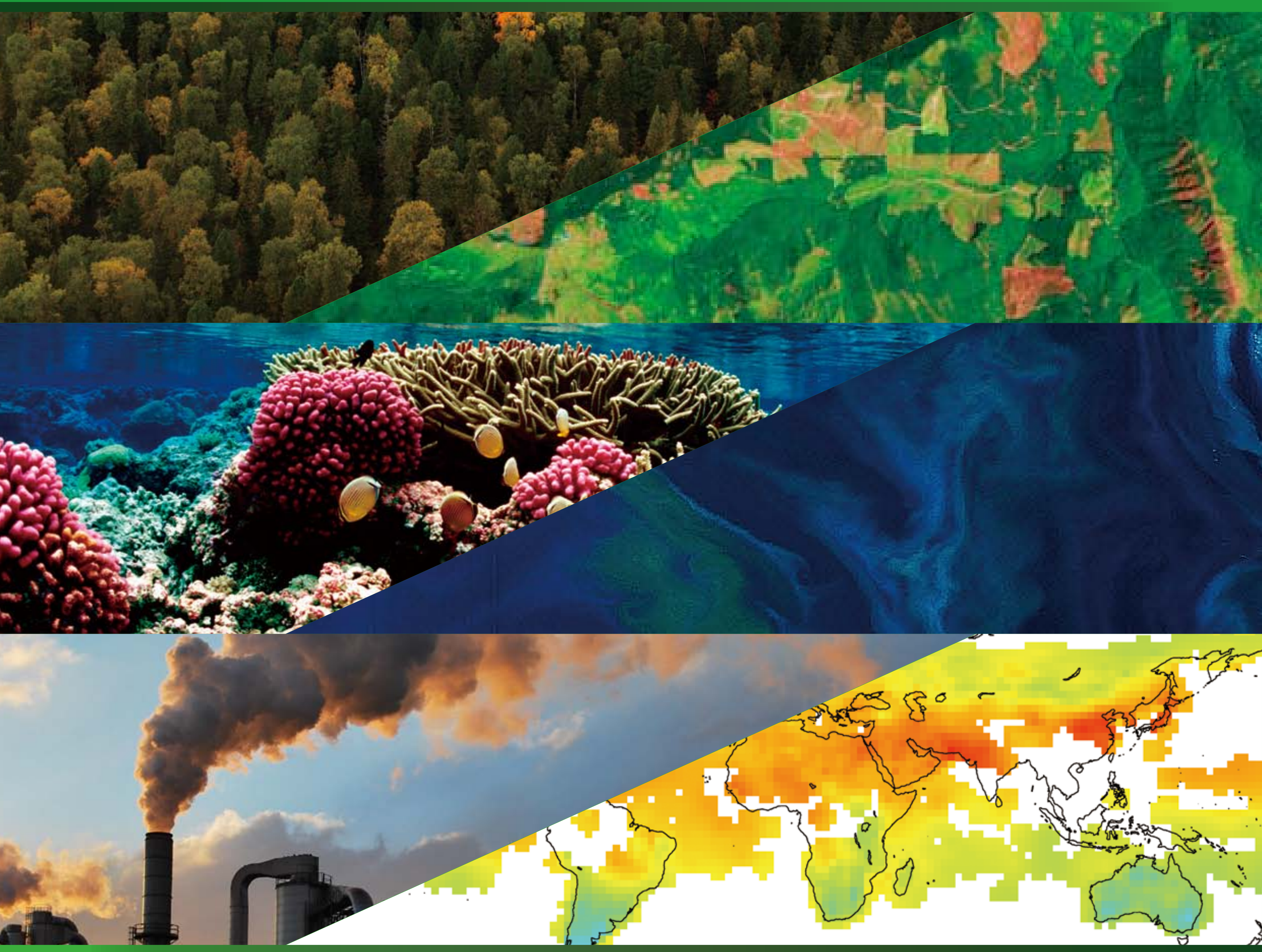
CEOS STRATEGY FOR CARBON OBSERVATIONS FROM SPACE

APRIL 2014



CEOS Strategy for Carbon Observations from Space

The Committee on Earth Observation Satellites (CEOS) Response to the Group on Earth Observations (GEO) Carbon Strategy

Developed under the auspices of the CEOS Carbon Task Force

The front cover of the CEOS Strategy For Carbon Observations From Space is a derivative work that uses a number of Creative Commons licensed images, as follows:

Coral Reef at Palmyra Atoll National Wildlife Refuge (https://flic.kr/p/9tPDCU) by Jim Maragos/U.S. Fish and Wildlife Service, used under Creative Commons license CC BY 2.0 (https://creativecommons.org/licenses/by/2.0/). The image was cropped to fit the cover design.

Yuganskiy Nature Reserve Aerial View (https://flic.kr/p/diNuJH) by Tatiana Bulyonkova, used under Creative Commons license CC BY-SA 2.0 (https://creativecommons.org/licenses/by-sa/2.0/). The image was cropped to fit the cover design.

Smoke stack - Ilirska Bistrica, Slovenia (https://flic.kr/p/dTYqpY) by why 137, used under Creative Commons license CC BY 2.0 (https://creativecommons.org/licenses/by/2.0/). The image was horizontally flipped and cropped to fit the cover design.

The following satellite images also appear on the cover:

GOSAT Image, The global distribution of XCH4 for the month of September in 2010, courtesy JAXA/NIES/MOE, http://www.gosat.nies.go.jp/eng/related/2010/img/XCH4_L3_201009010930_v01_30.png. The image was cropped to fit the cover design.

A Southern Summer Bloom, courtesy ESA, http://www.esa.int/spaceinimages/Images/2012/01/A_southern_summer_bloom. The image was cropped to fit the cover design.

Landsat false-color images shows clear cutting and forest regrowth between 1984 and 2010 in Washington State, northeast of Mount Rainier, courtesy NASA Earth Observatory, http://earthobservatory.nasa.gov/Features/CarbonCycle/page6.php. The image was cropped to fit the cover design.

This document should be cited as: CEOS.
(2014) CEOS Strategy for Carbon Observations from Space.
The Committee on Earth Observation Satellites (CEOS) Response to the Group on Earth Observations (GEO) Carbon Strategy.
Issued date: September 30 2014
Printed in Japan by JAXA and I&A Corporation

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Group on Earth Observations (GEO) published the *GEO Carbon Strategy* in 2010 (Ciais et al. 2010). This report, the *CEOS Strategy for Carbon Observations from Space,* is a response from the Committee on Earth Observation Satellites (CEOS) to the *GEO Carbon Strategy*. It details the adequacy of past, present, and planned satellite measurements of carbon in the land, oceans and inland waters, and atmosphere domains to support GEO, and it identifies important challenges that CEOS must face and actions CEOS and its agencies must take to meet needs for carbon observations from space. Specifically, it identifies what can be achieved through CEOS actions to better coordinate existing and future capabilities as well as those challenges that require additional resources and/or mandates beyond the present capacity of CEOS and its member agencies.

The *GEO Carbon Strategy* calls for an Integrated Global Carbon Observing system (IGCO) to meet pressing needs for policy-relevant scientific information about the carbon cycle. Carbon observations deserve very special attention because the increasing concentrations of atmospheric CO_2 and CH_4 play a central role in driving global climate change. Carbon cycling is also fundamental to the Earth system because of its intimate coupling across the land, oceans and inland waters, and atmosphere domains, and with Earth's climate. As the nations of the world experience the impacts of climate change and act in response to those changes, their needs will include observations and monitoring of the effects of their actions – and the knowledge to distinguish the effects of those actions ("anthropogenic") from those of other changes ("natural") in the system. In no area is this more evident than in global carbon cycling. Information about carbon cycle changes will be absolutely essential for climate policy development, implementation, and verification.

The *GEO Carbon Strategy* clearly explains the limitations of our current knowledge of the global carbon cycle and explains why improved scientific understanding will be essential to underpinning societal responses to global climate change. The report unequivocally states that "*a key reason for our lack of understanding of the global carbon cycle is the dearth of global observations*," and calls for "*an increased, improved and coordinated observing system for observing the carbon cycle* as a *prerequisite to gaining that understanding*." CEOS recognizes that the GEO requirements for carbon observations from space are well judged and technically feasible, but challenging in terms of a complete, sustained and coordinated response.

CEOS, as the primary international forum for coordination of space-based Earth observations, is well positioned to provide needed coordination for the space-based and related supporting observations called for in the *GEO Carbon Strategy*. At its 24th plenary meeting in Rio de Janeiro, Brazil in 2010, CEOS charged its Carbon Task Force (CTF) to develop a response to the *GEO Carbon Strategy*, describing the approach CEOS will take in meeting the GEO requirements for space-based observations of carbon.

This report was written by an international team of scientists from a range of research institutions and CEOS agencies who were recruited by the CEOS CTF. In directly responding to the *GEO Carbon Strategy*, the authors felt it important to provide updates on scientific developments and measurement capabilities that occurred since the 2010 publication of the *GEO Carbon Strategy* and to anticipate the carbon information needs for climate policy (e.g., United Nations Framework Convention on Climate Change (UNFCCC) and Intergovernmental Panel on Climate Change

(IPCC)). This report also takes account of, and attempts to be consistent with, the Global Climate Observing System (GCOS) Implementation Plan and its requirements for Essential Climate Variables (ECVs).

The authors of this report have identified high-priority needs for decisions, resources, and actions that go well beyond the scope of what CEOS alone can do and that exceed the mandates and current capacities of many of its agencies. These needs can be viewed as contextual challenges that CEOS should acknowledge. Thus, this report takes the unusual step of offering recommendations of two types: *Challenges* and *CEOS Actions*. The *Challenges* are recommendations that CEOS will acknowledge as important, legitimate needs and commit to factor into its priorities and the activities it coordinates and acts to influence. The *CEOS Actions* are specific activities that CEOS commits to implement, track, and report on following established procedures.

Actions to coordinate existing and planned satellite missions and challenges associated with developing and deploying missions to make new, high-priority measurements feature prominently in this report's findings. The report also calls for CEOS to devote additional attention to improvements in data products; development of new data products; calibration and validation work; and promoting long-term archive and availability of carbon-related satellite data and products for science and policy. In total, the *CEOS Strategy for Carbon Observations from Space* identifies 20 contextual Challenges and 42 CEOS Actions. The CEOS Actions are summarized as follows:

- Ensure the continuity of satellites and established time series data records for carbon-related measurements of land surface properties, ocean color and related physical properties, coastal and inland water properties, and atmospheric column measurements of carbon dioxide and methane. (5 CEOS Actions)
- Develop and deploy new missions to acquire high priority measurements for carbon science and policy, including new observations to estimate aboveground biomass and its carbon content, geostationary observations of carbon-containing constituents in coastal ocean waters, improved resolution ocean salinity measurements, and measurements of atmospheric carbon dioxide and methane from complementary Low Earth Orbit (active and passive) and geostationary (passive) satellite constellations. (5 CEOS Actions)
- Improve satellite data products, including establishment of standard formats and protocols, enhanced validation, securing access to essential *in situ* data, merger of data from multiple sensors and platforms into enhanced products, and rigorous intercomparison of data products. (9 CEOS Actions)
- Produce new data products from existing missions, including maps of wetlands, inundated areas and small water bodies, ocean color products for inland water bodies, ocean carbon pool products, river discharge and sediments, and anthropogenic emissions of carbon. (4 CEOS Actions)
- Improve the accessibility and utility of the satellite data and carbon data products derived from them, including transparency in data processing procedures, complete documentation, long-term archive, and provision of products in forms scientists and policy makers will use. (1 CEOS Action)
- Continue and enhance calibration and validation activities, including expanded quality assessments, cross-calibrating additional sensors (e.g., for carbon dioxide and methane), securing access to essential *in situ* validation data, expanding the number of land variables to be validated, and establishing an ocean product validation subgroup. (10 CEOS Actions)

- Improve institutional arrangements, communications, and joint activities with the carbon community and organizations with carbon interests. (3 CEOS Actions, plus numerous references to such linkages in other actions)
- Improve or establish CEOS Mechanisms to implement this report's recommendations or to engage in the future planning activities called for in it (5 CEOS Actions)

To address these challenges and actions, the following way forward is proposed:

- CEOS and its member agencies make note of the important and wide-ranging challenges and actions identified in this report. They will work within their own capacities and with their governing bodies to identify and secure the resources that are required to implement the actions and meet the long-term challenges.
- CEOS identifies a group to be responsible for carbon-related observations within CEOS and for advancing the findings of this report. This group will take responsibility for overseeing, coordinating, and reporting on the actions identified in this report and will establish strong working relationships with relevant CEOS Virtual Constellations and Working Groups.
- CEOS works with GEO, GCOS, UNFCCC and other relevant bodies to strengthen understanding, communications, and cooperation on carbon observations for science and policy.
- CEOS recognizes the importance of periodically assessing progress and reporting on actions and will establish internal (to CEOS) procedures for these purposes and will also report to relevant external bodies, as appropriate and when requested.

To conclude, carbon cycling is an Earth system process, with intimate coupling among its land, oceans and inland waters, and atmosphere domains and with Earth's climate. Satellite observations for an IGCO must address carbon pools in all domains as well as the fluxes among them. CEOS and its agencies must promote and facilitate an end-to-end approach so that data are not just acquired, but relevant data products are produced, delivered in carbon units, and used to advance scientific understanding and meet societal needs. CEOS can meet these challenges by providing leadership, sharing this vision for carbon observations, and working to coordinate agency space missions and activities in ways that maximize the scope, coverage, quality, accessibility, and utility of satellite-derived carbon data.

CHAPTER 1: INTRODUCTION

**LEAD AUTHORS: MASAKATSU NAKAJIMA (JAPAN AEROSPACE EXPLORATION AGENCY),
DIANE E. WICKLAND (NATIONAL AERONAUTICS AND SPACE ADMINISTRATION),
STEPHEN PLUMMER (EUROPEAN SPACE AGENCY),
AND STEPHEN WARD (JAPAN AEROSPACE EXPLORATION AGENCY)
CONTRIBUTORS: RALPH DUBAYAH (UNIVERSITY OF MARYLAND), BERRIEN MOORE (UNIVERSITY OF OKLAHOMA) AND SHUBHA SATHYENDRANATH (PLYMOUTH MARINE LABORATORY)**

The carbon cycle is central to the Earth system, being inextricably coupled with climate, the water cycle, nutrient cycles, and the production of biomass by photosynthesis on land and in the oceans (Canadell et al. 2004). In the natural system, the balance among carbon in the oceans and inland waters, land, and atmosphere is regulated through fluxes between these three main pools or reservoirs. In addition to these natural components, there are the contributions to the atmosphere from human activities, namely, fossil fuel burning, cement production, and a range of land management practices. Over the past 250 years, the atmospheric carbon dioxide (CO_2) concentration has increased by roughly 40% from its pre-industrial value of roughly 280 parts per million by volume (ppm) to nearly 400 ppm today. In the same timeframe, atmospheric methane (CH_4) nearly tripled, reaching approximately 1900 ppb today from 700 ppb in the pre-industrial times. Recent patterns of exchanges of carbon with the atmosphere may also be affected by CO_2 fertilization, ocean acidification, changes in surface runoff of sediments, changes to wetlands and peatlands, warming of permafrost, and changes to natural disturbance regimes. Thus, a comprehensive carbon monitoring strategy must consider all of these components (land, oceans and inland waters, and atmosphere) and the interactions among them to correctly assess changes in the global carbon cycle.

From the perspectives of the Committee on Earth Observation Satellites (CEOS) and the Group on Earth Observations (GEO), observations of carbon in the land, oceans and inland waters, and atmosphere are only a subset of the essential observations needed to understand the Earth system. Nonetheless, carbon observations clearly deserve very special attention because increasing concentrations of atmospheric CO_2 and CH_4 are driving global climate change. In order to respond to global climate change, there are many things we need to measure and understand about carbon and its cycling through the land, oceans and inland waters, and atmospheric domains of the Earth system. These include:

- Measurements of CO_2 and CH_4 in the atmosphere to quantify changes in emissions and greenhouse forcings as well as to identify locations, intensities, and durations of their major sources and sinks.
- Measurements of carbon stocks on the land and in the oceans and inland waters to quantify carbon storage (i.e., sequestration) and monitor climate mitigation and carbon management effects.
- Observations of key carbon cycling processes in the land, oceans and inland waters, and atmosphere to explain how changes are occurring and to identify the causes and consequences.

A complete and integrated understanding of the changing carbon cycle and the effects of attempts to manage carbon in the environment can only be achieved through an observational system that addresses all components of the carbon cycle and their interactions and is optimized to integrate the information obtained.

Surface-based observation sites provide high-quality measurements of greenhouse gas concentrations and fluxes, but they are sparse, unevenly distributed globally, and do not always provide data at regular intervals or use consistent protocols for data collection. Satellites can acquire abundant global measurements at regular, if sometimes infrequent, intervals. These measurements have different properties and complement the surface-based measurements. One great advantage of satellite data is that they are usually internally consistent, i.e., the satellite sensor employs the same observing procedures and methodologies for observations around the world. Many important components of the land-oceans and inland waters-atmosphere carbon system are now routinely observed from satellites, and these measurements are making major contributions to our understanding of Earth's carbon pools and fluxes. The world's space agencies provide and manage operational and experimental remote-sensing platforms that observe carbon-related properties. The international scientific community has developed innovative methods to convert the directly observed radiances into scientifically useful biogeophysical products, often in combination with observations from surface-based networks or airborne *in situ* instruments. However, it is important to note that such an observing system does not constitute a carbon observation system until the data products have been expressed in carbon units and can contribute to accurate estimates of carbon pools and fluxes. To be of value in this context, observations from space must be useful for evaluating and reducing uncertainties in the estimates of these pools and fluxes and for monitoring, on a routine basis, variations in these pools and fluxes over time. Because the natural system is highly variable, even over decadal time scales, the observations must be sustained in a systematic manner over a very long time, to identify true trends and to discriminate anthropogenic changes from natural variability. Because of the interconnected nature of the carbon system, an effective observation system must be a multidisciplinary, integrated system, capable of detecting changes.

1.1 Purpose

This report presents the Committee on Earth Observation Satellites' (CEOS) strategy for the planning and coordinated provision of space-based observations of the carbon cycle and its components in support of scientific and societal needs for carbon-related information. It is a direct response to the needs expressed in the *Group on Earth Observations (GEO) Carbon Strategy* (Ciais et al., 2010) and the ambitions therein for the realization of an Integrated Global Carbon Observing system (IGCO; sometimes also referred to as Integrated Global Carbon Observation and Analysis System (IGCOAS)). It can also be considered responsive to the United Nations Framework Convention on Climate Change (UNFCCC) Copenhagen Accord (Decision 9), which urges countries that support space agencies involved in global observations to continue to implement those observations in a coordinated manner through CEOS to meet the relevant needs of the UNFCCC. Specifically, the *CEOS Strategy for Carbon Observations from Space* focuses on the satellite observations and the efforts of space agencies to provide them and of CEOS to coordinate and encourage a well-balanced and integrated suite of space-based observations.

The primary purpose of this report is to guide future CEOS actions, priorities, and planning and provide the basis for systematic monitoring and reporting of progress toward satisfying science and society's carbon information needs -- specifically with regard to the establishment, sharing, and coordination of space-based Earth observations of carbon and related Earth system properties. CEOS identifies what can be achieved through better coordination of existing and future capabilities as well as acknowledges those improvements, advancements, and challenges that will require additional resources and/or mandates beyond the present capacity of the world's space agencies. These needs are assumed to be broad – spanning support to national and international policy formulation and implementation and the needs of industry, of the science community, and of the public in engaging in and understanding carbon matters, including and especially how they relate to climate change.

1.2 Audience

The main audience for this report is CEOS and the organizations that comprise its membership, hereafter referred to as CEOS member agencies. It will serve primarily as an internal document to highlight priorities, identify opportunities for improved coordination and to create synergy, and provide guidance in planning for future carbon-related activities.

Additionally, this report will serve to inform other organizations regarding the space-based observations of carbon and carbon-related properties that are and will become available, as well as what CEOS and its member agencies are doing overall to help meet their needs for information about carbon in our environment. In particular, this report is intended to inform and be a resource for the Group on Earth Observations (GEO) as it works to coordinate efforts to build a Global Earth Observation System of Systems (GEOSS) and for the United Nations Framework Convention on Climate Change (UNFCCC) as it strives to set the framework for nations to limit average global temperature increases and resulting climate change, and to cope with the impacts of climate change. Other stakeholders that will find the information and plans for future CEOS activities and coordination of interest include the international scientific community and the International Council for Science's (ICSU) International Geosphere-Biosphere Programme (IGBP), Earth System Science Partnership (ESSP), and new Future Earth initiative.

1.3 Background and Context

The Intergovernmental Panel on Climate Change's (IPCC) Fourth and Fifth Assessment Reports (AR) both conclude that warming of the climate system is unequivocal, and anthropogenic emissions of greenhouse gases are responsible for most of the increase in global average temperatures (IPCC 2007, IPCC 2013). The ocean and terrestrial biosphere are currently absorbing about half of the CO_2 emitted by anthropogenic activities (primarily fossil fuel combustion), reducing the rate of atmospheric CO_2 buildup and its effects on the climate. However, the nature and location of these carbon sinks is still inadequately understood. The efficiency of CO_2 sinks and CO_2 and CH_4 sources may also change as the climate warms, introducing large uncertainties in the future net flux of these gases. An improved understanding of global carbon cycling processes and quantitative measurements of changes in carbon pools and fluxes are urgently needed to reduce uncertainties in projections of future global warming and climate change due to increases in atmospheric carbon dioxide and methane concentrations. They are also needed to inform planning for societal actions to mitigate and/or adapt to climate change and to monitor and quantify the effects of those actions.

The 2010 *GEO Carbon Strategy Report* identified the need for and possible approach to the implementation of an IGCO to address the three components of the carbon cycle (atmosphere, land and ocean) and their interactions. The Report noted:

> *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… **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.***

The basis for GEO's IGCO was initially developed through the Integrated Global Observing Strategy partnership (IGOS-P) in 2004-5 and described in the *Integrated Global Carbon Observations Theme Report* (IGOS-P, 2003). The IGOS-P was a particularly effective framework in bringing together user communities, scientists, and *in-situ* and space observation organizations to produce a focused and coherent statement of needs and capabilities for a number of selected Earth system components -- of which the carbon cycle was one. The IGOS-P Themes have since been integrated into the GEO framework, as Communities of Practice (CoP), and the Carbon CoP continued the task started by the IGOS-P Carbon Theme team. Given significant advances in science and changes in observing system capabilities and plans, the GEO Carbon CoP produced the 2010 *GEO Carbon Strategy* report as an update of the *Integrated Global Carbon Observations Theme Report*. The *GEO Carbon Strategy* was followed by a publication in which many of the same authors highlighted the needs for a policy-relevant carbon observing system (Ciais, et al. 2013).

Measurement, Reporting, and Verification (MRV; also referred to as Monitoring, Reporting and Verification or Measuring, Reporting, and Verifying) has emerged recently as a central issue for effective tracking of progress by parties to the UNFCCC in meeting their national commitments and achieving the Convention's overall goals (see http://unfccc.int/2860.php; and http://unfccc.int/focus/mitigation/items/7173.php). MRV involves quantitative measurement of carbon emissions to the atmosphere and/or of the efficacy of mitigation actions to reduce carbon emissions; compilation and integration of the information into reports and inventories; and independent evaluation of the accuracy and utility of the information. It seems clear that satellite data products could have enormous value within an MRV system. However, the requirements of decision makers with respect to the need for MRV are not yet completely clear. They will depend on the policies that are enacted, the spatial and temporal scales of significance for monitoring, and the accuracies desired. Projects in support of Reducing Emissions from Deforestation and Forest Degradation (REDD) provide current examples (e.g., the Global Forest Observation Initiative (GFOI)).

CEOS plays an influential role in coordinating the implementation of the satellite component of the Global Earth Observation System of Systems (GEOSS) – which is the vision pursued by GEO for the linking of existing and planned observing systems around the world and supporting development of new systems where gaps currently exist. This responsibility includes the coordination of space observations in support of the Climate Societal Benefit Areas (SBA) -- there are nine SBAs in GEO -- whose requirements are expressed in the *Global Climate Observing System (GCOS) Implementation Plan (IP)* (2006, updated in 2010) and complemented by detailed requirements on space agencies, gathered in the GCOS Satellite Supplement (GCOS 2011). Upon the request of GCOS, CEOS already has implemented a systematic process for reporting to the UNFCCC on space agency progress made in responding to the space-related needs of the GCOS IP of 2010 – and this process represents a model that could be adopted for the implementation of recommendations from this report. Recognizing the increasing importance of carbon observations to a range of societal needs (including, but not restricted to the Climate SBA and potentially MRV), CEOS considers that this report presents an important opportunity to develop a more specific and detailed assessment focused on the planning for carbon-related observations from space. Through CEOS, space agencies worldwide will be able to provide a concerted response to the needs identified in and to work with GEO towards the vision of an IGCO.

1.4 Scope and Objectives

CEOS has determined that its *Strategy for Carbon Observations* from space should:

- Be comprehensive, defining an strategy for space-based observations in support of global carbon measurement requirements and all active pools and fluxes therein – covering atmospheric, terrestrial, and oceanic observations as well as observations of the interfaces among them;
- Require the acquired data to be cross-calibrated and validated to make it possible to use the data in combination and over long time periods;
- Provide a long-term outlook, to 15 years hence, with the goal of a sustained observation system in support of societal needs and in recognition of the long-term nature of climate data records and needs for on-going measurement, monitoring, and assessment strategies;
- Address the full range of societal needs and applications related to space-based carbon observations; in addition to the scientific requirements detailed in the *GEO Carbon Strategy*, the CEOS Strategy will take into account the needs for carbon information expressed in the IPCC's Fourth Assessment Report, by the UNFCCC, and in the GCOS Implementation Plan; the CEOS Strategy will address the needs of science, policy, industry, and the public for information about carbon in the environment;
- Address the establishment of appropriate and effective institutional arrangements, within CEOS and between CEOS and other institutions, for realization of the space component of the IGCO; the emphasis will be on satellite observations of or related to carbon with appropriate context given to complementary (non-satellite) observations, supporting climate observations, and the activities and infrastructure required to make effective use of satellite observations;
- Provide a framework for monitoring, reporting and communicating progress towards implementation of the space component of IGCO.

1.5 Content

1.5.1 Domain Chapters

The next three chapters in this report (Chapters 2, 3 and 4) address the Land, Oceans and Inland Waters, and Atmosphere domains, respectively. Each considers and characterizes the nature of the requirements for satellite observations in its respective domain. The current status of carbon and carbon-related observation provision is summarized and the prospects and trends for the coming years outlined. These capabilities are assessed for their adequacy versus the requirements identified to fulfill future needs in support of the IGCO. This assessment then provides the basis for the recommended actions regarding future CEOS efforts.

Each of the three domain chapters reinforces the requirements for space-based carbon observations articulated in the *GEO Carbon Strategy* and also provides an updated perspective, incorporating information available since 2010 as well as new information and additional detail on satellite measurement capabilities and plans. The CEOS System Engineering Office provided gap analyses for the ocean and atmosphere domain chapters that greatly informed their analyses of current and planned satellite missions and the adequacy of the data from these missions. A preliminary analysis was performed for the land domain chapter, but a full-scale analysis was not requested because a significant fraction of the land variables of interest for carbon are not reported in the CEOS Mission, Instruments, and Measurements (MIM) database (http://database.eohandbook.com/). The balance of content and emphasis within each of the domain chapters differs as a result of the maturity and diversity of space-based carbon and carbon-related observations currently available, planned, and needed for that domain.

1.5.2 Integration Chapter

Chapter 5 discusses observations at the interfaces among the three domains, integration of information across the different domains, and common requirements for observations, data products, supporting activities, and infrastructure. Many of the latter requirements may apply to other types of satellite observations as well, but it is important that they be addressed for carbon in this report.

1.5.3 Way Forward Chapter

Chapter 6 discusses the way forward for CEOS in implementing this *Strategy for Carbon Observations from Space* and meeting the space component needs of the IGCO. The challenges ahead are described. The recommendations, Challenges and CEOS Actions, are summarized. Recommendations regarding CEOS mechanisms for implementation, oversight, and reporting are described.

1.5.4 Two Types of Recommendations: Challenges and CEOS Actions

Throughout the report, important missions, data products, and related activities are identified to move carbon cycle science and its policy applications forward and to achieve the IGCO called for in the *GEO Carbon Strategy*. In some cases, the ability and authority to take action falls outside the purview of CEOS and its coordination functions, and it is unreasonable to think CEOS alone could accept full responsibility for the recommendation or act to complete it. These needs, however, represent major challenges that nations, inter-governmental organizations, the scientific and policy communities, and CEOS must work together to address in the long run. These needs can be viewed as contextual challenges for CEOS to acknowledge and commit to factor into the activities it coordinates and influences, now and into the future.

Thus, this report takes the unusual step of offering recommendations of two types: Challenges and CEOS Actions. "Challenges" are recommendations that CEOS will acknowledge as important, legitimate needs and agree to factor into its planning for future CEOS coordination activities and priorities. The Challenges are often accompanied by specific CEOS Actions that represent small steps toward meeting the larger challenge. "CEOS Actions" are specific activities that CEOS commits to implement, track, and report on following established procedures. The CEOS Actions are grouped in each chapter according to the following types: Mission-Related, Product-Related, Calibration/Validation-Related, Interactions/Linkages/Communications-Related, and CEOS Mechanisms- and Future Planning-Related. Actions are numbered in order of occurrence in this document and may be repeated (but with same number) if pertinent to the recommendations of more than one chapter.

When possible, specific CEOS Working Groups, Virtual Constellations, or other internal CEOS entities are identified as appropriate recipients of a CEOS Action. In some cases individual CEOS agencies may be associated with an action.

1.5.5 Supporting and *In Situ* Observations

This report does not analyze or discuss in depth priorities for supporting observations of climatic and other variables (satellite or *in situ*) that are needed for use in conjunction with observations of carbon and carbon-related properties (e.g. to drive carbon models, to analyze or evaluate data products). However, the need for such observations is noted in relevant sections within this report. In order to keep a sharp focus on carbon and not repeat the work of others, this report relies on GCOS and IGOS reports, the ongoing work of the CEOS Working Group on Climate, and other relevant reports and groups to analyze and detail the requirements for supporting climatic and other observations. Unless otherwise specified in this report, the detailed measurement specifications (sampling frequency, resolutions, accuracies, etc.) are to be assumed as the same as those detailed in the GCOS report on Essential Climate Variables (ECVs; GCOS, 2010).

Chapter 2: Land Domain

Lead Authors: Ralph Dubayah (University of Maryland) and Christiane Schmullius
(Friedrich-Schiller University Jena);
Co-Authors: Warren Cohen (USDA Forest Service), Nadine Gobron (Joint Research
Centre), Eric Kasischke (University of Maryland), Kyle McDonald (City College of New
York), Shaun Quegan (The University of Sheffield) , Jean Ometto (Instituto Nacional de
Pesquisas Espaciais), Stephen Plummer (European Space Agency), Steven Running
(University of Montana) , Sassan Saatchi (NASA Jet Propulsion Laboratory), and
Masanobu Shimada (Japan Aerospace Exploration Agency)

2.1 Introduction: The Importance of Land in the Carbon Cycle

The carbon cycle is central to the Earth system, being inextricably coupled with climate, the water cycle, nutrient cycles and the production of biomass by photosynthesis on land and in the oceans (Canadell et al. 2004). In the natural system the balance between carbon in the atmosphere, land and ocean is regulated through fluxes between these three main pools or reservoirs. In addition to these natural components, there are the contributions to the atmosphere from human activities, namely, fossil fuel burning, cement production, and a range of land management practices, where the net fluxes are relatively small with respect to the sizes of the pools and fluxes from natural processes (Fig. 2-1, IPCC 2007). Recent patterns of exchanges of carbon between the land, oceans and atmosphere may also be affected by CO_2 fertilization, ocean acidification, changes in surface runoff of sediments, changes to wetlands and peatlands, warming of permafrost, and changes to

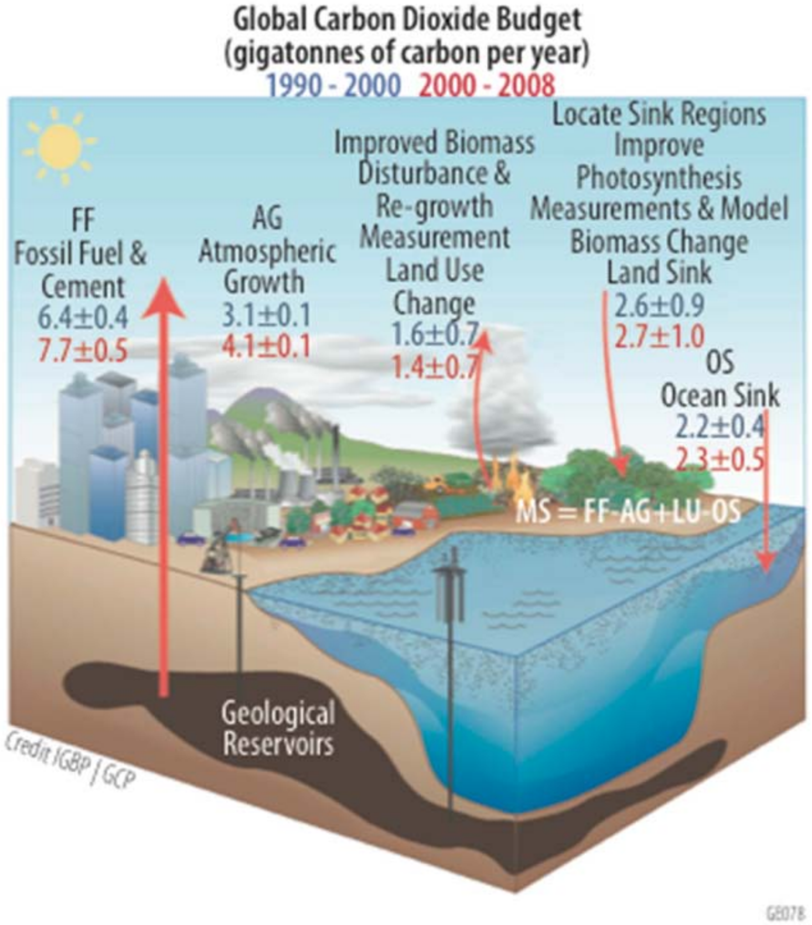


Figure 2-1. Carbon source and sink strengths and the uncertainties in their estimates (from Le Quéré 2009)

natural disturbance regimes such as fire and infestations by insects and disease. Thus a comprehensive carbon monitoring strategy must consider many and varied terrestrial components to correctly assess changes in the global carbon cycle.

The key elements of a terrestrial carbon monitoring system include monitoring or modeling of: (a) fluxes of CO_2 and CH_4 between the atmosphere and land surface; (b) changes to terrestrial carbon pools; (c) ecosystem dynamics; (d) key disturbance regimes; and (e) the export of carbon from terrestrial biomes, in particular, the use of carbon-based products by society and the removal of carbon via transport of particulate and dissolved organic carbon through aquatic systems (Fig. 2-2; see also sections 3.1.1 and 3.1.2).

Over the past two decades our ability to quantify several important components of the terrestrial carbon cycle has improved due to the information available through analysis of data from satellite remote sensing systems. First, land use change patterns in tropical regions, specifically the large-scale clearing and conversion of forests for agriculture, resulted in an average flux to the atmosphere of 1.3 to 1.6 GtCy^{-1} for the 1990s and 2000s (Pan et al. 2011), which is partially included in the global fire carbon emissions from biomass burning, during natural and human caused fires since 1997, adding an average 2.0 GtCy^{-1} to the atmosphere, performed by van der Werf et al. (2010). Measurement of changes to atmospheric carbon concentrations and estimates of the oceanic sink has led to the conclusion that the land surface is currently serving as a 3 GtCy^{-1} carbon sink. While many believe that regrowing forests provide the bulk of this terrestrial carbon sink, inventory-based

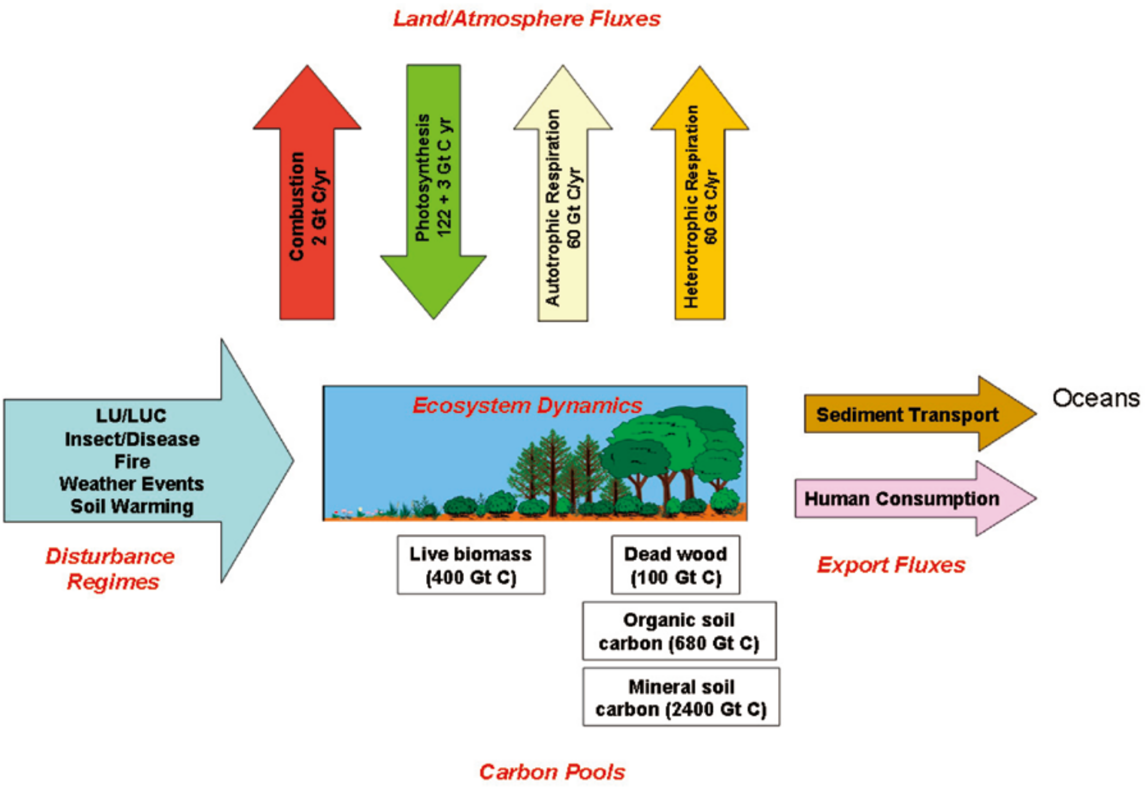


Figure 2-2. The major elements of the terrestrial carbon cycle: (1) Disturbance regimes; (2) Land/Atmosphere fluxes; (3) Ecosystem dynamics; (4) Terrestrial cabon pools, and; (5) Export fluxes. A key challenge for CEOS is identifying and supporting the development of satellite observations required for monitoring and modeling of these elements. (Data presented in this figure are largely adapted from Houghton 2007, with the combustion estimates from van der Werf et al. (2010) and the soil carbon estimates modified to account for recent studies by Tarnocai et al. (2009))

methods suggest the forest sink is only 1.1 GtCy^{-1} (Pan et al. 2011). Additional research is needed not only to determine the strength of various terrestrial carbon sources and sinks, but also to integrate the results of different modeling approaches.

In addition to determining the sources for the present terrestrial carbon sink, the continuing projected increases in average global temperatures are resulting in increased vulnerability of soil carbon stocks that, until recently, have represented stable, long-term reservoirs for atmospheric carbon. These soil carbon reservoirs are vulnerable for two reasons. First, soil warming in permafrost soils in northern high latitude regions threatens to thaw permafrost and expose large amounts of soil carbon to decomposition (Schuur and Abbott 2011; Harden et al. 2012). Second, the drying of organic soils in tropical and boreal peatlands, boreal forests, and tundra, combined with increases in fire frequency, results in large emissions of carbon to the atmosphere well beyond historical levels (Page et al. 2002; Mack et al. 2011; Turetsky et al. 2011a,b).

Recent research has demonstrated the critical role that the world's near-shore coastal oceans and inland waters play in the global carbon cycle (see Chapter 3). Lakes are the lowest points in the landscape and act as integrators and regulators of climate change (Tranvik et al. 2009). The amount of carbon stored annually in lake sediments and the amount of carbon outgassed from lakes and rivers as CO_2 and CH_4 annually both exceed the amount of carbon transported from land to ocean (Tranvik et al. 2009). A key element of the coastal ocean carbon budget is the carbon present in organic carbon and dissolved organic carbon being transported from land areas in river discharge. Understanding the processes and factors that control the export of carbon from land to oceans and inland waters is an additional important component of the terrestrial carbon cycle (see Chapters 3 and 5 for additional discussion of oceans and inland waters and interactions with the land).

Thus, there are number of critical needs for improvements in the monitoring and modeling of Earth's terrestrial carbon cycle, in terms of understanding the current carbon sink and the vulnerability of terrestrial carbon stocks to joint effects of human activities and the impacts of climate change. The key information and observation needs, specifically those provided by satellite remote sensing systems, are discussed in this chapter relative to priorities outlined in the *GEO Carbon Strategy* (Ciais et al. 2010).

2.1.1 Scientific and Societal Significance

As highlighted above, the scientific priority of improving the understanding of the role of the terrestrial domain in the global carbon cycle can hardly be overstated. The societal significance is equally important. Trends in climatic change and non-sustainable land-use are dramatically affecting the Earth's environment. For example, the U.S. National Academy (National Research Council 2007) states that "nearly all ecosystems are under pressure from these two trends." Human and natural forces are rapidly modifying the global distribution and structure of terrestrial ecosystems, altering the global carbon cycle, and affecting our climate now and for the foreseeable future. Observing and quantifying the dynamics of the terrestrial carbon cycle are a prerequisite for understanding and managing these challenges.

The implementation of international carbon emission reduction initiatives has been one response, most notably in the form of the emerging UNFCCC agreement on Reducing Emissions from Deforestation and Degradation and associated activities (REDD+) program, which requires measuring, reporting, and verifying anthropogenic forest-related carbon emissions by sources and removals by sinks in developing countries. GEO itself has highlighted the importance of the terrestrial domain via the *GEO Carbon Strategy* and other tasks, such as Global Terrestrial Observations, Global Land Cover, Forest Carbon Tracking and its successor the Global Forest Observation Initiative (GFOI), Forest Mapping and Change Monitoring, and Integrated Global Carbon Observations (IGCO).

The societal impacts resulting from rising levels of atmospheric CO_2 have been well documented. What is now clear, however, is that formulation of rational policy to mitigate these impacts must rest on well-parameterized and validated models that step outside of traditional domain-based frameworks, and into the realm of so called integrated assessment models. Evaluating alternative climate mitigation and adaptation strategies for the future requires an integrated modeling capacity to accurately project carbon and biological resources in a changing world intimately linked to human activities. Such modeling, in turn, rests upon achieving a better terrestrial carbon measurement system with sufficient resolution to meet both policy and scientific needs (at the scale of hectares). Any discussion of observational requirements must recognize the fact that policy, and therefore societal relevance, will soon dictate much finer resolution modeling than is currently being used, which in turn will require appropriate observations from space.

