI from optical remote sensing observations; it requires additional information about the structure and architecture of the canopy, e.g. gap size distributions, at the appropriate spatial resolutions. This implies designing meaningful sampling schemes at the site level that account for the internal variability of the variables at best at the appropriate spatial resolution. Documenting this internal variability for a series of validation sites distributed over the various biomes is an essential component of the LAI validation exercise. The consistency between these domain-averaged "true" and effective LAI and the FAPAR (ECV T10) at the same spatial resolution, a radiation flux itself related to domain-averaged effective LAI, must be guaranteed.

Therefore, validation protocols for LAI and FAPAR should include basic additional in situ radiation measurements (surface albedo and leaf/branch optical properties) which contribute to the assessing the quality of the albedo products.

5.3.5. FAPAR

Incident PAR is monitored as part of the standard protocol at ecological research sites (e.g. Fluxnet, LTER), but few sites generate reliable measurements of FAPAR that can be meaningfully used for validation of satellite products. The FAPAR can be approximated from the intercepted flux measured in situ using transmission measurement devices. The validation of space-derived FAPAR products must recognize and account for the different definitions of the FAPAR quantities including dependency on solar angle and illumination conditions as well as to the canopy elements contributing to the absorption process. As for LAI, the estimation of domain-averaged quantities as obtained from satellite measurements requires that the issue of internal variability, and hence the sampling protocols, is addressed carefully. Community efforts are underway to document the accuracy of available space-derived data sets while ground-based networks, coordinated by CEOS-WGCV, perform measurements relevant for validation exercises; but these must be linked to activities on LAI and ideally albedo.

5.3.6. Disturbance (fire, harvest, land clearing, insects)

The accurate estimation of global fire disturbance is a critical requirement for realistic climate modeling, since emissions of GHG from fires account for between 25-30% of the total annual CO_2 emissions into the atmosphere. Models capable of incorporating fire disturbance data from satellites are in their infancy, but initiatives within the carbon, coupled-carbon and climate communities are underway to improve this situation. Satellite-derived estimates of global burned area have recently been generated through the ESA GlobCarbon project, L3JRC and MODIS MCD45A1. However, all of these exhibit differences and both omission and commission where they have been tested against high resolution observations. More comprehensive observations at high resolution are required for validation purposes, and efforts are underway through CEOS WGCV to address this in a co-ordinated fashion. As part of the ESA Climate Change Initiative fire disturbance will be revisited.

Damage by insects and disease are often important nationally and regionally and can outweigh disturbance due to fire, for example in Canada insects are estimated to damage from 10 to 25 million ha annually. Evidence from palaeo studies and climate model projections indicate that global warming could bring about a veritable insect explosion. New research is therefore needed on mapping insect damage and its rate of change.

Remote sensing techniques can be used to detect partial disturbances or degradation such as high-grade harvest in the tropics, and require annual to sub-annual satellite data to detect changes before forest canopies fill in. Remote sensing technical expertise is limited in some countries and analysis may need to be conducted independently. Calibration and accuracy assessment of satellite-derived land cover and change can be assessed with independent data collected in ground surveys or aerial photos. Accuracy assessments are critical for monitoring treaty agreement compliance.

The planned launch of the Landsat Data Continuity Mission carries with it some risk. If the launch fails it would be virtually impossible to monitor land use change, which might significantly undermine the REDD component (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) of a future global treaty by limiting the capability of tropical countries to produce realistic national inventories.

5.4. Fossil fuel emissions

Data sets of estimated CO_2 emissions from fossil fuel burning averaged by country and year are maintained by the IEA (based on the IEA energy data set), by the Carbon Dioxide Information Analysis Center (CDIAC) (based on the UNSO energy data set), and by RIVM in The Netherlands (based on the IEA energy data set). Detailed comparison of the CO_2 emission estimates produced by CDIAC and by RIVM reveal the agreement is within a few per cent for most countries.

The global total values are estimated to have an uncertainty of 6 to 10%, depending on whether or not the data for the three primary fuels (gas, oil and coal) are independent of each other. Estimates for individual countries can have much larger uncertainty, especially for developing countries with weak systems of data collection and management. In fact, the UNSO finds that in a typical year only about one third of African countries respond to their annual questionnaire, and they are obliged to rely on within-country reports and international energy companies to piece together national summaries. Negative values for emissions of CO_2 have been reported for a country when, for example, a small difference between two large numbers results in reported exports exceeding reported production; calculated internal consumption then ends up as a small negative value. The comparison between CDIAC and RIVM values found that the largest percentage differences were between estimates for some developing countries, but the largest absolute differences were between some of the estimates for countries with the best data systems. The two estimates for the US differed by only 0.9%, but in absolute terms this difference was larger than the total of emissions from 147 of the 195 countries considered.

An effort currently underway aims to produce estimates of global CO_2 emissions by month and by state for the larger countries. The initial objective is to accumulate appropriate data for the 21 countries that are collectively responsible for over 80% of global total emissions. Papers have already been published describing US emissions by state and by month and additions will soon result in a data set for all North America (US, Canada, and Mexico) by month and state. The US monthly data go back to 1981 but some of the requisite, monthly time series are very short. In many cases monthly data on fuel consumption are not available at all and proxy data will be used to estimate the pattern of fossil-fuel use. For example lack of monthly data on coal consumption in Brazil has led to data on steel production being used to estimate coal consumption, since the iron and steel industry is responsible for 80% of coal consumption in the country.

Proxy data will probably play a major role in many CO_2 emission estimates. Estimates of CO_2 emission have been produced on a 1° by 1° latitude/longitude grid using population density as a proxy. Estimated emissions for each country were used with population density data to distribute emissions within each country. By this method, emission totals were constrained within the respective countries, but the underlying assumption was that emission per capita was constant within each country. Analysis of state-by-state US data reveals some of the weakness in this assumption, per capita emission varies by a factor of 10 between Wyoming and California.

These data sets also need to distribute the emissions from fuels used in international commerce, e.g. from ships at sea and from international air travel. Formal energy statistics generally account for these bunker fuels at the point of their last sale.

CO_2 emission by sector or activity, that will be important in evaluating mitigation efforts, is reported by the IEA and is required in the national reports of all developed countries in compliance with their commitments under the UNFCC. The IPCC has published guidelines for countries to use in these reports (the Guidelines are currently in the process of being updated) and this helps to improve completeness and comparability among the reports. These reports provide considerable sectoral detail, but are national and annual in scope.

At the annual, global level, the largest source of uncertainty in the estimated CO_2 emission is the energy data themselves. The UN Statistics Office is not adequately funded. The IEA seems to be better off in both respects but does not cover all countries and is reliant on UN questionnaires for some of its data. Many countries do not report at all. Data at finer spatial and temporal scales are spotty in both time and space. Some monthly and state data do not exist.

There are now some data from monitoring large point sources at the point of emissions. This requires monitoring both the concentration and the flow rate of CO_2 in the stack. Roughly one third of global emission is from large point sources and thus could potentially be monitored. Another roughly one third of global emission is from transportation, which in current estimates is tabulated at the point of the last fuel transaction. As the spatial scale decreases it will become increasingly important to identify where the fuel is burned as opposed to from where it was last purchased. Similarly, most fuel is not burnt near the time of its last sale; burning is distributed over time. Identifying the exact time of combustion will also become more important as the temporal scale of emission estimates shrinks.

The following elements are seen as key on the path towards the establishment of such comprehensive and operationally robust forest and carbon monitoring systems:

i) **improved access to geospatial and temporal fossil fuel emission information** at a spatial scale appropriate for interfacing with other components of IGCO. Relevant scales are 1 km for satellite observations to verify emissions from large point sources, and 10 km for high-resolution transport models to calculate fossil fuel CO_2 gradients at stations to be verified, e.g. by radiocarbon observations;

ii) **improved definition in the temporal variability of emission**, implying the resolution of local and sectorial emission at time scales ranging from hourly to multi-annual;

iii) **regular reanalysis of past fossil fuel emission maps and recent trends**, using available long term information such as that available from regional energy use statistics, light observations from space or land-cover data sets;

iv) **spatial-data infrastructure, GIS and web-delivery systems to transfer data**, hold and present maps, and to produce reports according to prescribed UNFCCC accounting and reporting rules;

v) **continuous programs to improve fossil fuel emission mapping and integration**, as well as more direct estimates of emissions by local monitoring instruments;

vi) **web reporting of results and accuracy assessment, including uncertainty analyses and traceability in the basic elements used to construct fossil fuel CO_2 emission maps** such as geospatial economic activity information, land cover, light observations from space, emission factors, energy consumption statistics, with version documentation.