Finally, beyond their role in regulating variations in atmospheric CO_2 and CH_4, the world's terrestrial biomes and land surfaces provide society with a number of critical goods and services. Across all areas of Earth's surface, a range of land use activities directly impact the terrestrial carbon cycle. In addition, variations in climate (including climate warming) drive a range of disturbances to natural ecosystems which have important impacts not only on carbon cycling, but on a range of services that ecosystems provide to society. As a result, the observations made by satellite remote sensors needed to reduce uncertainties in terrestrial carbon cycling will also be used in a variety of ways to provide information on how changes to terrestrial ecosystems impact society and of how societal use of those goods and services affects carbon storage and emissions.

2.1.2 Current Status and Trends

Within the terrestrial domain, significant research has focused on providing better estimates of key parameters required to measure and monitor changes in the terrestrial carbon cycle and to provide the inputs for diagnostic and prognostic model evaluations. Advances are continuously being made to approaches to utilize remotely sensed observations and to measure or infer terrestrial domain information needed to initialize, update, and validate carbon models. These variables are discussed in Section 2.2. In addition, new satellite remote sensing systems are in development or being planned that will provide additional information critical for monitoring and reducing uncertainties in the key elements of the terrestrial carbon cycle. These new satellite remote sensing systems are based on results from extensive deployment of airborne remote sensing systems specifically designed to collect data required to monitor the carbon cycle in terrestrial ecosystems, such as assessment of aboveground carbon pools using lidar, Synthetic Aperture Radar (SAR), and advanced SAR methods such as polarimetry and interferometry.

The spatial resolution of the satellite sensors and derived data products are of fundamental importance to their uses for carbon science and decision making. For the purposes of this chapter, the following definitions apply:

- High Resolution: <30 m spatial resolution
- Medium resolution: 30-100 m spatial resolution
- Medium to moderate resolution: 101-249 m spatial resolution
- Moderate resolution: 250m-1km spatial resolution
- Coarse resolution: >1km spatial resolution

As discussed in section 2.1.1, the utility of information products derived from satellite remote sensing data has been the key to reducing uncertainties in two important components of the global terrestrial carbon cycle: (a) the net transfer of carbon to the atmosphere as a result of tropical deforestation (DeFries et al. 2002); and (b) carbon emissions to the atmosphere as a result of biomass burning (van der Werf et al. 2010). For tropical deforestation, a stratified sampling approach using medium resolution (30 m) satellite imagery to calibrate deforestation estimates derived from moderate resolution (500 to 1000 m) satellite data has reduced uncertainties associated with rates of tropical deforestation (Achard et al. 2002; Hansen et al. 2010). Uncertainties have further been reduced by using improved satellite maps of forest cover distribution based on continuous field approaches (Hansen et al. 2002). Three distinct satellite remote sensing data products are used to estimate global fire emissions (van der Werf et al. 2010): (a) burned area (Giglio et al. 2010); (b) vegetation cover (Friedl et al. 2002); and (c) fuel loads based on a model (CASA) of net primary production driven by satellite data products (van der Werf et al. 2003).

Further reduction in uncertainties associated with deforestation and forest regrowth and biomass burning are being achieved through the availability of a global Landsat TM/ETM+ dataset since the mid-1980s. Approaches to annually map forest disturbances at medium resolution using Landsat TM/ETM+ at continental scales have been developed (Huang et al. 2010). These products are being used to assess the impacts of forest disturbance on the terrestrial carbon budget (Williams et al. 2012). Similarly, information on burned area derived from Landsat TM/ETM+ data combined with medium resolution maps of vegetation cover are key inputs to improved models for estimating carbon consumed during fires across North America (Stinson et al. 2011; Ghimire et al. 2012; Kasischke and Hoy 2012). Incorporation of these new approaches on a global scale will provide the foundation for further reductions in uncertainties in the terrestrial carbon budget. In addition, these new information products will be able to drive finer spatial resolutions in models. Since global carbon models operate at scales far too coarse (about ½ deg.) to provide adequate prognostic information at policy relevant spatial scales, models that use inputs from medium and moderate resolution satellite remote sensing data will fill this important information need.

Finally, one of the large inadequacies of current approaches to terrestrial carbon modeling and monitoring is the inability to measure canopy structure and hence to infer biomass at fine spatial scales. Canopy structure is also intimately connected with seral or successional state. Remote sensing has thus far been unable to reliably distinguish between primary and young secondary forests, severely hampering modeling efforts given the large differences in carbon uptake between young, rapidly growing forests and more mature forests. The former are carbon sinks whereas the latter are generally assumed to be in carbon equilibrium with the atmosphere (Dubayah et al. 2010).

Estimates of carbon sources and sinks across all vegetation types are poorly known from existing inventory data and must be improved because change in these sources and sinks may have large effects on climate forcing. While the area of deforestation can be readily mapped from optical remote sensing (Hansen et al., 2010), the lack of information on forest biomass limits the precision with which we can estimate deforestation emissions (Houghton et al., 2000 and 2009). Thus, accurate measurements of aboveground biomass stocks are required to constrain both the vegetation source and sink terms. Without knowledge of forest structure, biomass, and inferred age, model initialization efforts will continue to be unsatisfactory.

New approaches to map aboveground biomass using remotely sensed data have been developed. For example, Asner et al. (2010) used airborne lidar coupled with land cover type classification to produce high spatial resolution biomass inventories for a small portion of the Peruvian Amazon with 20% accuracies, demonstrating the potential of this emerging technology. Saatchi et al. (2011) and Baccini et al. (2012) both produced biomass maps for global pan-tropical forests using spaceborne instruments (ICESat, MODIS and others), but they achieve adequate accuracies only by aggregating to coarse spatial resolutions of >10,000 ha (100 km^2) under an assumption of no bias, which is unlikely. Santoro et al. (2013) was able to estimate growing stock volume for the Northern hemisphere above 30° N latitude using 'hyper-temporal' Envisat ASAR radar observations at a 0.01° pixel size with consistent agreements of 15-30% with inventory information only after downscaling to 0.5°. Thurner et al. (2014) inferred from this radar product forest carbon density to estimate carbon stocks at regional scale with an $R^2 = 0.70–0.90$. He used the spatial information and corresponding uncertainties as a new benchmark to improve his carbon cycle model.

A major new source of information capability will be provided by the ESA Earth Explorer "Biomass" (planned to launch around 2020). The Biomass mission will provide global scale, regionally limited, consistent, annual maps of above-ground biomass, biomass change and measurements related to forest height. The fusion of active remote sensing data with passive optical and other data also holds great promise. For example, Pflugmacher et al. (2012) used disturbance history information from Landsat time series data to greatly reduce biomass prediction error relative to a single date of Landsat and to lidar in Oregon, USA and had good success predicting aboveground dead biomass using disturbance causal agent (e.g., fire, insect, harvest) as a predictor. Moreover, because the approach is based on Landsat time series history, it was possible to accurately predict past biomass density (and thus change in biomass density) as compared to field re-measurement data.

2.2 Key Information and Observation Needs

2.2.1 Terrestrial Domain Information Needs

Figure 2-2 presents a conceptual diagram that depicts five key areas or components that are needed to understand and quantify the relationship between terrestrial ecosystem dynamics, variations in the atmospheric concentration of CO_2 and CH_4, and exports of carbon from the land to the oceans and inland waters. Critical information needs in each of the five key areas given in Fig. 2-2 include carbon pools, land-atmosphere fluxes, disturbance regimes, ecosystem dynamics, and export fluxes.

2.2.1.1 Carbon Pools

The terrestrial carbon reservoir contains some 3.6 Gt C distributed among four major pools or reservoirs. The estimated size of the mineral soil C pool has recently increased because of more detailed assessments of the amount of carbon present in frozen soils in permafrost ecosystems (Tarnocai et al. 2009; Grosse et al. 2011). Significant uncertainties in the sizes of other terrestrial pools exist, in particular in the amount and distribution of aboveground live biomass (Dubayah et al. 2010).

A critical information need for modeling the carbon cycle is the amount of dead woody debris present in forested lands, which is important for quantifying fluxes to the atmosphere from heterotrophic respiration (Harmon et al. 2011). Reducing uncertainties in terrestrial carbon pools requires increasing the number and frequency of inventories, in particular of live biomass and dead woody material in forests, organic soils in wetlands, peatlands, and tundra, and mineral soil in all terrestrial biomes.

2.2.1.2 Land-Atmosphere Fluxes

Understanding the sources of variation in the atmospheric concentration of CO_2 and CH_4 requires quantifying the fluxes of these gases between the atmosphere and land surface as well as from the oceans. For land surfaces, flux measurements from eddy covariance towers and chambers provide critical measurements used to understand not only flux rates, but the processes that control fluxes as a result of photosynthesis, autotrophic respiration, and heterotrophic respiration. Continuation and expansion of the number of sites with flux towers is needed to reduce uncertainties in the terrestrial carbon budget, particularly in sites which are recovering from disturbance (Amiro et al. 2010), as well as in wetlands and peatlands. Refinement of the approaches used to scale the surface flux observations over space and time is also required.

Key controls to land-atmosphere fluxes include surface temperature (including freeze/thaw state in boreal/arctic biomes) and surface moisture. NASA's Soil Moisture Active Passive (SMAP) mission, currently scheduled for launch in 2014, will provide a capability to quantify moisture and temperature controls to land-atmosphere carbon fluxes. A validation exercise of ESA's Soil Moisture and Ocean Salinity (SMOS) mission by Jackson et al. (2012) indicated that soil moisture estimates are approaching anticipated performance levels with an overall root mean square error of 0.043 $m3m^{-3}$ for the watershed networks.

For emissions from biomass burning, more accurate maps on the distribution of biomass and fuels that burn are needed, as are studies on factors controlling biomass consumption during fires, especially in sites with deep organic soils. Recent research suggests that estimates of burned area derived from moderate-resolution satellite remote sensing systems (500-1000 m) may underestimate area burned in small fire events (Randerson et al. 2012), yet may overestimate area burned in large fire events because a fraction of the area within a large fire perimeter does not burn (Kasischke and Hoy 2012).

2.2.1.3 Disturbance Regimes

A number of natural and anthropogenic disturbances are the primary drivers of changes to terrestrial ecosystems which, in turn, directly impact land/atmosphere carbon fluxes and carbon pools. While significant progress has been made for monitoring burned area and to forest-cover change caused by clear-cut harvesting, significant challenges remain in developing the datasets needed to quantify areas impacted by logging activities that employ partial clearing techniques, by insects and disease, and by weather-related events such as hurricanes, tropical storms, tornados, and snow and ice damage (Kasischke et al. 2013). An emerging information need is the ability to monitor the impacts of soil warming in permafrost ecosystems, in particular quantifying areas that experience thermokarst activity, thermo-erosion or other changes to geomorphology caused by thawing permafrost (Grosse et al. 2011). Forest disturbances due to this thawing permafrost are of growing importance (Forkel et al. 2012).

2.2.1.4 Ecosystem Dynamics

Quantifying the processes responsible for variations in land/atmosphere carbon fluxes requires information on ecosystem dynamics. This includes information on vegetation condition and productivity related to variations in growing-season length, the impacts of drought, and longer term variations in climate. Information is also needed on changes in plant community composition and structure (including canopy height and biomass) over time, especially following disturbance and as a function of disturbance severity. The recent development of information products from medium-resolution, passive optical VIS/IR data that give time since disturbance (Huang et al. 2010) is an important development, though limited by the relatively short length of the satellite record and the lack of associated biomass data (required to determine the net impact of disturbance and subsequent regrowth). Information is also needed on critical characteristics of the abiotic environment (excluding climate variables, though those are obviously required for modeling) that control all CO_2 and CH_4 fluxes, including the temperature and moisture of vegetation and soils, and the levels of water inundation. The latter determines the areal extent of wetlands and controls CH_4 emissions from wetlands.

2.2.1.5 Export Fluxes from Lateral Transport

Finally, the export of carbon out of terrestrial ecosystems must be quantified. In particular, information is needed on factors that control the rates of surface runoff from terrestrial into aquatic systems, the rates of sedimentation that occur in reservoirs, the rate of CO_2 and CH_4 fluxes from inland water bodies, and the rates of sediment and dissolved organic carbon transport in rivers that flow into coastal oceans, again determined by levels of water inundation and flooding, such as occur in the Amazon (Marengo et al. 2011; Mangiarotti et al. 2013). Forest harvesting and thinning rates are also required to estimate the amount of wood products consumed by humans (i.e. exports caused by human consumption).

2.2.2 Key Elements Identified by the *GEO Carbon Strategy*

The *GEO Carbon Strategy* report (Ciais et al. 2010) identifies two sets of observations. ***Core Observational Elements*** are needed to "observe the reservoirs and exchange fluxes of the Integrated Global Carbon Observing (IGCO) system." ***Satellite Observations*** are required for "delivering global observations of the required ancillary variables required to estimate surface atmospheric fluxes by modeling." By definition, these two sets of observations are complementary and deal with the specific components of the terrestrial carbon cycle illustrated in Fig. 2.

The six Core Observational Elements for the terrestrial domain of the IGCO are:

1. *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.
2. 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.

3. 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.
4. *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.
5. Carbon harvested as crops and wood products, as well as peat and biomass harvested and used for energy production.
6. Changes in the carbon content of water reservoirs, lakes and freshwater sediment pools.

The categories of Satellite Observations defined for the terrestrial domain of the IGCO are presented as:

1. Land cover, land use and land use change.
2. Fires and other ecosystem disturbances.
3. Land ecosystem biophysical variables.
4. Permafrost area and its dynamics.
5. Wetland area.
6. Satellite information relevant to fossil fuel emissions.
7. Satellite information about the amount, area and volume of inland water bodies and their carbon content (see Chapters 3 and 5)

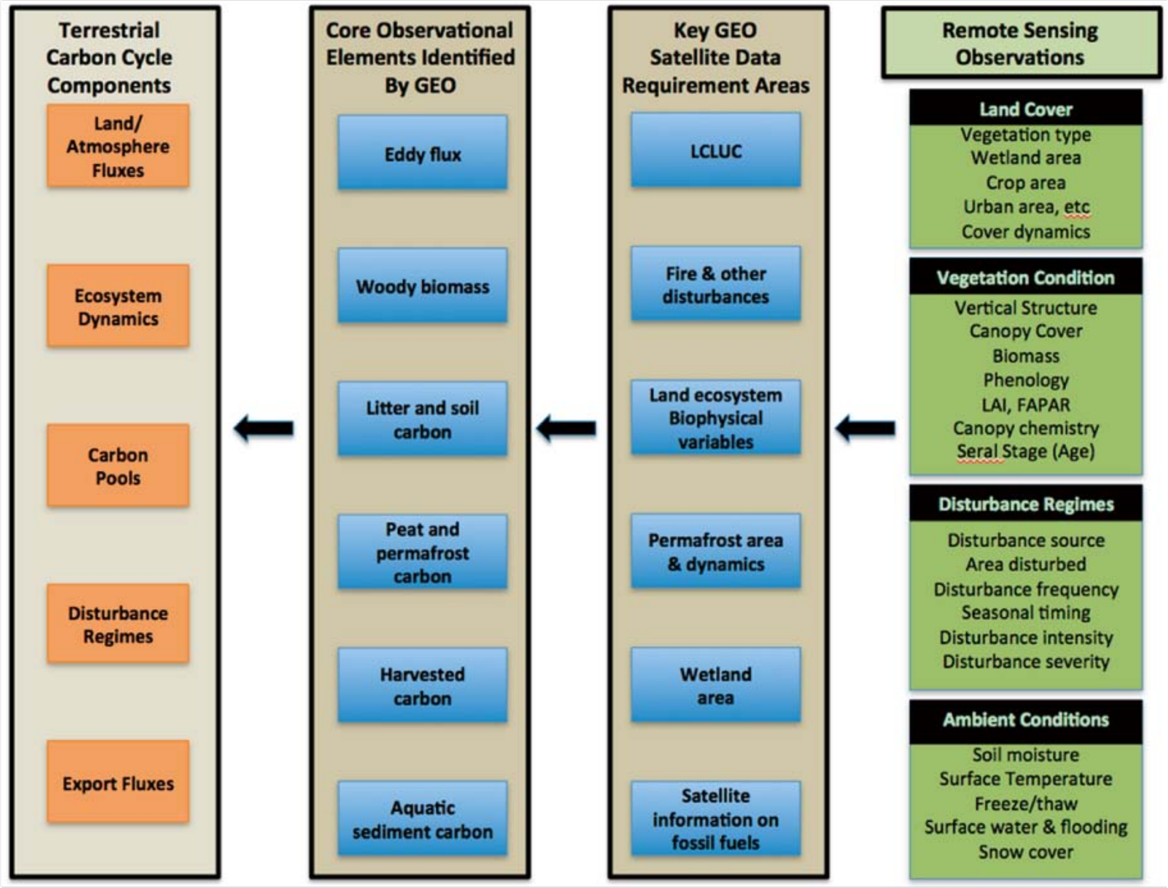


Figure 2-3. The relationship of remote sensing observations to key GEO ancillary data requirements, core GEO observational elements, and the five components of the terrestrial carbon cycle.

We thus have a progression and framework which links processes to elemental observations to key satellite requirements and eventually specific satellite observables. The core observational requirements defined for the IGCO can be directly related to the five key components of the terrestrial carbon cycle (Fig. 2-3). These five components, in turn, have informed the selection of the six key areas for IGCO satellite requirements (note that satellite requirements for inland waters are addressed primarily in Chapter 3). To inform these six areas requires derivation of specific biophysical and other variables from remote sensing data. This forms the basis of the discussion in Section 2.3 on the role of satellite observations.

2.2.3 Need for Supporting Climate Observations

While remote sensing observations are critical we underscore the continued need for basic climate observations (e.g. precipitation, temperature, wind) that are required drivers for carbon modeling efforts. While great progress has been made in creating gridded data sets at regular time intervals, as models increase in spatial resolution (from 1 degree to 1 ha) they will require climate data at increasingly fine resolutions. Producing such data sets should be a priority for without them both diagnostic and prognostic modeling efforts will be limited in their ability to capture fine scale heterogeneity in land surface processes. For example, Hurtt et al. (2010) have shown that coarse scale climate data inputs can cause large errors in carbon flux estimates (compared to using fine scale inputs).

2.3 The Role of Satellite Observations

A number of models of the primary components of the terrestrial carbon cycle have been developed that are based on information products derived from data collected by satellite remote sensing systems, including models of carbon emitted from biomass burning, gross primary production, net primary production, and net ecosystem production (Potter et al. 1993; Goetz et al. 1999; Turner et al. 2006). In addition, a number of other terrestrial carbon models depend on inputs that in many cases are provided by analyses of remotely-sensed data, which are used to either provide critical input parameters or are used for model calibration and validation. For example, the Ecosystem Demography model has used observations of canopy height from airborne lidar to initialize ecosystem system state and for validation (Hurtt et al. 2004).

2.3.1 Characterizing the Role of Satellite Observations

Regardless of the modeling approach, the information from analysis of satellite remote sensing data is used to address the key components of the terrestrial carbon cycle, and can be divided into four major groups of observations as shown in Fig. 2-3.

1. **Land cover**. All terrestrial carbon cycle models require the types of land cover that exist within the study domain. This information includes the area occupied by land converted from natural landscapes for use by humans (e.g., croplands, urban/ex-urban areas, road and utility corridors, etc.), areas that are impacted by human activities, and areas where natural disturbances prevail. Information products include specific vegetation cover type (e.g., forest, grassland, shrubland, etc.) as well as broad categories that include different vegetation covers (e.g., wetlands, permafrost areas).
2. **Disturbance regimes**. A variety of satellite-based information products have been

developed to characterize disturbances to terrestrial ecosystems, including disturbance type or source, area disturbed, frequency of disturbance, seasonal and diurnal timing of disturbance, intensity of the disturbance event, and severity of the disturbance in terms of its impacts on a range of ecosystem characteristics.

3. **Vegetation characteristics and condition**. Information products generated from satellite remote sensing data provide information on key characteristics of the vegetation cover at a single point in time (e.g., characteristics) as well as how vegetation changes over shorter time-periods in response to changes to the ambient environment (e.g., condition). Vegetation characteristics provided from satellite remote sensing data include vegetation structure and aboveground biomass, canopy cover and stand age. Vegetation condition information includes plant phenology, Leaf Area Index (LAI), Fraction of Photosynthetically Active Radiation (FAPAR), vegetation temperature and moisture, and some aspects of canopy chemistry.
4. **Ambient conditions**. Remotely sensed data from satellites provide a range of information products that describe the ambient (non-climate) environmental conditions that are important in controlling ecosystem physiological processes that result in carbon fluxes between the land surface and atmosphere. These characteristics include soil moisture and temperature (including its freeze/thaw status), permafrost depth, areas inundated by flooding, and the depth of flooding.

These four general categories are used to organize specific sets of *remote sensing variables* as listed in Fig. 2-3. These are variables that are either derived directly from remotely sensed observations or are the outputs of models that are used to derive the variables (e.g. biomass). The variables are based on existing *satellite data records*. Satellite data records refer to specific sets of observations from specific satellite remote sensing instruments (e.g. MODIS, MERIS, or ALOS PALSAR). Gaps may exist in our ability to derive the variable in question because, for example, the satellite or sensor is no longer in operation, the observations may not be available due to institutional reasons, or the record may have had limited spatio-temporal coverage. Effective gaps may occur because the existing record is not efficacious with respect to deriving a particular parameter (e.g. high biomass density from SAR backscatter). Of critical importance are the identification of these gaps and the forecast of their future availability based on planned missions. Gaps that remain must be the focus of coordinated international efforts to obtain such observations from space. These topics are discussed in more detail in Sections 2.4 and 2.5.

Table 2-1 lists in summary form the contribution of remote sensing (the last column of Fig. 2-3) towards the terrestrial carbon cycle components, the core GEO observational elements and key satellite requirement areas identified by GEO (the three leftmost columns in Fig. 2-3). The remote sensing inputs represent *classes* of observation in some cases. These observations are then listed in Table 2-2 along with the broad categories of satellite remote sensing data that support those observations.

Table 2-1. Summary of contribution of classes of remote sensing observations to the components of the terrestrial carbon cycle and GEO core observational and remote sensing areas given in Fig. 2-3. Each of the remote sensing observation columns is related to specific sensor and data records in Table 2-2.

	Land Cover					Vegetation Condition							Disturbance Regimes					Ambient Conditions				
	Veg. Type	Wetland Area	Crop Area	Cover change	Urban areas	Vegetation Condition	Canopy Cover	Biomass	Phenology	LAI/FAPAR	Canopy Chemistry	Age	Source	Area	Frequency	Timing	Intensity/Severity	Soil Moisture	Soil/Canopy Tempertaure	Freeze/thaw	Surface Water/Flooding	Snow Cover
Terrestrial Carbon Cycle Components																						
Land/Atmosphere Fluxes																						
– GPP, NPP, NEP	🟩	🟩	🟩	🟩			🟩	🟩			🟩											
- Biomass burning emissions	🟩							🟩					🟩	🟩	🟩	🟩	🟩	🟩				
Ecosystem Dynamics																						
- Succession	🟩			🟩		🟩		🟩					🟩	🟩			🟩					
- Mortality/growth	🟩			🟩		🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩			🟩	🟩	🟩			
- Decomposition	🟩	🟩																🟩		🟩	🟩	🟩
Carbon Pools																						
- Live/dead woody biomass	🟩					🟩		🟩	🟩			🟩	🟩	🟩			🟩					
- Organic/mineral soil	🟩	🟩	🟩														🟩					
Disturbance Regimes	🟩							🟩					🟩	🟩	🟩	🟩	🟩	🟩				
Export Fluxes																						
- Human Consumption	🟩		🟩	🟩				🟩					🟩	🟩								
- Sediment Transport [*see Oceans*]																					🟩	
Core GEO Observational Elements																						
Eddy Flux																						
Woody Biomass	🟩					🟩		🟩	🟩			🟩	🟩	🟩			🟩					
Litter and Soil Carbon	🟩	🟩	🟩														🟩					
Peat and Permafrost Carbon	🟩	🟩				🟩							🟩	🟩								
Harvested Carbon			🟩	🟩				🟩														
Aquatic Sediment Carbon	🟩	🟩																			🟩	
Key GEO Satellite Requirement Areas																						
LCLUC	🟩	🟩	🟩	🟩	🟩								🟩	🟩	🟩							
Fire and Other Disturbances	🟩			🟩				🟩					🟩	🟩	🟩	🟩	🟩					
Land Ecosystem Biophysical Variables						🟩	🟩	🟩	🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩	🟩
Permafrost Area and Dynamics	🟩																				🟩	
Wetland Area	🟩	🟩																			🟩	
Satellite Information on Fossil Fuels					🟩																	

Notes: Some of the remote sensing variables are classess of variables, e.g. disturbance source may refer to fire, insects, etc. These should be distinguished and the appropriate satellite records used

[1] Vertical structure also should refer to topography in the case of peatlands and permafrost

Table 2-2. Contribution of sensors to key remote sensing classes of observations for the terrestrial domain. If a corresponding CEOS database observation parameter exists, it is listed by its CEOS name. References are indicative and not intended to be exhaustive. Please note that inland and coastal waters are addressed in Chapter 3.

Land Remote Sensing Observations (Products)	Corresponding CEOS MIM database observation	Area Coverage, Type	References & Comments
Land Cover			
Vegetation Type (including Crop Area)	Land Cover, Vegetation Cover, Vegetation Type	Global – VIS/IR	Arino et al. (2008); Achard et al. (2004); Townshend et al. (1994); DeFries et al. (1998, 2002); Hansen et al. (2000, 2002); Loveland et al. (2000); Foody et al. (1997); Mayaux and Lambin (1997); Mayaux et al. (1998); Moody and Woodcock (1996); Cihlar (2000); Goetz et al. (2005); Bartalev et al. (2003); Friedl et al. (2002): GEOGLAM Work Plan; Gallego and Bamps (2008)
		Regional – VIS/IR	Chambers et al. (2007); Kaptue Tchuente et al. (2011); Jiao et al. (2011); Melis and Pilloni (2011); Hansen and Loveland (2012); Ippoliti-Ramilo et al. (2003); Kuenzer and Knauer (2013); Wu et al. (2012); Johnson (2013)
Wetland Area	Land Cover	Regional – VIS/IR	Niu et al. (2012)
		Regional - SAR	Bourgeau Chavez et al. (2002); Richey et al. (2002); Melack et al. (2004); Rebelo et al. (2009) ; Silva et al. (2008); Whitcomb et al. (2009); Souza Filho et al. (2011)
Cover Change			See Land Cover/ Vegetation Type, Disturbance/ Area Disturbed
Urban Areas/GHG Emissions		Global - VIS/IR	Ghosh et al. (2010); Rayner et al. (2010)
Vegetation Condition			
Vegetation Characteristics			
Canopy Cover	Vegetation Cover	Global – VIS/IR	DeFries et al. (1999);
		Regional – VIS/IR	Hansen et al. (2003) Hansen et al. (2011) Chopping et al. (2008)
Vertical Structure	Vegetation Canopy Height	Global – Lidar	Lefsky (2010) Simard et al. (2011)
Aboveground Biomass		Regional - Lidar	Boudreau et al. (2008)
		Regional – SAR	Saatchi et al. (2011); Mitchard et al. (2009) Santoro et al. (2011)
		Regional – VIS/IR	Baccini et al. (2008); Blackard et al. (2008)

Land Remote Sensing Observations (Products)	Corresponding CEOS MIM database observation	Area Coverage, Type	References & Comments
Stand Age		Regional – VIS/IR	Masek et al. (2008); Huang et al. (2010); Kennedy et al. (2007); Goward et al. (2008)
Vegetation Conditions			
Plant Phenology		Global VIS/IR Global Microwave	Myneni et al. (1997); Cihlar et al. (1997); Gobron et al. (1999); Huete et al. (2002); Tucker et al. (2004); Delbart et al. (2006); Ganguly et al. (2010); Jones et al. (2010)
Leaf Area Index (LAI)	LAI	Global – VIS/IR	Plummer et al. (2006) Knyazikhin et al. (1998); Myneni et al. (2007); Pinty et al. (2007); Baret et al. (2007)
Fraction of Photosynthetically Active Radiation (FAPAR)	FAPAR, PAR	Global VIS/IR	Myneni et al. (1997); Gobron et al. (2006); Pinty et al. (2007)
Vegetation/Land Surface Temperature	Surface Temperature	Global – Thermal IR	Justice et al. (1998); Wan et al. (2004); Gusso et al. (2007); Coll et al. (2009); Hulley and Hook (2009); Kogler et al. (2012)
Canopy Moisture	NDVI	Global – Microwave Radar/Radiometer Regional VIS.IR	Gao (1996); Zarco-Tejada et al. (2003); Yilmaz et al., (2008)
Disturbance			
Area Disturbed			
Forest area disturbed		Global – VIS/IR	Achard et al. (2002); Potter et al. (2003); Hansen et al. (2010); Eva et al. (2010); Midrexler et al. (2009)
		Regional – VIS/IR	Skole and Tucker (1993); Huang et al. (2009); Margono et al. (2012); Masek et al. (2008); Brandt et al. (2012)
		Regional – SAR	Almeida-Filho et al. (2009); Ryan et al. (2012); Santoro et al. (2010); Whittle et al. (2012); Zhang et al. (2012)

Land Remote Sensing Observations (Products)	**Corresponding CEOS MIM database observation**	**Area Coverage, Type**	**References & Comments**
Burned area	Fire Area	Global – VIS/IR	Plummer et al. (2006); Roy et al. (2008); Tansey et al. (2008)
		Global – VIS/IR/ Thermal IR	Giglio et al. (2010);
		Regional – VIS/IR	Alencar et al. (2011); Eidenshink et al. (2007); Fraser (2004); Levin and Heimowitz (2012); Matricardi et al. (2013); Rosa et al. (2011); Loboda et al. (2007)
		Regional – Thermal IR	Roberts and Wooster (2008)
		Regional - SAR	Bourgeau-Chavez et al. (2002); Siegert and Ruecker (2000)
Areas impacted by insects/diseases - Defoliation		Regional – VIS/IR	de Beurs and Townsend (2008); Eklundh et al. (2009); Fraser and Latifovic (2005); Hall et al. (2003); Townsend et al. (2012)
Areas impacted by insects/diseases - Mortality		Regional – VIS/IR	Franklin et al. (2003); Hatala et al. (2010); Hicke et al. (2012); Ishimura et al. (2011); Kharuk et al. (2004, 2009); Meddens et al. (2011); Wulder et al. (2006)
Areas experiencing partial forest damage		Regional – VIS/IR	Kennedy et al. (2012); Matricardi et al. (2010); Myint et al. (2008); Negron-Juarez et al. (2010, 2011); Ramsey et al. (2001); Wang and Xu (2009)
		Regional - Lidar	Dolan et al. (2011)
Timing			
Fire seasonality		Global - Thermal IR	Giglio et al. (2006);
Fire spread	Fire Area	Regional – Thermal IR	Kasischke and Hoy (2012); Loboda and Csiszar (2007)
Intensity/Severity			
Fire Intensity	Fire Temperature	Global – Thermal IR (Fire Radiative Power)	Ellicott et al. (2009); Vermote et al. (2009)
Fire Severity		Regional – VIS/IR	Eidenshink et al. (2007)
Ambient Conditions			
Soil moisture	Soil Moisture at Surface	Global – Radar scatterometers	Naeimi et al. (2009)
		Global –microwave radiometers	Parinussa et al. (2011); Jackson et al. (2012); Li et al. (2010); Kerr et al. (2010); Entekhabi et al. (2010)
		Regional – SAR	Doubková et al. (2012); Hornacek et al. (2012); Pathe et al. (2009)

Land Remote Sensing Observations (Products)	Corresponding CEOS MIM database observation	Area Coverage, Type	References & Comments
Surface temperature (soil & leaf)	Surface Temperature	Global - TIR	French et al. (2005); Liu et al. (2006); Yu et al. (2008); Wan (2008); Trigo et al. (2008); Francois, (2002). Guillevic et al. (2012); Huang et al. (2008). Kustas et al. (2003); Lu and Weng (2006); Yang et al. (2011)
Freeze-thaw		Global – Radar scatterometers	Bartsch (2010) and refs therein; Kimball et al. (2004); Naeimi et al. (2012); Wismann (2000); Sabel and Bartsch (2012)
		Global –microwave radiometers	Kim et al. (2011, 2012); Rautiainen et al. (2012); Kimball et al. (2004); Rautianen et al. (2012) Park et al. (2011)
Surface water & inundation			
Surface water area		Global – radar scatterometers	Schroeder et al. (2010)
		Global –microwave radiometers	Watts et al. (2012); Prigent et al. (2007); Schroeder et al. (2010)
		Global – SAR	Bartsch et al. (2009, 2012)
		Global – VIS/IR	Carroll et al. (2009, 2011)
Inundation		Regional – SAR	Siqueira et al. (2000); Rosenqvist et al. (2002); Bourgeau-Chavez et al. (2002); Martinez and Le Toan (2007); Haruyama and Shida (2008); See also **Land Cover** -> **Wetland Area**
Snow cover			
Snow extent		Global and regional – VIS/IR and microwave radiometers	Brown et al. (2010); Hall et al. (2006) and refs therein
Start and end of snow season; snow duration		Global –microwave radiometers	Takala et al. (2009)

2.3.2 Summary of Contribution of Satellite Data Records

A number of modeling approaches have been developed that depend on satellite derived observations of the global terrestrial carbon cycle to calculate land/atmosphere fluxes driven by photosynthesis, autotrophic respiration, and heterotrophic respiration. These models calculate gross primary production (GPP), net primary production (NPP), net ecosystem production (NEP) and net biome production (NBP). Global and regional calculations of NPP quantify the carbon sequestered and available for plant growth, to provide food, fiber and fuel for humanity. As such, NPP is of greatest practical societal value (Zhao and Running 2010). Net ecosystem production quantifies the final CO_2 and CH_4 exchange between the land surface and the atmosphere, so is of greatest value for quantifying global carbon/climate interactions (Raupach 2011). Global GPP can be derived from satellite measures of LAI and/or FAPAR using either simplified algorithms for plant production efficiency or more mechanistic models of canopy photosynthesis and respiration. The conversion of incident radiation, Photosynthetically Active Radiation (PAR), ultimately to plant biomass is modulated by the vegetation cover type provided from satellite-based global datasets, and by canopy biochemical properties that define photosynthetic capacities. Algorithms continue to accumulate and improve.

About 50% of GPP is almost immediately respired due to plant metabolism, and the remainder (the NPP) is available for growth (Beer et al. 2010). Respiration losses of CO_2 by the vegetation are usually computed from knowledge of the vegetation type and allometric relationships with LAI (Mahecha et al. 2010). The integrated annual NPP gives the total carbon taken into vegetation for the entire growing season, which globally can vary from 3 to 12 months of plant growth. The step from NPP to NEP requires estimates of heterotrophic respiration from soil, litter and dead plant matter. Finally, to recover NBP, disturbance dynamics must be taken into account. Disturbances and land-cover change are typically monitored by satellite at global scales, and are potentially a very important component of REDD+ monitoring (Mildrexler et al. 2009). Stand-alone global vegetation dynamics models, and land process models in global climate models usually initialize the land surface using information derived from passive optical data satellite data (Keenan et al. 2012). However, some models have the ability to initialize aboveground states via canopy height (from lidar), biomass (from lidar and radar), and from stand age (from disturbance products) (Hurtt et al. 2010).

In the remainder of this section, examples of the different information products that are used to model the terrestrial carbon cycle are presented to demonstrate the contribution of satellite records. Discussions are also presented on how these products are used to model the terrestrial carbon cycle at different spatial and temporal scales.

2.3.2.1 Land Cover

The sources and sinks of carbon from land use and land cover change (LULCC) are significant in the global carbon budget. The net flux of carbon from LULCC accounted for 12.5% of anthropogenic carbon emissions from 1990 to 2010 and is the most uncertain term in the global carbon budget (Houghton 2012). A number of global-scale models use land-cover products to define the basic units to assess variations in terrestrial carbon cycling (Potter et al. 1993; Goetz et al. 1999; Turner et al. 2006). However, there is a need to equate the land cover classes with Plant Functional Types (PFT) used by these models (Poulter et al. 2011). For example, in the framework of the on-going ESA Land Cover Climate Change Initiative, MERIS-retrieved land cover products are being translated into PFTs for carbon-flux assessments in Dynamic Global Vegetation Models (DGVM) (Bontemps et al. 2012). Wetlands contribute both carbon dioxide and methane to the atmosphere. The vastness, inaccessibility and dynamics of the major wetlands in the boreal and tropical zones have resulted in applications of wetland mapping products from satellite data to assess carbon cycling (Takeuchi et al. 2003; Schneider et al. 2009). The distribution and extent of crops represent important parameters for integrated assessment models (Pereira et al. 2010; Wise et al. 2009). See Chapter 3 for inland waters.

2.3.2.2 Vegetation Condition

Vegetation characteristics such as canopy cover and spatial heterogeneity, vertical height, aboveground biomass, and stand age are important indicators of the carbon stocks of vegetation types and their state of recovery from past disturbance. Leaf area index, phenology, FAPAR, and canopy temperature, moisture, and chemistry quantify vegetation condition and their contribution to both slow and rapid processes of carbon exchange within a number of terrestrial carbon cycle models. Data products used to analyze vegetation phenology (NDVI), LAI and FAPAR are routinely generated from moderate-resolution VIS/IR satellite data and have been integrated in several ecosystem process models at regional to global scales (Field et al. 1995; Potter et al., 2005; Xiao et al. 2004, Rayner et al. 2005). Other vegetation condition parameters such as canopy temperature, moisture and chemistry have been derived from thermal, microwave and hyperspectral sensors. Among vegetation characteristics, canopy cover is the only parameter routinely produced from MODIS data, using the vegetation continuous field approach. The limited but global samples of canopy height and waveform metrics from the ICESat lidar have been converted to vegetation biomass and mapped regionally to assess the carbon stock along soil, climate and topographical gradients (Lefsky 2010; Saatchi et al., 2007; 2011, Baccini et al., 2012). These maps have been used to estimate emissions from deforestation (Baccini et al. 2012; Harris et al. 2012), biomass burning (van der Werf et al. 2009), and in ecosystem models to predict net ecosystem exchanges (Antonarakis et al. 2011).

New and proposed satellite observations of chlorophyll fluorescence can be converted into an indicator of photosynthetic activity, which in turn could be used to improve estimates of GPP (Frankenberg et al, 2011; Joiner et al, 2011) and potentially our understanding of how much carbon is stored in plants. Similarly, hyperspectral observations of canopy chemical constituents have the potential to improve estimates of GPP as well as to provide additional information for modeling of ecosystem and biogeochemical cycling processes (Martin and Aber 1997; Thenkabail 2012). Accordingly, these two types of satellite measurements of physiological properties and processes may play an important role in future carbon cycle science. However, they are not further analyzed in this report to keep a sharp focus on methods and measurements that are more well-established with regard to the estimation of carbon stocks and fluxes.

2.3.2.3 Disturbance

Products from satellite remote sensing systems are used in a variety of ways for characterizing important components of different terrestrial disturbance regimes central to carbon cycle modeling. At global scales, disturbed area products are essential for determining deforestation and burned areas and their impacts on carbon cycling (DeFries et al. 2002; van der Werf et al. 2010). Global fire emissions models also use information on the seasonal timing of fire activity derived from remotely sensed products (van der Werf et al. 2010). Recently, new global-scale products have been developed to estimate biomass consumed/carbon emitted during fires (Ellicott et al. 2009; Vermote et al. 2009; Kaiser et al. 2012). A large number of remote sensing data products are used for quantifying the impacts of various kinds of disturbances on terrestrial carbon cycles at regional scales, which in turn, can be used to evaluate and improve global-scale carbon cycle models. Regional-scale products are often similar to global scale products, but are generated using finer resolution satellite data, thus providing improved accuracy. Regional-scale products used for modeling the terrestrial carbon cycle include forest area disturbed (Williams et al. 2012), burned area and forest clearing (Stinson et al. 2011), damage from hurricanes (Chambers et al. 2007), insect mortality (Edburg et al. 2011), selective logging (Huang and Asner 2010), burned area and daily progression of fire activity (de Groot et al. 2007, Kasischke and Hoy 2012), burned area and fire severity (Ghimire et al. 2012), and burned area and severity and levels of carbon consumed in a tundra fire (Mack et al. 2011).

2.3.2.4 Ambient Conditions

The physiological processes controlling fluxes of carbon between the land surface and atmosphere (photosynthesis, heterotrophic respiration, and autotrophic respiration) are all strongly influenced by the temperature, moisture, and water conditions of terrestrial ecosystems. These ambient conditions also strongly influence plant competition, growth, and mortality, thus shaping community structure over longer time periods. Because of these dependencies, terrestrial carbon cycle models need to represent various aspects of the ambient conditions, and many of these models have the capability to directly assimilate information products derived from satellite remote sensing data. Uses of remotely-sensed data products include land surface temperature for estimating GPP (Goetz et al. 1999), use of freeze-thaw data (including permafrost depth and thaw depth) for vegetation growth and CO_2 flux (Kimball et al. 2006; Kim et al. 2012; Jones et al. 2012; McDonald et al. 2004), lake area to estimate methane fluxes in boreal regions (Walter et al. 2006), inundation patterns to estimate methane fluxes in tropical forests (Melack et al. 2004) and tundra (Morrissey et al. 1994), and soil moisture to determine patterns of post-fire vegetation regrowth (Kasischke et al. 2007).

2.3.3 Institutional Issues

The realization of an integrated global carbon observing system requires the removal of some institutional barriers both in the Earth observation (EO) community and in the carbon cycle community and the interface between these communities. Issues that need to be resolved are indicated in the following subsections.

2.3.3.1 Consistency of Definitions

An underlying problem affecting, in particular, the terrestrial domain is inconsistency in definition of communally used terminology. Examples of this include radiation budget variables (e.g., Land Surface Temperature (LST) and surface albedo), ecosystem variables (e.g., leaf area index (LAI) and the fraction of absorbed photosynthetically active radiation (FAPAR)), and land-cover characteristics (e.g., surface type, phenology, and the location of active fires). These terms are used frequently by different agencies and elements of the research community, but their definitions can vary significantly preventing effective inter-comparison between different products. This applies at the space agency level but also more importantly between the EO community and the ecosystem modeling/ecology/carbon communities. This inevitably leads to misunderstandings and inappropriate use of the products generated. Steps have been introduced between international bodies, including Global Terrestrial Observing System (GTOS), GCOS and the Land Product Validation sub-group (LPV) of the CEOS WGCV to achieve harmonization of definitions of terrestrial essential climate variables (ECVs), but this requires approval and adoption by stakeholder agencies. While it may not be possible to achieve a common single definition throughout the EO and ecosystem model/ecology/carbon communities, the space agencies must be explicit regarding the definition to be applied to their products and should strive for consistency in the definitions used whenever possible. As an example, for LAI, the definition agreed by GTOS, GCOS and CEOS WGCV LPV is as follows:

> *The LAI is defined as one half the total green leaf area per unit ground surface area (Chen and Black 1992). On sloping surfaces, the LAI should be projected to the normal to the slope.*

It is important, however, to emphasize that this term is not the term that EO is capable of measuring, rather EO will give the effective LAI (as defined by the absorption of optical radiation in the canopy). It is thus equally important to be very clear as to what assumptions are made in order to arrive at an estimate of the effective term and subsequently in cases where LAI is derived from the effective LAI what assumptions are made to do so. In the same way the term LAI used by ecosystem model/ecology/carbon community must be clearly explained to avoid cases where there is inappropriate use of products. It is recommended that, in the same way as has been achieved for LAI, the CEOS WGCV LPV, GCOS, GTOS, and FluxNet should agree a common understanding of the definition of the key variables for terrestrial carbon identified above.