5.5.Lateral carbon fluxes

Over land, significant amounts of carbon are transported from where it is removed from the atmosphere by photosynthesis to where it is either stored for long periods or returned to the atmosphere by decomposition (e.g. movement by rivers, or as agricultural products and timber). This transport needs to be treated as a surface process, and be calculated and included in assessments of carbon fluxes based on atmospheric CO_2 gradients. While individually not very large, the sum total of their individual contributions is significant in the calculation of small and large scale carbon budgets.

5.5.1.Groundwater.

Production of dissolved and particulate (in)organic carbon could be monitored at the 500 stations located in different biomes and ecosystems (see Section 5.3). Stations should be equipped with erosion traps, wells or lysimeters and tensiometers to continuously monitor chemical composition and fluxes of carbon in groundwater.

5.5.2.Surface water and river discharge

Surface waters, such as streams, rivers and estuaries, ponds, lakes and reservoirs, receive a remarkable carbon input from terrestrial ecosystems. Monitoring not only the fluxes and fate of this carbon, but also the carbon production in the aquatic ecosystem itself, requires the establishment of an additional network of surface stations across boreal, temperate and tropical inland waters.

Regions with ecosystems that are particularly susceptible to climate change (i.e. melting permafrost) should be sampled.

Loads and ages of dissolved and particulate carbon should be determined at existing aquatic surface stations, in addition to continuous measurements of pCO_2, pH, DIC, alkalinity and CH_4 fluxes.

Continuous monitoring of DOC and POC is also required for relevant rivers, with the frequency of data acquisition capable of capturing the contribution of floods and extreme events which can make a dominant contribution to annual budgets.

Sediment cores and traps sampled at 10-year intervals to quantify carbon burial in inland waters.

Remote sensing should be further developed to use water color as a proxy for DOC, and to properly assess the global surface area and residence time of water in these ecosystems. The ocean discharge, which represents the residual between autochthonous and allochthonous production, its mineralization and sedimentation must also be monitored.

5.5.3.Harvest of carbon in food and wood

Globally, the amount of harvested carbon is a significant fraction of Net Primary Productivity (3 Pg C yr^{-1}). It should be determined from agricultural and forestry statistical information, with the best geospatial resolution at which the statistics are collected (e.g. counties or small regions).

Basic requirements in the next 5 years are:

i) **geospatial information on crop and wood biomass annual harvest at typical resolution of at best 1 km** in regions with good agricultural and forestry statistics, and at worst of 100 km in regions with poor statistics;

ii) **geospatial information about use of wood and food products**, including burning for energy production and cooking, consumption by the population and by animals as food products and decay in landfills;

iii) **web reporting of results** and accuracy assessment, including uncertainty analyses and yearly updates.

5.6.Regional hotspots

Hotspots of carbon-climate feedbacks are regions of the world with large carbon reservoirs or CO_2 sinks whose stability is threaten by progressive climate and land use change. The consequences of their destabilization are increased GHG emissions and dramatic acceleration of climate change. Examples are the large reservoirs of carbon in permafrost threatened by global warming, methane hydrates on land and ocean reservoirs threaten by resource extraction and global warming, biomass in tropical forests threaten by deforestation and climate change, and northern and tropical peatlands threaten by drainage, deforestation and climate change. An example of a key CO_2 sink is the Southern Ocean sink threatened by global warming and ozone depletion.

A higher density of observations is required for these large and vulnerable carbon pools, to detect early changes in their stability and attribution of higher emissions. These observations should include particularly high resolution CO_2 and CH_4 concentration with their isotopes, high resolution land cover and use change, and key ground-based measurements such as flux measurements, permafrost active layer dynamics, peatland drainage depth, and carbon densities of all reservoirs.

5.7.Integration of regional carbon budgets

A coordinated, international approach to establishing both land and ocean budgets is clearly required to ensure that such assessments are self-consistent and can be compared with each other and with top-down approaches. In the context of top-down estimates of carbon fluxes, ocean and land approaches to determining regional carbon budgets must be harmonized.

The priority is to support the development of regional carbon budgets (sub-continental and smaller scales) and their dynamics over time. These are spatially discrete components of the global carbon cycle which are now required to support the development of carbon mitigation policies which are regionally based but require global consistency. Regionalization of the global carbon cycle will also provide additional bottom-up constraints and resolution to the global quantities and trends.

The methodology used by the Global Carbon Project for regular assessment of the global CO_2 budget should be enhanced and used for regional estimates and CH_4 fluxes. This methodology is based upon harmonization of data-streams, and multi-model ensembles.

This effort requires a scale-appropriate carbon observatory to resolve higher resolution needs with model-data assimilation systems that will be an integrated component of the global carbon observatory. Deployment of harmonized systems across regions is crucial to maintain global consistency and to be able to build a seamless and well constrained regional to global carbon observatory strategy.

The requirements are:

i) **establish the mean carbon balance of regions of the globe at the typical scale of continents and ocean basins**, including their component fluxes, using a combination of bottom-up data and models from regional carbon cycle programs and global analyses;

ii) update regularly, typically each year, regional and global estimates;

iii) **establish an International Carbon Office to operate a program to produce annuallly updated regional and global carbon budgets**, giving a continually updated global database of estimated carbon fluxes;

iv) **compare bottom-up estimates with the results of regional top-down atmospheric inversions**, and thereby test the compatibility of regional bottom-up estimates with global atmospheric constraints;

v) **assess regional "hot-spots" of flux variability** and the trends and underlying processes over the past decades by combining long-term observations and model results;

vi) **assess the different uncertainty sources and establish a common framework for uncertainty** reporting and analysis.

6.Data Management and Processing

The overall strategy of building a coordinated system of global carbon cycle observations requires a **highly integrated data and information management system**. Key to this system is the ability to synthesize carbon observations from a wide variety of platforms and techniques within a coherent modeling framework based on data assimilation and model-data fusion methods. To achieve these aims is the establishment of distributed data management system that enables access, understanding, use, integration, and analysis of large volumes of diverse data at multiple scales. The data management and analysis systems for the entire data life cycle will deliver high quality products that will be freely accessible to the scientific, resource management, and policy communities around the world.

The challenge is to manage high quality, consistent, long term data in a manner that directly supports the data assimilation models, while maintaining enough flexibility to respond to new observations and models and information technology developments. Currently, the systems are not in place to support the data requirements of the Integrated Global Carbon Observing system. It is thus vital to plan at an early stage for improved data calibration, harmonization, and quality assurance procedures to ensure that observations produced by different networks and observing systems and covering differing spatial and temporal domains are fully compatible and readily integrated in data assimilation systems.

In accordance with the GEOSS Data Sharing Principles, existing sets of well-calibrated, high precision GHG observations should be made available to the international community. While not legally binding, open access to data, metadata and data products within a reasonable time after acquisition is the most efficient and cost-effective way to fill observational gaps. The WMO-sponsored World Data Center for Greenhouse Gases (WDCGG) is an existing framework for both accepting and distributing data and meta-data in a transparent manner. However, more international laboratories could submit data, and many laboratories that submit data could submit more ,currently still inaccessible and hard-to-access, GHG data. This will advance the GEOSS data sharing goals and simultaneously add to our collective understanding of the global carbon cycle.

The following sections describe data management and processing actions required to establish and operate a coordinated carbon cycle data system.