2.3.3.2 Calibration and Validation at Product Level

A critical measure of relevance for the issue of confidence in the products generated from Earth observation is that not only are the data but also the products calibrated and checked against international agreed-upon standards. Currently this is conducted in a piecemeal fashion by individual agencies on a sensor or data product basis over limited spatial extents and time intervals. At the same time the product validation is seen as one of the six key measures of the maturity of a given product (see Bates and Privette 2012) for the purposes of generating climate data records. While the concept of maturity is still under discussion in particular between CEOS WG Climate, World Climate Research Programme (WCRP), and GCOS it is unlikely that the issue of product validation will disappear from its definition.

The same approach is applicable in the context of a sustainable global carbon observing system and hence the space agencies and CEOS, as the coordinating body, must dedicate specific resources to product validation. This requires greater coordination between the space agencies and CEOS-level agreement that each sensor record and its data product(s) be backed by validation efforts to ensure that the product reaches an appropriate level of maturity. CEOS already has a defined and agreed terminology for levels of validation but the issue is simply to harness the resources for its implementation globally and long-term. In this regard it is expected that the ecological/carbon science community will be an invaluable resource in providing appropriate *in situ* data at the resolution of satellites to support any effort by the space agencies. The two communities should coordinate efforts to maximize the return from existing infrastructural investments (e.g. FluxNet, NEON, Tall Towers, LTER, ILTER).

2.3.3.3 Cross-Agency Intercomparison Exercises

A fundamental concern for an integrated carbon observing system is to have long time series of consistent products that can be used to assess the quality of and also to constrain terrestrial carbon models. To achieve this it is necessary to conduct open and transparent inter-comparison exercises to ensure that the outputs from projects conducted or sponsored by individual agencies are consistent and also that there is clarity on the strengths and weaknesses of each individual product with reference to the carbon cycle community. It is suggested that this be overseen through the auspices of an 'independent' organization with no specific interest in a given product, e.g. CEOS, although clearly it will be down to the individual agencies to contribute to and/or fund the participation in any such exercise. Such activities, if effectively organized, are extremely useful for making communities more cohesive and the products more useful.

An example of a very successful inter-comparison exercise, which could serve as a template, is the Ice sheet Mass Balance Inter-comparison Exercise (IMBIE http://imbie.org), jointly organized and funded by NASA and ESA. This brought together experts from Europe and North America to reconcile measurements of ice sheet mass balance using satellite altimetry, gravimetry and the input-output method and resulted in a paper in *Science* (Shepherd et al. 2012) and provided critical results for IPCC AR5 (IPCC 2013).

2.3.3.4 Traceability, Transparency, and Documentation

To achieve a free and fair inter-comparison, but also to ensure data products are used appropriately by the carbon cycle community it is critical that all products should be accompanied by clear and concise documentation written in a traceable and transparent manner such that the assumptions embedded within individual processing chains do not impact on the consistency between individual products pertaining to a given variable or, even more important, that consistency between different variables is assured e.g. FAPAR, LAI, land cover. This requirement on individual agencies, but also the collective EO community, can be summarized by reference to GCOS Climate Monitoring Principle 3:

> *The details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data (i.e., metadata) should be documented and treated with the same care as the data themselves.*

While the GCOS Climate Monitoring Principles have been defined for climate purposes they are generically transferable to requirements for the carbon cycle community.

In addition to the need for such clarity and associated documentation being generated by producers of individual products there is also a need to ensure that the carbon cycle community is able to understand such documentation. It should be assumed that many members of the carbon cycle community have little experience with satellite observational datasets and hence an appropriate length for information to be provided is 3-5 pages, excluding tables and figures. Following guidelines generated by the Observations for Model Intercomparison Projects (OBs4MIPS) community (http://obs4mips.llnl.gov:8080/wiki/requirements) these 3-5 pages should contain the following information (paraphrased from Obs4MIPS Technical Note Guidance v3):

1. Intent of the Document and Point of Contact

2. Data Field Description

3. Data Origin

description of:

- *the origin of the dataset in terms of the measurement principle and actual on-orbit measurements made including an observation map, if coverage is not global,*
- *the processing applied to the on-orbit observations that were used to generate the geophysical variable. If the data processing involved is complex, provide only the gross overview, and references. Note any models or a priori assumptions used in the processing.*
- *the sampling used in creating the gridded product, and its spatial variation. If the sampling varies significantly across the dataset, the observation count per datum should also be provided.*

4. Validation and Uncertainty Estimate

- *error/uncertainty estimate and description of any systematic biases, including any variation spatially or temporally,*

5. Considerations for [Model-Observation] Comparisons

- *description of key aspects that distinguish this data product from any other outputs, which the user of this product should be aware of in order to make judicious [model-] observation comparisons. Examples of what to include are: diurnal cycle sampling biases, space sampling biases, inhomogeneity of sampling resolutions, scene dependent sampling biases and retrieval biases related to the retrieval algorithm*

6. Instrument Overview

- *Description of the instrument science objective, capability, measurement principle, satellite and orbit characteristics. Critically includes a description of the strengths and weaknesses of the instrument measurement.*

7. References

8. Dataset and Document Revision History

2.3.3.5 Consistency Across Spatial Resolutions

An important objective in realizing the integrated carbon observing system is to aim to have consistency in so far as it is possible across spatial scales. This will have the dual benefit of 1) permitting the assessment of initiatives such as the Global Forest Observation Initiative (GFOI) to be considered coherently with coarser resolution assessments such as the Global Carbon Budget and Regional Carbon Cycle Assessment and Processes (RECCAP) and b) providing higher resolution datasets for the validation of global products. While it cannot be expected that in all cases consistency can be assured across spatial scales, every effort should be made to ensure that assumptions and differences in approaches are minimized and where differences do exist there should be a clear reasoning, transparency of explanation and full documentation.

2.3.3.6 Data and Product Access and Maintenance

Since the assessment of the carbon cycle inter alia requires consideration of long time scales, this requires that the input data sets are as extended as possible. It also means that these data products must be available in the long-term. Therefore, CEOS agencies producing output products should act to ensure their products are safeguarded in the long term and also to ensure that the products are made publicly accessible through established long-term archives as well as through project websites or CEOS. The GCOS Climate Monitoring Principle 17 underlines this point and is applicable in addition to needs of the carbon cycle community.

> *Data systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained.*

2.3.3.7 Data Availability for Global/Regional Scientific Studies

The IGCO will require inputs from archived data to allow the evolution of the carbon cycle over time to be assessed. The contribution of the satellite data, while still relatively short temporally, provides a very detailed global picture of many of the key variables in the carbon cycle. There is therefore a critical need that the data sources, on which key products are based, are available as widely as possible and the ability to obtain the baseline data is as streamlined as possible when the data are needed for scientific and research purposes. These baseline data should include necessary sensor performance characterization data and calibration and validation data. This should apply to all data/ satellites that are critical for specific carbon product inputs. Again with reference the GCOS it is important that Space Agencies adhere as much as possible to Principle 5, in the context of the carbon cycle:

> *Consideration of the needs for environmental and climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional and global observing priorities.*

For the terrestrial carbon cycle an example of where there is a critical need for this to be assessed by the CEOS space agencies is for estimation of aboveground biomass. For the future two dedicated SAR missions are currently planned, the ESA Biomass mission and a NASA-ISRO SAR mission (L-band and S-band). Aspects of the latter derive from the SAR portion of the Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission concept recommended by the U.S. National Research Council (National Research Council 2007). Today, more generic purpose SAR missions in L, C and X-band can provide information for estimating low to medium levels of biomass if acquired systematically. Currently major efforts and progress have been made using SAR data to estimate aboveground biomass based on ALOS PALSAR and ENVISAT ASAR. The JAXA Kyoto & Carbon Initiative (http://www.eorc.jaxa.jp/ALOS/en/kyoto/kyoto_index.htm) is currently focused on two key global biomes, forests and wetlands, and generates key products like land cover, forest change maps, and forest biomass and structure. The utility of C-band SAR was demonstrated in boreal and temperate forests through BIOMASAR (Santoro et al. 2011), which relies on multiple ASAR data stacks from the ESA Envisat mission. The same methods could be applied to Radarsat and future Sentinel-1 data since these systems share a common microwave frequency. There is a need to coordinate effectively between projects and to enable full access to multiple data sources. For example, the BIOMASAR methodology would benefit tremendously from JAXA Kyoto & Carbon Initiative data in increasing the capacity to estimate AGB into tropical regions and reducing overall the estimation errors. ESA plans a new project called GlobBiomass to combine these scientific approaches and foster cooperation between regional activities. A common denominator for all research and development activities related to the carbon cycle is the need for systematically acquired satellite data and full access to the global and regional data sets. Given that neither Biomass nor the NASA-ISRO SAR mission will be launched before 2019 and now that the Envisat and ALOS missions have concluded there is a vital need to ensure that the progress made to date is not lost and thus the Radarsat SAR and the planned ALOS-2 and Sentinel-1 missions become vital as global data sources to continue estimation of aboveground biomass beyond 2013.

2.4 Satellite Observations Adequacy

For the four classes of remote sensing variables discussed above (Vegetation Characteristics, Vegetation Condition, Disturbance Regimes and Ambient Conditions) we briefly summarize the adequacy of the satellite observation records from the perspective of past provisions, and the present/future provisions. It is helpful to refer back to Fig. 2-3 at this point. We have outlined how remote sensing variables support the components of the terrestrial carbon cycle, and the relationship of these variables to the core observational areas and satellite observations identified by for the IGCO. By identifying the adequacy of past and present/future provisions we can identify important gaps and other issues that must be addressed by remote sensing to support a comprehensive carbon observation strategy. This discussion leads to a set of specific actions for CEOS in Section 2.5.

2.4.1 Land Cover

Under the term land cover we investigate the contribution of satellite data records for the following carbon-relevant surface conditions: "traditional" land cover and its use in modeling, land cover change analysis, crop monitoring, wetland monitoring and urban mapping and modeling (which is also used to estimate fossil fuels emissions).

Adequacy of satellite data – Based on the availability of the 1 km AVHRR time series data set starting in 1992, two global land-cover maps were produced: IGBP Discover Map (Loveland et al. 2000), and the University of Maryland Land Cover Map (Hansen et al. 2000). Friedl et al. (2002) developed the MODIS land cover mapping chain using time series data, a procedure adopted by the GLC2000 Land Cover Map (Bartalev et al. 2003) using SPOT4-VEGETATION data, and Defourny et al. (2012) for the GlobCover maps using MERIS data (Kalogirou et al. 2013). A different approach was developed by Hansen et al. (2002) based on the idea of continuous fields, e.g. percent forest cover, more recently including a component identifying change (Zhan et al. 2002). General Circulation Models (GCMs) use satellite-retrieved land cover information as representation of boundary conditions. In the framework of the on-going ESA Land Cover Climate Change Initiative, MERIS-retrieved land cover products are being translated into Plant Functional Types (PFT) for carbon-flux assessments in Dynamic Global Vegetation Models (DGVM) (Bontemps et al. 2012). The Group on Earth Observations Global Agricultural Geo-Monitoring Initiative (GEOGLAM) aims to strengthen the operational capacities to produce and disseminate agricultural forecasts at various scales through the use of Earth observations. For wetland monitoring in the boreal and tropical zone satellite data have been extensively applied, e.g. the multi-year studies in circumpolar regions by Sitch et al. (2007) using 20-year data records and the Amazon basin by Melack et al. (2004) using 10-year data records. Urban areas are characteristic features of the global land cover affecting surrounding ecosystems in many ways. New Landsat-based global products have recently been developed that move land cover and change mapping forward to a new spatial domain (Townshend et al. 2012; Gong et al. 2013). A combined approach for a consistent global mapping of urban areas has been published by Schneider et al. (2003) where MODIS, Defense Meteorological Satellite Program (DMSP) nighttime lights and population density data have been used in synergy.

Remotely-sensed nightlights data from both DMSP and the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on the Suomi-National Polar-orbiting Partnership (Suomi-NPP) satellite can also be used to estimate the spatial distribution and quantity of fossil fuel emissions (Doll 2008; Ghosh et al. 2010; Rayner et al. 2010).

Adequacy of methodology – While well-defined, robust classification methodologies are available, inconsistencies exist between the different land cover legends (despite general agreement on Food and Agriculture Organization's (FAO) Land Cover Classification System after Di Gregorio 2005) and thus change monitoring systems. This complicates the ability to successfully synthesize land cover assessments on regional and global scales between products (Herold et al. 2009). Land cover change estimates require multi-temporal fine-resolution satellite observations. An independent accuracy assessment using a sample of ground-reference data is an integral part of any land cover monitoring effort. Standard methods for land cover validation have been developed (e.g., Foody 2002) and have been implemented by the international community through the CEOS WGCV Global Land Cover Validation report (Strahler et al. 2006). Vegetation type mapping is poorly developed for tropical regions, with efforts needed to constrain carbon flux estimates and climate models for this biome. The mapping of wetland type and wetland area is critical for reducing uncertainties in modeling of the terrestrial carbon cycle. The utility of time-series data collected by SARs for mapping wetlands has been demonstrated in a number of settings (Melack et al. 2004; Bourgeau-Chavez et al. 2005), but these approaches have not been tested on a global scale. Methodologies for relating nighttime lights from DMSP to CO_2 emissions exist, but relationships are complex (Ghosh et al. 2010). New methods for use with VIIRS are under development (Elvidge et al. 2013).

Adequacy of provisions - Archived image data (e.g. global Landsat data) and methods are available to implement a global land cover change monitoring system. With the launch of Landsat-8 and the upcoming Sentinels-2a and -2b (2014 and 2016), data provision is good. Finer spatial resolution (5 m and better) is critical for validation and vegetation classification for carbon dynamics and budget estimates. Data in this resolution domain are widely retrieved from commercial satellites via Google Earth. Multisensor data in a multi-scale approach are necessary to assess ecosystem dynamics. Remote sensing provides useful metrics to interpolate ground level estimates. Global assessments of historical forest change processes based on multiple data sources are available from regional and national programs (e.g. the European Commission program to COoRdinate INformation on the Environment (Corine), Brazil's project for Monitoring the Brazilian Amazon Rainforest (PRODES)) and international initiatives such as the Remote Sensing Survey of FAO's Global Forest Resources Assessment (Lindquist et al. 2012). For wetland mapping, until efforts are taken to evaluate using SAR data to map wetlands in a variety of settings, the adequacy of existing and planned SAR data sets cannot be evaluated. Provisions for nighttime lights are excellent with VIIRS. The concept for a multi-spectral sensor (Nightsat, Elvidge et al. 2007) would improve spatial resolution and overcome limitations of panchromatic approaches currently in use.

Adequacy of access, longevity and infrastructure – The CEOS agencies have developed procedures for wall-to-wall mapping of land-cover and spatially explicit monitoring of land-cover change: http://lcluc.umd.edu, http://www.esa-landcover-cci.org. These infrastructures ensure longevity and access. In the US, continued production and archiving of land cover products is ensured. In Europe, due to ESA's mandate, archiving is ensured, but continued production not. China is the third entity developing a global land cover product, of which access is limited and continuity unknown.

2.4.2 Vegetation Conditions

Table 2-2 presents a large number of vegetation condition data sets that have been or can potentially be developed from satellite data sets. Here we focus on the adequacy of existing global satellite data products.

2.4.2.1 Leaf Area Index and FAPAR

Adequacy of satellite data – Historical global and regional data sets of LAI/FAPAR are available from AVHRR data. Multi-decadal global regional data are available from data collected by the MODIS and the SPOT-VGT sensors at resolutions of 1 km to 1° in service of several national and international initiatives (Chen et al. 2002; Fernandes et al. 2003; Ganguly et al. 2008; Myneni et al. 2002; Zhu et al. 2013). Satellite data from the recently launched Suomi National Polar-orbiting Partnership (Suomi-NPP) VIIRS, PROBA-V, and from planned future missions such as the Joint Polar-orbiting Satellite System (JPSS) VIIRS and within the EU Copernicus Programme (former GMES), Sentinel-3 OLCI and SLSTR ensure availability of satellite data into the future.

Adequacy of methodology – Existing methods for LAI retrieval are comprehensive in terms of physical modeling and inversion strategies. Capabilities of producing medium-resolution regional-to-continental LAI products, e.g. from the Landsat sensor, have been demonstrated (Ganguly et al. 2012). Several inter-comparison exercises are already being performed to evaluate LAI products from different sensors (Garrigues et al. 2008; Fang et al. 2013; Ganguly et al. 2014). The satellite-based estimation of FAPAR, which is derived from the balance of multiple fluxes, may depend on the atmospheric and illumination conditions prevailing at the time of the measurements (Knyazikhin et al. 1998a,b; Gobron et al., 2006, 2009). In particular, estimates can be generated using direct, diffuse, or global radiation inputs. Knowledge on the type of incoming solar radiation fluxes is essential to properly interpret the data. Similarly FAPAR can also be angularly integrated or instantaneous (i.e., at the actual sun position of measurement). Similar to LAI, methodologies are mainly based on physical models such as radiative transfer models, but definition and assumptions may differ from providers. Current products are from MODIS, and have gone through several validation and calibration programs (Justice et al. 2002; Morisette et al. 2006). The potential for future products is high given the existence of recently launched VIS/IR satellites.

Adequacy of provisions – The validation of existing LAI products requires comprehensive field-based datasets. The retrieval of LAI variables requires atmospherically corrected spectral surface reflectances as well as land cover types. The uncertainties in present atmospheric correction algorithms and land cover classification need to be better quantified and reduced. Inter-comparison efforts need to converge to a uniformly accepted retrieval technique. Efforts are needed for validation of effective LAI and FAPAR that imply production of higher-resolution products over specific sites, such as FluxNet. Continuity is essential to generate daily global-scale effective LAI and FAPAR using physical retrieval methods for providing independent sensor products.

Adequacy of access, longevity and infrastructure – The continued production of LAI/FAPAR data sets is to varying degrees dependent upon grants provided by national agencies. Continued production is therefore entirely contingent on the individual data producers having adequate funding for staff, hardware maintenance, and quality assurance.

2.4.2.2 Land Surface Phenology

Adequacy of satellite data – Historically, AVHRR data (1981-present) provide the data sources required to develop vegetation seasonal profiles as derived from vegetation indices (e.g. NDVI, Enhanced Vegetation Index (EVI)). At present, satellite-derived phenology products are available from moderate spatial resolution sensors such as MODIS and SPOT-VGT (White et al. 2009; Ganguly et al. 2010; Dash et al. 2010). Global products on the phenological cycle and quantification of the date of onset of vegetation greening and the length of growing season have been produced from SPOT-VGT and AVHRR data using NDVI time series (Delbart et al. 2006).

Adequacy of methodology – Since phenology is assessed using standard data products (NDVI, EVI), the methods to generate baseline datasets are consistent and adequate. Ground truth validation datasets are available globally through several regional-to-continental initiatives (e.g., National Phenology Network, Plantwatch), however methodologies are inconsistent. Inter-comparison between satellite-derived phenology products from moderate-to-medium resolution sensors suggests qualitative agreement across different spatial resolutions (Liang et al. 2011; White et al. 2009). However, inconsistencies amongst phenology estimation algorithms result in large biases in metrics derived from vegetation indices. Part of the inconsistency is related to the lack of a globally accepted definition of phenological events used in most ground monitoring systems (Thomas et al. 2010). Several new indices to monitor phenological events to enhance NDVI performance have been introduced (Reed and Brown 2005), including Soil Adjusted Vegetation Index (SAVI) and Soil and Atmospherically Resistant Vegetation Index (SARVI).

Adequacy of provisions – Current holdings and continuity of data extend over 30 years (AVHRR) at coarse spatial resolution. Data from AVHRR (1-8 km) and MODIS, SPOT-VGT, and MERIS (250 m -1000m) are adequate to generate a global reanalysis of vegetation phenological changes at regional to global scales. The data sets are available at various data archive centers in the U.S. (LP DAAC) and SPOT-VGT from Europe (Geoland 2). Current holdings of medium to moderate-resolution products (30-250 m) are inadequate in extent and accuracy to overcome the spatial heterogeneity of the phenological signal at landscape scales.

Adequacy of access, longevity and infrastructure – The continued production of NDVI/EVI data sets is to varying degrees dependent upon grants provided by national agencies. Continued production is therefore entirely contingent on the individual data producers having adequate funding for staff, hardware maintenance, and quality assurance. There are several commercial centers distributing phenology data products in Europe at global and regional scales with moderate cost (e.g. VEGETATION, www.vgt.vito.be; data older than three months are freely available through www.vito-eodata.be).

2.4.2.3 Vegetation Height and Biomass

Adequacy of Satellite Data – There is no existing satellite observation to meet the requirements of vegetation biomass estimations from space. Scattered maps of vegetation biomass at various spatial scales (500-5000 m) exist that are derived either from extrapolation of limited *in situ* data or ICESat GLAS vegetation height data using optical (MODIS) or radar imagery (ALOS PALSAR) (Saatchi et al. 2007, 2011; Baccini et al. 2012; Simard et al. 2012). There is no standardized ICESAT height product and the existing ones do not compare well due to differences in data processing and filtering. Three missions are planned to provide global data on vegetation biomass: Biomass, NASA-ISRO SAR, and ICESat-2. Among them, Biomass, a European mission using P-band Polarimetric and Interferometric SAR is the only one to meet the requirements for global forested ecosystems (Le Toan et al. 2011). Biomass has been selected by ESA for the next Earth Explorer Mission with launch planned for 2020. NASA-ISRO SAR will provide biomass and biomass change in regions with biomass less than 100 Mgha^{-1} and aims at providing a global monitoring system for forest disturbance and recovery. The ICESat-2 lidar data may provide forest height for some vegetated ecosystems, but is likely to have limited application for global forest height and biomass estimation. There is also a suite of international, more general-purpose, radar sensors in L, C and X-band with capability to provide data on global forest structure and estimate low to medium levels of aboveground biomass, specifically if acquired systematically. Longer wavelengths like P- and L-band data are more strongly correlated with aboveground biomass than the shorter wavelengths in C- and X-band. Historical sensors include in L-band JERS and ALOS PALSAR from Japan and in C-band ERS-1/2 and ENVISAT ASAR from ESA and Radarsat-1 from Canada. Currently active sensors are Radarsat-2 from Canada; TerraSAR-X and TanDEM-X, with single-pass InSAR capability, from Germany (Zink et al. 2010); and COSMO-SkyMed X-band SARs from the Italian Space Agency. The situation will improve in the near future with the launch of Sentinel-1 C-band SAR from ESA and the L-band SAR sensors ALOS-2 from JAXA, and SAOCOM from Argentina.

Adequacy of Methodology – Methodologies to produce forest height and biomass from lidar measurements are adequate to strongly encourage the development of systematic space observations from waveform lidar sensors (Lefsky 2010; Dubayah et al. 2010; Drake et al. 2002; Le Toan et al. 2011; Saatchi et al. 2011; Le Toan et al. 1992; Dobson et al. 2002). These methodologies have been tested and improved using a variety of airborne lidar and radar measurements. The planned ICESat-2 photon counting approach for global vegetation height measurements may have large errors and limitations for estimating forest heights in all global biomes (Harding and Carabajal 2005; Lefsky et al. 2005). The JAXA Kyoto and Carbon Initiative tested and improved methods based on L-band SAR. The utility of C-band SAR has been demonstrated in boreal and temperate forests through BIOMASAR (Santoro et al. 2011), based on multiple ASAR data stacks from the ESA Envisat mission. Radar polarimetric backscatter techniques from long wavelength sensors (L-band and P-band) are adequate to estimate vegetation biomass over different biomes with limitations depending on the loss of sensitivity at high levels of biomass. A combination of P-band polarimetric radar and waveform lidar sensors would be optimal for providing global estimation of vegetation height and biomass. Efforts have begun to develop, verify and validate techniques using polarimetric and interferometric SAR (Pol-InSAR) and tomographic SAR measurements at L-band and P-band for global vegetation observations. The planned Biomass mission using combined P-band SAR polarimetry along with Pol-InSAR and tomographic techniques will provide adequate systematic observations to quantify global vegetation biomass.

Adequacy of provisions – Inventory of vegetation height and biomass requires systematic observations with spatial and temporal diversity over widely heterogeneous and dynamic vegetation cover globally. Current satellite observations are inadequate to provide a consistent assessment of vegetation height and biomass at the various scales. There is a strong demand for the development of satellite observations of forest height and biomass from such sensors as high resolution waveform lidar data, and P- and L-band SAR with Polarimetry and interferometry capability. Current and planned missions for L-band measurements, such as ALOS, SAOCOM, and NASA-ISRO SAR, are just marginally adequate for meeting the requirements of global observation of vegetation biomass and biomass change from disturbance and recovery. New satellites using P-band SAR and/or lidar, both in mature state of technological readiness, are recommended to provide global observation of forest biomass and biomass change. Technology development to support advances in space lidar capabilities, including scanning lidar technologies, is needed to achieve seamless observations of vegetation vertical structure and biomass. Data fusion and data assimilation algorithms using a combination of lidar, radar, and passive optical sensors at medium to moderate resolutions (100-250 m) are needed to improve and enhance the global estimation of forest carbon pools.

Adequacy of access, longevity and infrastructure – The continued production of global forest height and biomass from airborne sensors is critical to understand and quantify the forest biomass at local to regional scales in synergism with other sensors. Joint efforts are required, in particular for conducting airborne experiments in critical forest types. Continued production of forest biomass and height is therefore entirely contingent on available funding and provisions for collecting extensive sub-orbital data over regions of the world with scarcity of forest inventory as in tropical forests. Access to new height products from Tandem-X is unclear. Access to required data from ALOS-2 is also unclear. The existing ALOS data set is not freely accessible.

2.4.3 Disturbance

Table 2-2 presents a large number of disturbance data sets that have been or can potentially be developed from satellite data sets. Here we focus on the adequacy of existing global satellite data products.

2.4.3.1 Forest Area Disturbed

Adequacy of satellite data – Reliable mapping using data from moderate resolution satellite remote sensing systems such as MODIS and AVHRR is not possible; thus, data from these systems have been used to develop indicator products for deforestation. Landsat data are preferred for mapping the area of disturbed forest primarily because the spatial resolution is more appropriate for the detection and quantification of human-induced forest disturbance. Most wall-to-wall forest change products using Landsat data are national-scale, not global. Landsat 5 was the sensor of choice compared to Landsat 7 due to the preference for per scene processing and the failure of the Scan-Line Corrector (SLC) on Landsat 7 (INPE PRODES, CSIRO NCAS, as examples). SLC-off gaps require per pixel compositing methods; such approaches, while common with coarse resolution data, are not common with Landsat, but have been prototyped for many regions. The newly commissioned Landsat-8 satellite, and the Sentinel-2 to follow in 2014, will be critical for deforestation monitoring moving forward.

Adequacy of methodology – There is a division in the preferred methods for quantifying global forest change between sampling approaches versus mapping approaches. Sampling is methodologically simpler and not as data intensive. The UN FAO's Remote Sensing Survey has a global product using this method (Lindquist et al. 2012). Examples of hybrid approaches include Achard et al. (2002) and Hansen et al. (2010). Whether using samples or wall-to-wall approaches, different answers often result due to variation in methods (per pixel versus segmentation, minimum mapping units, processing to overcome data limitations such as clouds, etc.). Additionally, forest disturbance is divided into stand-replacement and degradation types. Degradation is an unsettled dynamic in terms of definition and methods for quantification. Global wall-to-wall mapping using Landsat data is currently being investigated in a research mode, for example, the recent release of deforestation maps by Hansen et al. (2013; see http://earthenginepartners.appspot.com/science-2013-global-forest).

Adequacy of provisions – A limited number of deforestation data products are available at global scales, and are archived by the organizations at which they were created (e.g., MODIS-derived products at South Dakota State University: http://globalmonitoring.sdstate.edu/projects/gfm/global/gindex.html); NASA-CASA: http://geo.arc.nasa.gov/sge/casa/latest.html; FORMA: http://www.cgdev.org/initiative/forest-monitoring-action-forma; Terra-I: http://www.terra-i.org/terra-i.html; and http://earthenginepartners.appspot.com/science-2013-global-forest).

Adequacy of access, longevity and infrastructure – The continued production of deforestation data sets is to varying degrees dependent upon grants provided by national agencies. Continued production is therefore entirely contingent on the individual data producers having adequate funding for staff, hardware maintenance, and quality assurance. Looking forward, the USGS is supporting the Global Land Cover Initiative, which has as its aim the production of annual continuous field estimation of tree cover and change using Landsat data. The USGS should be a repository for products derived from this activity.

2.4.3.2 Fire Timing (Active Fire Products)

Adequacy of satellite data – Robust active fire mapping and characterization was not possible until the advent of the MODIS instruments on-board NASA's Terra and Aqua satellites, for which the data archive begins in April 2000 and July 2002, respectively. Prior to MODIS more limited (e.g., nighttime) mapping and fire characterization has been possible using multiple sensors which include the NOAA AVHRR series of instrument, the Along Track Scanning Radiometer series (ATSR-1, ATSR-2, and AATSR), and the Tropical Rainfall Measuring Mission (TRMM) Visible and Infrared Scanner (VIRS). Data records exist for MODIS from April 2000 to present, for ATSR from June 1995 to February 2012, and from Suomi-NPP VIIRS from May 2012 to present. There is a gap in the MODIS product from August 2000 to June 2001 and in the ATSR product from January to June 1996.

Adequacy of methodology – There is adequate methodology for active fire detection for fully fire-capable systems such as MODIS, VIIRS, and the forthcoming Sentinel-3 SLSTR. The MODIS algorithm is being ported to each sensor, and will provide a succession of semi-consistent products that will ultimately be assembled into a long-term active fire data record. For the older sensors not specifically designed for fire monitoring a well-defined and consistent methodology is generally not available since numerous sensor- and platform-specific limitations must be accommodated.

Adequacy of provisions – There are a number of archives that provide access to active fire products, including: MODIS (https://reverb.echo.nasa.gov/ and ftp fuoco.geog.umd.edu), ATSR World Fire Atlas (http://due.esrin.esa.int/wfa/), TRMM VIRS monthly fire product (ftp fuoco.geog.umd.edu and http://pps.gsfc.nasa.gov/fireintro.html), and Suomi-NPP VIIRS (http://www.class.ngdc.noaa.gov/saa/products/welcome).

Adequacy of access, longevity and infrastructure – The continued production of each data set is to varying degrees dependent upon grants provided by national agencies. Continued production is therefore entirely contingent on the individual data producers having adequate funding for staff, hardware maintenance, and quality assurance. Forward production of the entire suite of MODIS fire products (burned area and active fire), for example, is dependent upon renewed funding every few years. An extensive infrastructure is in place for those products archived and distributed at large, agency-sponsored data centers, which include the MODIS and VIIRS fire products, and the ATSR World Fire Atlas. The infrastructure used to archive and distribute the remaining data sets tends to be much less permanent (e.g., a single ftp server at a university) and much more reliant on soft money. Data sets developed by NASA-supported efforts are housed and maintained long-term by the NASA Distributed Active Archive Centers (DAACs).

2.4.3.3 Burned Area

Adequacy of satellite data – Routine, generally high quality mapping commenced with the MODIS sensor due to its band selection, good coverage, and precise geolocation. Prior to MODIS, more limited mapping was performed with the NOAA AVHRR series of sensors to as far back as 1981, though at reduced quality due to the limited band selection, imprecise geolocation, and spotty archive of native 1.1-km AVHRR observations. Several hybrid products based on combining information from different sensors (e.g., multiple sensors for burned areas, adding hot spots) are available (Global Fire Emissions Database (GFED), 1995-present and the GlobCarbon Product, 1998-2007). The Landsat series of sensors enables precise mapping of fire scars as far back as the early 1970s, although the spatial coverage is extremely spotty due to the relatively small number of cloud-free Landsat scenes in the global archives and limited temporal coverage of the platform. The Landsat Global Archive Consolidation (LGAC) program to incorporate all data archived by Landsat international cooperators within one global and consistently processed archive will ensure that most data acquired become available to the user community (http://landsat.usgs.gov/Landsat_Global_Archive_Consolidation.php). Very high fidelity global burned area mapping of recent fire scars is now underway using Landsat imagery, including Landsat 8, though to achieve this fidelity it is necessary to incorporate active fire data as part of the mapping process. At present the only longer-term data of sufficient quality come from MODIS, hence this mapping is presently restricted to the MODIS era from 2000 onward to present. AVHRR burned area data products are available from 1981 to 2000. Burned area products from SPOT Vegetation are available from 2000 to 2007. For products using AVHRR data, there is a permanent gap for much of 1994, MODIS data are not available from August 2000 and June 2001, and those from GlobCarbon cover 1998-2007 only. The GFED product has a permanent gap from January to June 1996. Future polar-orbiting satellites carrying sensors capable of burned area mapping include the Sentinel-3 SLSTR (2014) and JPSS VIIRS (2016).

Adequacy of methodology – For MODIS era data and later, robust methods for mapping of burned area have been developed, except in the following situations: 1) agricultural burning, 2) understory burns, and 3) extremely persistent cloud cover. However, with the exception of the GFED product, extensive validation has not occurred. A recent study by Kasischke et al. (2011) indicated the standard MODIS, GlobCarbon, and L3JRC SPOT VEGETATION products were not reliable for mapping burned area across North America. Prior to MODIS, a well-defined, robust, and consistent methodology is generally not available, and the various burned area mapping methods can give substantially different answers.

Adequacy of provisions – A number of data archives currently provide access to global burned area data products, including: GLOBCARBON (http;//www.geosuccess.net/), GFED (http://globalfiredata.org), L3JRC (http://bioval.jrc.ec.europa.eu/products/burnt_areas_L3JRC/

GlobalBurntAreas2000-2007.php), and MODIS (https://reverb.echo.nasa.gov/, http://modis-fire.umd.edu/BA_getdata.html, and ftp fuoco.geog.umd.edu).

Adequacy of access, longevity and infrastructure – The continued production of each data set is to varying degrees dependent upon grants provided by national agencies. Continued production is therefore entirely contingent on the individual data producers having adequate funding for staff, hardware maintenance, and quality assurance. Forward production of the entire suite of MODIS fire products (burned area and active fire), for example, is dependent upon renewed funding every few years. An extensive infrastructure is in place for those products archived and distributed at large, agency-sponsored data centers, which include the MODIS and VIIRS fire products, and the ATSR World Fire Atlas. The infrastructure used to archive and distribute the remaining data sets tends to be much less permanent (e.g., a single ftp server at a university) and much more reliant on soft money. Data sets developed by NASA-supported efforts are housed and maintained long-term by the NASA Distributed Active Archive Centers (DAACs).

2.4.4 Ambient Conditions

2.4.4.1 Soil Moisture

Adequacy of satellite data - Many microwave satellites, both passive and active, can provide useful soil moisture information. There is a long time series record of global passive microwave remote sensing data, initiated with low resolution observations from NASA's Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) covering 1978-1988, SSM/I since 1988, TRMM TMI since 1997, and AMSR-E, Windsat and SMOS in the last decade. Active sensors include the ERS scatterometers, used for global soil moisture estimation on a scale of 50 km from 1991 until mission end in 2007 (CEOS 2006) and their continuation with ASCAT on Metop. Combining all these different satellite datasets allows a very long soil moisture record to be built, and this is being accomplished under the ESA Climate Change Initiative (CCI). The Soil Moisture Active Passive (SMAP) Mission, currently scheduled for launch in October 2014, will employ a combined L-band radar-radiometer instrument suite to provide global measurements about every three days of soil moisture (~10 km and ~ 40 km resolution) and landscape freeze-thaw state (~ 3 km) (Entekhabi et al. 2010).

Adequacy of methodology– Several soil moisture data sets derived exclusively with various remote sensing methods are currently available. However higher-level processing and reprocessing capabilities have improved significantly under the soil moisture element of the ESA CCI, allowing the capabilities of the existing remote sensing segment to be more fully exploited, bringing consistency to the data sets. Many science needs and applications require soil moisture estimates through the soil profile, extending through the entire vegetation rooting zone, however remote sensing measurements provide estimates of moisture in the upper 5-10 cm of soil only. Hence the required full complement of soil moisture information may be provided only through a combination of satellite measurements and modeling.

Adequacy of product provision - (a) From 2002-2011, AMSR-E provided soil moisture products with spatial resolution of 60 km, available from the NSIDC DAAC as part of standard AMSR-E products and at 25 km postings as part of the global land parameter bundle developed at the University of Montana (both datasets are in distribution at http://nsidc.org/daac); (b) WindSat soil moisture products are available from the Center for Spatial Information Science and Systems, George Mason University; (c) from 2006-2011, ALOS-PALSAR L-band data provided soil moisture products; (d) since 2009, SMOS has formed part of the suite of sensors yielding global soil moisture products; (e) soil moisture products derived from ERS scatterometer data (1991-2007) are available from the Institute of Photogrammetry and Remote Sensing, Vienna University of Technology; (f) operational near real time soil moisture products are available from Metop-ASCAT scatterometer data (http://www.ipf.tuwien.ac.at/radar/dv/ascat/ (Bartalis et al. 2008). L-band radiometer capability is limited due to radio frequency interference in many populated regions of the world (e.g., the US, Europe, Japan). Over Europe, Asia, and some other regions of the world, Radio Frequency Interference (RFI) badly affects SMOS, which results in unusable data (GCOS 2011), but the situation improves continuously so that the number of RFI sources decreases every year. The typical 30-50 km spatial resolution of most soil moisture products is insufficient to monitor regional soil-moisture heterogeneity even when temporal resolution is sufficient (e.g. for SMOS it is 3 days globally).

Adequacy of access, longevity and infrastructure – The integrated dataset from the ESA CCI is still being completed, and access details are not yet finalized, but this will be a community resource. Both the National Snow and Ice Date Center (NSIDC) and ESA provide infrastructure and archiving making sure the datasets they hold will have longevity and are secure. Data sets developed by NASA-supported efforts are housed and maintained long-term by the NASA Distributed Active Archive Centers (DAACs).

2.4.4.2 Land Surface Temperature

Adequacy of satellite data – Land surface temperature (LST) data products are available since 1978 from the AVHRR data sets. There are numerous other past or current instruments, including ATSRs, AATSR, MODIS, SEVIRI and the new SLSTR (Sentinel-3). Also, new data sets can be generated from VIIRS.

Adequacy of methodology – Current sensors typically provide LST accuracies of better than 2° K. Accuracies are improving rapidly in part because new retrieval schemes are providing better atmospheric corrections. LST is the effective radiative temperature of the integrated land surface and vegetation canopy at the spatial scale of the sensor. Therefore determinations of canopy and soil temperatures separately, except in bare soil and densely vegetated conditions, usually require the use of models. Hence, there are no standard satellite products providing soil surface and vegetation canopy temperatures separately. Use of high spatial resolution land cover and vegetation indicators are being used alongside improved emissivity measurements for soil and vegetation canopies. Soil temperatures (skin) can be directly taken from the LST datasets if auxiliary information is used to confirm that no/little vegetation is present at the scale of the pixel or grid-cell; results depend on the accuracy of the assumed bare soil emissivity. MODIS LST has been assimilated into a model to derive soil temperature profiles (Huang et al. 2008; Francois 2002) by accounting for vegetation in a simple way. In very densely vegetated canopies, the LST will likely represent the temperature of the upper canopy and hence could be directly taken from the LST datasets, however little information is available to define this level of vegetation using auxiliary datasets. In more moderate vegetation, a model would be needed to represent the components from soil and vegetation (Francois 2002). For heterogeneous pixels numerous spectral unmixing studies (Guillevic et al. 2012; Kustas et al. 2003; Lu and Weng 2006; Yang et al. 2011) have shown success in disaggregating the LST signature into end-member components, such as bare soil and canopy temperatures, but these are not yet intrinsic to LST datasets.

Adequacy of product provision – There are numerous satellites capable of providing LST (e.g. http://modis.gsfc.nasa.gov/index.php), however, as noted above, these data sets reflect the integrated soil-vegetation medium. The decomposition of LST into canopy and soil temperature is currently a research field and hence there are no such products in standard distribution.

Adequacy of access, longevity and infrastructure – LST is not identified by GCOS as an Essential Climate Variable. This has contributed to the lack of any clear institutional or agency commitment to take responsibility for this variable. However MODIS and AVHRR data are in standard distribution.

2.4.4.3 Freeze-thaw

Adequacy of satellite data – Measuring land surface freeze-thaw (FT) state is best performed using active or passive microwave datasets as the associated measurements provide a direct indication of the state of the water, liquid or solid, in the integrated soil-snow-vegetation medium. Hence FT may be assessed by essentially the same sensors as soil moisture, i.e., passive and active microwave satellites, with the adequacy of the satellite provision being essentially the same. Hence, satellite remote sensing data sets are available for monitoring FT globally at course resolution (~25 km) using radiometers since the 1970s. Scatterometer data sets are available globally since 1991/92, and include, e.g., ERS, SeaWinds-on-QuikSCAT, and ASCAT on Metop. Synthetic Aperture Radar (SAR) data have been applied to monitor FT over geographically limited regions at higher spatial resolutions (~100 m). FT data sets developed from the suites of radiometers, scatterometers and SARs have elucidated the fundamental trade-off between high temporal resolution measurements provided by radiometers and scatterometers and high spatial resolution SARs. NASA's Soil Moisture Active Passive (SMAP) mission, currently scheduled for launch in October 2014, will allow high temporal repeat (1-3 days) monitoring of land surface FT state at 3 km resolution with its L-band radar.

Adequacy of methodology – Various techniques have been employed for retrieval of land surface FT state. All techniques capitalize on the pronounced difference in the microwave dielectric constant of water between liquid and solid phases. Hence, time series change detection classification schemes have proven effective and are widely used to estimate FT state. As with LST retrievals described previously, the remote sensing signature from the landscape represents a sampling of the aggregate landscape components (soil, snow, vegetation). Hence the composite remote sensing signature represents a sampling of the aggregate landscape dielectric and structural characteristics, with sensor wavelength having a strong influence on the sensitivity of the remotely sensed signature to the various landscape constituents. The dependence of the microwave signatures on vegetation characteristics is complex, with vegetation structure influencing radar signatures to a greater extent than radiometer signatures. At higher frequencies, the effects of the vegetation are increasingly significant with higher frequency sensors generally less sensitive to properties of surfaces underlying dense vegetation canopies. Higher microwave frequencies therefore reflect more so the freeze/thaw state of the vegetation canopy whereas lower frequencies are increasingly sensitive to the underlying surface state. The sensitivity of the microwave signature to FT state is also influenced by the amount of water transitioning between solid and liquid phases. Generally, landscapes with relatively little water content exhibit comparatively little radiometric response to FT state changes.