6.1.Integrated and harmonized data products

The ultimate goal 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, measurements from a variety of sources with vastly different spatial, temporal and process resolutions need to be integrated with remote sensing observations within a modeling framework. The requirements are :

i) **Document and harmonize in situ data** from diverse sources. At present problems with in situ data include, inconsistent parameter definitions, differing data formats, incomplete data, differing spatial and temporal scales, and sampling bias in measurements.

ii) **Harmonize data reporting methodologies**. Many core measurements of carbon pools and fluxes are entirely nationally-based, so the harmonization of existing data and the standardization of methodologies is a central issue. Many pool and flux synthesis products exist only in research mode products, e.g., Global Carbon Project ; or the Fluxnet La Thuille activity. Considerable further development is required before these products can be included in hindcasting, analysis, or regular carbon budget updates in the context of an operational system. Among other international initiatives, the Global Terrestrial Observing System (GTOS) has the specific goal of integrating in situ and space-based observation, and can provide standards and harmonization guidelines for atmospheric data integration.

iii) **Implement a data architecture that facilitates the combination of different datastreams**, in particular combine atmospheric observations with observations on the surface and subsurface, both on land and in the ocean, and include ancillary observation of ecosystem condition.

6.2. Priority data products and services

The strategies for data collection and model-based assessment of fluxes and pools should be integrated. Using inverse modeling and data assimilation to place constraints on the fluxes of CO_2 and CH_4 between the Earth's surface and the atmosphere requires reliable, quality assured, and well-calibrated measurements of key carbon stocks and fluxes. In addition there are a number of control parameter observations that are crucial to the data assimilation and model-data fusion activities of IGCO. The requirements are:

i) **Generate the priority data products identified in Section 5**.

ii) **Implement model-data fusion techniques to routinely assimilate data streams of carbon measurements to produce consistent and accurate estimates of global CO_2 and CH_4 flux fields** with typical resolution of 10 km over land and 50 km over oceans, and temporal resolution of days. These products will need to be indexed and made available for assessment, policy, and resource management.

iii) **Merge and synthesize carbon observations within process oriented carbon models**, eventually leading to data-fusion and consistent carbon pools and carbon fluxes estimations. Comprehensive advanced Carbon Cycle Data Assimilation Systems will be required, that are expected to analyze large amounts of data, routinely diagnose carbon quantities, and provide error diagnostics.

iv) **Implement a global data management system to provide access to various data products** based on open source collaboration principles in system development (portal design, data filters, format conversion, web mapping services, cross-platform compatibility). The specific functions required for the data management system to support innovative data assimilation methods need to be identified and plans made to provide that support. Several of the required data streams exist today and systems are in place for handling many of these individual data streams. The data and information management system should build on these existing systems. However, some of the data streams are not produced consistently at the time and space resolution needed, and the data are not harmonized, as a result they cannot be readily assembled into an integrated set for data fusion.

v) **Establish and coordinate feedback paths** between those making the observations, data managers, modelers, and other data users. Dialogue between the research teams and the data system teams is critical to define and implement data product requirements.

6.3. Common data policy

Managing and integrating data for an Integrated Global Carbon Observing System requires an overarching global data policy that provides full and open access to global and regional observational data, and ensures interoperability of the system. Such a data policy could be derived from ICSU and WMO data policies and be tailored to meet the specific needs of a global carbon observing system.

A clear Data Policy will provide a continuing commitment to the establishment, maintenance, description, accessibility and long-term availability of high-quality data and information.

6.4. Metadata standards

In line with international programs such as GCOS and GTOS, it is recommended that interoperability principles and metadata standards be followed to facilitate cooperation and effective use of collected data and information. Metadata enables users to discover data products and understand the content of those products. In addition systems and tools rely on consistent and interoperable metadata to enable automatic processing, including analysis, visualization and subsetting.

Members of GEO will have to **promote the development and use of flexible, open and easy-to-use community standards for metadata** (e.g. CF-1 standards for netCDF). These standards should be interoperable and independent of specific hardware and software platforms. Guidelines for their use should be widely circulated and incorporated into data management training courses.

6.5. Data uncertainty

Potential data sources can be assessed for the reduction in uncertainty they provide for model parameters. Importantly, this modeling approach requires the uncertainty characteristics of the data be an integral component of the data system.

Assimilation models that integrate multiple data types will be more vulnerable to bias than inverse models that 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.

The main recommendation is to take stock of the data and information by **documenting its character, uncertainty, and quality in ways that are responsive to the needs of its end users**, now, for both basic and applied uses, and into the future as they provide the climate-quality, long-term records of Earth system change. As the carbon observing system is expected to deliver information for policy-makers (e.g., IPCC reports, other agencies), the data product inputs to these analyses need to be **evaluated and published in the peer-reviewed literature or in some equivalent**, of documented quality.

6.6.Preservation of data.

Carbon data products, including value-added products and the algorithms used to produce them, need to be archived when the data sets are finalized. A data archive plan for carbon cycle data products is critical, because of the distributed nature of the data management system with individual agencies holding active data products. We highly recommend formulating a strategy for archiving data and products developed to prevent loss of data.

Archiving procedures must take data security, integrity, and routine technological updating into account, and archives should support data discovery and access.

Many data products used for IGCO are currently being archived by agency or national data centers and coordinated by GEO, and one should not duplicate those efforts. The goal here is to identify agency roles and responsibilities, commitment, and the issues/concerns of international collaborators associated with long-term data archival.

7.Integration: Bringing the Whole System Together

The objectives of integration are:

i) spatial integration, to combine measurements from different regional programs;

ii) completeness, to ensure that all important processes of the carbon cycle are observed;

iii) temporal integration, to provide long time series for improved model prediction, and evaluation of policy-decision impacts;

iv) process integration, combining data to form a single, consistent view of the carbon cycle balancing inferences from atmospheric, oceanic, terrestrial and socioeconomic data.

Previous sections have dealt with the first three objectives and here we focus on the fourth – how observations will be used.

Integrating multiple streams of observations into carbon cycle models requires assimilation techniques that modify model behavior to match observations. This is known as model-data fusion, the multiple constraint approach or carbon-cycle data assimilation. Such techniques were first applied long ago to the tuning of the seasonal cycle of atmospheric CO_2 concentration, but around the year 2000 formal data assimilation methods were introduced, allowing the field to develop rapidly. Examples of applications are the estimation of phenology parameters from satellite observations, estimates of photosynthetic parameters using CO_2 and heat fluxes, and a suite of parameters in terrestrial models derived from biomass inventory data. Oceanic applications are rarer, but several notable applications exist. For example, atmospheric data assimilation techniques (e.g. 4DVAR) were used in the atmospheric inverse models to establish the atmosphere-