Adequacy of product provision – A global record of daily landscape FT state has been developed under NASA's MEaSUREs program using the SMMR and SSM/I time series data and is in distribution at the NSIDC DAAC. Extending from 1978 onward and with subsequent updates on-going, this data set represents one of the most consistent and long-term records available from Earth remote sensing data sources. Data sets available from other sources include freeze and thaw maps for the years 2005 through 2010 for parts of Alaska, and the Mackenzie and Ob estuaries, the Laptev Sea Coast and Central Yakutia regions, and are available from the Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, produced under the Data User Element initiative of the European Space Agency.

Adequacy of access, longevity and infrastructure – The archiving and maintenance of the global freeze-thaw datasets by the NSIDC DAAC ensures ready access, infrastructure and long-term security and maintenance of this data record.

2.4.4.4 Surface Water and Inundation

Adequacy of satellite data – Satellite data useful for retrieval of land surface inundation include passive and active microwave (radiometers, scatterometers, SARs), as well as optical sensors. Microwave radiometers offer the best option for consistent, long time series collections albeit at coarse (~25 km) resolution. This series begins with SMMR in 1978, the SSM/I series initiated in 1988, and complemented by AMSR-E from 2000-2011, and AMSR-2 in 2012. The passive microwave record is complemented by radar scatterometers beginning with ERS in 1991, and continuing with SeaWinds-on-QuikSCAT, and ASCAT. Medium-resolution (~100 m) SAR data provided by, e.g., JERS SAR, ALOS PALSAR, RADARSAT and Envisat are very effective at mapping surface water and characterizing wetlands biomes but lack the long time record established by the coarse resolution sensors. Optical sensors (e.g. MODIS, VIIRS) are also appropriate albeit limited by cloud cover and vegetation cover. However, long time series data do allow for the production of nearly cloud free maps of the Earth. For example, the Landsat archive has been used to produce GeoCover datasets of global land masses with 14.25 m spatial resolution, and regional and global maps of water bodies are currently under development.

Adequacy of methodology – Methodologies for retrieval of surface water have been well established and are specific to the capabilities afforded by the sensor technology employed. Hence the accuracy and utility of the inundation data sets are mostly limited by sensor capabilities and by the consistency of the respective sensor data. With their ability for consistent observation even under cloudy conditions, their ability to penetrate vegetation canopies to map inundation beneath vegetation canopies, and their radiometric sensitivity to water, microwave sensors offer the technology of choice for mapping and monitoring inundation and wetlands biomes. Techniques employing decision trees applied to SAR imagery (Simard et al. 2000; Hess et al. 1995) and more recently utilizing machine learning approaches such as Random Forest (Whitcomb et al. 2009) have proven effective for SAR-based mapping and monitoring. Classification techniques utilizing radiometric modeling (Jones et al. 2013) have been successful when applied to microwave sensors providing multiple wavelengths and polarizations. Mixture modeling that employs datasets from multiple satellite sensors (Prigent et al. 2007) and calibration across a single satellite's program archive (Schroeder et al. 2010) are useful in developing long time series records that span the lifetime of individual sensor data sources. Products from optical sources (e.g. MODIS) are commonly derived using spectrally based classification techniques.

Adequacy of product provision – A global record of surface inundation state has been developed under NASA's MEaSUREs program. Coarse resolution (25 km) time series datasets are openly available without restriction at long-term archives housed at NASA DAACs at the Alaska Satellite Facility (ASF, housing NASA MEaSUREs dataset; https://portal.asf.alaska.edu/wetlands/) and NSIDC (http://nsidc.org/data/nsidc-0451.html based on AMSR-E). Updates to the ASF data holdings are on-going. High resolution (~100 m) inundation datasets from JERS and ALOS PALSAR are archived and maintained at the ASF DAAC.

Adequacy of access, longevity and infrastructure – The archiving and maintenance of the land surface inundation and wetlands datasets by the ASF DAAC ensures ready access, infrastructure and long-term security and maintenance of this data record.

2.4.4.5 Snow Area Extent and Timing

Adequacy of satellite data - Snow area extent monitoring using satellite imagery has been performed by NOAA since 1968 using the Television Infrared Observation Satellites (TIROS)/AVHRR series of sensors and is on-going using AVHRR, SSM/I and GOES, with data extending from the mid-1980s. Since 2000 daily snow cover maps have been produced globally by NASA MODIS at 500 m resolution, although limited by cloud cover. This data series continues and will be supplemented by data from the VIIRS and Sentinel-3 (250 to 300 m resolution). Further passive microwave sensor usage with polar orbiting imagers is required to achieve continuous daily global coverage of snow cover.

Adequacy of methodology – In the visible and near-infrared part of the spectrum, robust methods exist for mapping snow extent and albedo. However, snow reflectance in the visible and near-infrared region is sensitive to neither snow depth (except for very shallow snow) nor free liquid water in the snow pack. Active and passive microwave sensor data are highly sensitive to the phase of water, ice or liquid, and have demonstrated sensitivity to snow properties and melt-freeze processes. Common retrieval techniques applied to microwave data include spectral gradient algorithms which identify snow presence and state based on the difference in scattering between two microwave frequencies. These approaches work well for snowpack delineation except for very shallow snow, wherein the microwave scattering in the snowpack is less than that detectable by the instrument, and for very deep snow packs where the microwave signature may saturate. Also, globally available microwave datasets currently have spatial resolutions too coarse for use in hydrologic modeling of all but the largest river basins. Snow modeling can assimilate data from passive microwave sensors to more closely mimic the temporal evolution of snow cover. Synthetic Aperture Radar (SAR) has higher spatial resolution. However, current and planned SAR sensors lack the right combinations of microwave frequencies, sensor stability, spatial resolutions, repeat cycles, and data acquisition and processing strategies to adequately measure properties of the terrestrial cryosphere, such as freeze/thaw status, and snow properties. Both optical and microwave techniques have limitations sensing snow packs beneath vegetation canopies.

Adequacy of product provision – Current holdings of historical remote sensing data are available and, together with *in situ* data, are adequate to generate global reanalysis products for the past 20-30 years, if national archives make these data freely available. AVHRR and geostationary imagery can offer sufficient resolution for mapping of snow area back to the mid-1980s with adequate reprocessing. Operational snow cover areal extent products are generated for the Northern

Hemisphere by the NOAA National Environmental Satellite Data and Information Service (NESDIS), with weekly data since 1966 and daily data since 1999. The NSIDC (National Snow and Ice Data Center) Northern Hemisphere Equal-Area Scalable Earth Grid (EASE-Grid) Weekly Snow Cover and Sea Ice Extent product gives snow cover and sea ice extent on a weekly basis since 1978, and snow cover since 1966. The NSIDC Near Real-Time SSM/I EASE-Grid Daily Global Ice Concentration and Snow Extent product (NISE) provides daily, global, near real-time maps of snow extent, based on SSM/I and MODIS snow products, beginning in February 2000. These post-2000 products are adequate, with the exception of some temporal gaps due to cloud cover. NOAA also produces daily snow-cover products at 4 km resolution.

Adequacy of access, longevity and infrastructure – The provision of snow products by NSIDC and NOAA ensures dependable access, infrastructure and long-term security for snow extent and duration products.

2.5 Land Domain Recommendations and CEOS Actions

The adequacy of provisions discussed in section 2.4 leads to a set of CEOS actions. These include actions that are needed to support key GEO satellite data requirement areas and GEO core observational elements as discussed in Section 2.4.

2.5.1 Mission-Related Recommendations

Overall Motivation/Rationale-1: The *GEO Carbon Strategy* calls for quantification of carbon pools and their changes in response to human intervention and climate to meet the needs of science and policy and, specifically, estimates from space of vegetation aboveground biomass and carbon storage. Satellites can provide global information about changes in carbon storage through accurate measurements of forest canopy height and/or estimates of aboveground biomass. Current and planned SAR missions, especially the P-band Biomass mission of ESA, will advance toward this goal. New space-based measurements using lidar, as envisioned to follow the ICESat mission (e.g., the Vegetation Canopy Lidar (VCL) and Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission concepts), and tandem PolInSAR (such as the Tandem-L concept) should have high priority and are recommended to provide complementary information on forest height and structure. Such missions would clearly support the needs of climate treaty frameworks as exemplified by the REDD+ component of the UNFCCC. Airborne lidar measurements to complement SAR missions, e.g., ESA's Biomass mission, are highly desirable in the near- and mid-term to improve accuracy.

Carbon-Challenge-1: CEOS acknowledges the challenge to provide accurate measurements of forest canopy height and estimates of aboveground biomass and will influence and coordinate the activities of its Member Agencies toward this goal.   CEOS Agencies will consider efforts to provide the needed lidar data and/or interferometric SAR data (i.e., by considering a new satellite mission and/or by cooperating to assemble existing airborne lidar data and making it available for validation of satellite SAR height and biomass data products).

Carbon-Action-1: CEOS Member Agencies with interests in missions and data products for forest canopy height and aboveground biomass will sponsor or co-sponsor one or more workshops (and require a written report) to define the scientific and policy requirements to quantify aboveground carbon storage in vegetation. These meetings should involve the key international science, applications, and remote sensing communities in specifying the technical foundation and scientific requirements for as well as the societal benefits of future missions to quantify aboveground carbon storage in vegetation globally. The workshops should consider these requirements in the context of the added value to be derived from coordinated mission planning and associated data compilation activities both in the future and by exploiting archive data.

Overall Motivation/Rationale-2: The IGCO called for in the *GEO Carbon Strategy* requires continuous time series records from satellites of land surface properties (e.g., land cover, land cover change, disturbance, fires, LAI, FAPAR, wetlands, permafrost areas) at mid resolution. To document and analyze changes over time requires continuity of satellite measurements of land surface properties used to estimate carbon pools and fluxes. In order to meet this need, CEOS member agencies must develop and deploy satellites that can provide continuity measurements of land cover, land cover change, disturbance, fires, LAI, FAPAR, wetlands, and permafrost areas at moderate (~250 m - 1 km) and medium (~30 - 100 m) resolution with adequate on-board calibration and sustained calibration/validation operations. Some redundancy to cover contingencies and improve coverage should be part of the overall plan.

Carbon-Challenge-2: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies so that high-quality, well-calibrated continuity satellite measurements of land cover, land cover change, disturbance, fires, LAI, FAPAR, wetlands, and permafrost are available to estimate carbon pools and fluxes, data gaps are avoided, and satellites flying at the same time, in constellations, and in time series are cross-calibrated and well-validated.

Carbon-Action-2: The relevant CEOS VCs and CEOS WG Climate will act to include IGCO priorities for continuity carbon-related observations of the land surface from space in their respective activities to coordinate the VCs and climate-related measurements.

2.5.2 Product-Related Recommendations

Overall Motivation/Rationale-3: The *GEO Carbon Strategy* calls for a continuous supply of mid-resolution Earth observing satellite data (LAI, FAPAR, disturbance, land cover change; and notes the extreme value of moderate resolution and high (i.e., referred to as “medium” in the land domain chapter) resolution satellite data for carbon science. Data products that document the historical records of land surface properties (i.e., forest disturbed area, burned area, timing of burning, LAI, FAPAR, NDVI, land cover, snow cover) at moderate resolution (250 m - 1 km) are needed. Activities that need to be conducted include reprocessing of data to address cloud cover issues in a consistent fashion; merging data from different sensors (e.g., AVHRR, MODIS, (A) ATSR, MERIS, VIIRS, GCOM-C); and, when possible, developing finer spatial resolution products (e.g., 250 m compared to current products at resolutions of 1000 m and greater). The continuity of these moderate resolution records into the future must be assured.

Carbon-Challenge-3: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the continuity and systematic improvement of moderate-resolution (~250 m - 1 km) satellite time series data products.

Carbon-Action-3: CEOS Agencies with historical moderate-resolution (~250 m - 1 km) satellite data records will strive to ensure these data are publicly available and used to create the moderate-resolution (~250 m - 1 km) records of land properties over the historical satellite record that are useful for carbon science. They will coordinate their efforts with relevant CEOS WGs and VCs.

Overall Motivation/Rationale-4: The *GEO Carbon Strategy* calls for a continuous supply of mid-resolution Earth observing satellite data (LAI, FAPAR, disturbance, land cover change; and notes the extreme value of moderate resolution and high (i.e., referred to as "medium" in the land domain chapter) resolution satellite data for carbon science. Data products that document the historical records of land surface properties (e.g., land cover, land cover change, LAI, FAPAR, forest area disturbed, burned area, areas impacted by insects and storms, and fire severity) at medium resolution (30-100 m) are needed. The collection of global data sets using medium resolution satellite remote sensing systems (vis/IR sensors such as Landsat, SPOT, and IRS and radar sensors such as ERS-1, Radarsat, and JERS-1) has resulted in complete, global-scale data since the late 1990s, with data being available for some regions back to the mid-1970s. Improvement in computer processing speeds and data storage capacity makes processing remote sensing data at medium resolutions at continental and global scale feasible. A number of land remote sensing products listed in Table 2-2 have been developed from medium resolution data, and generation of these products at global scales would provide the ability to reduce uncertainties in terrestrial carbon cycle models. This activity should be extended to the radar archives of ESA, JAXA and CSA.

Carbon-Challenge-4: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the continuity and systematic improvement of historic medium-resolution (~30 - 100 m) satellite time series data products.

Carbon-Action-4: CEOS Agencies with historical medium-resolution (~30 m -100 m) satellite data records will strive to ensure these data are publicly available and used to create the medium-resolution records of land properties over the historical satellite record that are useful for carbon science. They will coordinate their efforts with relevant CEOS WGs and VCs.

Overall Motivation/Rationale-5: The IGCO called for in the *GEO Carbon Strategy* requires continuous time series records of land, ocean, and atmosphere properties (e.g., land cover, land cover change, wetland area, LAI, ocean color and marine ecosystem composition, wetlands, permafrost areas, CO_2 and CH_4) at mid resolution. It is now possible to develop data fusion and data assimilation algorithms using a combination of remote sensing data (vis/IR, SAR, Lidar) at medium to moderate resolutions to improve the accuracy of land and ocean products. Most of the currently available global remote sensing products are all based on a single instrument approach. To realize the full discrimination potential of the data collected by planned and future remote sensing systems and those currently in orbit, multi-sensor approaches must be developed and tested and a product-based (rather than mission-based) approach must be adopted. To ensure long-term continuity of time series data records, the satellite data provider may need to transition from a research satellite program to an operational satellite program; thus, there must be a continuous interface between the research agencies (e.g., ESA, NASA) and those with operational mandates (e.g., NOAA, Eumetsat) .

Carbon-Challenge-5: CEOS acknowledges this challenge and will influence and coordinate the activities of the CEOS Member Agencies toward the continuity and systematic improvement of long time series of multi-sensor, multi-mission data products.

Carbon-Action-5: CEOS Agencies with interests in and/or mandates for developing multi-sensor, multi-mission time series data products for the land (and ocean) will strive to ensure consistent, well-calibrated, bias-free satellite time-series carbon products are produced and continued into the future. They will coordinate their efforts in consultation with relevant CEOS WGs and VCs to ensure appropriate merging of data and products from multiple sensors.

Overall Motivation/Rationale-6: The IGCO called for in the *GEO Carbon Strategy* requires improved approaches for developing global land inventories and related data products of 1) the spatial distribution and extent of wetlands and peatlands and of changes in their organic carbon pools and 2) carbon content of reservoirs, lakes, ponds, and rivers. Satellite observations of inland waters must have appropriate spatial resolution and sensitivities. Lakes and reservoirs cover around 3% of the Earth's land surface, but the majority are small. Use of moderate to coarse resolution ocean-color sensors such as MODIS or MERIS is therefore fairly limited in lake carbon research. On the other hand, many medium to moderate resolution land remote sensing sensors (such as Landsat-7) do not have sufficient sensitivity to estimate lake content of colored dissolved organic matter (CDOM) and monitor long-term trends. At present there are only a few sensors (such as ALI on EO-1) that are suitable for mapping lake CDOM, dissolved organic carbon, and pCO2, but they do not provide full global coverage. Landsat-8 and Sentinel-2 will change the situation, as sensors on both these missions provide data with sufficient spatial and radiometric resolution as well as the global coverage needed for lake research. Space agencies must ensure the continuity of such measurements. Maps of lakes and ponds are needed annually and maps of flooding and inundation are needed seasonally. Estimates of associated carbon-related biophysical properties (e.g., dissolved and particulate carbon, river discharge) and biological productivity are needed as a contribution to terrestrial carbon budgeting. Research agencies must implement projects to develop these essential products at regional and global scales.

Carbon-Challenge-6: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the continuing deployment of satellites and development of satellite data products for mapping wetlands, wetland types, wetland inundation, rivers, flooding, reservoirs, lakes, and ponds and estimating their associated carbon-related biophysical properties (e.g., dissolved and particulate carbon, river discharge) and biological productivity. CEOS will encourage its Member Agencies to coordinate the launch of satellites that meet requirements in a timely fashion and to avoid gaps. CEOS Agencies will strive to implement projects to develop these essential wetland and inland water data products at regional and global scales and with appropriate spatial and temporal resolutions and sensitivities to the carbon constituents in inland waters.

Carbon-Action-6: CEOS Agencies with interests in and/or mandates for developing 1) satellites to observe wetlands and inland waters and 2) wetland and inland water data products will coordinate their efforts in consultation with relevant CEOS WGs and VCs.

2.5.3 Calibration/Validation-Related Recommendations

Overall Motivation/Rationale-7: The *GEO Carbon Strategy* calls for robust carbon tracking and accurate carbon budgets, and these major products require quantitative analysis of changes in Earth system carbon properties over time. This in turn requires well-calibrated satellite sensors and well-validated data products. Development of specific remote sensing products often requires use of surface reference data sets. In some cases, land-based networks have been developed to provide *in situ* data for validation of specific products (e.g., soil moisture, atmospheric CO_2), where in others, networks either need expansion or considerable development (such as biomass dynamics). For the ocean, this requires global-scale validation of algorithms for estimating ocean carbon pools from satellite data, in carbon units, in close collaboration with *in situ* observation systems. It is also necessary to provide adequate error characterization of remote sensing variables and carbon products derived from satellite data, ideally on a pixel-by-pixel basis, to ensure their appropriate use in quantifying and modeling carbon dynamics. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure *in situ* data are accessible to the satellite community for validation of satellite data products. The CEOS WGCV and its relevant subgroups have conducted and coordinated much-needed calibration and validation work over the years, and this work needs to continue and be expanded. The CEOS VCs are also conducting valuable work in this area. There is a need to strengthen mechanisms within CEOS and at the individual space agency level, in particular investment as part of satellite development, for product validation to establish validation methodologies, protocols and benchmark datasets. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure *in situ* data are accessible to the satellite community.

Carbon-Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its Member Agencies, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.

Carbon-Action-7: CEOS and CEOS Agencies will encourage national and international agencies to improve and expand upon the availability of the *in situ* observations needed for the calibration and validation of satellite land data products used for carbon science. This will include coordinating with national and international agencies collecting *in situ* data to 1) assess the quality and coverage (spatial and temporal) of validation data and 2) employ design features that entice data sharing and provide safeguards.

Carbon-Action-8: The CEOS WGCV's Land Product Validation (LPV) Subgroup will continue its work to validate satellite land data products and expand the number of land variables addressed as priorities are identified and available resources permit, and where no other body takes responsibility (e.g., GOFC-GOLD).

Overall Motivation/Rationale-8: The two major products called for in the *GEO Carbon Strategy* (i.e., a robust and transparent carbon tracking system and accurate carbon budgets) require quantitative analysis of changes in Earth system carbon properties over time. Desirable increases in spatial and temporal coverage can be achieved if data from two different, contemporaneous sensors can be combined seamlessly. To facilitate such data merger or fusion, data products acquired by differing sensors and satellites for each of these properties must be intercomparable, and systematic intercomparison activities must be conducted.

Carbon-Challenge-8: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the systematic intercomparison of satellite data products of relevance to the carbon cycle. CEOS Agencies will participate, as appropriate, in major intercomparison activities, including model-data, data-data, and multiple data stream intercomparisons. CEOS recognizes that intercomparison activities will require coordination with relevant non-CEOS organizations and activities.

Carbon-Action-9: CEOS WGCV and its relevant subgroups, in consultation with the CEOS Carbon Subgroup (recommended in Carbon-Action-38), will organize and coordinate carbon data product intercomparison activities as they are identified as priorities for CEOS action and in coordination with the wider carbon cycle science community.

CHAPTER 3: OCEANS AND INLAND WATERS DOMAIN

LEAD AUTHOR: SHUBHA SATHYENDRANATH (PLYMOUTH MARINE LABORATORY)
CO-AUTHORS: PRAKASH CHAUHAN (INDIAN SPACE RESEARCH ORGANIZATION),
WATSON GREGG (NASA GODDARD SPACE FLIGHT CENTER),
NICOLAS HOEPFFNER (JOINT RESEARCH CENTRE), JOJI ISHIZAKA (NAGOYA UNIVERSITY),
JOHNNY A. JOHANNESSEN (NANSEN ENVIRONMENTAL AND REMOTE SENSING CENTRE),
MILTON KAMPEL (INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS), TIIT KUTSER (UNIVERSITY OF TARTU), TREVOR PLATT (PLYMOUTH MARINE LABORATORY), AND JOO-HYUNG RYU (KOREA INSTITUTE OF OCEAN SCIENCE AND TECHNOLOGY)

3.1 Introduction: Why are the Oceans and Inland Waters Relevant?

Oceans constitute some of Earth's greatest reservoirs of carbon in various forms: organic and inorganic, particulate and dissolved (see Figure 3-1). It is estimated that the pool of carbon in the oceans is 50 times more than that in the atmosphere; the flux of carbon through the ocean is much greater than that attributed to burning fossil fuels; and the atmospheric exchange of carbon with the ocean is larger than that with the land. Primary production in the ocean is responsible for converting 50 Gt of carbon per annum into organic material (commensurate with terrestrial primary production), and a fraction of the produced material is exported to the deep ocean through sinking particles, leading to its sequestration from contact with the atmosphere. Ocean circulation transports carbon-rich waters from the surface into the deep ocean. The difference in partial pressure of carbon dioxide between the surface ocean and the atmosphere leads to exchanges of carbon between the two domains. Globally, the net exchange of carbon dioxide across the ocean-atmosphere interface has been such that some 25% of anthropogenic carbon-dioxide emitted into the atmosphere now resides in the oceans: without this uptake, the accumulation of anthropogenic carbon dioxide in the atmosphere would have been that much greater than it is today. But, over the years, the cumulative dissolution of atmospheric carbon dioxide into the oceans has modified the buffering capacity of oceans; this evolving role of the oceans has to be taken into account in planning for a carbon-neutral planet.

The planetary carbon fluxes and the role of the oceans in them cannot be discussed without considering the heat budget of the ocean and air-sea fluxes of heat and momentum: the solubility of carbon dioxide in seawater changes inversely with temperature; and the distribution of temperature and salinity in the surface and near-surface layers of the ocean determine the total alkalinity in these waters. The air-sea exchange of the gas is determined by the air-sea difference in partial pressure of carbon dioxide and processes at the air-sea interface related to sea state, often parameterized as a function of wind speed. The physical and chemical processes that transport carbon in dissolved form from the surface to the interior are often referred to as the solubility pump and the biological processes that transport carbon (mostly in particulate form) to the deep ocean are referred to as the biological pump. Together, they create a complex picture, of which many details are yet to be clarified. The details of the biologically mediated carbon cycle in the ocean are presented schematically in Figure 3-2.

Climate change has the potential to modify many chemical and physical processes in the ocean, and hence the capacity of the oceans to take up anthropogenic carbon dioxide from the atmosphere. For example, changes to stratification and circulation would impact cycling of dissolved inorganic

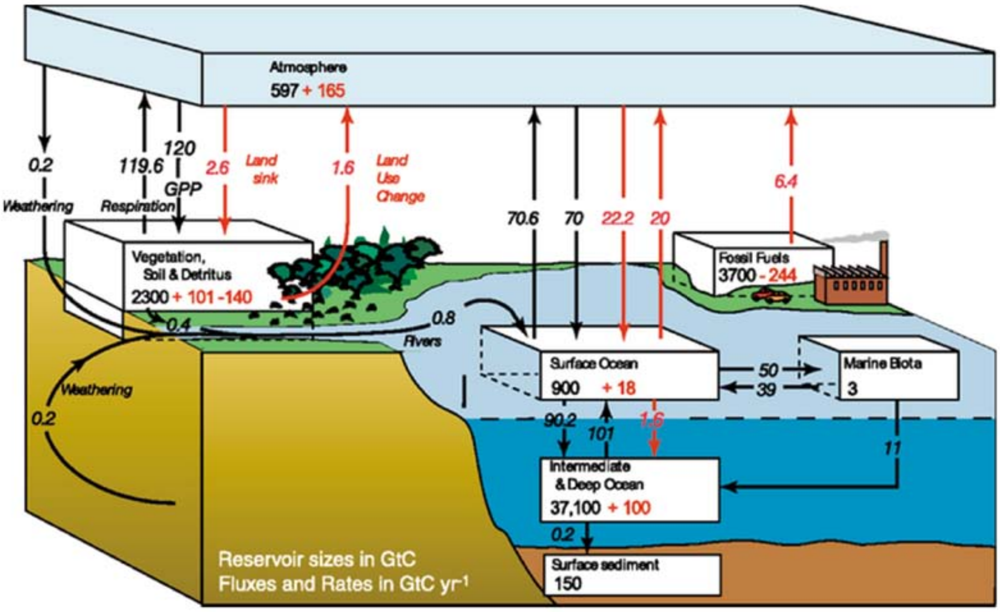


Figure 3-1. From IPCC AR4 – Working Group I: The Physical Science Basis (2007), Chapter 7, Figure 7.3. Reservoir sizes in GtC, and fluxes and rates in GtC yr-1. Known changes are indicated in red. Absence of red arrows does not indicate there is no change, but rather that at present we do not know the change in many reservoirs and rates, for example ocean biomass, primary production or biological pump. Note that these pools and fluxes are not static: for example, there have been changes in the nutrient cycle, which controls ocean biology.

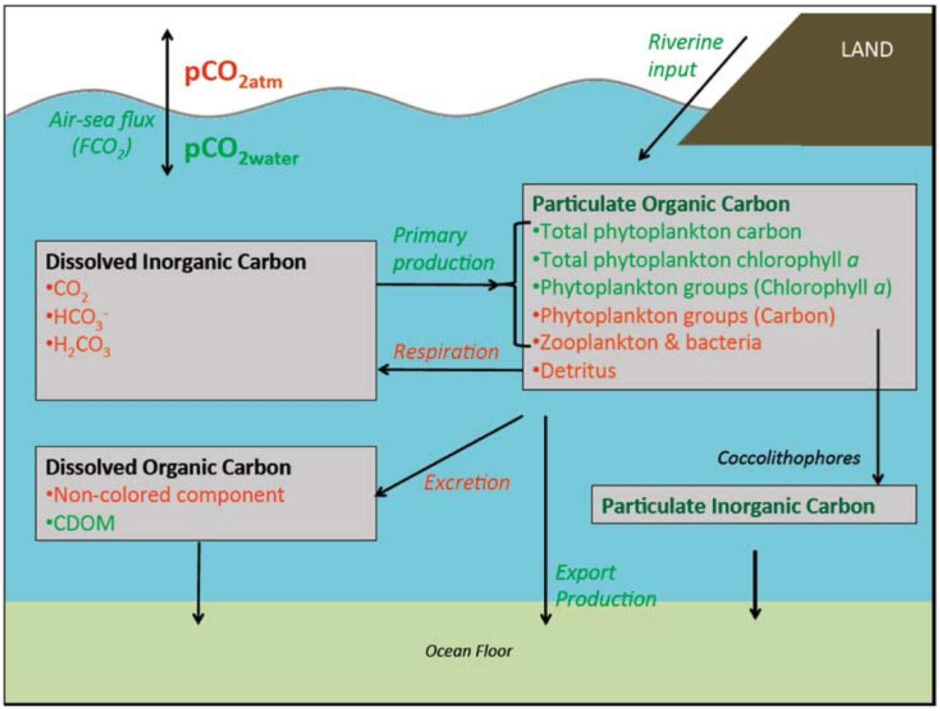


Figure 3-2. Details of biologically mediated carbon fluxes in the ocean; the dependencies of the components on other aspects of the carbon cycle are not shown. Green text illustrates those for which satellite-based methods have been proposed in peer-reviewed literature and red those that are not. (courtesy of C.S. Rousseaux and W. W. Gregg)

carbon (labile and refractive components), and warmer ocean temperatures and increasing partial pressure of carbon dioxide in the oceans would affect the further uptake carbon dioxide from the atmosphere.

When considering the relevance of the ocean carbon cycle in the context of climate change, it is not sufficient to examine how the carbon cycle through the oceans dictates the accumulation of carbon dioxide in the atmosphere and hence the strength of the green-house effect. It is also important to recognize that it is the flow of carbon through the marine food chain that sustains the marine ecosystem and the marine resources, particularly fisheries and seafood. We do not yet know how climate change might modify the marine ecosystem services that we now take for granted, including marine primary production, and food from the sea.

Although it is well recognized that the ocean acidification due to dissolution of anthropogenic carbon dioxide in the ocean is a serious threat to marine calcifying organisms including corals, shell fish and many types of phytoplankton and zooplankton, it remains yet to be established what the long-term impact of acidification on marine biodiversity might be: it will depend, among other factors, on the ability of the organisms to adapt to the change. Changes in temperature, circulation and stratification are modifying the distribution of many organisms, and further effects are anticipated in the future. Stratification determines the light available in the surface mixed layer for phytoplankton growth, and at the same time, absorption of light energy by phytoplankton modifies the heat content of that layer, thus setting in motion feedback mechanisms between biological and physical processes in the surface layer, and hence the carbon cycle. The implications for sustainable management of living resources of the sea are yet to be determined. Many geo-engineering schemes for sequestration of anthropogenic carbon involve perturbation of the pelagic ecosystem (for example by iron enrichment, or by pumping of nutrients to the surface ocean from the deep). Before any such schemes can be considered seriously, we have to understand the flow of carbon through the ecosystem, and the natural variability in this flow. Only then would we be able to evaluate the potential adverse effects on the ecosystem, as well as the magnitude of any potential sequestration. This also implies that the understanding of air-sea interactions and mesoscale (order 100 km) to sub-mesoscale (1-5 km) dynamics in the ocean associated with the presence of eddies, meandering fronts and upwelling zones (Kudryavtsev et al. 2012) and their interaction with, and influence on, the biogeochemical state of the ocean (Levy et al. 2001; Godø et al. 2012) must be advanced.

3.1.1 The Coastal System

Apart from the relevance of carbon pools and fluxes of the oceanic domain in the context of climate change, it is also important to recognize the role of coastal ecosystems and nearshore habitats in the carbon biogeochemistry. The coastal zone also represents a large reservoir of particulate organic carbon resulting from local high productivity rates, as well as large inputs of land-derived organic material via river runoff. Upwelling of the cold nutrient-rich waters is a typical phenomenon regularly observed in both *in situ* and satellite data (e.g., Kowalewski and Ostrowski 2005; Kozlov et al. 2012), which favors enhanced primary production. Approximately 30% of the oceanic primary production occurs in the coastal zone, which covers ca. 8% of the global ocean surface. Along the coastal fringe, sea grasses, seaweeds, benthic micro algae, rooted aquatic macrophytes such as mangroves and coral reefs are major primary producers in the shallow environment ecosystems with very high rates of annual net productivity. Seagrass meadows occupy less than 0.2% of the global ocean area, but are estimated to contribute ca. 10% of the annual organic carbon burial in the oceans. The fate of fixed carbon by these components varies with physical, chemical and biological processes. The fixed carbon may be lost to sediments through burial or recycled within the system, consumed by herbivores, consumed within the detritus food web through microbial breakdown, or transported offshore by tides and currents as particulate or dissolved organic and inorganic carbon (continental shelf pump) and eventually become sequestrated for several hundred years in the open ocean below the permanent pycnocline.

Although considered for a long time as a net source of carbon to the atmosphere, coastal waters can turn into a net carbon sink under increasing atmospheric CO_2. These fluxes are subject to large variability given that coastal zones are among the most dynamic, rapidly changing and most vulnerable environments on earth. The coral reef ecosystems are particularly vulnerable to increased carbon dioxide concentration that results in ocean acidification, coral bleaching and loss of productivity. Understanding the fates of carbon sources and sinks within the coastal ecosystem, especially in the tropics is important to establishing the global carbon budget and to informing carbon-cycle models.

3.1.2 Inland Water Bodies

Current carbon-climate models, such as those used by the IPCC or the Integrated Global Observing Strategy-Partnership (IGOS-P), ignore inland waters treating them as inert pipes simply transporting terrigenous organic carbon into the oceans. Recent estimates (Cole et al. 2007, Tranvik et al. 2009, Battin et al. 2008, 2009) show that the role of lakes is by no means limited to transporting carbon from land to oceans; rather, they are land-carbon hot spots. Tranvik et al. (2009) estimated that land exports of carbon to inland waters are twice as high as land exports of carbon to the ocean. Subsequently most of this carbon is either exported to the oceans (0.9 Pg C y^{-1}, Figure 3-3), buried (0.6 Pg C y^{-1}), or oxidized and outgassed to the atmosphere as CO_2 and CH_4 (at least 0.9 Pg C y^{-1}); emission of methane from lakes is greater than emissions from oceans (Bastviken et al. 2004). Globally, lake sediments may contain as much as 820 Pg C (Cole et al. 2007).

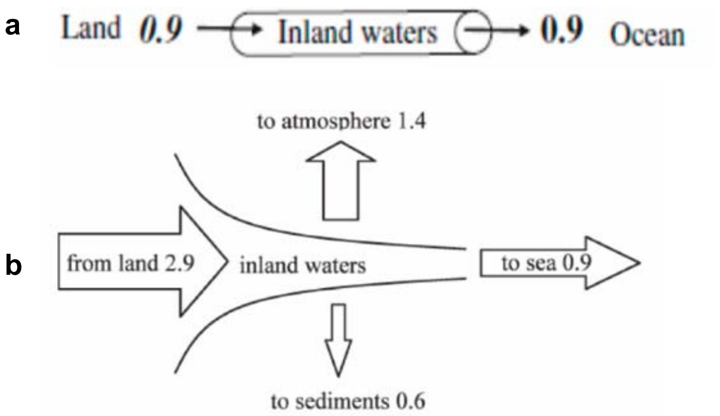


Figure 3-3. Estimated carbon fluxes through inland waters a) traditional approach used in global carbon cycle models (from Cole et al. 2007); b) recent estimate (Tranvik et al. 2009). Units in Pg C y-1.

The terrestrial dissolved organic carbon (DOC) entering waters from surrounding land, and DOC produced in the water itself, are food sources for bacteria. DOC is also photo-oxidized in surface water due to sunlight. Carbon dioxide is released in both of the processes. Climate-carbon models (IPCC 2007; IPCC 2013) predict warmer and wetter climate in higher latitudes. As a result, significant amounts of carbon may be released, since the stores of carbon locked up in just the northern peatlands and permafrost soil are equivalent to the entire pool of atmospheric CO_2. A great part of the release would take place in thaw ponds (i.e., lakes). Besides the effects described above, colored dissolved organic matter (CDOM) has an impact also on the underwater light climate – increased amount of CDOM reduces the amount of light available for primary production, as CDOM absorbs light strongly in blue part of spectrum, which corresponds to the absorption maximum of the main photosynthetic pigment chlorophyll-a. Consequently, changes in lake CDOM may cause shifts in lake ecosystems from a phytoplankton-based food loop to a microbial loop.

Compared with terrestrial and marine carbon fluxes, estimates of carbon fluxes in inland waters still remain poorly constrained. Yet they are being revised at a fast pace. For instance, net CO_2 outgassing from inland waters worldwide has most recently been estimated at 3.28 Pg C y^{-1} (Aufdenkampe et al. 2011). However, the implications of inland waters for the terrestrial carbon cycle (e.g., lateral fluxes) and for the marine carbon cycle (e.g., carbon sink) remain elusive. Hence, the need for integrating the inland water and terrestrial carbon cycles into a seamless cycle is thus evident and becomes increasingly recognized.

3.2 The Role of Satellites in Monitoring the Carbon Cycle and Pools in Oceanic, Coastal, and Inland Water Bodies

Carbon dioxide is reactive in the ocean, with biological processes adding to the possible pathways for carbon, such that it occurs in many particulate and dissolved forms. The oceans, which are dynamic and subject to variability on multiple scales, are perennially under-sampled. *In situ* observations based on ships and buoys cannot, by themselves, provide the adequate coverage necessary to detect any potential change superimposed on long-term variability. Satellites provide repetitive observations with global coverage, serving as an extrapolation and integration tool, filling gaps in *in situ* observations, especially in the horizontal plane at the surface. Ironically, it is sometimes easier to detect particular carbon fluxes in the ocean, such as primary production, by combining remotely sensed data with auxiliary information, than to detect some of the carbon pools themselves. Furthermore, satellites are able to inform us on many physical factors that influence the transport of carbon through the ocean, and the flux of carbon at the air-sea interface.

The contributions that satellites can make to monitoring of the pools and fluxes of carbon in the ocean are summarized in Table 3-1. It is noted that many of the important components of the surface ocean carbon system are now routinely observed from satellites. It is a credit to the international space agencies that have provided and managed operational remote-sensing platforms, and to the scientific community for innovation in finding methods to convert the raw radiances directly observed into scientifically useful geophysical products. It is moreover reassuring that the sensors required are consistent with the Essential Climate Variables (ECVs) identified by the Global Climate Observing System (GCOS). However, it is important to note that such an observing system does not constitute a carbon observation system until the satellite products have been refined to the point where they can be expressed in carbon units, or can contribute to measurements of carbon fluxes. This is particularly true of ocean color, where many novel and emerging products have to be exploited and developed further, before they can be established as elements of a carbon observation system. To be useful in this context, space observations have to be capable of evaluating and reducing uncertainties in the estimates of these pools and fluxes and to be able to monitor, on a routine basis, small changes in these fluxes. Because the natural system is highly variable, even over decadal time scales, the observations have to be sustained in a systematic manner over a very long time, to be able to isolate any anthropogenic trends from natural variability. Because of the interconnected nature of the ocean carbon system, the observation system has to be a multidisciplinary integrated system, capable of identifying any potential changes to the marine ecosystem and its services, in addition to the role of the oceans in removing anthropogenic carbon dioxide and other greenhouse gases from the atmosphere.

Remote sensing observations of the ocean carbon cycle are restricted to the surface layer of the ocean. A broad representation of the surface ocean carbon cycle (Figure 3-2) illustrates the main components, and also shows what is uniquely observed from space by a single sensor class of observations (e.g., ocean color radiometry) or indirectly estimated with more than one sensor class (e.g., thermal infrared and optical scanners, radar altimeters and scatterometers). Table 3-1 provides the sensor class used for the observation and references.

There are also major gaps in the observing systems. The entire dissolved inorganic carbon component is not observed, though it is the biggest pool, and also one that is undergoing change. Unfortunately, this component has insufficient electromagnetic signal to be detectable from space using current technology. But the ongoing Sea Surfase Temperature (SST) measurements and the new salinity measurements have the potential to contribute to inferences of changes in this pool.

The criterion adopted here for stating that a variable can be observed from space is simply that a method for it has been published. This by no means suggests that the method has scientific consensus. Although total chlorophyll and particulate inorganic carbon have well-established methodologies, CDOM, phytoplankton carbon, and pCO_2 are the subjects of active, intense research with less scientific consensus. Furthermore, all of the flux estimates are subject to active scientific debate. Many fluxes are derived using empirical correlations among several satellite products that may or may not have direct influences on the fluxes themselves. Consequently, there is a considerable divergence among the estimates, which suggests additional information is required to refine them. For example, carbon-to-chlorophyll ratios, phytoplankton physiological state, ocean spectral irradiance, mixed layer depth, local average temperature, and physical processes all bear on the local value of primary production, which is estimated from satellite observations of chlorophyll, SST, and Photosynthetically Active Radiation (PAR) in the various algorithms currently used. Disparities in estimates of primary production stem in part from the differences in the ways these subordinate variables and processes are parameterized. Advances in the observation of any of these subordinate variables would improve the quality of primary production estimates, and would therefore be a priority for future satellite missions.

However, at the highest level, the most pressing needs for remote sensing in support of ocean carbon science are 1) continuity of the current observational methodologies; 2) new missions with improved capabilities; and 3) new observations of atmospheric pCO_2. Since no methods exist at present to measure pCO_2 in the atmosphere by remote sensing, it is important to have adequate *in situ* coverage of atmospheric pCO_2 measurements to complement satellite measurements, as well as to serve as validation points for any future methods that may be developed for remote sensing of this quantity. Note that it is the difference in the partial pressure of CO_2 at the air-sea interface along with winds speed (and sea state) that determines the air-sea exchange of this gas.

Although much has happened in the field of Earth observations since the publication of the 2006

CEOS report (GEOS 2006), its strongest recommendation for continuity of missions remains the most important recommendation today (see example for Ocean Color in Figure 3-4). Continuity is still not assured, although in the case of ocean-color there are some firm plans for missions with expanded capabilities following Suomi NPP-VIIRS. For example, continuity of ESA's MERIS ocean observations will be ensured with data from the highly sensitive Ocean and Land Color Instrument (OLCI) on Sentinel-3, which will deliver multi-channel, wide-swath optical measurements. Development is on track for the launch of Sentinel-3A in 2014 with Sentinel-3B being launched 18 months later. Furthermore, NASA's 2010 Climate Plan includes the Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) mission which will make global ocean color measurements, along with polarimetry measurements to provide extended data records on clouds and aerosols. Based on the mission requirements in the 2012 Report of the Science Definition Team for the PACE Mission (http://decadal.gsfc.nasa.gov/pace_documentation/PACE_SDT_Report_final.pdf), this new-generation instrument will provide scientific and societal benefits that cannot be achieved by existing technologies. The U.S. President's FY2013 budget request enables the development of PACE for launch in the 2019/20 timeframe. In addition to ensuring continuity of missions, it is also paramount that the sensors be designed to meet mission requirements (see for example, IOCCG, 2012, for mission requirements for ocean-color sensors).