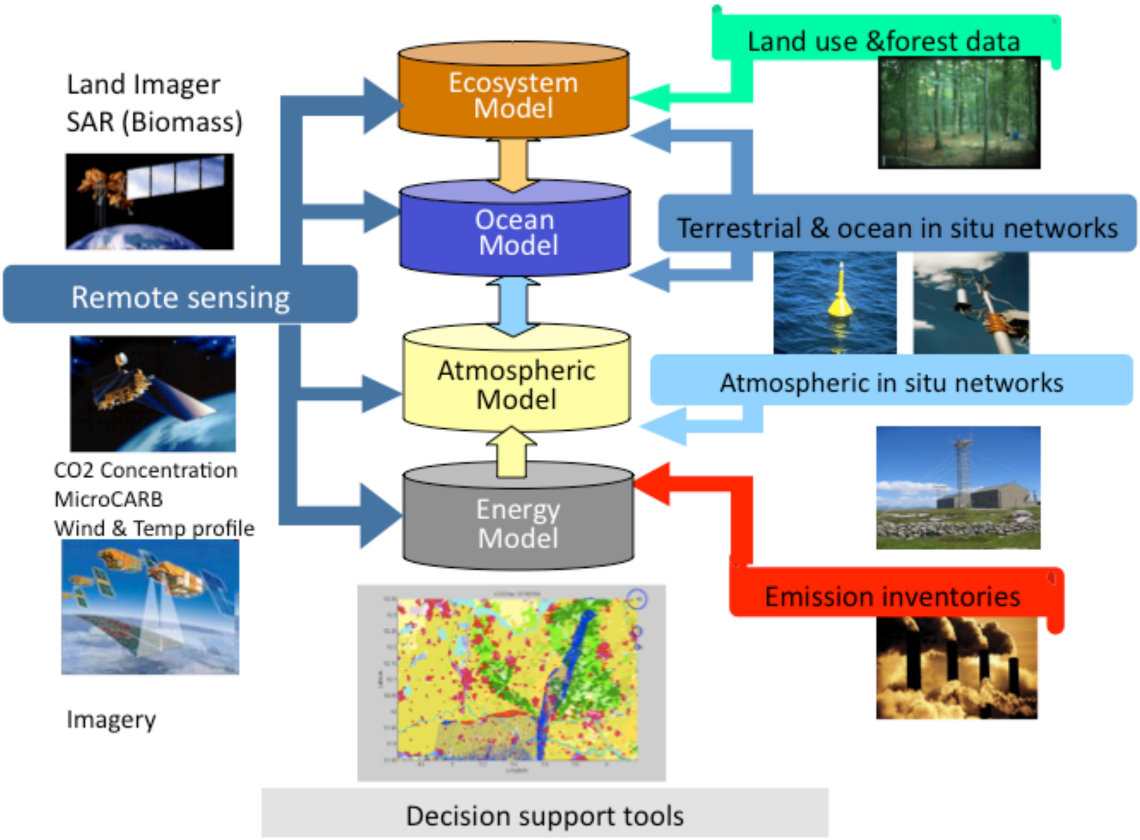

Figure 17. Overview of the envisioned global carbon-cycle data assimilation system applied to the production of a GHG sources and sinks maps.

ocean fluxes of CO_2 and CH_4. The envisioned global data integration system is depicted in Fig. 17.

There are two broad categories of applications:

i) those that constrain the internal state of the model by assimilating state variables;

ii) those that estimate poorly known internal parameters of the model.

Clearly, state-variable assimilation will produce a closer fit to observations and so is preferred where the best possible performance within the observing period is required (i.e. diagnostic applications), while estimating parameters is intended to improve the underlying behavior of the model and targets prognostic applications.

The requirements for data have been set out in Section 6 of this document. Most importantly, every observation must be associated with an uncertainty since this is necessary to weight each observation's influence on the model. Beyond this, use of any observation in a data assimilation system requires an operator that can map the internal state of the model nto the observed variable. Here there are practical choices to be made if the published data are themselves the result of a complex model such as a radiative retrieval. In general it is best to bring these observation operators into the data assimilation process itself since otherwise the error statistics of the observation are really those of the observation operator. This can be difficult to represent. As an example, uncertainties in calibration can generate coherent errors that will not be captured by pointwise descriptions of error. Experience with numerical weather prediction suggests that the generation of observational operators requires close collaboration between the modeler and the expert observer. As a scientific task, the generation of these observation operators is as equally important as the generation of the data sets of observations made using them.

7.1.Quantitative network design

Given the errors in the measurements, it is possible to quantify the value of a given data set in terms of the information it brings. This always requires some kind of model of the underlying statistics and usually of the dynamics of the system as well. The approach has been used to quantify the value of in situ measurements of concentration for constraining surface fluxes and to assess the likely value of satellite measurements of CO_2. The application of such methods to the more complex task of dynamical data assimilation has been demonstrated by the IMECC Network Design Tool (http://imecc.ccdas.org). One can even attempt to construct an optimal network, but the task of defining optimality and the assumptions of prior knowledge suggest that the more conservative option of testing potential networks is more reliable.