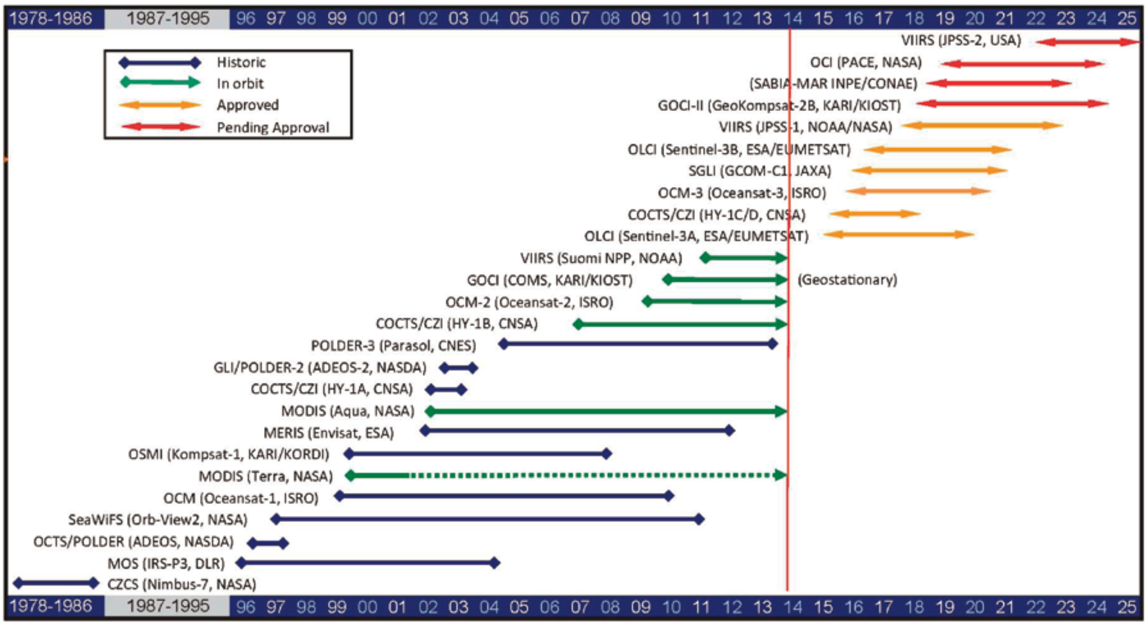


Figure 3-4. Timeline for ocean-color missions, including those in orbit, approved and pending approval. From IOCCG (Note: Similar timelines needed for other types of sensors essential for carbon monitoring.)

Availability of sustained observations is necessary to face new challenges in the decades to come related to the detection of long-term trends and cycles of variability. A continuous dataset also supports the development and application of data assimilation and reanalyses. Models constrained by satellite data will allow us to examine how our ocean responds to climate variability, identify potential long-term trends and improve the carbon estimates in regions of low and biased sampling such as the Southern Ocean. Satellite observations serve as inputs to models designed to study the flow of carbon through the oceans, and to validate model outputs. This broader role of remote sensing in contributing to our understanding of the ocean carbon cycle should not be overlooked in designing the satellite component of an ocean carbon observing system. In fact, programs such as the Climate Change Initiative of the European Space Agency, are moving away from a mission perspective to a product perspective, highlighting the need for bringing many missions together in a consistent fashion to produce long time series of essential climate variables, i.e. Climate Data Records as defined by GCOS (2011), and of linking data with models to achieve an integrated view of the Earth's climate system.

Of the missing carbon components in Figure 3-2, the most critical for the ocean carbon cycle, and possibly the entire global cycle, is routine, frequent, global observations of atmospheric CO_2 concentrations, enabling estimates of surface atmospheric pCO_2. Air-sea fluxes are also a priority, despite strong global efforts using estimates of oceanic pCO_2 from SST, reanalysis wind speeds, and *in situ* observations of atmospheric CO_2 (Park et al. 2010). Here again, global time-varying observations of atmospheric pCO_2 are critical for furthering our understanding of the global cycling and fate of carbon on Earth.

Similarly, ocean pCO_2 is a priority, despite the existence of several methods to estimate it. There is little consensus on a global method, and the regional methods depend on the use of climatologies for salinity, or indirect correlations with chlorophyll. Some rely entirely on SST (Boutin et al. 1999; Lefevre and Taylor 2002). Others use various combinations of SST and chlorophyll (Ono et al. 2004), sometimes additionally with salinity climatologies (Sarma et al. 2006), or mixed-layer depth from a model (Jamet et al. 2007; Watson et al. 2009). On the other hand lake pCO_2 has been found to be correlated with DOC (Sobek et al. 2003) which can be mapped from space using CDOM as a proxy (Kutser et al. 2005a,b). With the advent of space based salinity data from Aquarius and SMOS missions, it is expected that temporally varying salinity information can be used for pCO_2 estimation.

Although these efforts have provided impressive results, observations of new ocean variables can provide a more mechanistic approach to ocean pCO_2. Specifically, new observations of global time-varying salinity can provide crucial information on the precipitation-evaporation dynamics that are important for surface alkalinity estimates. Alkalinity plays a key role in the estimation of ocean pCO_2. Reul et al. (2009) have also demonstrated that sea-surface salinity of intense freshwater areas associated with river runoff (e.g., Amazon River) can be derived and tracked into the equatorial Atlantic from the CDOM absorption coefficient obtained from SeaWiFS and MODIS. This relationship also emphasizes the importance of sustainable salinity observations from space.

High on the list of aspects of the carbon cycle that are poorly observed and quantified are the pools and process in coastal regions as well as inland water bodies. For example, ocean-color remote sensing continues to suffer from degraded quality in these optically complex areas, where the carbon cycle remains poorly understood. New observations are needed with modern engineering advances, especially broad spectral ranges, high spectral resolutions, and a capability to observe the smaller scale biological and chemical dynamics that characterize these regions. Advances in signal detection can potentially provide the high signal-to-noise observations that are critical. Missions like Sentinel-2 are important to address the requirements of observing coastal and inland water bodies.

Remote sensing is the only realistic way for determining the global amount of dissolved organic carbon, DOC, and the true role of lakes in the global carbon cycling. DOC contains a colored component called CDOM (Colored, or chromophoric, Dissolved Organic Matter). There is a strong correlation between DOC and CDOM in many water bodies (Tranvik 1990). Moreover, there is also correlation between lake DOC and CO_2 supersaturation (Sobek et al. 2003). It implies that both DOC and pCO_2 can be estimated from space using CDOM as a proxy provided that the CDOM retrieval methods are sufficiently accurate.

Lake CDOM retrieval algorithms have been proposed (Kutser et al. 2005a,b, 2009; Kallio et al. 2001, 2008). However, their validity has been tested predominantly only in the boreal zone. Model simulations (Kutser et al. 2005a) show that the CDOM-retrieval algorithm should perform well over a wide range of natural conditions. However, some further validation tests on the performance of the lake CDOM-retrieval algorithm are needed in different conditions (i.e. tropics, extremely turbid lakes, saline lakes) before the global DOC estimates can be made. Validating the CDOM/DOC/pCO_2 relationships outside the boreal zone is also needed.

Also high on this list of poorly observed facets are the many subordinate variables that affect the higher-level components of the ocean carbon cycle shown in Figure 3-2. Several of the unobserved variables that affect and confound primary production estimates have already been described. There is a strong possibility that some of these (such as carbon pools in phytoplankton groups) can be estimated using high spectral resolution sensors covering a larger portion of the visible and ultraviolet spectra. Such advanced sensing capabilities may potentially produce breakthroughs in our estimates of the ocean carbon cycle and reduce the disparities among different algorithms leading to reduced uncertainty.

Not mentioned in the CEOS 2006 report and typically missing in most reports on the need for satellites is the importance of supplementary *in situ* data. However, the *GEO Carbon Strategy* Report does highlight this need. Initiatives such as Argo, OceanSITES, AERONET, ChloroGIN and Bio-Argo float programs are welcome developments in this context (also note the *in situ* component of the OCR-VC initiative of IOCCG and CEOS). The usefulness of long-term sustained *in situ* observations increases with the value of the data record, as has been well demonstrated, for example, in the case of the Continuous Plankton Recorder (CPR) program. The value of satellite observations is enhanced when coupled with *in situ* observations for testing and validation of the methods, but the need goes far beyond that. Modern estimates of air-sea fluxes utilize *in situ* archives of atmospheric data and *in situ* measurements of partial pressure of carbon dioxide and the concentration of dissolved inorganic carbon in sea water. *In situ* observations of temperature are essential for correcting biases in satellite SST data. New methods integrating *in situ* chlorophyll data have been shown to reduce inconsistencies among different ocean color data sets and minimize biases (Gregg et al. 2009). Similarly, *in situ* observations to estimate parameters of vertical structure in chlorophyll and parameters of photosynthesis-irradiance models are invaluable to constrain satellite-based computations of primary production (see Table 3-1), and accurate, direct measurements of water-column primary production are needed to test and improve primary-production models for use in remote sensing. Along with the need for *in situ* data is the need to archive and distribute data. The international data centers must play a continuing role in the ocean carbon community to collect and freely distribute these *in situ* data sets. *In situ* data are also required for extrapolation in the vertical dimension, for example, to link surface chlorophyll with vertical structure in chlorophyll profiles (e.g., Platt et al. 2008). *In situ* observations are essential to establish the indirect methods for detecting carbon pools, and to ensure that methods stay robust over time, in a changing ocean. Ideally, the ocean-carbon observation system would be an integrated system, incorporating both *in situ* and satellite observations, rather than treating individual observing elements as stand-alone tools. The need for *in situ* observations is often undervalued, but together with satellite data the combination can lead to major improvements, especially when combined also with modeling and data assimilation efforts, potentially producing the types of scientific advances in carbon cycle science that are needed.

Table 3-1. Carbon products for the ocean domain based on satellite data inputs. Examples are from the literature. Underscored variables in italics are compliant with the GCOS ECVs.

Ocean Domain Carbon Product	Inputs Required	Sensors	References & Remarks (Note: references are indicative,not exhaustive)
In-Water Fluxes of Organic Carbon			
Total or net Primary production	*Chlorophyll* (for computation of photosynthesis and for light transmission underwater) Photosynthetically-active radiation at the sea surface (PAR, light available for photosynthesis; also known to affect photosynthesis parameters) Colored dissolved organic matter (for light transmission) Particulate back-scattering (for light transmission) *Temperature* (for photosynthesis parameters) Sea-ice changes (for enhanced production at retreating ice edge) Mixed-layer Depth (for estimation of mixed-layer production)	Ocean color Ocean color Ocean color Ocean color Thermal Infrared, Microwave SST Satellite SAR, Altimeter Models	Longhurst et al. 1995 Antoine and Morel 1996 Behrenfeld and Falkowski 1997 Platt and Sathyendranath 2008 Milutinović et al 2009 Carr et al., 2006; Friedrichs et al. 2009 Frouin and Wang 2000 Liang et al. 2006 Sathyendranath and Platt 1988
	Diffuse attenuation coefficient for downwelling light (for estimation of light penetration) Vertical profile of chlorophyll (for water-column production, especially the component below the below the mixed layer)	Ocean color Ocean color, in *situ* observations	Antoine and Morel 1996; Behrenfeld and Falkowski 1997; Bouman et al. 2003; Platt et al. 2008

Ocean Domain Carbon Product	Inputs Required	Sensors	References & Remarks (Note: references are indicative,not exhaustive)
Primary production by phytoplankton group	Inputs in addition to requirements above for total net primary production, include photosynthetic parameters for each group as well as: *Spectrally-resolved water-leaving radiances or reflectances* (for computation of fractions of chlorophyll in each phytoplankton class)	Ocean color	Uitz et al. 2010
Riverine input	CDOM, suspended sediment load	Ocean color	Thomas and Weatherbee 2006
Export production	*Temperature* (for calculation of nutrient fluxes; for model-based estimation of e-ratio, the fraction of export production to total production) *In situ* measurements of f-ratio f-ratio: new (or export) production as fraction of total production Particle size structure (for computing sinking velocities)	Thermal Infrared and Microwave SST Thermal Infrared, Microwave SST Ocean Color	Sathyendranath et al. 1991; Laws et al. 2000; Goes et al. 2000; SatyaPrakash et al. 2008; Kumar et al. 2010
Pools of Carbon in Pelagic Ocean			
Total phytoplankton *chlorophyll*	*Spectrally-resolved water-leaving radiances or reflectances*	Ocean color	McClain 2009
Total Particulate Carbon	*Chlorophyll* (empirical relationship)	Ocean color	Sathyendranath et al. 2009
Particulate Organic Carbon	*Chlorophyll*, particle back-scatter, reflectance ratios, diffuse attenuation coefficient for downwelling light at 490 nm (empirical relationships)	Ocean color	Loisel et al. 2002; Gardner et al. 2006; Sathyendranath et al. 2009; Stramska 2009
Phytoplankton carbon	*Chlorophyll*, particle backscatter	Ocean color	Behrenfeld et al. 2005; Sathyendranath et al. 2009
Dissolved colored organic matter	Absorption by colored dissolved organic matter	Ocean color	Siegel et al. 2002, 2005; Maritorena and Siegel 2005

Ocean Domain Carbon Product	Inputs Required	Sensors	References & Remarks (Note: references are indicative,not exhaustive)
Dissolved organic matter		Ocean color	Mannino et al. 2008
Phytoplankton functional types	*Chlorophyll*, phytoplankton absorption, back-scattering(Note: need carbon-to-chlorophyll ratio for each type, to convert from chlorophyll to carbon units)	Ocean color; hyperspectral ocean color	Nair et al. 2008; Brewin et al. 2011 a,b; Devred et al. 2011
Phytoplankton size	Fractions of pico, nano and micro-phytoplankton; size spectrum, phytoplankton absorption coefficient; particle backscatter	Ocean color	Montes-Hugo et al. 2008; Kostadinov et al. 2009, 2010; Brewin et al. 2011b; Devred et al. 2011; Fujiwara et al. 2011
Factors affecting air-sea fluxes of carbon-dioxide			
Air-sea fluxes	Wind speed, sea state, Ice cover, sea surface temperature	Scatterometer, Satellite SAR, Passive microwaves, Infrared radiometers, altimeter winds	Chelton et al. 2004; Park et al. 2010
Mesoscale eddies	Surface geostrophic *current, sea surface temperature, ocean color*	Altimeter, radiometer, spectrometer	Eddies in the ocean influence the concentration and distribution of plankton. Hence the ecosystem and the biological pump will be modified. Kudryavtsev et al. 2012; Godø et al. 2012
Carbon transport	Geostrophic *current, wind vector* (wind-driven currents), range Doppler velocity	Altimeter, Scatterometer, Envisat ASAR	Chapron et al. 2005; Johannessen et al. 2008
Upwelling	Wind-stress curl, *Sea surface temperature*	Scatterometer, SAR, passive microwaves, infrared radiometer	An upwelling index should be established, Kozlov et al. 2011
Sea ice extent	Inhibit air-sea fluxes. Upwelling along the ice edge	Active-passive microwaves	Wind driven upwelling along the ice edge is a recurrent event, Buckley et al. 1979
Ocean acidification, carbon chemistry			

Ocean Domain Carbon Product	Inputs Required	Sensors	References & Remarks (Note: references are indicative,not exhaustive)
Ocean pCO2	*Chlorophyll, Sea surface temperature, salinity, wind speed, sea ice*	Ocean color, SST, salinity, wind speed, sea ice	Ono et al. 2004; Sarma et al. 2006
Total Alkalinity at the sea surface	*Sea-surface temperature, Salinity*	Thermal Infrared, Microwave SST, Microwave salinity sensor	Lee et al. 2006 (note: approach developed using in situ data, but applicable to satellites with the advent of salinity sensors)
Calcite liths from phytoplankton (particulate inorganic carbon)	Near-true color images	Ocean Color, Thermal Infrared, Microwave SST	Brown and Yoder 1994; Balch et al. 2005; Shutler et al. 2010
Diazotrophs, Algal blooms	*Sea surface temperature*, particle backscatter, *chlorophyll*, Phycoerythrin concentration or (Phyco/chl a conc.), accessory pigments	Hyperspectral Ocean color Thermal Infrared, Microwave SST	Subramaniam et al. 2002 Westberry et al. 2005; IOCCG 2008, 2009b Watson et al. (2009)
Ecosystem variability			
Phytoplankton phenology	Time series of chlorophyll and primary production data	Ocean color, SST	
Phytoplankton physiology	Phytoplankton Fluorescence	Ocean color	Topliss and Platt 1986; Gower and Borstad 1990; Falkowski et al. 1995; Behrenfeld et al. 2009
Phytoplankton size classes (chlorophyll)		Ocean color	Uitz et al. 2006; Brewin et al. 2010; Devred et al. 2011; Ciotti and Bricaud 2006
Ecological Provinces of the Ocean	*chlorophyll, sea surface temperature*, bathymetery, *currents, salinity*	Thermal infrared& Microwave SST, Ocean Color, Altimeter, salinity sensor	IOCCG 2009a

Table 3-2. Readiness of ocean satellite products as elements of an ocean carbon observation system

Sensor	Products	Remarks
Ocean Color	*Chlorophyll*	More work required to convert between chlorophyll and carbon
	Absorption by colored dissolved organic matter (estimated from *water-leaving radiance*)	Directly applicable in computation of light penetration in primary production models; but needs work to establish relationships between absorption and concentration of dissolved organic carbon
	Daily Photosynthetically Available Radiation	Operational algorithms of PAR calculation exists, however aerosol and cloud effects needs to be better parameterized
	Particulate Organic Carbon, phytoplankton carbon (estimated from *water-leaving radiance*)	Many emerging algorithms; need global validation; selection of best algorithm, if possible
	Primary production	Many models exist at the global scale; considerable effort has been invested (especially by NASA) on comparison of algorithms; outputs extensively used by carbon modelers
	Particle Size Distribution (estimated from *water-leaving radiance*)	Not available in carbon units
	New (export) production	Many models exist at the global/ regional scale; limited validation
	Phytoplankton Functional Types (estimated from *water-leaving radiance*)	Not available in carbon units
Infrared radiometer, passive microwave	*Sea surface temperature*	Accurate algorithms for SST from NIR and passive radiometers exist; Continuity of SST needs to be ensured.
Active and passive microwaves	*Wind speed, vector wind, sea state*	Space based scatterometry is facing a continuity problem; At present on OCEANSAT-2 Scatterometer is the only operational system
Altimeter	Surface geostrophic *currents* and eddies	Space borne altimeter data sets appear to be secure, however, wide swath altimeters needs to be pursued.
Active-passive microwaves	*Sea ice* extent, ice edge structure	Ice edge upwelling is a recurrent phenomenon under favorable wind directions. Retreat in ice extent is also leading to larger ocean areas being subject to CO_2 exchange.

3.3 Oceans and Inland Waters Domain Recommendations and CEOS Actions

3.3.1 Mission-Related Recommendations

Overall Motivation/Rationale-9: The IGCO called for in the *GEO Carbon Strategy* requires continuous satellite time series records of ocean properties (e.g., ocean carbon state, ocean color and marine ecosystem composition, and ocean physical state) at mid resolution. These biological and physical properties of the ocean are needed to estimate ocean carbon pools and fluxes and document and analyze their changes over time. In order to meet this need, CEOS Member Agencies must develop and deploy satellites that can provide continuity moderate resolution (~0.5 km - 10 km) satellite measurements of ocean color, sea surface temperature, surface winds, salinity, sea state, currents and eddies, sea ice extent and ice edge structure with adequate on-board calibration and sustained calibration and validation operations. Some redundancy to cover contingencies and improve coverage should be part of the overall plan.

Carbon-Challenge-9: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies so that high-quality, well-calibrated, moderate-resolution continuity measurements of ocean color, sea surface temperature, surface winds, salinity, sea state, currents and eddies, sea ice extent and ice edge structure are available, data gaps are avoided, and satellites flying at the same time, in constellations, and in time series are cross-calibrated and well-validated. CEOS notes that these requirements are commensurate with corresponding GCOS requirements.

Carbon-Action-10: The relevant CEOS VCs and CEOS WG Climate will act to include IGCO priorities to extend the time series of moderate-resolution carbon-related observations of the open ocean from space into their respective activities to coordinate the VCs and climate-related measurements.

Overall Motivation/Rationale-10: The *GEO Carbon Strategy* points out that carbon fluxes in the coastal ocean are important, yet the coastal ocean is particularly challenging to observe from space. The reasons range from the diurnal cycles of the biota to the complex optical properties of coastal waters. In contrast to the open ocean, the high spatio-temporal complexity of coastal regions requires a dedicated, oriented coverage rather than a global coverage. This requires continuity satellite ocean-color measurements with spatial resolution better than 0.5 km and/or repetition rate of less than a day and the capability to observe transitory events (e.g. unusual or transient algal blooms). In addition the challenging optical nature of coastal turbid waters requires more spectral channels in the visible spectrum (e.g., as are available on MERIS) on moderate and coarse resolution sensors than are necessarily required for the open ocean. To meet these needs, CEOS Member Agencies must coordinate the launch of satellites that meet these requirements in a timely fashion to avoid gaps.

Carbon-Challenge-10: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Member Agencies so that high-quality continuity satellite measurements of coastal waters, with appropriate spatial, temporal and spectral sampling properties, are available for ocean carbon science.

Carbon-Action-11: The relevant CEOS VCs and CEOS WG Climate will act to include IGCO priorities for continuity in high-resolution (better than 0.5 km) carbon-related observations of coastal waters from space in their respective activities to coordinate the VCs and climate-related measurements, noting the higher temporal and spatial resolutions and spectral coverage required, compared with open-ocean measurements.

Overall Motivation/Rationale-11: The *GEO Carbon Strategy* points out that carbon fluxes in the coastal ocean are important, yet the coastal ocean is particularly challenging to observe from space. The reasons range from the diurnal cycle of the biota to the complex optical properties of coastal waters. Future geostationary missions dedicated to the observation of the coastal ocean are likely to hold the key to solving this problem. New missions and new types of missions are needed to provide higher resolution data than the continuity missions in order to further our understanding of the carbon cycle, especially with respect to phytoplankton functional types, phytoplankton carbon by type, detritus, particulate organic carbon, and aerosols for improved atmospheric corrections. Additionally, it is recognized that there are specific applications in coastal and inland-water bodies that require higher resolution in time, space, and spectral domains to further understanding of carbon cycling. Higher spatial resolution for certain coastal applications (of order 30 m, for applications including floods, tides, river discharge) is needed. Some of these requirements may be met through geostationary satellites. The Geostationary Ocean Color Imager (GOCI) launched by Korea has demonstrated the value of sensors capable of resolving the diurnal signal. Such high temporal resolution is particularly important for dealing with coastal waters because the temporal and spatial scales of relevance in coastal waters are typically smaller than those of the open ocean. Proposed high-spectral resolution polar-orbiting missions for global observations such as NASA's Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) should also be emphasized.

Carbon-Challenge-11: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the development and deployment of new satellite mission types to provide new information on phytoplankton functional types, phytoplankton carbon by type, detritus, particulate carbon, and aerosols, and 2) provide higher spatial, temporal, and spectral resolution data for coastal and inland waters.

Carbon-Action-12: CEOS Member Agencies with interests in and/or mandates for developing and deploying new types of satellite missions to provide 1) new information on phytoplankton functional types, phytoplankton carbon by type, detritus, particulate carbon, and aerosols, and/or 2) higher spatial, temporal, and spectral resolution data for coastal and inland waters will coordinate their efforts in consultation with relevant CEOS WGs and VCs.

Overall Motivation/Rationale-12: The *GEO Carbon Strategy* notes that satellite observations of sea surface salinity will benefit efforts to improve estimates of pCO_2. Continuity of measurements of sea surface salinity is needed in support this requirement. Improvements in spatial resolution over that of the current SMOS and Aquarius-type sensors will be needed, especially for coastal and inland water applications.

Carbon-Challenge-12: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the development and deployment satellites to extend the time series of measurements of sea surface salinity and to improve their spatial resolution in the future.

Carbon-Action-13: CEOS Member Agencies with interests in and/or mandates for developing and deploying new satellites to measure ocean salinity will coordinate their efforts in consultation with relevant CEOS WGs and VCs.

3.3.2 Product-Related Recommendations

Overall Motivation/Rationale-6: The IGCO called for in the *GEO Carbon Strategy* requires improved approaches for developing global land inventories and related data products of 1) the spatial distribution and extent of wetlands and peatlands and of changes in their organic carbon pools and 2) carbon content of reservoirs, lakes, ponds, and rivers. Satellite observations of inland waters must have appropriate spatial resolution and sensitivities. Lakes and reservoirs cover around 3% of the Earth's land surface, but the majority are small. Use of moderate to coarse resolution ocean-color sensors such as MODIS or MERIS is therefore fairly limited in lake carbon research. On the other hand, many medium to moderate resolution land remote sensing sensors (such as Landsat-7) do not have sufficient sensitivity to estimate lake content of colored dissolved organic matter (CDOM) and monitor long-term trends. At present there are only a few sensors (such as ALI on EO-1) that are suitable for mapping lake CDOM, dissolved organic carbon, and pCO2, but they do not provide full global coverage. Landsat-8 and Sentinel-2 will change the situation, as sensors on both these missions provide data with sufficient spatial and radiometric resolution as well as the global coverage needed for lake research. Space agencies must ensure the continuity of such measurements. Maps of lakes and ponds are needed annually and maps of flooding and inundation are needed seasonally. Estimates of associated carbon-related biophysical properties (e.g., dissolved and particulate carbon, river discharge) and biological productivity are needed as a contribution to terrestrial carbon budgeting. Research agencies must implement projects to develop these essential products at regional and global scales.

Carbon-Challenge-6: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the continuing deployment of satellites and development of satellite data products for mapping wetlands, wetland types, wetland inundation, rivers, flooding, reservoirs, lakes, and ponds and estimating their associated carbon-related biophysical properties (e.g., dissolved and particulate carbon, river discharge) and biological productivity. CEOS will encourage its Member Agencies to coordinate the launch of satellites that meet requirements in a timely fashion and to avoid gaps. CEOS Agencies will strive to implement projects to develop these essential wetland and inland water data products at regional and global scales and with appropriate spatial and temporal resolutions and sensitivities to the carbon constituents in inland waters.

Carbon-Action-6: CEOS Agencies with interests in and/or mandates for developing 1) satellites to observe wetlands and inland waters and 2) wetland and inland water data products will coordinate their efforts in consultation with relevant CEOS WGs and VCs.

Overall Motivation/Rationale-5: The IGCO called for in the *GEO Carbon Strategy* requires continuous time series records of land, ocean, and atmosphere properties (e.g., land cover, land cover change, wetland area, LAI, ocean color and marine ecosystem composition, wetlands, permafrost areas, CO_2 and CH_4) at mid resolution. It is now possible to develop data fusion and data assimilation algorithms using a combination of remote sensing data (vis/IR, SAR, Lidar) at medium to moderate resolutions to improve the accuracy of land and ocean products. Most of the currently available global remote sensing products are all based on a single instrument approach. To realize the full discrimination potential of the data collected by planned and future remote sensing systems and those currently in orbit, multi-sensor approaches must be developed and tested and a product-based (rather than mission-based) approach must be adopted. To ensure long-term continuity of time series data records, the satellite data provider may need to transition from a research satellite program to an operational satellite program; thus, there must be a continuous interface between the research agencies (e.g., ESA, NASA) and those with operational mandates (e.g., NOAA, Eumetsat) .

Carbon-Challenge-5: CEOS acknowledges this challenge and will influence and coordinate the activities of the CEOS Member Agencies toward the continuity and systematic improvement of long time series of multi-sensor, multi-mission data products.

Carbon-Action-5: CEOS Agencies with interests in and/or mandates for developing multi-sensor, multi-mission time series data products for the (land and) ocean will strive to ensure consistent, well-calibrated, bias-free satellite time-series carbon products are produced and continued into the future. They will coordinate their efforts in consultation with relevant CEOS WGs and VCs to ensure appropriate merging of data and products from multiple sensors.

3.3.3 Calibration/Validation-Related Recommendations

Overall Motivation/Rationale-7: The *GEO Carbon Strategy* calls for robust carbon tracking and accurate carbon budgets, and these major products require quantitative analysis of changes in Earth system carbon properties over time. This in turn requires well-calibrated satellite sensors and well-validated data products. Development of specific remote sensing products often requires use of surface reference data sets. In some cases, land-based networks have been developed to provide *in situ* data for validation of specific products (e.g., soil moisture, atmospheric CO_2), where in others, networks either need expansion or considerable development (such as biomass dynamics). For the ocean, this requires global-scale validation of algorithms for estimating ocean carbon pools from satellite data, in carbon units, in close collaboration with *in situ* observation systems. It is also necessary to provide adequate error characterization of remote sensing variables and carbon products derived from satellite data, ideally on a pixel-by-pixel basis, to ensure their appropriate use in quantifying and modeling carbon dynamics. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure in situ data are accessible to the satellite community for validation of satellite data products. The CEOS WGCV and its relevant subgroups have conducted and coordinated much-needed calibration and validation work over the years, and this work needs to continue and be expanded. The CEOS VCs are also conducting valuable work in this area. There is a need to strengthen mechanisms within CEOS and at the individual space agency level, in particular investment as part of satellite development, for product validation to establish validation methodologies, protocols and benchmark datasets. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure in situ data are accessible to the satellite community.

Carbon-Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its individual space agency members, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.

Carbon-Action-14: The CEOS WGCV, in close consultation with the relevant VCs (that are doing some of this work now), will establish a subgroup dealing with validation and error characterization of ocean carbon-relevant products analogous to the Land Product Validation Subgroup.

3.3.4 Interactions/Linkages/Communications-Related Recommendations

Overall Motivation/Rationale-13: The *GEO Carbon Strategy* calls for robust carbon tracking and accurate carbon budgets. This requires global-scale validation of algorithms for estimating pools and fluxes of carbon from satellite data, in carbon units, in close collaboration with *in situ* observation systems. The Blue Planet Initiative brings together many ocean observation programs with a societal benefit angle, including all the existing ocean observation programs within GEO as well as new ones and fosters synergies among them. Its objectives, as stated on its Web page, are to *1) provide sustained ocean observations and information to underpin the development, and assess the efficacy, of global-change adaptation measures (such as those related to vulnerability of coastal zones, sea-level rise, and ocean acidification), 2) improve the global coverage and data accuracy of coastal and open-ocean observing systems (remote-sensing and in-situ), 3) coordinate and promote the gathering, processing, and analysis of ocean observations, 4) develop a global operational ocean forecasting network, 5) establish a global ocean information system by making observations and information, generated on a routine basis, available through the GEOSS Common Infrastructure, 6) provide advanced training in ocean observations, especially for developing countries, and 6) raise awareness of biodiversity issues in the ocean.* The GEO Task for "Oceans and Society: the Blue Planet" (Task SB-01) thus provides an excellent forum for CEOS and GEO to work together on these issues and CEOS should act to further strengthen and nurture this interaction.

Carbon-Action-15: CEOS Agencies will maintain and/or act to strengthen their linkages with the Blue Planet initiative and support of GEO Task SB-01, which brings together the ocean communities engaged in satellite as well as *in situ* observations, to ensure that user requirements are taken into account and products are produced in carbon units.

CHAPTER 4: ATMOSPHERE DOMAIN

LEAD AUTHOR: BERRIEN MOORE (UNIVERSITY OF OKLAHOMA)
CO-AUTHORS: JOHN BURROWS (UNIVERSITÄT BREMEN), DAVID CRISP (NASA JET PROPULSION LABORATORY), MICHIO KAWAMIYA (JAPAN AGENCY FOR MARINE-EARTH SCIENCE AND TECHNOLOGY), MARTIN HEIMANN (MAX PLANK INSTITUTE FOR BIOGEOCHEMISTRY, JENA), RAY NASSAR (ENVIRONMENT CANADA), PETER RAYNER (UNIVERSITY OF MELBOURNE)

4.1 Introduction: The Importance of the Atmosphere in the Carbon Cycle

Over the past 250 years, the global mean atmospheric carbon dioxide (CO_2) concentration has increased by roughly 40% from its pre-industrial value of roughly 280 parts per million by volume (ppm) (e.g., Etheridge et al. 1996) to nearly 400 ppm today, with recent single measurements (during May 2013 at the Mauna Loa station) passing 400 ppm. Since 1800, the Earth's population increased from less than 1 billion to over 7 billion, powered by relatively cheap energy obtained from fossil fuel combustion. These changes have been accompanied by increasing urbanization, with over 50% of the world's population now living in urban areas. By 2011, fossil fuel combustion, deforestation, and other human activities were adding over 38 billion tons of CO_2 (equivalently, 10.4 PgC) to the atmosphere each year, and these emissions have been growing at an average rate of 3.1% per year since 2000; the global recession of 2008-2010 significantly reduced the rate of emissions growth; however, the economic recovery has created an even greater increase in recent emissions (Peters et al. 2012; Le Quéré et al. 2013).

In the same timeframe, atmospheric methane (CH_4) has nearly tripled in boundary layer mixing ratio reaching ~ 1900 ppb today from 700 ppb in the pre-industrial times. CH_4 started to rise slightly before CO_2 did, in response to early livestock domestication and rice agriculture—an increase in carbon rich anaerobic zones on the planet. There is also the likelihood of an increase in wildfires, which also contributed to an increase in both CO_2 and CH_4 fluxes from terrestrial systems to the atmosphere (IPCC 2007; IPCC 2013).

Precise, systematic, ground based *in situ* measurements of atmospheric CO_2 began in 1957, the International Geophysical Year, at Mauna Loa Observatory in Hawaii (Keeling 1960). Precise measurements of atmospheric CO_2, CH_4, and other greenhouse gases (GHG) are now being made from a global network of nearly a hundred surface stations. These measurements indicate that the CO_2 emissions from human activities are superimposed on an active carbon cycle, driven primarily by photosynthesis and respiration by the land biosphere and the solubility of CO_2 in the ocean. These natural processes emit about 20 times as much CO_2 into the atmosphere each year as human activities, and then reabsorb a comparable amount, along with about half of the human contributions (SOCCR 2008). However, the largest net flux is the fossil fuel flux to the atmosphere. The atmosphere has a central role in the carbon cycle as the primary medium for exchange between the larger land and oceanic carbon reservoirs. (Much more carbon is transferred between the land and ocean via the atmosphere than is transferred directly via rivers.) Unfortunately, the spatial and temporal distribution of the sources and sinks of CO_2, the strength and distribution of CH_4 sources, the underlying dynamics of the carbon cycle, and the characteristics of the climate-carbon connection are less well understood (e.g., Keeling and Severinghaus 2000). Consequently, for several decades, understanding these natural processes and the human perturbation has been among the most important goals of the carbon cycle scientific community.

The ground-based GHG monitoring network now provides the CO_2 and CH_4 data needed to accurately quantify the atmospheric growth rates and inter-annual variations, providing a strong integral constraint on the total net surface flux of CO_2 and CH_4 between the surface and the atmosphere. However, this network is still too sparse and spatially non-uniform to constrain the spatial-temporal distribution of CO_2 and CH_4 natural sources and sinks globally. Chapters 2 and 3, which focused on the terrestrial and oceanic systems and associated scientific issues, highlight the importance and challenges associated with the determination of these fluxes.

Assessments of the mass-balance between anthropogenic emissions, measured atmospheric increases in CO_2, and model-derived estimates of the ocean uptake (Tans et al. 1993; Ballantyne et al. 2012) indicate the presence of an apparently large (~2 PgC y^{-1}) net terrestrial sink of CO_2. While this terrestrial sink is similar in size to the ocean sink (~2 PgC y^{-1}), the ocean flux is relatively well understood from models or measurements of partial pressure of CO_2 in the ocean's surface waters; what is not well understood is the cause of the net terrestrial sink. An improved understanding of this sink (which must also off-set the respiration of carbon in long-lifetime industrial products) is of particular importance since together, the terrestrial biosphere and ocean reduce the atmospheric CO_2 growth rate from ~4 ppm y^{-1} to about ~2 ppm y^{-1}. However, anthropogenic CO_2 emission evaluations from China, India, and the Russian Federation are uncertain (15-20% uncertainty) (Marland et al. 2009; Guan et al. 2012; Andres et al. 2012). This is important because China, India, and the Russian Federation are the 1st, 3rd, and 4th largest emitters of industrial CO_2, and the share of emissions from the developing economies is growing (Peters et al. 2012, Le Quéré et al. 2013; Gurney and O'Keefe 2013). Therefore, estimating the apparent terrestrial sink for CO_2 by "mass-balance" is problematic. It also does not give insight into the location of the terrestrial sink or the processes that might be involved. Furthermore, for all nations, accurate knowledge of the fine-scale spatial and temporal distribution of fossil fuel emissions is important for understanding the effectiveness of emission reduction strategies.

The CH_4 component of the global carbon cycle presents similar challenges. Rice paddy and wetland ecosystems are significant sources that are inadequately measured or known; moreover, CH_4 emissions from rice paddies are affected by a number of factors (Jain et al. 2004; Li et al. 2005; Pathak et al. 2003; Rath et al. 2005). Several approaches have been used to scale-up from measurements at individual plots to estimate CH_4 emissions at the landscape scale, including the emission factor and the biogeochemical modeling approaches (Li et al. 2004; Pathak et al. 2005; Yan et al. 2003). These bottom-up methods require information on crop type, cropping calendar, water management, and cropping intensity, which vary substantially over time and space. To date, there has not been a comprehensive top-down observational system to validate these results. There are important uncertainties in other regions; Arctic permafrost soils thaw in the spring and summer, creating the potential for significant CH_4 and CO_2 release, but the flux is poorly measured. With regards to CH_4 in the global carbon cycle, the balance between sources and sinks is not yet well known (IPCC 2007). This is exemplified by surface-based, global observations showing a suspension of the increase of atmospheric CH_4 concentrations between 2000 and 2006, followed by a resumption of growth since 2007. Neither the suspension nor the re-initiation of increasing CH_4 is well understood.

Because the identity and processes controlling natural sources and sinks of CO_2 and CH_4 are not currently well understood, it is difficult to determine how they might respond to climate change. Moreover, the coupling between the climate system and the carbon cycle could, itself, set up feedbacks (Cox et al. 2000; Friedlingstein et al. 2001; IPCC 2007; Schuur et al. 2008; IPCC 2013) between both systems. For example, warmer oceans decrease CO_2 solubility, and thereby increase the concentration of atmospheric CO_2, which could lead to increased warming. Degradation of soil organic carbon may be enhanced under a warmer and wetter climate, releasing CO_2 from land, again resulting in increased warming. This warming could create longer growing seasons, which could increase the flux of CH_4 from the land to the atmosphere (positive feedback) and increase the CO_2 flux from the atmosphere to the land (negative feedback). Climate projections suggest an increase in Arctic permafrost thawing, which could produce rapid and massive releases of carbon in the form of CO_2 and CH_4 from this reservoir, which holds an estimated 1672 Pg of carbon (Tarnocai et al. 2009), or twice the amount of carbon in the atmosphere. With these uncertainties in the magnitude and net sign of the feedbacks, it is currently impossible to reliably predict the trajectory of CO_2 and CH_4 emissions required to achieve a particular stabilization level for their atmospheric concentrations.

4.2 Estimating Sources and Sinks of CO_2 and CH_4 with Atmospheric Measurements

One way to quantify the distribution of the sources and sinks of CO_2 and CH_4 is to analyze the observed spatial and temporal differences in the atmospheric concentrations within the context of an atmospheric tracer transport model. This approach, commonly referred to as carbon flux inverse modeling, is a valuable tool, but places significant demands on measurement accuracy, resolution, and coverage. The Intergovernmental Panel on Climate Change (IPCC) 3rd Assessment Report noted:

> "Because of the [relatively small] finite number of monitoring stations, the mathematical inversion problem is highly underdetermined. In principle, a multitude of different surface source/sink configurations are compatible with the atmospheric data, within their measurement accuracy. Therefore, in order to extract a meaningful solution, additional information on the sources and sinks has to be introduced into the calculation. Examples of this additional information include maps of air-sea fluxes from observations or ocean models, patterns of terrestrial CO_2 exchanges inferred by terrestrial models, and remote sensing data." (Prentice et al. 2001)

If the spatial and temporal density of atmospheric CO_2 and CH_4 measurements can be substantially improved, without compromising their accuracy, these data could be used in inverse models to reduce the indeterminacy and thereby enhance the inference of the land-atmosphere flux of CO_2 and CH_4 and ocean-atmosphere CO_2 exchange (Enting 1993; Gloor et al. 2000; Rayner and O'Brien 2001; Rayner et al. 2002; Tans et al. 1989; Gourdji et al. 2008; Baker et al. 2006; Gurney et al. 2002). This was noted in the IPCC Report cited above, and also discussed in the *GEO Carbon Strategy* (Ciais et al. 2010):

> "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 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."

Because atmospheric inversions can be used to estimate the surface-atmosphere CO_2 and CH_4 exchange, they have potential as a tool for verifying national greenhouse gas budgets; and perhaps even to resolve industrial and agricultural fluxes at high spatial and temporal scales, although this is extremely challenging. However, this application places extreme demands on the accuracy and consistency of the observations. The existing network of *in situ* atmospheric CO_2 and CH_4 ground stations and aircraft has continued to grow over the past half century, but its spatial resolution and coverage are still not sufficient for quantifying anthropogenic emissions on sub-continental scale around the globe. This is partially due to the fact that most of the ground-based stations were purposefully deployed away from large fossil fuel sources or natural sinks to obtain reliable, long-term, global trends in CO_2, CH_4, and other greenhouse gases. Other regions of the world, including tropical and high latitude continents and most of the ocean basins, remain very sparsely sampled, due to the complexity and expense of maintaining surface stations there. Furthermore, the interpretation of surface *in situ* measurements near major sources is often far more challenging than interpreting column integrated measurements, which better match the spatial scales of models (McKain et al. 2012).

The need for a more comprehensive system for measuring CO_2 and CH_4 has been recognized by the Global Climate Observing system (GCOS), which is a joint undertaking of the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational Scientific and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP), and the International Council for Science (ICSU). GCOS defined the atmospheric amounts of CO_2 and CH_4 as Essential Climate Variables (ECVs; https://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables). GCOS notes that accurate knowledge about ECVs is required to support the work of the UNFCCC and the IPCC. Recent advances in space-based remote sensing techniques provide new opportunities to address these needs. The eventual system will be satellites in different orbits (e.g., LEO, GEO, HEO) and a dense network of ground sites.

4.3 Ground and Aircraft Based Observations of CO_2 and CH_4

As noted above, atmospheric CO_2 and CH_4 measurements are now being collected from a global network of surface stations. These very precise global measurements of CO_2, CH_4 and other greenhouse gases in the atmosphere are coordinated through the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) Programme. This coordination ensures global compatibility of observations and harmonization of greenhouse gases measurement techniques. About half of these observations represent a contribution from the Carbon Cycle Greenhouse Gas (CCGG) Cooperative Air Sampling Network, which is operated by the NOAA Earth System Research Laboratory (ESRL) Global Monitoring Division (GMD) and its partners (cf. http://www.esrl.noaa.gov/gmd/ccgg/flask.html). NOAA's ESRL performs measurements at 71 surface stations and 17 vertical profile sites. Most of these sites deliver standard air sampling flasks to NOAA/ESRL/GMD for analysis at weekly intervals, but an increasing number are recording continuous measurements using non-dispersive infrared (NDIR) and cavity ring-down spectrometers (CRDS). The flask measurements typically yield accuracies of 0.1 micro-mole/mole. These measurements, along with those from Environment Canada, CSIRO and from other approved WMO GAW greenhouse gas measurement sites, along with coordination between sites and calibration against WMO standards, define the world reference scale for CO_2 and CH_4. The primary limitation of this network is its spatial extent and resolution. Most of these stations are located in North America, Europe, and East Asia. There are very few stations in central or north Asia, Africa, South America, the Arctic, Antarctic, or in the ocean basins. Contrary to the optimistic predictions and strong recommendations in the 2010 *GEO Carbon Strategy* report to substantially expand this surface *in situ* network, the number of stations in the NOAA/ESRL/GMD/CCGG network has actually decreased in recent years, though some new stations has been established by the other countries and institutions.

There have been some additions to the in-atmosphere measurement capabilities, however. Earth Networks, a commercial company, has added ~25 continuous monitoring sites (mostly in North America) over the past few years, and is planning to add more. *In situ* measurements are now being obtained from flask and continuous monitoring instruments on commercial aircraft, including the Comprehensive Observation Network for Trace Gases by Airliner (CONTRAIL, Machida et al. 2008), the Civil Aircraft for the Regular Investigation of the Atmosphere Based on an Instrument Container (CARIBIC; Brenninkmeijer et al. 2007) and the In-Service Aircraft for a Global Observing System (IAGOS, Petzold et al. 2013). Vertical profiles collected during aircraft ascent and landing are useful for deriving surface carbon fluxes, and measurements made near the cruising altitude (> 10 km) provide information the large scale transport of CO_2 and CH_4. Campaigns employing well-equipped, high performance aircraft, such as the HIAPER Pole-to-Pole Observations (HIPPO; Wofsy et al. 2011) have provided intriguing, high resolution, 2-d (latitude/altitude) snapshots of CO_2 and CH_4 distributions along their extended flight paths. Other, more focused aircraft campaigns have provided insights into processes in specific regions, such as the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE; Miller and Dinardo, 2012).

These *in situ* measurement networks have recently been augmented with high-precision ground based remote sensing measurements from the Total Carbon Column Observing Network (TCCON; Washenfelder et al. 2006; Wunch et al. 2011; Messerschmidt et al. 2011; Geibel et al. 2012). TCCON stations use fully autonomous, high resolution Fourier transform spectrometers (FTS) to record the absorption of direct sunlight by CO_2,CH_4, N_2O, CO, H_2O, HDO, and O_2. These spectroscopic measurements are analyzed to retrieve estimates of the column averaged, dry air mole fractions of these gases (X_{CO2}, X_{CH4}, X_{N2O}, X_{CO}, X_{H2O}, and X_{HDO}). TCCON has now expanded to over 20 sites, spanning the latitude range from ~45 °S (Lauder, New Zealand) to 80 °N (Eureka, Canada) and contributes to the GAW Programme. The X_{CO2} and X_{CH4} estimates from several TCCON stations, have been validated against *in situ* profile measurements collected by aircraft carrying instruments traceable to the WMO *in situ* standards. These comparisons indicate network-wide precisions of ~0.8 ppm, and 5 ppb, and accuracies of 0.8 ppm and 7 ppb for X_{CO2} and X_{CH4}, respectively (Wunch et. al. 2011). Data from many TCCON sites are now available from http://www.tccon.ipac.caltech.edu. TCCON is currently the only observing system that systematically provides a tie between the satellite total column measurements and the surface *in situ* network. TCCON measurements are now providing independent information about the atmospheric carbon cycle on regional scales. They are also being used as transfer standards to validate estimates of X_{CO2} and X_{CH4} from space based remote sensing measurements against the WMO standards (c.f. Wunch et al. 2011). TCCON FTS measurements are well suited for this application because they have much higher spectral resolution and higher signal to noise than the space based X_{CO2} and XCH_4 instruments. In addition, because the TCCON FTS instruments view direct sunlight from near the center of the solar disk, rather than reflected solar radiation, they are far less sensitive to optical path length uncertainties introduced by atmospheric scattering than nadir-looking space based remote sensing observations (c.f. Crisp et al. 2012). As TCCON stations provide total column measurements, their data are the key input for the validation of satellite measurements.

4.4 Space-Based Observations of CO_2 and CH_4

One way to improve the spatial and temporal coverage and resolution is to retrieve precise, spatially resolved, global measurements of CO_2, CH_4, and other greenhouse gases from space-based platforms. Both daytime and nighttime measurements of CO_2 and CH_4 are made by thermal infrared sensors, such as the Atmospheric Infrared Spectrometer (AIRS, http://airs.jpl.nasa.gov/; Chahine et al. 2008; Xiong et al. 2008), the Tropospheric Emission Spectrometer (TES, Kulawik et al. 2010; Payne et al. 2009), and the Infrared Atmospheric Sounding Interferometer (IASI, http://www.eumetsat.int/Home/Main/Satellites/Metop/Instruments/SP_2010053151047495; Crevoisier et al. 2009; Razavi et al. 2009). However, these measurements are primarily sensitive to the distribution of these gases in the middle to upper troposphere, and much less sensitive to their variations near the Earth's surface, where surface sources and sinks produce their strongest signatures of emissions and uptake. The Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) measures limb solar occultation profiles of CO_2 (Foucher et al. 2011) and CH_4 (De Mazière et al. 2008) spanning the upper troposphere and stratosphere, but also lacks the capability to measure variations in these gases near the surface. The MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) on ESA's Envisat satellite measured limb emission in the infrared wavelength providing information about CH_4 in the upper troposphere and stratosphere from 2002 to 2012 (von Clarmann et al. 2009).

High resolution spectroscopic observations of reflected sunlight by CO_2, CH_4 and molecular oxygen (O_2) bands are better suited for monitoring surface CO_2 fluxes because these measurements can be analyzed to yield surface-weighted estimates of the column-averaged dry air mole fractions of CO_2 and CH_4 (X_{CO2} and X_{CH4}). This is still a very challenging space-based remote sensing measurement. The pioneering Envisat SCanning Imaging Absorption spectroMeter for Atmospheric ChartograpHY (SCIAMACHY) and GOSAT Thermal And Near infrared Sensor for carbon Observations-Fourier Transform Spectrometer (TANSO-FTS) were the first two instruments designed to exploit this approach. These two sensors are described below, along with a series of future instruments for measuring X_{CO2} and X_{CH4}.

High precision is essential in this application because CO_2 and CH_4 are long-lived gases and thus well mixed in the atmosphere such that perturbations are relatively small in comparison to the background values. Furthermore, sources and sinks produce their largest perturbations in CO_2 and CH_4 near the surface and these signals decay rapidly with height. For example, rapidly growing crops can absorb enough CO_2 to change its atmospheric mixing ratios by up to 8% (>30 ppm) in the planetary boundary layer, and strong industrial emission sources can produce even larger local increases in this gas. However, the corresponding X_{CO2} variations rarely exceed 2% (8 ppm), and are typically no larger than 0.5% (~ 2 ppm) on scales that range from ~100 km over continents to 1,000 km over the ocean (Miller et al. 2007; Wofsy 2011; Wunch et al. 2011). The requirements for detecting CH_4 sources are just as demanding, where a precision of 0.25% to 0.5% is needed to resolve typical (5 and 10 ppb) regional scale variations in X_{CH4}.

Envisat SCIAMACHY: The SCanning Imaging Absorption spectroMeter for Atmospheric ChartograpHY (SCIAMACHY, https://earth.esa.int/web/guest/missions/esa-operational-eomissions/envisat/instruments/sciamachy) provided a decade of global measurements of key trace gases in the troposphere and stratosphere from Envisat, which operated from 2002-2012 (Burrows et al. 1995). Measurements collected within the shortwave infrared (SWIR) CO_2 bands near 1580 and 1610 nm and the CH_4 band near 1670 nm were combined with spectra of the near-infrared (NIR) molecular oxygen (O_2) A-band at 765 nm to estimate X_{CO2} and X_{CH4}, respectively, providing the first, space-based global maps of these quantities (http://www.iup.uni-bremen.de/sciamachy/NIR_NADIR_WFM_DOAS/). The latitudinal dependence of the X_{CO2} and X_{CH4} for SCIAMACHY from 2003 to 2012 is shown in Figure 4-1. The hemispheric gradient and the growth of the atmospheric loading are both clearly identified.

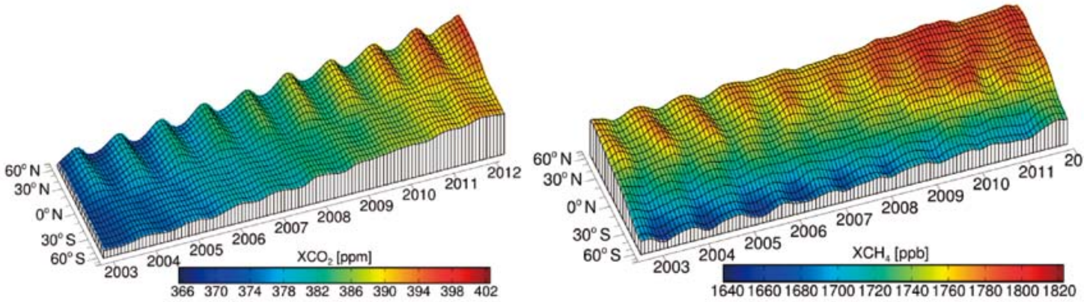


Figure 4-1. The time dependent, latitudinal zonal average retrieved from SCIAMACHY retrieval of X_{CO2} and X_{CH4} (courtesy of Schneising, Buchwitz, and Burrows, Institute of Environmental Physics, University of Bremen).

SCIAMACHY ECV data sets have been generated within the ESA CCI (Climate Change Initiative) and are available at http://www.esa-ghg-cci.org/?q=node/106.

The signal to noise ratio of the SCIAMACHY nadir observations is dependent on the solar incidence angle and surface reflectance. Liquid water, snow and ice have strong absorption in the SWIR spectral regions used to retrieve CO_2; thus, the most precise retrievals are obtained over snow- and ice-free land. Some observations of the bright ocean "glint" were acquired, but these data have not yet been analyzed. SCIAMACHY's large surface footprint (FOV ~30 x 60 km^2) reduced its sensitivity to compact sources of CO_2 and CH_4. In addition, with this large footprint, a substantial fraction of its measurements were contaminated by clouds, which introduce uncertainties in the optical path lengths, and must be screened out in the retrieval process. These factors reduced the spatial and temporal coverage and precision of the SCIAMACHY measurements.

GOSAT: Japan's Greenhouse gases Observing SATellite (GOSAT, nicknamed "Ibuki" http://www.gosat.nies.go.jp/index_e.html) is the world's first satellite mission dedicated to monitoring CO_2 and CH_4. The satellite was developed jointly by the Japan Aerospace Exploration Agency (JAXA), the Ministry of the Environment (MoE) Japan, and the National Institute for Environmental Studies (NIES) Japan and was launched in 2009. The spacecraft flies in a 666 km altitude, 98° inclination, sun-synchronous orbit with a 12:49 PM nodal crossing time and a three-day (44-orbit) ground track repeat cycle. The satellite carries two instruments. The primary instrument is the Thermal And Near infrared Sensor for carbon Observations-Fourier Transform Spectrometer, (TANSO-FTS).

The second instrument is the TANSO Cloud and Aerosol Imager (TANSO-CAI), a high spatial resolution imager designed to facilitate the detection of clouds and optically thick aerosols within the TANSO-FTS field of view.

The goal of the GOSAT project is to produce more accurate estimates of the fluxes of CO_2 and CH_4 flux on a subcontinental basis (several 1000 km). The GOSAT is unique in adopting an FTS, instead of a grating spectrometer, in order to achieve high spectral resolution and high signal to noise at the expense of ground resolution. The TANSO-FTS is a double pendulum interferometer that records reflected sunlight in molecular oxygen (O_2) A-band at 765 nm (13020 cm^{-1}), the CO_2 bands near 1600 nm (6250 cm^{-1}) and 2060 nm (4850 cm^{-1}), and the CH_4 band near 1670 nm (5990 cm^{-1}), yielding spectra with resolutions (full width at half maximum, FWHM) varying from ~0.36 cm^{-1} at 765 nm to ~0.26 cm^{-1} in the CO_2 and CH_4 bands (Kuze et al. 2009). It is extremely important to monitor the molecular oxygen (O_2) A-band in order to detect and correct for clouds and aerosols, thereby enabling accurate observation of the troposphere. It also measures thermal emission in a broad (700 to 1800 cm^{-1}, or 5.56 to 14.3 μm) band to retrieve water vapor (H_2O), ozone (O_3), and mid-tropospheric CO_2 and CH_4. TANSO-FTS collects interferograms at 4-second intervals within a 0.0158-radian diameter, circular, instantaneous field of view, yielding footprints that are about 10.5 km in diameter at nadir. High spectral resolution and high signal to noise data are achieved by integrating signal from the same IFOV for four seconds and by compensating for satellite movement using a pointing mirror mechanism. A two-axis pointing mirror is used to direct this IFOV within ± 35° of nadir in the cross-track direction and within ± 20° of nadir along the spacecraft ground track.

Prior to August 1, 2010, routine science observations over land were collected on a 5-point grid pattern, with footprints that are separated by about 158 km cross-track and about 152 km along track. Since August 2010, observations over land are collected on a 3-point grid pattern, with footprints that are separated by about 260 km cross-track and about 280 km along-track. Over the ocean, the pointing mechanism directs the TANSO-FTS field of view to the bright "glint" spot, when the spacecraft is within 20° of the sub-solar latitude to ensure adequate signal for CO_2 and CH_4 retrievals. At other latitudes, the 5- or 3-point grid pattern is used. This approach yields about 10,000 soundings over the sunlit hemisphere of the Earth each day. Between 5 and 10% of these soundings are sufficiently cloud-free and have adequate signal to yield reliable X_{CO2} estimates (Figure 4-2).

As with SCIAMACHY, parallel efforts by multiple teams working on independent CO_2 and CH_4 retrievals from GOSAT observations has contributed to a vibrant exchange of ideas and methods amongst the teams and has advanced retrieval performance (Yoshida et al. 2011, 2013; Butz et al. 2011; O'Dell et al. 2012; Crisp et al. 2012; Cogan et al. 2012). Comparisons of GOSAT TANSO-FTS X_{CO2} retrievals with surface-based X_{CO2} estimates from the Total Carbon Column Observing Network (TCCON) have helped to identify and correct subtle biases associated with air mass, surface pressure, optically thick aerosols, ice-covered surfaces, and other environmental factors (Wunch et al. 2011). Persistent spectral residuals common to TCCON and TANSO-FTS retrievals have revealed limitations in the spectroscopy of CO_2 and O_2, which are being addressed with new laboratory measurements. These calibration, retrieval algorithm development, and validation activities are now yielding X_{CO2} estimates with regional-scale errors < 2 ppm over much of the globe.

GOSAT observations have filled gaps in the *in situ* terrestrial networks. International science collaborations for calibration and validation and science have been carried out, resulting in improved data accuracies. Important scientific outcomes include documentation of seasonal changes in the

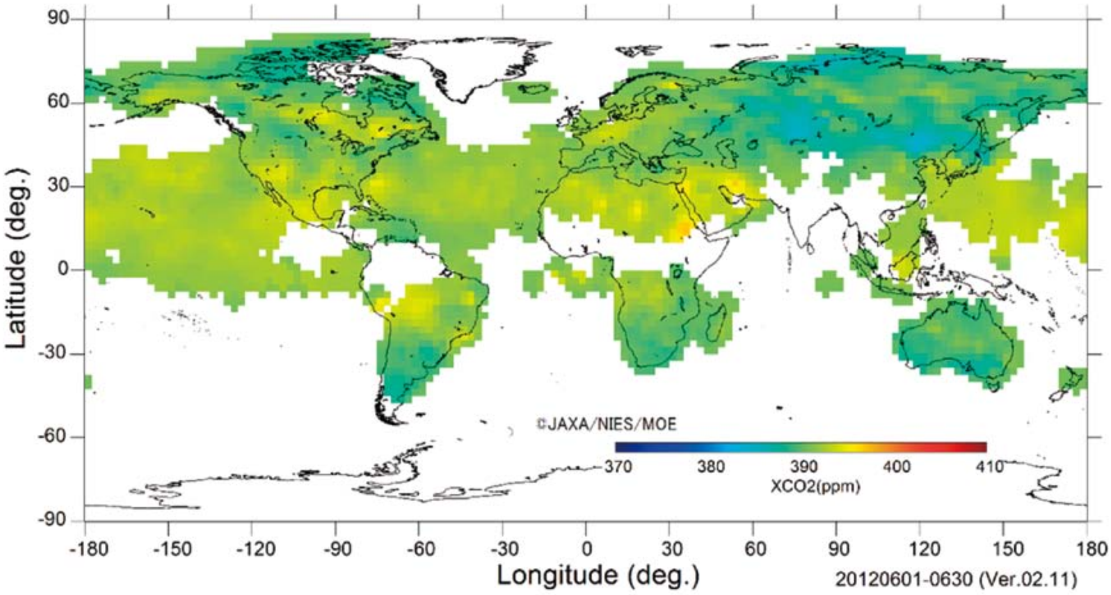


Figure 4-2. X_{CO2} observations for one month (June 2012) from GOSAT illustrating the extent of its nadir and glint coverage. Uptake of CO_2 by forests in Siberia are notable (TANSO-FTS SWIR Level 3 Ver.02.11; http://www.gosat.nies.go.jp/index_e.html)

carbon balance of southern Amazonia (Parazoo et al. 2013), megacity carbon dioxide fluxes (Kort et al. 2012), carbon dioxide and methane emission ratios in wildfire plumes (Ross et al. 2013), and reduced carbon uptake during the 2010 Northern Hemisphere summer (Guerlet et al. 2013).

Although GOSAT CO_2 observations will help to constrain CO_2 fluxes from the biosphere and oceans on regional scales, its spatial sampling pattern is not optimized for monitoring emission plumes from large fossil fuel point sources, and its sensitivity is not adequate to detect typical CO_2 enhancements produced by the emissions of a large power plant, even when it is located within its 10.5 km diameter (~85 km^2) surface footprint. Higher sensitivity (signal-to-noise-ratio), a smaller surface footprint, and denser sampling are needed to detect and quantify these signals.

GOSAT ECV data sets have been generated within the ESA CCI (Climate Change Initiative) and are available at http://www.esa-ghg-cci.org/?q=node/106.

OCO-2: NASA authorized the Orbiting Carbon Observatory – 2 (OCO-2) in 2010, as a replacement for the Earth System Science Pathfinder (ESSP) Orbiting Carbon Observatory (OCO) mission, which was lost in February 2009 when its launch vehicle malfunctioned and failed to reach orbit. OCO-2 is currently scheduled to launch on a United Launch Alliance Delta II from Vandenberg Air Force Base in California no earlier than July 2014. Given this plan, it is particularly important to extend the GOSAT mission as long as possible to provide continuity/overlap with OCO-2. The observatory will be deployed in a 705 km altitude, sun-synchronous, near-polar orbit, at the head of an existing constellation of Earth Observing Satellites called the Afternoon Constellation (A-Train). This 98.8-minute orbit has a 1:30 PM nodal crossing time and a 16-day (233-orbit) ground-track repeat cycle. It is expected to operate for at least 2 years, but includes adequate fuel to maintain its orbit for more than 5 years.

The OCO-2 spacecraft carries and points a three-channel, imaging, grating spectrometer. This instrument is designed to collect high-resolution spectra of reflected sunlight within the molecular oxygen (O_2) A-band near 765 nm, and within the CO_2 bands near 1610 and 2060 nm. These three absorption bands overlap the NIR and SWIR channels used by the GOSAT TANSO-FTS to record O_2 and CO_2 spectra, but their spectral range and spectral resolution are slightly lower than those of the TANSO-FTS. Specifically, the OCO-2 resolution (FWHM) is ~0.045 nm (0.72 cm^{-1}) at 765 nm, 0.08 nm (0.31 cm^{-1}) at 1610 nm, and 0.1 nm (0.25 cm^{-1}) at 2060 nm. However the OCO-2 spectrometers have substantially higher spectral contrast and signal-to-noise-ratios than TANSO-FTS, and therefore are expected to yield substantially greater sensitivity to X_{CO2} variations.

Each OCO-2 spectral channel records 3 samples per second continuously in 8 spatial footprints along a narrow (14 mrad, or 0.8°) ground track. This sampling approach yields about one million soundings over the sunlit hemisphere each day or almost 100 times as many soundings as GOSAT. Clouds and optically thick aerosols will preclude observations of the full atmospheric column in many of these soundings, but 10-20% of the soundings are expected to be sufficiently transparent to allow full-column X_{CO2} measurements. The co-bore-sighted spectra of reflected sunlight recorded within the CO_2 and O_2 bands in each sounding will be combined and analyzed with a state-of-the-art remote sensing retrieval algorithm to yield spatially-resolved estimates of X_{CO2}. The OCO-2 algorithm has already been validated extensively using GOSAT data. In addition to X_{CO2}, it will return estimates of other environmental variables, including the atmospheric temperature, water vapor, cloud and aerosol optical depth, and chlorophyll fluorescence.

For routine science observations, the OCO-2 spacecraft points the instrument's field of view either at the local nadir or toward the “glint spot” where sunlight is specularly reflected by the Earth's surface. Nadir observations maximize the spatial resolution and minimize the surface footprint area, reducing biases associated with sub-footprint clouds or topographic variations over continents. Glint observations provide much higher signal levels over dark ocean and ice surfaces. The baseline plan is to alternate between glint and nadir observations on alternate 16-day ground track repeat cycles, to map the entire sunlit hemisphere in both observing modes once every 32 days (although alternate observing schemes are still being considered). In addition to these two pointing modes, OCO-2 can point the instrument at stationary surface targets and scan across the target acquiring thousands of soundings as it flies overhead. This mode was designed primarily for validation, but could also be used produce selected detailed maps of CO_2 mixing ratios over areas as large as a medium sized city (30 km x 30 km). One target observation will be acquired each day.

Routine science observations collect soundings along a narrow (< 10.6 km) swath near the observatory's fixed ground track. Individual ground tracks are separated by ~25° of longitude on any given day, but this distance is reduced to roughly half within two days and to only 1.5° of longitude after 16 days, but the atmosphere will have moved substantially over that period. The glint paths scan the region between these nadir paths over the seasonal cycle, as the sub-solar latitude traverses the tropics. The high sampling frequency and small (< 1.29 km x 2.25 km) sounding footprint area help to ensure that some cloud free soundings can be collected even in partially cloudy conditions. Cloud studies indicate that, when averaged over the globe, 18-20% of these soundings will be sufficiently cloud free to yield accurate, full-column CO_2 mixing ratios estimates. The accuracy and precision of these measurements will be validated through comparisons with ground-based remote sensing measurements from TCCON, and other internationally recognized CO_2 standards. The objective of this validation program is to achieve X_{CO2} accuracies of ~0.3% on spatial scales of ~1000 km.

OCO-3: As part of the OCO-2 mission, NASA authorized the development of a flight spare instrument to minimize schedule impacts of any delays introduced by problems with the flight instrument development. If this instrument is not needed for OCO-2, it will be available for a mission of opportunity. In November 2012, NASA approved a Phase-A effort to adapt this instrument for deployment on the International Space Station (ISS) as the Orbiting Carbon Observatory-3 (OCO-3). The plan is to install OCO-3 on the Japanese Experiment Module Exposed Facility (JEM-EF) as early as 2017 for a 3-year nominal mission. Because OCO-3 is based on the OCO-2 spares, its physical characteristics, capabilities, and performance are expected to be similar to that of the OCO-2 instrument. Like that instrument, OCO-3 can collect a larger number of useful soundings over land by pointing the instrument's field of view (FOV) near the local nadir, while over the ocean, the instrument's FOV must be pointed near the apparent glint spot to collect adequate signal for X_{CO2} retrievals. To validate estimates of X_{CO2} derived from OCO-3 measurements, its FOV must also be able to track stationary surface targets, such as TCCON stations, as the ISS flies overhead and collect large numbers of soundings. For OCO-2, the instrument's FOV is pointed by an agile spacecraft bus. To enable these pointing capabilities from a nadir-pointing platform like the ISS, the OCO-2 flight spare instrument was augmented with an agile, 2-axis pointing mechanism. While this pointing mechanism and other modifications needed to accommodate the sensor on the ISS will add complexity to the instrument, these changes provide new opportunities for mapping compact targets, such as cities, power plants, or coastlines.

Unlike SCIAMACHY, GOSAT, and OCO-2, which fly in near-polar, sun-synchronous orbits, ISS flies in a low inclination orbit, which overflies latitudes equatorward of 51°. This orbit will preclude coverage of higher latitudes, but will provide somewhat better coverage of mid-latitudes, where human activities emit the most CO_2. Mid-latitude measurements from OCO-3 would be most easily interpreted if they were acquired along with others from a polar orbiting system, like OCO-2 or GOSAT. The orbit precession will allow OCO-3 to sample different parts of the Earth at different times of day. This will provide the first opportunity to search for variations X_{CO2} and other carbon cycle variables, such as chlorophyll fluorescence, across the entire range of local times from dawn to dusk from a single space-based platform.

TanSat: The Chinese Carbon Dioxide Observing Satellite, TanSat, is currently under development by the Ministry of Science and Technology of China (MOST), Chinese Academy of Sciences (CAS), and National Satellite Meteorological Center (CMA). TanSat is currently scheduled to launch in mid-2015. It will fly in a sun-synchronous orbit, but the altitude and nodal crossing time have not yet been decided. The ~500 kg spacecraft will carry and point two instruments at nadir, sun glint and stationary surface targets. The primary CO_2 monitoring instrument is a high-resolution, 3-channel grating spectrometer designed to record spectra of reflected sunlight within the 0.76 μm O_2 A-band, and the CO_2 bands centered near 1.61 and 2.06 μm, with a resolving power, signal to noise ratio, and footprint size comparable to those adopted by OCO-2, over a swath that is twice as wide. The main instrument will be complemented with the Cloud and Aerosol Polarization Imager (CAPI). This instrument will record images in 5 spectral channels (0.38, 0.67, 0.87, 1.375, and 1.64 μm) with a spatial resolution of 0.5 km over a 400 km wide swath. The 0.67 and 1.64 μm channels sample 3 independent polarization angles. Soundings recorded by the spectrometer will be used to retrieve X_{CO2}, while data from CAPI will be used to correct cloud and aerosol interference. The target accuracy of the CO_2 measurements is 1 to 4 ppm on regional scales (500 km x 500 km) and monthly time scales. The current plan is to validate these results against a comprehensive, multi-site ground based measurement network in China as well as other internationally recognized standards.

GOSAT-2: JAXA, NIES, and the Ministry of the Environment, Japan, have started the development of a follow-on mission for GOSAT, called GOSAT-2. While GOSAT data are currently analyzed to yield single-sounding X_{CO2} estimates with precisions of ~0.5%, the goal for GOSAT-2 is to return results as much as four times more precise on regional scales at monthly intervals. The GOSAT-2 will monitor carbon monoxide (CO) and PM2.5, in addition to CO_2 and $CH_{4.}$ Addition of CO observation will improve identification of carbon emission sources which have relatively short life-times. This will require improved measurement sensitivity and accuracy together with more versatile pointing capability and retrieval algorithms which are more robust to cloud and aerosol contaminations and noise. To meet these objectives, GOSAT-2 will carry more advanced versions of the instrument TANSO-FTS and TANSO-CAI instruments carried by GOSAT. A number of updates are being studied for the TANSO-FTS, including updated optics and detectors that will produce larger signals for similar integration times and surface footprints, to yield at least a factor of 3 or more usable cloud-free soundings. The spectral ranges and spectral resolution within each spectral channel may be optimized to yield improved sensitivity to O_2, CO_2 and CH_4 variations, and an additional channel has been added near 2.3 µm to measure carbon monoxide (CO). Modifications to the scan mechanism are being studied to facilitate observations of the bright ocean glint spot over a much wider range of latitudes to improve the instrument's sensitivity to CO_2 changes over the ocean. Improvements in the performance of the TANSO-CAI are also needed to meet the much more stringent GOSAT-2 goals. The current plan is to launch GOSAT-2 in early 2018 and to operate it for at least 5 years. GOSAT-2 will operate in a near-polar, sun-synchronous orbit with a 3-day ground-track repeat cycle, similar to that currently being used by GOSAT.

MicroCarb: The French Space agency, Centre National d'Études Spatiales is currently formulating the MicroCarb mission. MicroCarb will be the first CNES satellite designed to measure atmospheric CO_2 from space with the precision and resolution needed to characterize CO_2 sources and sinks at regional scales. MicroCarb is currently being targeted to launch in 2019, and fly in the A-Train, providing opportunities to extend the CO_2 data record initiated by OCO-2. MicroCarb consists of a micro satellite that carries a compact, high resolution, 3-channel, grating spectrometer designed to measure the absorption of reflected sunlight in the same spectral bands used by OCO-2. A principal challenge of this instrument will be to obtain soundings with sensitivities similar to those from OCO-2, with an instrument that has about 1/3 the mass, size, and cost.

CarbonSat: ESA has selected the CarbonSat mission as a candidate for the 8th ESA Earth Explorer mission (http://www.esa.int/Our_Activities/Observing_the_Earth/Space_for_our_climate/Two_new_Earth_observation_missions_chosen_for_further_study). CarbonSat was originally targeting a 2019 launch, but if it is selected, this may be delayed by up to 3 years due to ESA funding constraints. CarbonSat will fly in a near-polar, sun-synchronous orbit with an 11:30 AM nodal crossing time. It is expected to operate for at least 3 years. CarbonSat carries a single, high spatial resolution imaging grating spectrometer that measures reflected sunlight in 3 broad spectral intervals covering the O_2 A-Band (747-773 nm, FWHM=0.1 nm), the CO_2 and CH_4 bands at 1590-1675 nm (FWHM=0.3 nm), and the CO_2 and H_2O bands at 1925-2095 nm (FWHM=0.55 nm), with 3 to 6 samples per FWHM in each channel. The CarbonSat spectrometer has somewhat lower spectral resolution than the GOSAT or OCO-2 and it records reflected sunlight in somewhat wider spectral regions to better characterize chlorophyll fluorescence near 750 nm and high cloud contamination near 1950 nm. Its ~4 km^2 surface footprints (at nadir) yield a spatial resolution that is comparable to that of OCO-2, but for a much broader cross-track swath (> 240 km), to provide complete coverage of the sunlit hemisphere on weekly to monthly intervals. With this broad swath, CarbonSat will collect up to 30 times as many cloud-free soundings each day as OCO-2. If the CarbonSat instrument and retrieval algorithm can yield accuracies as high as those anticipated from OCO-2, the high spatial resolution and complete global coverage will allow the creation of high resolution, two-dimensional images of strong surface sources of CO_2 and CH_4.

ASCENDS: All of the sensors described above record high resolution spectroscopic measurements of reflected sunlight, which are analyzed to retrieve spatially-resolved estimates of X_{CO2} across the sunlit hemisphere. As its name implies, the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission will use active laser (lidar) methods to extend this coverage to the night side as well. This approach will provide measurements at high latitudes during the winter, with similar sensitivity to the near-surface CO_2 variations. A larger fraction of the ASCENDS measurements are expected to be cloud free in partly cloudy conditions, because of the near-vertical nature of both its illumination and measurement paths. While the specific instrument and mission architecture have not yet been selected, current studies are targeting a measurement precision of ~1 ppm over 10-second integrations along the orbit path in cloud-free conditions. The spacecraft will most likely be deployed in a low altitude (400-500 km) sun-synchronous orbit with a midday/midnight sampling time. Measurements will be collected along a narrow (~0.1 km) ground track near the spacecraft nadir. Individual samples will have small ground footprints, but samples collected over periods as long as 10 seconds may have to be co-added to meet the X_{CO2} precision requirements.

A series of studies are currently underway to refine the science objectives and implementation approach for this mission. Observational System Simulation Experiments (OSSE's) are being performed to define the science, measurement, and mission operations requirements. Aircraft campaigns are being conducted to assess the relative performance of instrument architectures including continuous and pulsed lidar technologies for measuring CO_2 at 1.57 and 2.05 μm and O_2 at 0.764 and 1.26 μm. Mission studies are being performed to assess the spacecraft, launch vehicle, and mission operations requirements. While the final mission design has not yet been selected, these design activities have identified no technical impediments. Unfortunately, the launch date continues to be delayed (now sometime after 2022).

CH_4 Missions: The overall measurement strategy for CH_4 missions is similar to that for CO_2. As noted earlier, the AIRS, TES and IASI instruments measure CH_4 as well as CO_2 in the middle troposphere and above. The Atmospheric Chemistry Experiment (ACE) on SCISAT-1 collects and MIPAS on Envisat collected upper tropospheric and stratospheric CH_4 limb profiles. In fact, SWIR measurements of methane from SCIAMACHY have already proven their utility for constraining methane sources (Bergamaschi et al. 2007). GOSAT collects SWIR measurements of CH_4 over the land along with glint measurements over the ocean within 20° of the sub-solar latitude as well as TIR CH_4 measurements over both land and water. GOSAT-2 will improve upon GOSAT in multiple ways including extended SWIR glint coverage. TropOMI on ESA's Sentinel-5 precursor mission is scheduled for launch in 2015. TropOMI will measure CH_4 using nadir SWIR reflectance at wavelengths near 2.3 microns, along with other tropospheric trace gases important for air quality monitoring. With a moderately-sized footprint (7x7 km^2) and a wide (2600 km) swath, TropOMI will yield daily global coverage of XCH4 (prior to cloud-filtering) over its 7-year target lifetime. The MERLIN (Methane Remote Sensing Lidar) Mission (http://www.dlr.de/pa/en/desktopdefault.aspx/tabid-2342/6725_read-26662/) of CNES and DLR is the first space mission to use a lidar for measuring CH_4 (Kiemle et al. 2011). MERLIN will not make an oxygen measurement to infer the dry air mass, but rather it will use assimilated meteorological data products for surface pressure, temperature, and water vapor information. MERLIN will be launched in 2017. As with ASCENDS, this active sensing approach has a very narrow ground footprint and is capable of measurements during both day and night, in all seasons, and at all latitudes.

In summary, over the next decade, a succession of partially overlapping missions with a range of CO_2 and CH_4 measurement capabilities will be deployed in low Earth orbit. Each successive mission has been conceived with unique capabilities, designed to improve the measurement precision and accuracy, as well as the spatial and temporal resolution and coverage, to improve understanding of surface fluxes of GHGs from the continental to local scales. However, given their finite lifetimes, there may be minimum overlap between the operational phases of these missions, and there is still a significant chance that there will be measurement gaps, like the potential gap between the end of the nominal GOSAT mission and the start of the OCO-2 mission. Each mission must therefore be considered a critical link in a chain that must be successfully deployed to ensure a continuous climate data record over this coming decade.

For those periods when more than one mission is returning data, much greater benefits could be realized if these space-based measurements could be coordinated with each other and with the surface greenhouse gas monitoring network to produce a global monitoring system with the resolution and coverage needed to provide policy-relevant information. Some of the missions provide particularly strong synergies in this context, such as OCO-2 (polar, sun-synchronous orbit) and OCO-3 (low inclination, precessing orbit) or CarbonSat (wide swath dayside) and ASCENDS (narrow track, day and night coverage). Translating column information to reliably account for near-surface emissions and uptake is a significant challenge that requires on-going validation and a dense network of ground stations. To meet this objective of a continuous climate data record over this coming decade, the measurements must be cross-calibrated and the retrieved X_{CO2} and X_{CH4} estimates must be cross-validated against internationally recognized standards. All of these data could be assimilated into flux inversion models to quantify CO_2 and/or CH_4 sources and sinks on regional scales over the globe. A closely coordinated space-based constellation would also provide continuity and resiliency to losses of individual satellites.

4.5 Alignment of Future Space-based Observations with Science and Policy Objectives

Space-based measurements of CO_2 and CH_4 address *distinct, but linked* science and policy objectives:

1. To monitor, attribute, and assess natural sources and sinks, including the potential feedbacks of climate on these fluxes and on global atmospheric CO_2 and CH_4 concentrations. An extensive global sample of atmosphere concentrations of CO_2 and CH_4 provides an important independent check upon terrestrial and oceanic carbon cycle models and observations, and thereby, there is a natural complementarity between this chapter and the terrestrial and oceanic chapters. For example, estimates of the biological flux of CO_2, by instruments such as Biomass on land and by using ocean color phytoplankton measurements are highly complementary and synergistic. Together, they provide the long-term, global observations required to improve our understanding of the carbon cycle processes controlling the sources and sinks of atmospheric CO_2 and CH_4, to yield fundamental improvements in the carbon-climate models used to predict the future increases in the concentrations of these gases. High priority science objectives include:

  - Determining the controlling mechanisms for the time-varying terrestrial CO_2 sources and sinks;
  - Identifying the major CH_4 sources and their controlling mechanisms; and
  - Resolving spatial and temporal patterns in the oceanic CO_2 sources and sinks, especially those in under-observed regions such as the Southern Ocean.

2. To monitor, attribute, and assess anthropogenic sources and sinks, including the effectiveness of carbon sequestration and/or emission reduction activities on global atmospheric CO_2 and CH_4 concentrations. The uncertainty associated with fossil fuel CO_2 flux is increasing due to the fact that the flux from China, Russia, India and developing countries is both highly uncertain and these fluxes will dominate future emissions. Furthermore, the uncertainty increases dramatically when one examines fluxes at scales below the nation-state level. The monitoring should provide fine space (1 to 10 km) and time (daily to weekly) scale quantification and attributions of:

  - Fossil fuel CO_2 emissions from regionally distributed point sources such as cities and power plants (annual emissions greater than 5 million tons of CO_2) and other major CO_2 emissions disturbances such as fire, and
  - CH_4 emissions attributed to major industrial sources and energy generation systems, including coal mines; natural gas extraction; rice agriculture, natural wetlands, and portions of the northern tundra in the summer; livestock, landfills, and biomass burning.

Both of these objectives drive observational accuracy and coverage, with greater accuracy, precision, coverage and frequency required for constraining sources and sinks at finer space and time scales.

In addition, the objectives outlined above will not be reached by satellite measurements alone; therefore, the strategy will require a coordinated effort among those doing surface based, *in situ*, and remote measurements, as well as engagement with the broader community studying carbon fluxes from ecosystems.

4.6 *GEO Carbon Strategy* Report

The *GEO Carbon Strategy* Report (Ciais et al. 2010), published in June 2010 by the Group on Earth Observations (GEO) Carbon Community of Practice, was an update to the Integrated Global Carbon Observations Theme report (Ciais et al. 2004) that was developed through the IGOS partnership in 2004-5. The GEO Report brought into direct consideration the significant advances in science and observational capabilities over the last half decade.

As noted in this and other chapters of this report, the Committee on Earth Observation Satellites (CEOS) is assessing and detailing its plans for satellite observations in support of the *GEO Carbon Strategy* report. This CEOS response is important since a number of CEOS member agencies and countries are trying to understand community requirements for the next generation of atmospheric carbon monitoring missions, as well as missions aimed at terrestrial and oceanic observations, which are addressed in other chapters of this Report. The CEOS response across the domains (oceans, land, and atmosphere) is a key stepping-stone to understanding precisely what those future requirements are, and how they will be met, and in obtaining community guidance and endorsement. This stepping-stone is also essential to obtaining a coordinated set of agency responses that would include plans to meet these needs.

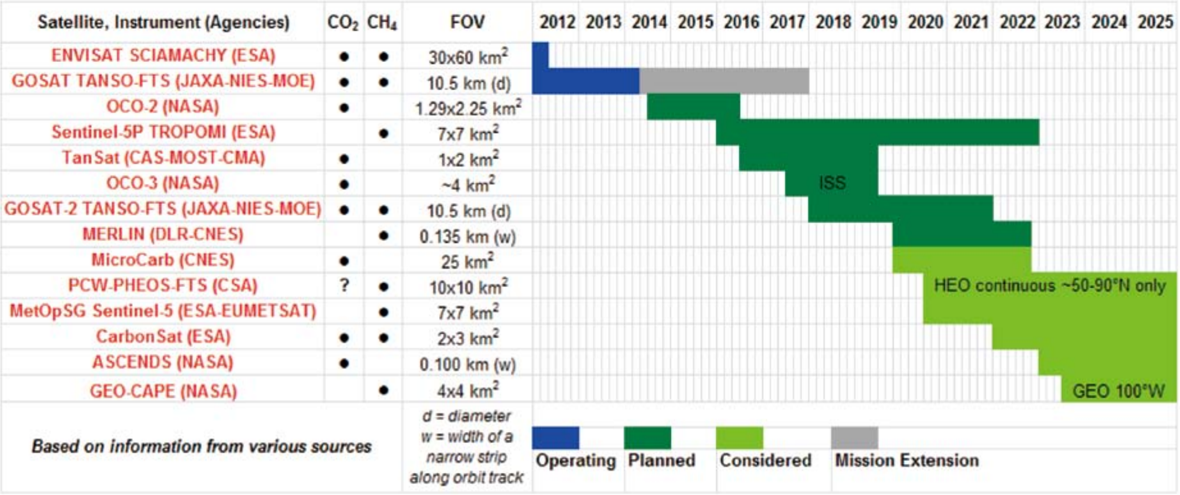
For the atmosphere, the *GEO Carbon Strategy* Report has four fundamental tenets:

1. The next generation of GHG satellite measurements needs to provide high accuracy measurements of CO_2 and CH_4 with high spatial resolution (1-2 km). This is required to observe and attribute surface fluxes and, more importantly, to minimize cloud contamination. In order to be representative, a daily repeat-frequency is required. Lower repeat cycles are valuable but clearly lose information on the variability of surface fluxes, whether natural or anthropogenic in origin.
2. Continuity of the time series of space-based planetary boundary layer CO_2 and CH_4 measurements, ideally in a GHG-satellite constellation. This could, for example, be managed within the international system of operational meteorological satellites or by a dedicated organization.
3. A strategy for easy access to GHG satellite observations should be developed.
4. A coordinated planning effort towards the next generation of a constellation of GHG satellite observations is also required.

Although the impact of global climate change and the need for measurements is well documented by the IPCC assessment reports and related studies, a central issue is that there is little hope that the observational tenets (# 1 and 2) will be even partially implemented before 2020, *at the earliest* unless there is a very significant change in Agency planning. *The fundamental challenge is the repeat frequency, which requires a small constellation of satellites, to meet the spatial coverage requirements globally within this time frame. Unfortunately, there is little on the horizon that demonstrates a reliable commitment to meeting the needed observational systems.*

This is not to suggest that the current plans of the space agencies are not of value and required for progress; however, the focus of the first generation of greenhouse gas satellites has been on accurate and precise measurements (useful) but with much less attention being given to ensuring adequate coverage, resolution, or repeat frequency (shortfall). The Agency plans that were documented in the *GEO Carbon Strategy* June 2010 are inadequate to address the two Objectives stated in Section 4.5; moreover, these plans are now quite out-of-date in critical areas: baseline missions have been moved out in time and/or left undefined. As a result, the *GEO Carbon Strategy* assumptions are not valid; the plans are even less adequate.

As a step to establishing an updated and hence more realistic baseline, an updated summary of agency plans based on the best available information is presented in Figure 4-3. This was done with the realization that the information presented as current at the time this report is published could also quickly become outdated.



Satellite, Instrument (Agencies)	CO_2	CH_4	FOV
ENVISAT SCIAMACHY (ESA)	●	●	30x60 km^2
GOSAT TANSO-FTS (JAXA-NIES-MOE)	●	●	10.5 km (d)
OCO-2 (NASA)	●		1.29x2.25 km^2
Sentinel-5P TROPOMI (ESA)		●	7x7 km^2
TanSat (CAS-MOST-CMA)	●		1x2 km^2
OCO-3 (NASA)	●		~4 km^2
GOSAT-2 TANSO-FTS (JAXA-NIES-MOE)	●	●	10.5 km (d)
MERLIN (DLR-CNES)		●	0.135 km (w)
MicroCarb (CNES)	●		25 km^2
PCW-PHEOS-FTS (CSA)	?	●	10x10 km^2
MetOpSG Sentinel-5 (ESA-EUMETSAT)		●	7x7 km^2
CarbonSat (ESA)	●	●	2x3 km^2
ASCENDS (NASA)	●		0.100 km (w)
GEO-CAPE (NASA)		●	4x4 km^2

Based on information from various sources

d = diameter
w = width of a narrow strip along orbit track

Figure 4-3. Satellite CO_2 and CH_4 missions with sensitivity to the planetary boundary layer. Missions classified as "considered" are candidate missions under active consideration within the various space agencies, but not necessarily selected for launch. While Sentinel-5 is in "planning" it is not yet fully funded or committed. Other GHG missions have been proposed e.g. SCIA-ISS, which are not shown above.