8. Implementation timetable for IGCO

Action	Agencies involved	Time frame
Produce routine annual global budgets	GCP, Research institutions, Future Carbon Agency ?	2010-2015
Produce routine annual regional budgets	GCP, Research institutions, Future Carbon Agency ?	2010-2015
Demonstrate production of CO_2 flux maps based upon satellite data (GOSAT, possibly OCO-2)	Satellite agencies, research institutions and universities,	2010-2015
Produce routine CO_2, CH_4 flux maps based upon satellite data (GOSAT, OCO successors)	Satellite agencies, research institutions and universities,	2015-2020
Demonstrate consistent global forest biomass/carbon storage maps based on data from lidar/radar satellite sensors	Satellite agencies	2015-2020
Produce routine consistent global forest biomass/carbon storage maps based on data from lidar/radar satellite sensors	Satellite agencies	2020-2050
Launch of CO_2 and CH_4 satellites with temporal continuity	Satellite agencies	2015-2050
Achieve construction of operational atmospheric + eddy flux network over North America, Europe, China	Research Institutions, agencies, WMO	2010-2015
Begin construction of atmospheric + eddy flux network over India, Brazil, Russia	Research institutions and universities, agencies, WMO	2010-2015
Achieve construction of operational atmospheric + eddy flux network over India, Brazil, Russia	Research institutions and universities, agencies, WMO	2015-2030
Implementation of global network O_2/N_2 and $\delta^{13}CO_2$, and fossil fuel emissions with $^{14}CO_2$ and halocarbons	Research institutions and universities, agencies, WMO	2015-2030
Construction of TCCON network of 50 sites	Research institutions and universities, agencies, WMO	2010-2030
Ocean flux monitoring over selected ocean basins	Research institutions and universities, agencies, IOP	2010-2015
Routine ocean flux monitoring over ocean basins	Research institutions and universities, agencies	2015-2030
High precision measurements of carbon, oxygen, and nutrients in ocean section and Argo floats	Research institutions, agencies	2012-2020
Develop and implement pCO_2 network for coastal areas	Research institutions and universities, agencies	2010-2020
Consistent reanalysis of last 30 years of global C cycle dynamics using carbon data assimilation systems	Reanalysis centers, research institutions	2010-2015
Produce global data-driven GPP, NPP, NEP maps based upon fluxnet data fusioned with other relevant fields	Research institutions and universities, agencies	2010-2015
Global high resolution fossil fuel emission maps, updated each year	Research institutions agencies	2010-2015

Action	Agencies involved	Time frame
Move Fluxnet observations to an operational reference network	Research institutions, agencies, WMO, FAO	2010-2015
Produce forest biomass, forest age structure, and biomass change global assessment	FAO, inventory agencies	Every five years, 2010,2015, 2020...
Develop operational forest carbon tracking system	FAO, research institutions and universities, agencies	2010-2020
Operational forest carbon tracking system	FAO, Research institutions and universities, agencies	2020-2050
Produce first global assessment of carbon in soils	Research institutions and universities, agencies , FAO	2015, every 10 years
Produce annual land cover change and LUC maps	Research institutions and universities, satellite agencies	2015, every year
Produce routine annual air sea flux maps	Research institutions and universities, satellite agencies	2010-2015
Coordinated pCO_2 observations around coastal oceans	Research institutions and universities, satellite agencies	2010-2015
Develop a satellite based on an active LIDAR concept	Satellite agencies, research institutions, universities	2020
Improved access to geospatial and temporal fossil fuel emission information	Satellite agencies, research institutions, universities	2010-2015, every year
Web reporting of results and accuracy assessment, including uncertainties analysis and traceability to the basic elements used to construct fossil CO_2 emission maps	Research institutions and universities, agencies, IEA	2010-1012
Ensure the documentation and harmonization of in situ data from diverse sources.	Research institutions and universities, agencies, WMO, FAO	2010-2020
Harmonization of existing data and the standardization of methodologies	Research institutions and universities, agencies, WMO, FAO	2010-2020
Develop a carbon portal to access all carbon data	Research institutions and agencies	2010-2015

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10.Important acronyms

CEOS	Committee on Earth Observation Satellites
CEOS-WGCV	CEOS Working Group on Calibration and Validation
CH_4	methane
CO_2	carbon dioxide
ECV	essential climate variable
FAPAR	Fraction Absorbed Photosynthetically Active Radiation
GAW	Global Atmosphere Watch
GCOS	Global Climate Observing System
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GHG	greenhouse gas
GOSAT	Greenhouse Gases Observing Satellite
GTOS	Global Terrestrial Observing System
ICOS	Integrated Carbon Observing System
IGACO	Integrated Global Atmospheric Chemistry Observations strategy
IGCO	Integrated Global Carbon Observing system
LAI	Leaf Area Index
MRV	monitoring, reporting, and verification
OCO	Orbiting Carbon Observatory
pCO2	CO_2 partial pressure difference between atmosphere and seawater
REDD	Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
SCIAMACHY	SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
TCCON	Total Carbon Column Observing Network
VOS	Volunteer Observing Ships
WDCGG	World Data Center for Greenhouses Gases

This report can be downloaded from:

http://www.earthobservations.org/documents/sbas/cl/201006_geo_carbon_strategy_report.pdf

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