4.7 Toward a Future Constellation for GHG observations

The spatial distributions of CO_2, CH_4, and other long-lived greenhouse gases are strongly influenced by atmospheric transport as well as the presence of surface sources and sinks. To discriminate these processes to the extent needed to accurately quantify emissions associated with human activities from the much larger natural sources and sinks will require high spatial and temporal resolution measurements over the entire globe. While such a measurement system would be challenging to implement, it is not unprecedented. The architecture of the operational meteorological observation system for numerical weather prediction (NWP) provides an ideal model. This observing system incorporates multiple coordinated satellites in low Earth orbit (LEO) and geostationary orbit (GEO), aircraft, balloon, and ground observing systems in a true system of systems. A similar approach could be developed for CO_2 and CH_4 emissions monitoring, perhaps even leveraging the existing operational meteorological infrastructure. The US Report of the Defense Science Board on Trends and Implications of Climate Change for National and International Security, October 2011 reached a similar conclusion (US Defense Science Board 2011).

To monitor point sources such as cities or power plants at latitudes equatorward of ~45°, GEO satellites might be the best approach (JASON 2011), since they provide continuous coverage of a selected area. To provide complete coverage of the globe, constellations of LEO satellites, have been proposed. Proposals for a balanced space-based observing approach that combines LEO and GEO measurements are consistent with those advanced a decade ago for trace gas monitoring in the CEOS Report of the Integrated Global Observing Strategy and the Integrated Global Atmospheric Chemistry Observations (IGACO 2004).

While each of the missions listed in Figure 4-3 has unique measurement capabilities that will contribute to our understanding of the atmospheric CO_2 distribution, much greater benefits could be realized if they can be coordinated as part of an *ad hoc* global network of surface and space-based CO_2 sensors, whose data can be cross calibrated, cross-validated, and assimilated into source-sink inversion models. This would be the first step in the implementation of a CO_2 monitoring system with the spatial and temporal coverage and resolution of the current weather monitoring system. CEOS could play a substantial role in the coordination of this constellation and in the evaluation and dissemination of its products.

All of the CO_2 and CH_4 satellites described in section 4.3 of this chapter are, or will be deployed in LEO. Those with near polar orbits can sample the full range of latitudes, but the actual coverage, longitude resolution, and repeat time depends on the orbit period, number of orbits in the ground track repeat cycle, and instrument's swath width. LEO platforms usually cover only a limited range of local time, since most Earth observing satellites in LEO use sun-synchronous orbits. A constellation of these satellites would be needed to sample a range of local times. Low inclination LEO platforms like ISS, offer opportunities to sample all local times, but these orbits preclude observations at high latitudes, and have longer revisit times than typical sun-synchronous orbits. In addition, as noted above, while the ISS orbit reaches ±51° latitude, covering ~95% of the world's population, CO_2 observations collected by OCO-3 near the turn-around latitudes may be challenging to interpret by themselves, due to uncertainties in the transport in and out of the domain being monitored. Fortunately, other, satellites in near polar orbits (e.g. GOSAT-2, MicroCarb) are scheduled to fly at the same time as OCO-3, providing opportunities to extend the range of observations if these data sets can be combined.

The next logical step will be to extend the constellation to GEO platforms, which provide continuous coverage over the diurnal cycle for a specific area. No full-column, SWIR X_{CO2} or X_{CH4} sensors are yet under development for GEO, but progress is being made for other trace gas sensors for monitoring air quality. For example, the ESA / EUMETSAT / EU Copernicus Sentinel-4 will carry a UV, visible, and NIR spectrometer, building on the SCIAMACHY and GOME heritage, together with IRS, a nadir sounding thermal IR (TIR) instrument building on IASI heritage. These sensors will fly on the Meteosat Third Generation Sounding platform (MTG-S) from 2020 to 2035. MTG-S will thus make measurements of CO_2 and CH_4 as well as other trace gases in the TIR, but does not address the objectives outlined above. The Korean space agency has selected its Geostationary Environment Monitoring Spectrometer (GEMS) mission for geostationary measurements, similar to those of Sentinel 4. NASA's Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission, currently scheduled to launch after 2022, aims to measure CH_4 and other gases relevant to air quality. In 2012, the NASA Earth Ventures program selected the Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission to address a subset of the GEO-CAPE objectives as a mission of opportunity on a commercial GEO platform. Due to the additional requirement for continuous, time-resolved CO_2 observations from GEO, the possibility of enhancing any planned GEO mission to include a near-surface CO_2 measurement capability is strongly encouraged.

Unfortunately, observing the high latitudes from GEO is problematic since viewing angles become too large beyond approximately 55°S/N. Highly Elliptical Orbits (HEOs) are recommended in the WMO Vision for a Global Observing System in 2025 and can be used for quasi-geostationary observations at high latitudes, but require at least 2 satellites for continuous coverage of a region. The Polar Communications and Weather (PCW) mission is being considered for launch around 2020 by the Canadian government. It would use two operational satellites in HEOs to obtain quasi-geostationary coverage of northern latitudes for Arctic communications capability and meteorological observations (Trishchenko and Garand 2012). An atmospheric research enhancement to the mission is being considered under the PHEOS (Polar Highly Elliptical Orbit Science) program, including a high spectral resolution imaging FTS with heritage from GOSAT for

NIR, SWIR, and TIR observations of northern CO_2, CH_4 (along with the O_2 A-band) and air quality gases (Nassar et al. 2014). Such a mission would provide important observations for detecting and monitoring potential CO_2 and CH_4 emissions from permafrost thaw, anthropogenic activity and other changes to the carbon cycle in the Arctic and boreal regions. The PCW and PHEOS atmospheric concept completed Phases 0 and A, but decisions on proceeding further must be made in the coming years.

Another complementary CO_2 and CH_4 observing method is limb sounding (as mentioned earlier for the ACE mission). Solar occultation limb measurements offer high vertical resolution CO_2 and CH_4 profiles from the upper atmosphere down to as low as 5 km altitude. The Chemical and Aerosol Sounding Satellite (CASS) is a follow-on mission to ACE, currently under consideration by the CSA, which would use an FTS and improved solar imagers to provide high resolution vertical profiles of CH_4, CO_2 and many other species. Although such measurements contain little direct information on surface fluxes, they can help to constrain CO_2 and CH_4 vertical and horizontal transport, as well as chemical processes in the upper troposphere and above, thus could play a unique role in a future constellation.

Constellations of nano- or pico-satellites are sometimes proposed as low-cost alternatives to the larger research and operational satellites considered above. This approach is not well suited for CO_2 and CH_4 observations because relatively large instruments are needed to yield the spectral resolving power and signal-to-noise-ratios needed to retrieve very precise (<0.3%) estimates of CO_2 and CH_4 (Fu et al. 2008). The need to cross calibrate the measurements and cross-validate the retrieved products to within a fraction of a percent will also drive the complexity and cost of large constellations of small satellites.

In addition, the ground based network of highly accurate surface *in situ* and remote sensing measurements of the mixing ratios of CO_2 and CH_4 and surface fluxes needs to be expanded and maintained, to provide a unique, near-surface data set and to facilitate the cross validation of the space based data sets. In a similar vein, there is a need and opportunity to learn and share from each of the differing satellite approaches to CO_2 and CH_4. Finally, the various approaches to using concentrations to obtain flux estimates would benefit from improved knowledge of the circulation of the atmosphere.

This observing system, which needs to be established as early as possible, is envisaged to measure for the next 20 -50 years and beyond to monitor the evolution of the CO_2 and CH_4 emissions from the local to the continental scales.

4.8 Atmosphere Domain Recommendations and CEOS Actions

Given the global importance of the carbon cycle and its intimate and intricate connection to climate, there is an urgent need to develop an internationally coordinated and comprehensive global observing system that would a) provide the necessary information for fundamentally increasing our knowledge of the global carbon cycle and b) support monitoring and verification of CO_2 and CH_4 emissions for international purposes. Based on the *GEO Carbon Strategy* and in agreement with the previous CEOS IGOS-P recommendations and the needs of GCOS, to understand the biogeochemistry and response of the Earth and provide policy-makers with an adequate evidence base, the following recommendations for the space segment are made.

4.8.1 Mission-Related Recommendations

Overall Motivation/Rationale-14: The *GEO Carbon Strategy* emphasizes the importance of satellite observations of CO_2 and CH_4 in the global atmosphere for monitoring, assessing, and attributing carbon sources and sinks and calls for a next generation constellation of greenhouse gas satellite observations. In addition, there are policy and management needs for this information to support monitoring and verification of CO_2 and CH_4 emissions for international purposes. A coordinated constellation of passive and active XCO2 and XCH4 remote sensing instruments in Low Earth Orbit (LEO) is needed, with retrieved, single-sounding measurement accuracy of 0.1 to 0.2% for XCO_2 and XCH_4, a spatial resolution of 1-2 km, and a temporal sampling yielding daily coverage of the entire globe. These missions should be considered in the context of the added value to be derived from coordinated mission planning and associated data compilation activities (spaceborne and in situ/aircraft) both in the future and by exploiting archive data.

Carbon-Challenge-13: CEOS acknowledges the challenge to achieve a LEO constellation of satellites to measure atmospheric CO_2 and CH_4, with appropriate coverage and sensitivity, and will influence and coordinate the activities of its Member Agencies toward this goal.

Carbon-Action-16: CEOS Member Agencies with interests in CO_2- and CH_4-measuring LEO missions will sponsor or co-sponsor one or more workshops (and require a written report) to refine the scientific and policy requirements for quantitative data on atmospheric CO_2 and CH_4 from low Earth orbit. These meetings should involve the key international science and applications communities in specifying the technical foundation and scientific requirements for as well as the societal benefits of future missions to quantify atmospheric CO_2 and CH_4 from low earth orbit.

Carbon-Action-17: The CEOS Atmospheric Composition VC will coordinate the detailed planning and preparation for a constellation of passive and active remote sensing instruments to measure CO_2 and CH_4 from low Earth orbit with the higher spatial and temporal resolution and accuracy needed to monitor carbon sources and sinks.

Overall Motivation/Rationale-15: The *GEO Carbon Strategy* emphasizes the importance of satellite observations of CO_2 and CH_4 in the global atmosphere for monitoring, assessing, and attributing carbon sources and sinks and calls for a next generation constellation of greenhouse gas satellite observations. In addition there are policy and management needs for this information to support monitoring and verification of CO_2 and CH_4 emissions for international purposes. A coordinated constellation of passive XCO2 and XCH4 remote sensing instruments in geostationary orbit is needed to cover all longitudes at a spatial resolution of 1-2 km, with a retrieved, single-sounding measurement accuracy of 0.1 to 0.2% for XCO2 and XCH4 over continents, and a temporal sampling interval of 20 minutes to 1 hour.

Carbon-Challenge-14: CEOS acknowledges the challenge to achieve a geostationary constellation of satellites to measure atmospheric CO_2 and CH_4, with appropriate coverage and sensitivity, and will influence and coordinate the activities of its Member Agencies toward this goal.

Carbon-Action-18: CEOS Member Agencies with interests in CO_2- and CH_4-measuring GEO missions will sponsor or co-sponsor one or more workshops (and require a written report) to refine the scientific and policy requirements for quantitative data on atmospheric CO_2 and CH_4 from geostationary Earth orbit. These meetings should involve the involve the broad, international science and applications communities in advancing the technical foundation and scientific requirements for as well as the societal benefits of future missions to quantify atmospheric CO_2 and CH_4 from geostationary orbit.

Carbon-Action-19: The CEOS Atmospheric Composition VC will coordinate the detailed planning and preparation for a constellation of passive remote sensing instruments to measure CO_2 and CH_4 from geostationary orbit covering all longitudes with the spatial and temporal resolution and accuracy needed to monitor carbon sources and sinks.

4.8.2 Calibration/Validation-Related Recommendations

Overall Motivation/Rationale-7: The *GEO Carbon Strategy* calls for robust carbon tracking and accurate carbon budgets, and these major products require quantitative analysis of changes in Earth system carbon properties over time. This in turn requires well-calibrated satellite sensors and well-validated data products. Development of specific remote sensing products often requires use of surface reference data sets. In some cases, land-based networks have been developed to provide *in situ* data for validation of specific products (e.g., soil moisture, atmospheric CO_2), where in others, networks either need expansion or considerable development (such as biomass dynamics). For the ocean, this requires global-scale validation of algorithms for estimating ocean carbon pools from satellite data, in carbon units, in close collaboration with *in situ* observation systems. It is also necessary to provide adequate error characterization of remote sensing variables and carbon products derived from satellite data, ideally on a pixel-by-pixel basis, to ensure their appropriate use in quantifying and modeling carbon dynamics. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure in situ data are accessible to the satellite community for validation of satellite data products. The CEOS WGCV and its relevant subgroups have conducted and coordinated much-needed calibration and validation work over the years, and this work needs to continue and be expanded. The CEOS VCs are also conducting valuable work in this area. There is a need to strengthen mechanisms within CEOS and at the individual space agency level, in particular investment as part of satellite development, for product validation to establish validation methodologies, protocols and benchmark datasets. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure in situ data are accessible to the satellite community.

Carbon-Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its individual space agency members, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.

Carbon-Action-20: The CEOS Atmospheric Composition VC, in cooperation with the CEOS WGCV Atmospheric Composition Subgroup, will provide coordination and support for the cross calibration of all satellite CO_2- and CH_4-measuring sensors, coordinate their observations, and cross validate their CO_2 and CH_4 products against accepted international standards, so that they can be integrated into single continuous global climate record.

CHAPTER 5 : INTEGRATION

LEAD AUTHOR: STEPHEN PLUMMER (EUROPEAN SPACE AGENCY)
CO-AUTHORS: WARREN COHEN (USDA FOREST SERVICE), MARTIN HEIMANN (MAX PLANK INSTITUTE FOR BIOGEOCHEMISTRY, JENA), NICOLAS HOEPFFNER (JOINT RESEARCH CENTRE), TIIT KUTSER (UNIVERSITY OF TARTU), PETER RAYNER (UNIVERSITY OF MELBOURNE), SHUBHA SATHYENDRANATH (PLYMOUTH MARINE LABORATORY), MASANOBU SHIMADA (JAPAN AEROSPACE EXPLORATION AGENCY)

5.1 Introduction: The Importance of Integration

The carbon cycle transcends traditional domains: ocean, land, and atmosphere, inter-connects them, and is intimately coupled with climate. Carbon cycle processes exhibit different behavior and the importance of these processes varies with both spatial and temporal scales. The impacts of any change tend to be seen with variable lag times and may also be present through tele-connections (e.g. changes in one part of the globe will be seen as impacts later in other parts). This has an important impact on policy and on both diagnosis of status and prognosis of effects. Policy in general requires information at a finer resolution whereas scientific research on the carbon cycle covers the full range of spatial and temporal resolutions. However, it is important to note that the impact of policy and its implementation also needs to be considered at coarser resolutions.

There are several elements to integration, which this chapter attempts to encompass. These include:

- Integration across disciplines: Understanding the planetary carbon cycle requires integration across multiple disciplines (physics, chemistry, biology, biogeochemistry, ecology, social sciences) because the pools undergo transformations and it would be difficult to understand fluxes and feedback mechanisms without an integrated approach (see Figure 5-1).
- Integration across domains: understanding the changing carbon cycle and advancing mitigation of its effects requires consideration of fluxes between the traditional domains of oceans, land and atmosphere.
- Integration across observing systems: both *in situ* and satellite observations are vital to the establishment of a planetary-scale observation system for carbon;
- Integration of observations and models: compatibility between observations and models is critical to understanding the carbon cycle and prognosis of the impact of changes and their effect on climate and vice-versa;
- Integration across multiple sensors: carbon in climate change studies requires long time series of data. However, individual sensors have life spans that are short in the context of carbon cycle and climate studies. Therefore, integration across multiple sensors over time is essential;
- Integration of products: While the provision of data is critical for an observing system, it is equally important to ensure that those data are acquired, processed and analyzed in a consistent manner and that the outputs are compatible and both accessible and available.

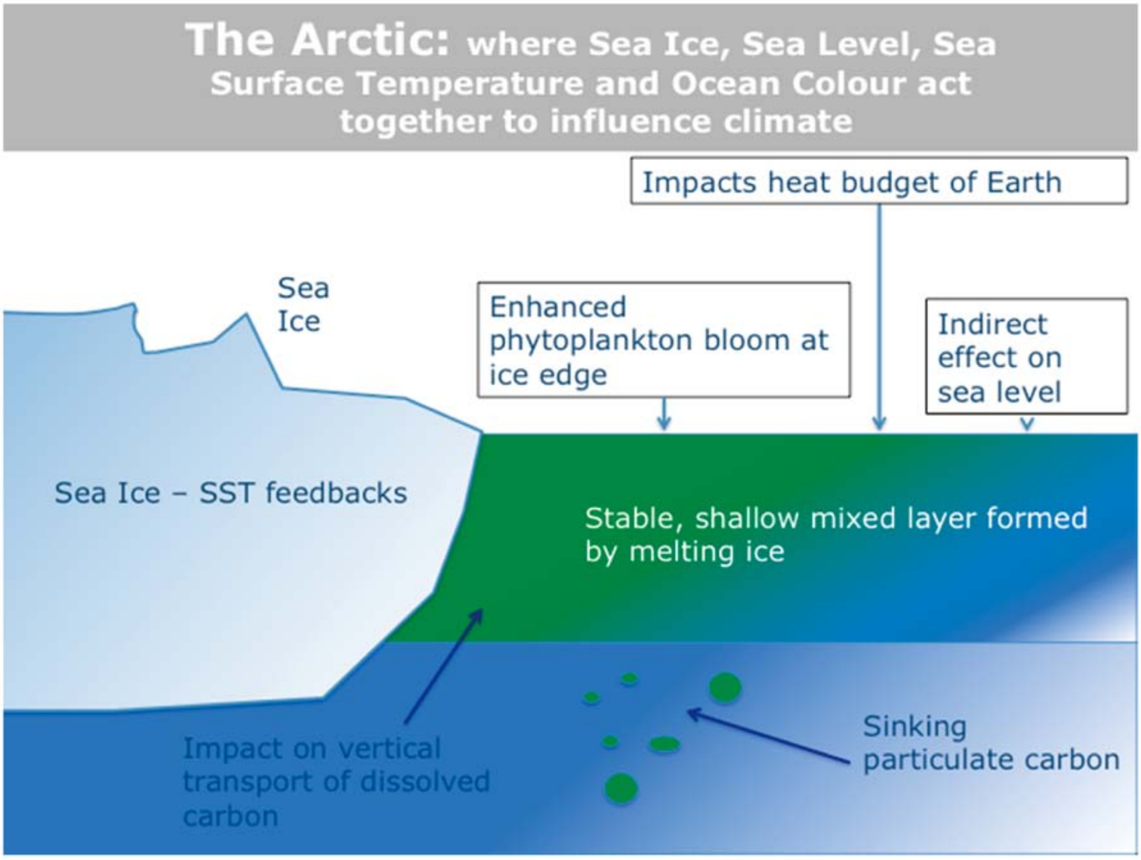


Figure 5-1. The Arctic, as an example where an integrating approach is required to understand the carbon cycle and carbon-related processes. Interaction processes in the Arctic Ocean carbon cycle - physical processes interact with biological processes, sea ice with sea water, and ocean with atmosphere, with multiple feedback mechanisms. Freshwater run-off and riverine input are also highly important features of the carbon cycle in the Arctic Ocean.

5.2 Understanding Interfaces, and Processes, between Domains

5.2.1 Land - Inland Water Interactions

The exchange between land and ocean, including inland waters, is covered in the *GEO Carbon Strategy* Report only under future requirements for lateral carbon fluxes. Compared with terrestrial and marine carbon fluxes, estimates of carbon fluxes in inland waters remain poorly constrained. Information is needed on factors that control the rates of surface runoff from terrestrial into aquatic systems, the rates of sedimentation that occur in reservoirs, and the rates of sediment and dissolved organic carbon transport in rivers that flow into coastal oceans, determined by levels of water inundation and flooding, such as those that occur in the Amazon (Marengo et al. 2011; Mangiarotti et al. 2013). However, the lateral transport of carbon, while it is known to be an important process, is not well characterized in modeling approaches or in inventories. For example, the total sum of best estimates of fluxes to carbon storage pools (rivers and reservoirs) and lateral fluxes (dissolved organic carbon export from soil through rivers to the ocean) are given as [a sink of] -0.119 PgC y^{-1} for North America (reported in Hayes et al. 2012) with an uncertainty of 100% for the period 2000-2006. This represents a relatively small fraction of the global estimates reported by Tranvik et al. (2009) (see section 3.1.2) but is approximately in line with the -0.076PgC y^{-1} reported for Europe (Ciais et al. 2008). However, as Tranvik et al. 2009 report, the exchange rates are highly variable and depend, for lakes, on the lake type and its location, with large variation in the proportions of incoming carbon going to sediments, emitted to the atmosphere or exported downstream.

The potential effect of anthropogenic perturbation on these processes has generally been ignored in budget estimates with the implicit assumption that the transformation and lateral transport of carbon along this aquatic continuum has remained unchanged since pre-industrial times. However recent evidence suggests that human alteration of the landscape has increased the influx of carbon into inland waters by up to 1 PgC y^{-1}, although this is largely either absorbed or emitted to the atmosphere and only one tenth reaches open ocean (Regnier et al. 2013).

In most global carbon models lateral flow between land and rivers, lakes and oceans is considered primarily in terms of hydrology, using schemes such as TOPMODEL (see e.g., Zulkafli et al. 2013). Carbon is generally not considered in these calculations although efforts are underway to understand the factors affecting carbon transport between terrestrial and aquatic ecosystems in terms of both dissolved organic and inorganic carbon (DOC and DIC respectively) and their particulate equivalents (POC and PIC) (Tranvik et al. 2009, Regnier et al. 2013, Raymond et al. 2013).

Since Earth observation cannot directly measure these carbon terms, the focus has to be on the variables that are important in the exchange processes between land-water and eventually water–atmosphere. These comprise lake distribution and size and its temporal variation, lake depth and its variation, inflow and outflow rates and water quality. These observations also apply to estuarine outflow and large rivers.

Lake size and distribution

Determination of the pools and fluxes associated with lakes requires knowledge of lake sizes and global distributions (see also section 2.4.4.4). The distributions are needed given fluxes to atmosphere, downstream and to sediment vary with location and lake type and the balance of inputs of DOC, DIC, POC and PIC reflect climate, soil texture, geochemistry and land use (see Tranvik et al. 2009, Cole et al. 2007). Size also affects the balance of processes converting the organic and inorganic components into CH_4 and CO_2 and their subsequent storage or emission. Variation in size and its duration also has an impact on carbon flux balance. Estimates of CO_2 evasion from inland waters to the atmosphere depend on the water surface area and the gas transfer velocity and the partial pressure, with recent estimates of global CO_2 evasion rates put at 1.8 Pg C y^{-1} from streams and rivers and 0.32 Pg C y^{-1} from lakes and reservoirs (Raymond et al. 2013).

Inflow and outflow

Inflow and outflow refer indirectly to the variation in lake size and potential inputs of carbon into the aquatic system. These terms can be determined at least for large aquatic systems in terms of inundation events (see 2.4.4.4) and river or lake height variation from altimetry (Michailovsky et al. 2012).

Water quality

Water quality is important for conversion of carbon inputs and also for primary production of organic carbon. Primary production depends on lake size, latitude, insolation and nutrient availability. Small lakes, which dominate the size distribution, are among the most productive systems on Earth, although the overall contribution to global primary production is relatively small. As reported in section 3.1.2, the DOC is a food source for bacteria and DOC is also photo-oxidized, with subsequent CO_2 release in both cases. Lake temperature is important in this process as higher temperatures favor bacterial metabolism. The colored dissolved organic matter (CDOM) also affects the light climate and thus primary production. Finally salinity (e.g. Lake Chad, Caspian Sea) is also important as it affects the processes and importance in exchange between the different carbon components (organic or inorganic). Saline, along with hard water, lakes represent almost half the volume of all inland waters and thus contribute significantly to the global carbon budget (see Tranvik et al. 2009).

Depth

Lakes can be sites of intense organic carbon mineralization with respiration dominating over primary production in most lakes. The relative importance of sediment respiration is strongly affected by water column depth. Most lakes are shallow and therefore are not strongly stratified, with the sediment being in contact with the upper mixed layer. This favors mineralization over burial, although the CH_4 that is produced is largely unaffected by oxidation by methanotrophic bacteria and escapes to the atmosphere (Tranvik et al. 2009). Despite this, lake sediments are estimated to contain 820Pg of organic carbon (see Cole et al. 2007) as well as inorganic carbon, in particular in hard-water lakes. The balance between mineralization and burial, both processes that are important in small, shallow, eutrophic lakes, is, however, poorly understood.

5.2.2 Land - Atmosphere Interactions

Natural Fluxes

At present, the *in situ* measurements of atmospheric CO_2 and CH_4 made by the ground-based network accurately capture the atmospheric growth rates and inter-annual variations but this network is too sparse to constrain the spatial-temporal distribution of CO_2 and CH_4 sources and sinks. Even adding current aircraft and satellites is not sufficient for estimating sub-continental scale anthropogenic emissions around the globe particularly as the *in situ* network was designed to avoid large local sources.

An improved understanding of the apparently large (~2 Gt C) net terrestrial sink of CO_2, is of particular importance since currently net terrestrial source/sink estimates are generated as the mass-balance between assessments of anthropogenic emissions, measured atmospheric increases in CO_2, and model derived estimates of the ocean uptake. Annual global budget calculations are produced by the Global Carbon Project (GCP; see for example, Le Quéré et al. 2013), each with improvements in method over the previous approach and a regional breakdown has been generated through GCP Regional Carbon Cycle Assessment and Processes (RECCAP). Information derived from satellite remote sensing data has been the key to reducing uncertainties in two important components of the global terrestrial carbon cycle: (a) the net transfer of carbon to the atmosphere as a result of tropical deforestation (DeFries et al. 2002, Achard et al. 2010); and (b) carbon emissions to the atmosphere as a result of biomass burning (van der Werf et al. 2010).

However, estimates of carbon sources and sinks across all vegetation types remain poorly known from existing inventory data. For example while the area of disturbance and deforestation can be readily mapped from optical remote sensing (Hansen et al. 2010), the lack of information on forest biomass limits the precision with which we can estimate deforestation emissions (Houghton et al., 2000, 2009). Similarly, global estimates of insect infestation and damage are missing. Thus, accurate measurements of aboveground biomass stocks and their change are required to constrain both the vegetation source and sink terms. Without knowledge of forest structure, biomass, and inferred age, model initialization efforts will continue to be unsatisfactory.

The CH_4 component of the global carbon cycle presents similar challenges and to date the global methane budget has not been closed using the combination of top-down and bottom-up approaches although attempts have been made (see Kirschke et al. 2013). Key unknowns or inadequacies include emissions from rice paddy and wetland ecosystems, permafrost thawing, coal mines, livestock, landfills, and biomass burning.

Fossil Fuel Emissions

The fossil fuel CO_2 flux is the largest net annual exchange in the carbon system and the uncertainty associated with this flux is increasing as less instrumented developing countries begin to dominate global emissions. At the country level uncertainty for these countries is around 20%, but this increases dramatically at scales below the nation-state level (Gurney et al. 2012). In addition, existing global fossil fuel CO_2 emission inventories (e.g., CDIAC, EDGAR and ODIAC) do not include variability in emissions over the short timescales (e.g., diurnal, weekly) that are typically exhibited (Nassar et al. 2013; Andres et al. 2011; 2012; Boden et al. 2013; Marland et al. 2009; Gregg et al. 2008). To monitor, attribute, and assess anthropogenic sources and sinks requires the monitoring of fossil fuel emissions from regionally distributed point sources such as cities, gas flares, and power plants at fine spatial and temporal scales (Schneising et al. 2013; Amekudzi 2011; Liu et al. 2013). While direct satellite estimates of CO_2 at spatial resolutions of 1 km have been called for to assess large point sources (see Chapter 4), such measurements will not be available in the medium term except from aircraft (e.g., Cambaliza et al. 2013) and will require additional constraints for their interpretation. Hence, alternative methods and additional information sources are vitally needed on the infrastructure and activity underpinning fossil fuel CO_2 emissions. The contribution from Earth observation comes in the form of nighttime lights, monitoring of industrial flaring, and through delineation of urban landscapes.

Nighttime lights have been used to obtain estimates of energy use (e.g., Oda and Maksyutov 2011), however, they only provide a rough estimate of emissions, because they are generally not sufficiently fine scale, do not differentiate between energy consumption from different sectors (industry vs. residential lighting), and only provide observations at night. Flaring and venting of natural gas from e.g. oil wells can be obtained from monitoring of fire activity using multi-wavelength radiances (SWIR, MIR and TIR) to estimate the effective flame temperature and size, thus providing a full characterization of the active flames (Casadio et al. 2012). However, this remains specific and is in general limited to nighttime observations.

Urban areas are the most important places to monitor because they generate more than 70% of global greenhouse gas emissions (Fragkias et al. 2013) and are projected to contain 68% of the world's population by 2050 (Gurney et al. 2012). How urban dwellers choose their infrastructure, technology, consumption, and lifestyle will determine global GHG emissions (Dhakal 2010). Information on urban land cover, particularly its delineation into (a) residential, (b) commercial, and (c) industrial sectors represents a valuable contribution from Earth observation. This is required at high temporal and spatial resolution to reflect the complexity of the urban landscape and the variability of emissions. The capability to monitor the urban landscape using Earth observation already exists but requires agreement on, and implementation of, standard methodologies. This, along with associated emissions from satellites (e.g. N_2O for monitoring local air pollution), power production, traffic and energy efficiency information (Gurney et al. 2012), coupled with *in situ* monitoring of emissions in and around urban locations (e.g., Gurney et al. 2009; McKain et al. 2012) would be very useful for improving existing emissions inventories (Nassar et al. 2013).

5.2.3 Oceans and Inland Waters - Atmosphere Interactions

Oceans

Ocean-atmosphere exchange of carbon is governed by two principal processes, the 'solubility pump' which transports carbon from the ocean surface to its interior as dissolved inorganic carbon, and the 'biological pump' which transports organic carbon, primarily through sinking particulate matter, to the ocean interior. The solubility pump represents the primary mechanism driving the flux of atmospheric CO_2 into the ocean.

Carbon dioxide is soluble in water and reacts with it to create dissolved inorganic carbon. This reaction is governed primarily by the difference in partial pressure of carbon dioxide between the surface ocean and the atmosphere and by the sea state (a function of strength of the winds at the air-sea interface). The net exchange of carbon dioxide across the ocean-atmosphere interface is such that the ocean absorbs approximately 25% of the anthropogenic carbon dioxide emitted into the atmosphere. However, the dissolution of atmospheric carbon dioxide modifies the ocean alkalinity because the buffering capacity diminishes as ocean carbon concentration increases and carbonate ions at the ocean surface are neutralized by reaction with carbon dioxide (see Omta et al. 2011). These processes have to be taken into account in understanding and determining the future evolution of the carbon cycle. Furthermore, it is important to note that the air-sea exchanges are not uniform in time and space: in fact, there are locations where oceans are a source of carbon to the atmosphere: a truly global, integrated system is essential to monitor adequately the air-sea exchanges of carbon.

The solubility of carbon dioxide is strongly and inversely dependent on temperature; and on the distribution of temperature and salinity in the surface and near-surface layers of the ocean, which determine the total alkalinity in these waters. This is also governed by the thermohaline circulation, which transports cool dense water at high latitudes to equatorial latitudes where it upwells, and in doing so, outgasses carbon dioxide to the atmosphere. In addition, air-sea exchange of the gas is also dependent on processes at the air-sea interface related to sea state, often parameterized as a function of wind speed. Since Earth observation does not directly measure the partial pressure of carbon dioxide, it contributes by providing knowledge on surface temperature, sea state (sea level and sea surface height) and ocean circulation.

Determination of these variables is discussed in Section 5.3 but it is important to emphasize the need for coordination to reduce product bias e.g. due to use of different atmospheric ancillary products, both across sensors and between different products. This applies equally to those satellite products relevant to the biological pump e.g. chlorophyll-a.

This emphasis on consistency also needs to be matched with the development of long time series of these observations, in particular covering a common time period, that is designed taking into account the need for compatibility (temporal and spatial resolution, grids, data formats). These inevitably require consideration of data from multiple satellite sensors and effort from multiple space agencies. The satellite data nevertheless are not sufficient for a carbon observing system (since they cannot measure all variables) and there is therefore the need to ensure that *in situ* observation networks are maintained to ensure temporal representativeness, rearranged to expand their spatial representativeness and augmented by other existing networks that are not currently available to the science community (operational networks), and extended in terms of their capabilities (e.g. addition of sensors to ARGO floats). This will provide not only vital observations for the carbon observing system but also a consistent source of validation data particularly for regional satellite analyses.

This will provide a basis for resolving oceanic CO_2 source and sink spatial and temporal patterns, with specific contributions for regions that are not observed well by the *in situ* networks e.g. lower southern latitudes, as well as providing strong constraints for the improvement of key processes in carbon-climate models, including the incorporation of better representations of ocean circulation and biogeochemistry.

Lakes, rivers and wetlands

The amount of carbon outgassed from inland waters is estimated to be higher than the amount of carbon reaching oceans from the land system (see 3.1.2, Tranvik et al. 2009) but the numbers vary depending on calculation methods. Tranvik et al. (2009), Aufdenkampe et al. (2011) and Raymond et al. (2013) give values of 0.53, 0.64 and 0.32 PgC y^{-1} for lakes and 0.87, 0.56 and 1.8 PgC y^{-1} for streams and reservoirs respectively all with large uncertainties. These numbers compare to wetland emissions of 2.08 PgC y^{-1} (Aufdenkampe et al. 2011). The regional variation of this efflux was reported with the largest contribution from both lakes and rivers being allocated to tropical regions while Raymond et al. (2013) identified high latitudes and tropical regions as lake and reservoir hotspots while rivers were primarily the tropics and temperate Europe. These hotspot regions contrast with concern about release of the carbon locked up in the northern peatlands and permafrost soils (IPCC, 2007) which contain more than twice the entire pool of atmospheric CO_2 (Tarnocai et al. 2009). This potential release is derived from predictions by the current climate-carbon models of a warmer and wetter climate in higher latitudes.

The global emission of methane from inland waters is also discussed by Tranvik et al. (2009) and occurs principally through ebullition release from sediments; diffusion, although this is controlled by oxidization by methanotrophic microbes; and, at lake edges, depending on plant species, sediment type, water temperature and fluctuation in lake water level. While methane release is relatively small in carbon budget terms, it estimated to be greater than emissions from oceans (Bastviken et al. 2004) and considered important because of its higher radiative forcing capacity and the likely increases in release with thawing permafrost. The variables that can be addressed from EO are described in 5.2.1 and in Chapters 2 and 3.

5.2.4 Consideration of the Whole System: Three-way coupling

As highlighted above there are strong interdependencies between the atmosphere, ocean and land. The fluxes between domains have been described for convenience as two-domain components yet it is important to recognize that there is also three-domain coupling since the system under assessment is a cycle as well as carbon-climate coupling (see below).

Specific examples of this three-domain coupling include black carbon emissions from fire disturbance and industrial activities and ocean nutrient fertilization from dust aerosols.

5.2.4.1 Black carbon

The formation of carbon-rich (>60%), aromatic residues (char) and condensates (soot) results from incomplete combustion of fossil fuels or biomass. These residues and condensates are commonly referred to as black carbon (BC) and are present in the atmosphere, marine sediment, soils and water and influence a wide range of biogeochemical processes. In soils and sediments, it is defined as a carbonaceous substance of pyrogenic origin, which is resistant to thermal or chemical degradation due to its aromatic structure or physical protection due to binding with minerals and other organic compounds (Hammes et al. 2007). BC, when it is emitted to the atmosphere, has a direct effect on Earth's radiative heat balance and atmospheric optical depth. BC has a residence time on the order of days to weeks, but it is important because it absorbs heat, can be transported significant distances, and when deposited it reduces albedo, particularly on snow and ice. These latter two characteristics are particularly relevant to the Arctic and Himalaya. The impact of these albedo changes is that glacier, sea ice and ice sheet melting is likely to increase with concomitant impacts for oceans in terms of sea level rise and potential effects on circulation through freshwater inputs and the opening of blocked passages (e.g., the Arctic across Canada from Atlantic to Bering Strait).

Black carbon in soils is also important for the terrestrial system because it contributes to soil fertility through its ability to absorb nutrients, by increasing cation exchange capacity (Liang et al. 2006), important to vegetation growth and an issue of particular value for nutrient poor tropical soils. While most BC produced ends up in the soil, where it can reside for hundreds to thousands of years, up to 40 per cent of the BC created annually is water-soluble and will thus be transferred as dissolved black carbon from the rivers to the ocean. The annual amount of black carbon flowing via rivers to the ocean is estimated to be 27 million tons per year (Jaffe et al. 2013), approximately ten per cent of the dissolved organic carbon in the ocean. This riverine black carbon is broken down slowly in the ocean (up to 4 cycles of circulation) and it also acts to alter the decomposition of bulk DOC (Masiello and Louchouarn 2013).

5.2.4.2 Aerosol Nutrient Fertilization in Oceans

Marine phytoplankton require inorganic nutrients (including nitrogen, phosphorus, and iron), which combine with carbon, to produce organic matter. In some oceans, the growth and reproduction of these algae are limited by the amount of iron in the seawater. Iron is a vital micronutrient for phytoplankton growth and photosynthesis that has historically been delivered by dust storms from arid lands and volcanoes as well as from anthropogenic activity. Considerable research has been done on the effects of anthropogenic and eolian iron addition to the ocean surface, but some nutrient-limited oceanic areas are limited in more than one nutrient, in which case the most-limiting nutrient prevails. A combination of nutrients such as nitrogen, phosphorus and iron can be provided by anthropogenic, eolian, and volcanic deposition. The rapid fertilizing potential of volcanic ash particles arises from a coating containing nutrient-bearing soluble salts formed from the gas phase during the eruption which can be rapidly released over large oceanic areas, and marine phytoplankton from low-iron oceanic areas can swiftly (within days) use these multiple nutrients although excess metal ions can be harmful to systems limited by nutrients (Duggen et al. 2007).

The main processes for delivery of aeolian iron to the ocean are dry deposition by gravitational settling of particles and turbulence in the surface layer of the atmosphere, and wet deposition through precipitation scavenging (Gao et al. 2003), and the total deposition of aeolian iron to the global ocean has been estimated at 14 Tg Fe y^{-1}, with the distribution, varying strongly with season and across ocean regions, and with the predominant fraction entering in the Northern hemisphere especially N. Atlantic in the summer by trade wind transport from the Sahara and N. Pacific and from Asian dust transport by westerly winds in the spring (Fan et al. 2006).

These two examples of black carbon and nitrogen fertilization are provided to indicate that the domains should not be considered in isolation but as part of the coupled Earth system with consideration of processes on land, in ocean and the atmosphere. This holistic approach should also extend to the development of an integrated observing system and observing strategy. The realization of such an observing system requires not just the collection of additional data but also the removal of a series of institutional barriers in the Earth observation and carbon cycle communities. Examples of existing problems include:

- Consistency of definitions
- Calibration and validation of products
- Product intercomparison exercises
- Traceability, transparency and documentation
- Consistency across spatial resolutions
- Data and product access and maintenance
- Data availability for global/regional scientific studies

These issues are addressed in section 5.4.

5.2.5 Climate-carbon Coupling

Whereas an understanding of the carbon cycle and the role of humans in it is an objective in itself, the principle driver for investment in this understanding is the intimate coupling of the climate system and the carbon cycle. This coupling is obviously manifest in the so-called 'Greenhouse Effect' but the interaction between the climate system and the carbon cycle could, itself, set up feedbacks between both systems.

5.2.5.1 Ocean and Inland Water Carbon and Climate

Ocean

Climate change has the potential to modify many chemical and physical processes in the ocean, which will affect the capacity of the oceans to take up anthropogenic carbon dioxide from the atmosphere (Le Quéré et al., 2010, Park and Wanninkhof 2012). There is a potential for both positive and negative feedbacks between the ocean and atmosphere, including changes in both the physics (e.g., circulation, stratification) and biology (e.g., export production, calcification) of the ocean (Sabine et al 2004). While the processes are not well understood most of the chemical processes are considered to be positive feedbacks, for example, increased partial pressure of CO_2 (pCO_2) will cause a decrease in carbonate ion concentration, an increase in hydrogen ion concentration and thus the ability to absorb CO_2 from the atmosphere is diminished. These changes also result in a reduction in ocean pH (ocean acidification) with potential damaging effects on marine organisms, in particular corals, phytoplankton and zooplankton. However the long-term impact on marine biodiversity is not well understood and will depend also on the ability of the organisms to adapt.

Changes in ocean salinity are likely to contribute to global changes in carbon dioxide absorption since more saline water has a lower potential to absorb this gas. In addition ocean circulation, which has a large potential impact on climate, is driven by global variation in density gradients created by fluxes of heat and freshwater, and thus both temperature and salinity. Density changes due to both salinity changes and temperature changes at the surface of the ocean produce changes in buoyancy, which cause the sinking and rising of water masses. This mass transport moves both energy (in the form of heat) and matter (solids, dissolved substances and gases) around the globe and encourages extensive mixing of water between ocean basins. This has indirect effects, for example, regulating the amount of sea ice in polar regions.

Reduced circulation, will impact mixing and transport of waters with concomitant effects on productivity and CO_2 uptake. This may also produce more stratified oceans and such stratification affects the light available within the surface mixed layer for phytoplankton growth, and at the same time, absorption of light energy by phytoplankton modifies the heat content of that layer. Increased heat content leads to warmer ocean temperatures, at least in the surface layers and this encourages the conversion of carbonate ions (HCO_3^-) into CO_2.

These inter-linked ocean processes and their coupling with climate necessitate the long term global monitoring of sea surface temperature (SST), ocean salinity, ocean color (primary production, phytoplankton type distribution) and ocean circulation. In addition, changes sea surface temperatures are associated with greater intensity of storm events, peak wind speeds and heavier precipitation at least in the tropics. Thus changes in sea state (sea level rise, wave intensity and variation) are likely coupled to the above changes and therefore need to be monitored.

Inland Waters

Globally, evidence exists for broadly coherent patterns of change in annual runoff with large regional variations (increases in high latitude and USA; Southern Europe, West Africa, southern South America showing decreases). This variation in runoff is coupled to large-scale climate patterns (ENSO, NAO) but also changes in temperature and evapotranspiration and CO_2 concentration. Changes in river flows, as well as lake and wetland levels, due to climate change depend primarily on changes in the volume and timing of precipitation and, crucially, whether precipitation falls as snow or rain (see Bates et al. 2008). It is also to be expected that there will be changes in snow cover, frozen ground and lake and river ice. For example, permafrost area is predicted to reduce by 20-35% in IPCC AR4 (IPCC 2007) with an associated increase in the depth of seasonal thawing. Glacier melt could lead to increased river flow in the short term but this is likely to be a transient effect. Changes in lake level will depend on the seasonal distribution of river inflows, precipitation and evaporation, with possible change in large lakes of the order of tens of centimeters.

As observed in 5.2.3, the changes above are likely to be associated with increases in the efflux of both CO_2 and CH_4, for example through carbon liberalization from thawing northern peatlands and permafrost soils. The ebullition of CH_4 from decomposing, thawing lake sediments in north Siberia has been estimated to produce a flux of ~4 $Tg(CH_4)\ y^{-1}$ (IPCC 2013) although the IPCC expressed caution given the complexity of the Arctic landscape and slowness of the processes of heat diffusion and permafrost thawing.

Changes in carbon fluxes will likely to be amplified through anthropogenic perturbation. A 20% increase in the transport of carbon through inland waters since 1750 has been reported, attributed to a combination of deforestation and more intensive cultivation practices (Regnier et al. 2013). However, these budgets are strongly limited by dataset availability for soil types, wetlands, inland waters and coastal systems. Critical regions in need of monitoring include the Amazon and the Congo riverine basins and their tropical coastal currents as well as the Ganges River system, the Bay of Bengal, the Indonesian Archipelago, the Southeast Asian seas and the Arctic rivers since they export large amounts of carbon into the coastal seas (Regnier et al. 2013).

5.2.5.2 Land Carbon and Climate

Soil organic carbon breakdown may be enhanced under climate change. Continuing projected increases in average global temperatures indicate an increased vulnerability of soil carbon stocks that, until recently, have represented stable, long-term reservoirs for atmospheric carbon. These soil carbon reservoirs are vulnerable for two reasons. First, soil warming in permafrost soils in northern high latitude regions threatens to thaw permafrost and expose large amounts of soil carbon to decomposition (Schuur and Abbott 2011; Harden et al. 2012). Second, the drying of organic soils in tropical and boreal peatlands, boreal forests, and tundra combined with increases in fire frequency (Hooijer et al. 2010; Mack et al. 2011; Turetsky et al. 2011a,b), lead to release of significant amounts of carbon to the atmosphere. These climate-carbon feedback processes may induce large emissions of carbon to the atmosphere well beyond historical levels, resulting in increased warming. In addition to these issues, there is also a question whether once triggered it will be possible to stop or to reverse the process (the so-called 'tipping points' thesis (Russill and Nyssa 2009)). However, currently because the identity and processes controlling natural sources and sinks of CO_2 and CH_4 are not well understood, it is difficult to determine how they might respond to climate change.

Estimates of carbon sources and sinks across all vegetation types remain poorly known from existing inventory data but may have large effects on climate. While improvements have been made on mapping vegetation type, disturbance, and deforestation, there remains a lack of information on forest biomass, which limits the precision with which emissions can be estimated. In addition to simply quantifying biomass, it is also important to assess the degree to which that biomass is changing and how the vegetation landscape is changing (vegetation type distributions). For example, it is postulated that warming will create longer growing seasons in the higher latitudes (Barichivich, et al. 2013). This implies that more CO_2 will be absorbed by the vegetation, increasing the CO_2 flux from the atmosphere to the land, although at the same time there could be an increase in the flux of CH_4 from the land to the atmosphere.

Beyond their role in regulating variations in atmospheric CO_2 and CH_4, the world's terrestrial biomes and land surfaces provide society with a number of critical goods and services. Across all areas of the earth's surface, a range of land use activities directly impacts terrestrial carbon cycling. In addition, variations in climate (including climate warming) drive a range of disturbances to natural ecosystems that have important impacts not only on carbon cycling but also on a range of services that ecosystems provide to society.

While the above is focused on understanding of the coupling of terrestrial carbon and climate, there is also a need to evaluate alternative climate mitigation and adaptation strategies for the future. This requires an integrated modeling capacity to accurately project carbon and biological resources as they are affected by human activities as well as more precise information on anthropogenic emissions themselves. Such modeling, in turn, rests upon achieving a better terrestrial carbon monitoring system with sufficient resolution to meet both policy and scientific needs (at the scale of hectares). Any discussion of observational requirements must recognize the fact that policy, and therefore societal relevance, will in the future require finer resolution in modeling than is currently being used and this in turn will require appropriate observations from space and an improved spatially representative ground *in situ* network.

5.2.5.3 Land-Ocean-Atmosphere Carbon and Climate

New, highly integrative activities to monitor and model carbon across the Earth's land, ocean, and atmosphere domains have been initiated to address three-way (land-ocean-atmosphere) carbon-climate coupling -- and airborne and satellite data have prominent roles within these activities. One example is the NASA Carbon Monitoring System (CMS). CMS is a prototyping activity designed to evaluate aircraft- and space-based remote-sensing approaches to characterizing, quantifying, understanding, and predicting the evolution of global carbon sources and sinks (http://carbon.nasa.gov). Significant effort is being devoted to rigorous evaluation of the carbon monitoring products being produced, as well as to the characterization and quantification of errors and uncertainties in those products. Another example is NOAA's CarbonTracker. It is a CO_2 measurement and modeling system to keep track of sources (emissions to the atmosphere) and sinks (removal from the atmosphere) of CO_2 around the world. CarbonTracker uses atmospheric CO_2 observations from a host of collaborators and simulated atmospheric transport to estimate surface fluxes of CO_2 (http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/)

5.3 Science, Policy, and Implementation of Directives

5.3.1 The Importance of Policy and the Difference from Scientific Drivers

The carbon cycle is important through feedback to climate both in terms of a driver for change and as a function of the effects of climate on the carbon cycle itself. These issues are discussed in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4; IPCC 2007) and there is a specific chapter on the carbon cycle in the Fifth Assessment Report (AR5; IPCC 2013). The IPCC reports are agreed on by the governments so the findings can be utilized as a scientific basis for the political actions required for them to fulfill the UNFCCC.

However, it is important to recognize that understanding the role of the changing carbon cycle, the effects of mitigation actions, and adaptations to climate change requires consideration of scientific information produced at spatial scales from global to local and their coupling and temporal scales from seconds to millennia. Further, both scientific studies and policy implementation and verification require consideration of the scales at which the processes that are important for these issues actually operate as well as the different scientific and policy information needs. For example, carbon science can be conducted at global but also at local ecosystem scales, while policy implementation may operate at the local scale yet will require independent verification and consistency checking at regional to global scales. It is also important to recognize that the definitions of terms relevant to policy and science may differ (e.g. definitions of forest) across both policy and science domains. Ultimately, however, the development of an integrated carbon observing system must take into account these issues and ensure that consistency is emphasized across spatial and temporal scales and that there is clarity in nomenclature, definitions of scope and linkages between components.

In developing an Integrated Carbon Observing System despite these differences in context, it is nevertheless important to ensure consistency of the products derived from satellite observations with, in so far as possible, emphasis on algorithm scale, compatibility, clarity of documentation and, in particular, clarity in the assumptions used to create a given output product. There should also be an endeavor to ensure that output products are appropriately validated using internationally agreed protocols and independently verified *in situ* data. The role of CEOS in this regard extends to ensuring product quality is a priority, independent verification mechanisms exist, there is continuity of data required, products generated are effectively and traceably documented, that inter-comparison between products is undertaken in a collaborative manner and that the appropriate data products are taken and used downstream to both improve scientific understanding of the carbon cycle and establish effective mechanisms in support of policy requirements. CEOS also has an important role to play in promoting policies of free, open, and easy access to data, data products, and documentation for the carbon cycle information needed in support of national and international policies.

5.3.2 Data in Support of Policy and Carbon Management

Quantitative information about carbon emissions to the atmosphere from all sources and carbon removal from the atmosphere through storage in biomass, soils and the ocean will be needed to support the development, implementation, and verification of climate mitigation policies as well as resource management efforts to maximize terrestrial or aquatic carbon storage or to minimize carbon emissions in combination with other beneficial management practices. Comprehensive policies are not in place, but a variety of approaches are being considered or evaluated at international, national, regional, and/or local scales. It is difficult to anticipate the particular needs of policies yet to be defined, but the carbon cycle and remote sensing communities can anticipate the types of scientific observations and analyses likely to inform decision makers. At a minimum, the global and regional context of actions taken will need to be assessed and independent verification of effects of reported actions will be needed. Satellite data will be able to provide the large-scale context and can be used to assess the consistency of reported emissions/storage with satellite data-based estimates of emissions/storage. Near-term assessments of errors and uncertainties in the satellite observations, integrated with the errors and uncertainties in the models and analytical tools best suited to meeting the anticipated needs for policies will provide valuable information about the capabilities and limitations of these essential monitoring tools for policy.

5.3.3 Exploitation of Existing Infrastructure and Coordination across Agencies, Research Facilities and Directive-driven Programs

To significantly improve the quality of the Integrated Global Carbon Observing system (IGCO), there is a need to foster better integration of *in situ* and satellite observations with model-output. Part of this involves bringing together measurements from a variety of sources with vastly different spatial, temporal and process resolutions. This applies to both satellite and *in situ* observations, and problems include inconsistent parameter definitions, differing data formats, incomplete data, differing spatial and temporal scales and sampling bias in measurements.

Such difficulty is associated with the existing data being acquired largely through *ad hoc* research programs, with these programs often driven by other objectives than carbon cycle research or with the data collection often being temporally or spatially restricted. The integration of existing *in situ* observations has moved forward significantly e.g. the GLOBALVIEW, SOCAT and FLUXNET programs have improved quality and accessibility to data. Nevertheless these data are generally spatially skewed and temporally limited, thus there is an urgent need to implement an improved, better-integrated network of routine observations to monitor carbon.

For oceans this includes the development of new automated measurement techniques but also the extension of existing measurements, following e.g. SOCAT-II. This includes bringing in operational networks designed for national monitoring requirements rather than scientific research. On land there is similarly a need to integrate the existing networks and to expand in particular spatial representativeness (e.g. LTER, ILTER, FLUXNET), but also to extend measurement capacity at such sites to take advantage of infrastructural investments. Coordination between the EO community and the *in situ* observation community in this regard is particularly important to ensure that what is measured is accessible broadly and freely and is fit for a number of purposes including satellite product validation. These issues with land observations similarly apply to atmosphere and in-water observational sites.

In addition to the requirements for coordination of *in situ* and satellite observations for scientific research there is also a need to improve coordination with data collection initiatives in the policy domain to ensure that data collected are appropriate and available to the carbon cycle community (e.g. for Forest Carbon Tracking sites), but vice versa that these sites are augmented with both expertise and observation capacity to contribute to an IGCO.

Similarly, improvements are required in the 'carbon use' domain, specifically, increases in local monitoring stations to capture large local sources of fossil fuel emissions (as well as access to those data already collected) as well as improved monitoring of urban emissions combining *in situ* monitoring with high resolution satellite spatial integration.

5.3.4 Spatial Integration

The issues identified in section 5.2 represent one aspect of the need to ensure spatial consistency and representativeness. It should be noted that carbon cycle processes operate at multiple scales complete with lagged tele-connections and thus it is important to ensure consistency in methodological approaches and at data-model interfaces across spatial scales. Satellite data are often referred to as spatial integrators in the sense that these data allow extrapolation between intensive observation sites and permit appropriate redistribution of *in situ* observations in specific biomes/ecosystems. While this is undoubtedly the case, there is a need to ensure that 'scaling-up' from *in situ* through high spatial resolution to global observations from low resolution systems are conducted in a rigorous and fully consistent, traceable manner. In addition to this, many global carbon cycle models at regional to global scales operate at grid scales (10 km - 0.5 degree) that are much larger than 'standard' satellite resolutions (1 km) and therefore it is important to:

- develop methods and guidance for the appropriate scaling of the satellite data to scales commensurate with the models
- work with the modeling community to make greater use of models that operate at spatial scales more compatible with the sampling scale of satellites.
- ensure that the assumptions and terminology behind both the models and the satellite and *in situ* data are consistent and errors are properly characterized (see below).

5.3.5 Temporal Integration

In common with spatial integration the carbon cycle transcends temporal scales with processes operating from seconds to millennia. Land and ocean satellite products tend to be generated however at scales from hours to months with temporal integration across these times from the baseline satellite observations. There is a need therefore to consider the interfaces in time between the satellite products, *in situ* observations, and models to ensure that observations from satellites are commensurate with the needs of the carbon cycle community. This issue should also take into account the potential for observation, associated with the satellite observations (optical, microwave, orbit, cloud cover) across time (seasonal variation in cloud cover for example, and in solar irradiance for some cases). Similarly it is important to consider that satellites themselves operate for a finite time (fortunately usually longer than their nominal design lives) and thus the need for long-term records must consider the availability of observations and the consistency of satellite-satellite estimates within and between different sensors and platforms. It should be noted here that the majority of satellite datasets used by the carbon cycle community come from research satellites (e.g. Terra-Aqua MODIS) and Space Agencies (NASA, ESA etc.) that do not have an operational mandate to ensure continuity of data supply.

5.4 Data Harmonization, Uncertainty, Traceability, and Consistency

Fundamental issues and criticisms frequently leveled at the satellite community are that the data products generated:

- Are inconsistent across sensors/platforms for a given variable – the values can vary enormously between products claiming to be the same variable e.g. LAI, FAPAR but also from satellite to satellite such that there is no long-term data record even if satellite records collectively stretch back 30 years. Measurement approaches that provide transfer standards between successive generations of satellites are hence an essential tool for scientific problems with long inherent time-scales.
- Are inconsistent between variables – Variables are generally produced as independent streams with hidden dependencies or assumptions which make them incompatible in terms of generating long-term data records (e.g. soil moisture dependence on vegetation optical thickness represented with an LAI or LAI/FAPAR dependence on land cover). The data are also treated in the modeling community as independent data sources and are picked up from wherever they are found without reference to the assumptions that were made in the generation of the products.
- Do not have traceability in their construction – As indicated above, products required by the carbon cycle community have been generated but transparency and traceability in the product generation is often partial and the documentation frequently unclear. Decision steps in processing are usually made for very good reason but the record of that decision step frequently is not recorded in a transparent manner. This is not a criticism of any particular dataset, but creates difficulty in free and fair inter-comparison and ensuring consistency from sensor-sensor, satellite-satellite and agency-agency. This also means it is difficult to develop the interface between observations and models appropriately.
- Are supplied with limited or no associated uncertainty – a common issue with the interface between models and satellite products is that there is a need to express the uncertainty in a

satellite estimate in a way that is both transparent and appropriate for use at the scales of models or for decision making. A common methodology between the communities is missing and the information on uncertainty expressed in satellite products is impenetrable to the model community and therefore frequently disregarded. This is partly due to documentation, partly due to the incompatibility between spatial scales, but also due to the difficulty in converting from signal counts into full estimates of error associated with a given product.

- Are not mature in the sense of a clear and comprehensive validation – verification of the quality of satellite estimates of required parameters depends on *in situ* observations of the same variable. These are relatively sparse and as a result the satellite data suffer from lack of robust validation.
- Are in satellite community formats – often the data produced are in formats agreed within the community generating them or within more generally the satellite community. Such formats tend to be those commonly available in image processing systems rather than in formats that are familiar to or used by the broader carbon cycle (including the 'carbon cycle modelers') community.
- Are not available in locations used by the non-satellite research community – a frequently overlooked problem in the satellite community is that the data products need to be made easily accessible. This means they should be in the appropriate formats as already indicated but also that the data are available in locations that are known by the carbon cycle community rather than simply being made available from the generating institution using a project website which may or may not live beyond the project lifetime. This applies not just to individual products but also to the complete set of products required by the carbon cycle community. This criticism does not contrast, however, with the clear need to ensure that the large volumes of data generated by the space agencies are properly managed in-house, rather it underlines the need to ensure that the carbon cycle community has access to the appropriate data by virtue of a common effort by the Space Agencies to share metadata and have that accessible, with maintained links back to the satellite archives held by the space agencies.

The above points all require action by CEOS and the individual space agencies, both in the carbon cycle domain but also with respect to climate. These are issues that are part of the remit of the CEOS WG Climate and should be explored in collaboration with them in the context of carbon.

5.5 Model Development and the Interface to Data

Models are a fundamental component of a carbon cycle observing system since they represent the mechanism by which understanding of the role of the carbon cycle in influencing climate and being influenced by climate will be determined and future evolution assessed. The interface between models and especially satellite data requires improvement on both sides. The issues with the data have been described in section 5.4 and in order to maximize the benefit of actions identified above there is a need also to improve the interface between the models and the data. This requires:

- Development of the models themselves to improve the representation of the carbon cycle, in particular incorporating key missing processes
- Improvement in the scale compatibility between models and data from both *in situ* and satellite data sources
- Reconciliation of definitions of quantities, terminology, assumptions between models (e.g. concepts of plant functional types (PFT), 'big-leaf' representations of radiative transfer,

approaches to mixing of vegetation types and vertical structure) and data products.
- Improvement of approaches to exploit data streams for model validation, model driving, model process representation and assimilation.

In addition it is important for the carbon cycle modeling communities in the different domains (land-atmosphere-ocean) to start to work on better coupling of the domains and in particular the interfaces between them (lateral and vertical transport of carbon).

There is a need for reconciliation also to be undertaken between these carbon models and methods for estimating carbon stock and stock change that are data driven (*in situ* and satellite) e.g. carbon accounting approaches to improve the future consistency between models and inventory reporting on which policy implementation is based.

The role of CEOS in this process involves:

- Reinforcing the interaction between the *in situ* and satellite communities to ensure that data for model parameterization and satellite validation are collected in the most efficient way possible.
- Ensuring a dialogue with the modeling community to develop better interfaces between the satellite data and the carbon modeling communities, in particular, dealing with appropriateness of the data for the model, clarifying definitions, and ensuring appropriate use of the satellite products. This involves development of test tools (e.g. Radiation transfer Model Intercomparison (RAMI)) and organization of specific data producer-model community meetings and increasing the interface with extant model inter-comparison exercises (e.g. TransCom, CxMIP, CMIP5)
- Promoting and being involved in model inter-comparison exercises, acting as a data product clearing-house/conduit, including those exercises comparing carbon accounting and carbon cycle models.

5.6 Timelines and Evolution

The development of a global carbon observing system will be necessarily evolutionary because the development of the required data products, models, other analytical tools, and specific policy requirements are not on the same timelines. Similarly, it is important to recognize that there is a long lead in development and availability of new products, particularly those coming from satellites. The timeline from a decision to launch a satellite to its actual launch and the provision of reliable data from sensors on-board is relatively long and thus the near future for satellite data provision has already been decided up to roughly 2020. In order to maximize the value of data coming from current and planned satellites it is necessary to ensure that the mechanisms for exploitation are in place for when these products become available. This means model and other analytical tool development must take into account data availability now and in the future. To do this effectively requires the development of a stronger interface between CEOS (as the representative of the Space Agencies) and the carbon community to ensure that the opportunities currently in planning are not lost and are effectively specified (i.e., Biomass, NASA-ISRO SAR, GOSAT-2, OCO-2, CarbonSat, ASCENDS) and also to identify what the key priorities are for the post 2020 timeframe. In addition there is a strong need to ensure that the already acquired data are effectively exploited through cross-calibration, inter-comparison of methods (leading to joint improvements in algorithms) and reprocessing.

5.7 Practical Considerations in Integration

The development of the Integrated Carbon Observing System as indicated in the GEO Carbon Strategy is an evolutionary process which takes into account and exploits existing activities not designed specifically for carbon cycle purposes, but of value to them to construct a comprehensive integrated system that functions much more effectively than the current piecemeal arrangement. This evolutionary process envisages minimizing cost outlays and dedicating investment in separate components of the network of inputs that carbon cycle studies currently depend on.

In the context of CEOS and the individual space agencies, this evolutionary approach is sensible and also reflects the nature of mission planning which already is relatively inflexible out to 2020. However, to achieve milestones towards an integrated system there is a need now for the carbon cycle community to identify the key priorities in terms of satellite observations in the period 2020 onwards (2020-2025 are key time slots for the *GEO Carbon Strategy*) since the planning process is already starting for this period. An example is provided in the recent report by the International Ocean Color Coordinating Group entitled *Mission Requirements for Future Ocean-Color Sensors* (IOCCG 2012).

In addition it requires the carbon community to also transmit needs in terms of improvements in the quality of existing data products, needs for reprocessing of data in the archives as well as providing collective backing for satellite missions relevant to the carbon cycle.

CEOS in turn needs to provide materials to and engage in discussion with the carbon cycle community and be involved in establishing better conduits for information exchange than currently exist such that a better collective case can be made to the funding agencies for investment.

5.8 Integration Recommendations and CEOS Actions

5.8.1 Mission-Related Recommendations

Overall Motivation/Rationale-16: In order to derive the maximum scientific and societal benefits from future satellite missions focused on carbon-relevant measurements, confirmed missions for continuity and new carbon data products must be launched as planned, and priority new missions should be confirmed as soon as required processes and resources permit. CEOS can identify any opportunities to develop additional items in support of these existing planned missions as joint activities and coordinate the planning of future satellite missions so as to optimize coverage, sampling, and utility of data products, adopting a virtual (or actual) constellation approach, when applicable.

Carbon-Challenge-15: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the timely confirmation and launch of carbon-related missions and provision of optimized carbon data products. For missions with similar objectives and being developed to fly in the same timeframe, CEOS will encourage coordination of mission attributes so that observations are made in ways that optimize areal coverage, time and space sampling, and/or accuracy. For missions with similar objectives that may follow one another in time, CEOS will encourage coordination of mission and data attributes so that the multiple data streams are compatible and can be integrated to create a consistent time series over a longer time period than any single mission alone could achieve.

Overall Motivation/Rationale-17: To ensure that new missions yield the greatest scientific and societal benefits, there is a need for carbon science and policy information priorities to be factored into sensor selection decision-making for future space missions. Thus, it is important that space agencies and their sponsors engage the carbon science community in their mission identification, review, selection, and implementation processes. This will also help to ensure that choices made in response to technical or budget constraints do not compromise mission objectives.

Carbon-Challenge-16: CEOS acknowledges this challenge and will encourage its Member Agencies to engage the carbon science and policy communities in their mission identification, review, selection, and implementation processes to the fullest extent possible.

5.8.2 Product-Related Recommendations

Overall Motivation/Rationale-6: The IGCO called for in the *GEO Carbon Strategy* requires improved approaches for developing global land inventories and related data products of 1) the spatial distribution and extent of wetlands and peatlands and of changes in their organic carbon pools and 2) carbon content of reservoirs, lakes, ponds, and rivers. Satellite observations of inland waters must have appropriate spatial resolution and sensitivities. Lakes and reservoirs cover around 3% of the Earth's land surface, but the majority are small. Use of moderate to coarse resolution ocean-color sensors such as MODIS or MERIS is therefore fairly limited in lake carbon research. On the other hand, many medium to moderate resolution land remote sensing sensors (such as Landsat-7) do not have sufficient sensitivity to estimate lake content of colored dissolved organic matter (CDOM) and monitor long-term trends. At present there are only a few sensors (such as ALI on EO-1) that are suitable for mapping lake CDOM, dissolved organic carbon, and pCO2, but they do not provide full global coverage. Landsat-8 and Sentinel-2 will change the situation, as sensors on both these missions provide data with sufficient spatial and radiometric resolution as well as the global coverage needed for lake research. Space agencies must ensure the continuity of such measurements. Maps of lakes and ponds are needed annually and maps of flooding and inundation are needed seasonally. Estimates of associated carbon-related biophysical properties (e.g., dissolved and particulate carbon, river discharge) and biological productivity are needed as a contribution to terrestrial carbon budgeting. Research agencies must implement projects to develop these essential products at regional and global scales.

Carbon-Challenge-6: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the continuing deployment of satellites and development of satellite data products for mapping wetlands, wetland types, wetland inundation, rivers, flooding, reservoirs, lakes, and ponds and estimating their associated carbon-related biophysical properties (e.g., dissolved and particulate carbon, river discharge) and biological productivity. CEOS will encourage its Member Agencies to coordinate the launch of satellites that meet requirements in a timely fashion and to avoid gaps. CEOS Agencies will strive to implement projects to develop these essential wetland and inland water data products at regional and global scales and with appropriate spatial and temporal resolutions and sensitivities to the carbon constituents in inland waters.

Carbon-Action-6: CEOS Agencies with interests in and/or mandates for developing 1) satellites to observe wetlands and inland waters and 2) wetland and inland water data products will coordinate their efforts in consultation with relevant CEOS WGs and VCs.

Overall Motivation/Rationale 18: There are strong interdependencies among the atmosphere, oceans and inland waters, and land. The fluxes between domains are important, yet it is important to recognize that there is also three-domain coupling since the system under assessment is a cycle and there is strong carbon-climate coupling. Examples of this three-domain coupling include black carbon emissions from fire disturbance and industrial activities and ocean nutrient fertilization from dust aerosols.

Carbon-Challenge-17: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies so that issues that transcend traditional scientific domains are not overlooked. CEOS will foster communications across CEOS in recognition of the need to support understanding of three-domain coupling of the carbon cycle and strong carbon-climate coupling in the Earth system.

Carbon-Action-21: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will coordinate with other relevant CEOS WGs and VCs to ensure that the carbon observations and data products that transcend traditional scientific domains (e.g. black carbon, nutrient fertilization) are accorded appropriate priority in CEOS activities and future plans and that key satellite products to permit scientific studies of these phenomena are produced and made available.

Overall Motivation/Rationale-19: In order to achieve the integrated, global carbon budget analysis called for in the IGCO and meet the needs of the global carbon and climate modeling communities, satellite carbon data products must be consistent and compatible (i.e., temporal and spatial resolution, grids, data formats, units) across the land, oceans and inland waters, and atmosphere domains (e.g., estimates of terrestrial and oceanic primary production should be compatible; ocean products must be compatible, consistent and comparable with the satellite observations of key atmospheric properties (CO_2, CH_4, NO_x, aerosol)).

Carbon-Action-22: CEOS Agencies engaged in development of carbon products will coordinate to achieve compatibility, comparability and consistency of carbon products across all relevant domains (land, oceans and inland waters, and atmosphere, as appropriate), in consultation with relevant CEOS VCs and WGs.

Overall Motivation/Rationale-20: The IGCO called for in the *GEO Carbon Strategy* requires improved information on natural emissions of carbon. In addition there are policy and management needs for this information to support monitoring and verification of CO_2 and CH_4 emissions for international purposes. CEOS member agencies must provide improved information from satellites on the spatial and temporal scale of anthropogenic emissions, in particular fossil fuel emissions from cities, gas flares and power plants and other industrial contributors through cumulation of existing satellite products and initiation of new projects and missions to tackle these issues at a global level. CEOS member agencies must improve the quality of satellite-derived information on emissions from biomass burning, coal mines, rice agriculture, livestock and landfills.

Carbon-Challenge-18: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies so that improved information on natural and anthropogenic emissions of carbon (CO_2, CH_4, but also CO and black carbon) is produced and made publicly available.

Carbon-Action-23: Individual CEOS Agencies with interests in and/or mandates for providing improved information on natural and anthropogenic emissions of carbon (CO_2, CH_4, CO and black carbon) will coordinate their efforts in consultation with relevant CEOS WGs and the Atmospheric Composition VC.

Overall Motivation/Rationale-5: The IGCO called for in the *GEO Carbon Strategy* requires continuous time series records of land, ocean, and atmosphere properties (e.g., land cover, land cover change, wetland area, LAI, ocean color and marine ecosystem composition, wetlands, permafrost areas, CO_2 and CH_4) at mid resolution. It is now possible to develop data fusion and data assimilation algorithms using a combination of remote sensing data (vis/IR, SAR, Lidar) at medium to moderate resolutions to improve the accuracy of land and ocean products. Most of the currently available global remote sensing products are all based on a single instrument approach. To realize the full discrimination potential of the data collected by planned and future remote sensing systems and those currently in orbit, multi-sensor approaches must be developed and tested and a product-based (rather than mission-based) approach must be adopted. To ensure long-term continuity of time series data records, the satellite data provider may need to transition from a research satellite program to an operational satellite program; thus, there must be a continuous interface between the research agencies (e.g., ESA, NASA) and those with operational mandates (e.g., NOAA, Eumetsat) .

Carbon-Challenge-5: CEOS acknowledges this challenge and will influence and coordinate the activities of the CEOS Member Agencies toward the continuity and systematic improvement of long time series of multi-sensor, multi-mission data products.

Carbon-Action-5: CEOS Agencies with interests in and/or mandates for developing multi-sensor, multi-mission time series data products for the land and ocean will strive to ensure consistent, well-calibrated, bias-free satellite time-series carbon products are produced and continued into the future. They will coordinate their efforts in consultation with relevant CEOS WGs and VCs to ensure appropriate merging of data and products from multiple sensors.

Carbon-Action-24: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will work to encourage the production and availability of high-quality, consistent long time series data products based on multiple sensors and missions for carbon and climate science and for model-data and data-data intercomparison exercises.

Carbon-Action-25: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) and relevant VCs will provide periodic technical information to the research and operational space agencies regarding readiness for and issues regarding transitions from research to operations for long-time series carbon observations.

Overall Motivation/Rationale-21: In developing an IGCO it is important to ensure consistency of the products derived from satellite observations with, in so far as possible, emphasis on algorithm compatibility, clarity of documentation and, in particular, clarity in the assumptions used to create a given product. Satellite products should be appropriately validated using internationally agreed protocols and independently verified *in situ* data. Efforts are also needed to ensure that the best auxiliary data (e.g., land cover, aerosol, cloud, DEM, reanalysis products of clouds, ozone, surface pressure, winds, aerosols, etc.) are used consistently across sensors and agencies in processing satellite data in order to avoid inter-sensor differences in products arising from differences in use of auxiliary data. The role of CEOS in this regard extends to ensuring that product quality is a priority, independent verification mechanisms exist, there is continuity of the required data, products generated are effectively and traceably documented, intercomparison between products is undertaken in a collaborative manner, and the appropriate data products are taken and used downstream to both improve scientific understanding of the carbon cycle and establish effective mechanisms in support of policy requirements. CEOS also has an important role to play in promoting policies of free, open, and easy access to data, data products, and documentation for the carbon cycle information needed in support of national and international policies.

Carbon-Challenge-19: CEOS acknowledges the challenges to see that products derived from different satellite sensors to represent the same carbon-related property are consistent and compatible with each other and that requirements for clarity and traceability in products are followed. When there are differences in the products (whether it be in the methods used, in the underlying assumptions, or in the applicability of the results), the documentation provided must help users to understand them. CEOS will use its influence to encourage CEOS Agencies toward this goal.

Carbon-Action-26: The CEOS Carbon Subgroup (recommended in Carbon-Action-38), in consultation with the CEOS WGCV, will encourage comparison of protocols for the generation of carbon products from satellite data and and recommend adoption of the best protocols by CEOS agencies to ensure long-term consistent datasets relevant to carbon cycle community needs. This work shall include accounting for ancillary data dependence (e.g., land cover, aerosol, cloud, DEM, reanalysis products, etc.) such that there is consistency across individual products and variables.

Carbon-Action-27: CEOS Agencies will make publicly available all information necessary to document the accuracy, clarity, and traceability of the satellite data and data products they produce.

Carbon-Action-28: CEOS Agencies will coordinate their efforts to develop compatible (e.g., temporal and spatial resolution, grids, data formats, common auxiliary data, units) carbon data products from multiple missions, in consultation with relevant CEOS WGs and VCs.

Carbon-Action-29: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will develop guidelines for the specification of uncertainty in products, from signal counts through the various CEOS Processing Levels.

Carbon-Action-30: CEOS Agencies will ensure the long-term accessibility of satellite data and data products for carbon cycle science and policy. This must include arrangement for secure archives, documentation, and metadata as well as provisions for easy discovery and access by the carbon science and policy communities.

5.8.3 Calibration/Validation-Related Recommendations

Overall Motivation/Rationale-7: The *GEO Carbon Strategy* calls for robust carbon tracking and accurate carbon budgets, and these major products require quantitative analysis of changes in Earth system carbon properties over time. This in turn requires well-calibrated satellite sensors and well-validated data products. Development of specific remote sensing products often requires use of surface reference data sets. In some cases, land-based networks have been developed to provide *in situ* data for validation of specific products (e.g., soil moisture, atmospheric CO_2), where in others, networks either need expansion or considerable development (such as biomass dynamics). For the ocean, this requires global-scale validation of algorithms for estimating ocean carbon pools from satellite data, in carbon units, in close collaboration with *in situ* observation systems. It is also necessary to provide adequate error characterization of remote sensing variables and carbon products derived from satellite data, ideally on a pixel-by-pixel basis, to ensure their appropriate use in quantifying and modeling carbon dynamics. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure *in situ* data are accessible to the satellite community for validation of satellite data products. The CEOS WGCV and its relevant subgroups have conducted and coordinated much-needed calibration and validation work over the years, and this work needs to continue and be expanded. The CEOS VCs are also conducting valuable work in this area. There is a need to strengthen mechanisms within CEOS and at the individual space agency level, in particular investment as part of satellite development, for product validation to establish validation methodologies, protocols and benchmark datasets. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure *in situ* data are accessible to the satellite community.

Carbon-Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the

activities of its Member Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its individual space agency members, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.

Carbon-Action-31: CEOS through its WGCV and relevant VCs will strengthen its mechanisms for product validation by establishing validation methodologies, protocols and benchmark datasets.

Carbon-Action-32: For each of the relevant variables in each of the domains CEOS will work with the carbon science community to assess the current provision of validation data in terms of quality (defined by protocols (e.g., WGCV LAI protocol) and or maturity matrices (e.g., WG Climate)) and spatial and temporal coverage. This work should identify potential additional sources and develop a strategy to improve global *in situ* data distributions in relation to satellite validation and model parameterization. It should also exploit existing infrastructures to develop key intensive collection sites.

Overall Motivation/Rationale-8: The two major products called for in the *GEO Carbon Strategy* (i.e., a robust and transparent carbon tracking system and accurate carbon budgets) require quantitative analysis of changes in Earth system carbon properties over time. Desirable increases in spatial and temporal coverage can be achieved if data from two different, contemporaneous sensors can be combined seamlessly. To facilitate such data merger or fusion, data products acquired by differing sensors and satellites for each of these properties must be intercomparable, and systematic intercomparison activities must be conducted.

Carbon-Challenge-8: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the systematic intercomparison of satellite data products of relevance to the carbon cycle. CEOS Agencies will participate, as appropriate, in major intercomparison activities, including model-data, data-data, and multiple data stream intercomparisons. CEOS recognizes that intercomparison activities will require coordination with relevant non-CEOS organizations and activities.

Carbon-Action-33: CEOS will reinforce the mechanisms already in place in CEOS for all domains (WGCV, and VCs, and WG Climate) and clarify their responsibilities to ensure intercomparison activities are well-coordinated and effective.

Carbon-Action-34: Individual CEOS Agencies producing the same (or similar) carbon data products will cooperate to ensure that their products are compared to the other relevant products and, if technically feasible, ensure efforts are made so that their products can be used quantitatively with these other products.

Carbon-Action-9: CEOS WGCV and its relevant subgroups, in consultation with the CEOS Carbon Subgroup (recommended in Carbon-Action-38), will organize and coordinate carbon data product intercomparison activities as they are identified as priorities for CEOS action and in coordination with the wider carbon cycle science community.

Overall Motivation/Rationale-22: In order for the satellite data and data products required for the IGCO to be identified, prioritized, developed, and utilized effectively, CEOS must establish effective linkages with the carbon science, applications, and policy communities. CEOS must work with organizations representing these communities to understand needs and priorities and to ensure satellite data products provided by CEOS Agencies meet needs and are utilized appropriately. CEOS should actively pursue a role within major model-data inter-comparison exercises dedicated to the carbon cycle (e.g., CxMIP, OCMIP, RECCAP) as the point of reference for appropriate satellite products. An effective way to proceed may be through the sponsorship of international workshops on the interface between models (land-oceans and inland waters-atmosphere) of the carbon cycle and satellite data products to reconcile methodological differences and spatial compatibility.

Carbon-Action-35: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will develop guidelines for appropriate data use of satellite data and data products. This will require improved interactions between the carbon cycle community and the satellite community; comprehensive review of the current use of data products, including current data limitations; and reconciliation of methodological differences and spatial compatibility. Such interactions may include co-sponsorship of joint workshops targeting specific data needs and investment in community product assessments, especially for key intercomparison exercises.

5.8.4 Interactions/Linkages/Communications-Related Recommendations

Overall Motivation/Rationale-22: In order for the satellite data and data products required for the IGCO to be identified, prioritized, developed, and utilized effectively, CEOS must establish effective linkages with the carbon science, applications, and policy communities. CEOS must work with organizations representing these communities to understand needs and priorities and to ensure satellite data products provided by CEOS Agencies meet needs and are utilized appropriately. CEOS should actively pursue a role within major model-data inter-comparison exercises dedicated to the carbon cycle (e.g., CxMIP, OCMIP, RECCAP) as the point of reference for appropriate satellite products. An effective way to proceed may be through the sponsorship of international workshops on the interface between models (land-oceans and inland waters-atmosphere) of the carbon cycle and satellite data products to reconcile methodological differences and spatial compatibility.

Carbon-Action-36: CEOS will strengthen linkages with relevant carbon communities and organizations to facilitate the communications and coordination necessary to ensure that the satellite data products provided by CEOS Agencies meet needs and are utilized appropriately.

Carbon-Action-37: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will serve as a point-of-contact for appropriate satellite products for major model-data intercomparison exercises related to the carbon cycle.

5.8.5 CEOS Mechanisms- and Future Planning-Related Recommendations

Overall Motivation/Rationale-23: In order for CEOS to act effectively on the findings and recommendations of this report, a responsible CEOS entity must be identified. The responsible entity must establish strong working relationships with all relevant VCs and CEOS Working Groups, especially the WG Climate and WGCV.

Carbon-Action-38: CEOS will establish a group to be responsible for carbon activities within CEOS and for advancing the findings and recommendations of this report. This group will take responsibility for overseeing, coordinating, and reporting on the actions identified in this report. It is recommended that CEOS establish a Carbon Subgroup within the CEOS WG on Climate as a most efficient way of implementing this action (this recommended group will hereafter be referred to as the "Carbon Subgroup"). The Carbon Subgroup will report to (and through) the WG Climate. It will establish strong working relationships with all relevant VCs and CEOS WGs, especially the WGCV.

Overall Motivation/Rationale-24: There is a strong need for CEOS to better understand and further prioritize the needs of the carbon community for space-based measurements in the context of time (2015-2020-2025) and space (i.e., needs for increased resolution) and then to reinforce multi-agency planning and preparation for satellites, as coordinated through the CEOS Carbon Subgroup (recommended in Carbon-Action-38) and relevant VCs to ensure that these priority observations are made in the future. It will be important to identify the priority missing components for emissions/stock assessment that are capable of being addressed with satellite data sources. Also, the *GEO Carbon Strategy* does not provide the level of detail for measurement specifications or observation attributes necessary for a space agency to design a mission or verify if a current or planned sensor can provide adequate data. These specifications, custom for carbon -- and especially when they differ from those for the ECVs -- are urgently needed.

Carbon-Challenge-20: CEOS acknowledges this challenge and will engage the carbon science and policy communities to develop a more refined understanding of requirements and priorities for carbon-related measurements from space. CEOS recognizes this will require coordination with GEO, IGBP, Future Earth, and other relevant international organizations.

Carbon-Action-39: CEOS and individual CEOS Agencies will sponsor (or co-sponsor) work (e.g., one or more workshops, a written report) to 1) develop more specific measurement requirements for continuing and new carbon observations from space that will fulfill science and policy needs and 2) encourage further prioritization of these measurements.

Carbon-Action-40: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will lead in the planning for activities to 1) develop more specific measurement requirements for continuing and new carbon observations from space that will fulfill science and policy needs and 2) encourage further prioritization of these measurements. It will work, in consultation with the relevant VCs, to coordinate the incorporation of the refined requirements and priorities into multi-agency planning and preparation for future satellites.

CHAPTER 6: THE WAY FORWARD

LEAD AUTHORS: DIANE E. WICKLAND (NATIONAL AERONAUTICS AND SPACE ADMINISTRATION) AND MASAKATSU NAKAJIMA (JAPAN AEROSPACE EXPLORATION AGENCY)

6.1 The Challenges Ahead

The challenges for CEOS are no longer limited to addressing national and international needs for scientific information about carbon cycling, climate, and climate change. As the nations of the world experience climate change and its impacts and act in response to those changes, their needs now include observations and monitoring of the effects of these human actions to mitigate and adapt to climate change – and the capability to distinguish the effects of those human actions from those of other changes in the system (i.e., in the so-called natural system). In no area of climate change science is this more evident than in that of global carbon cycling. This type of information will be absolutely essential for climate policy development, implementation, and verification. The information will also have value across the range of GEOSS societal benefit areas, and especially for the Climate, Energy, Health, Ecosystems, and Agriculture Society Benefit Areas.

6.1.1 Need for Improved Scientific Understanding of the Global Carbon Cycle

The *GEO Carbon Strategy* clearly explains the limitations of our current knowledge of the global carbon cycle and explains why improved scientific understanding will be essential to underpinning societal responses to global climate change. The report unequivocally states that *a key reason for our lack of understanding of the global carbon cycle is the dearth of global observations*, and calls for *an increased, improved and coordinated observing system for observing the carbon cycle* as a *prerequisite to gaining that understanding*. CEOS is well positioned to meet this challenge and provide needed coordination for the space-based and related supporting observations called for in the *GEO Carbon Strategy*. The CEOS agencies can act to meet this challenge by working together to implement their carbon observation programs in ways that recognize this priority and maximize the scope, coverage, accessibility, and utility of carbon observations from space.

6.1.2 Need for Greater Clarity in Requirements to Support Climate Policy

A major complicating factor in developing future plans for carbon observations from space derives from a lack of comprehensive national and international policies and regulations regarding climate change monitoring, mitigation, and adaptation. The authors of this report have had to make assumptions regarding the needs of policymakers for scientific information about carbon – especially with respect to the need for data and information useful for measurement, reporting and verification (MRV). What policies will be enacted? At what spatial and temporal scales will measurements be needed? At what accuracies will space-based observations need to be made to be useful? As these questions are answered, the role space-based observations will play and the role for CEOS in coordinating the best possible space-based observational network will become clearer. There should be a strong role for satellite observations, but end users may need to become more comfortable working with data that are globally comprehensive and internally consistent, but perhaps less accurate or less frequently measured than some traditional *in situ* observations.

The United Nations' Reducing Emissions from Deforestation and Degradation (REDD, REDD+)

Programme is one recent climate mitigation policy that has relatively clear MRV requirements. Remote sensing approaches have already been embraced by many developing nations as an element of their national MRV plan. The GEO Forest Carbon Tracking and its successor the GEO Global Forest Observation Initiative (GFOI) are examples where close collaboration between CEOS and GEO is demonstrating the value and utility of coordinated and systematically acquired remote sensing observations to meet climate policy needs. This is clearly demonstrated through the establishment by CEOS of the Space Data Coordination Group (SDCG) to facilitate the availability of remote sensing data to meet the needs identified by GFOI's work on methodological guidance for REDD+ and plans to publish a *Methods and Guidance Document*. Work to make such observations even more useful (finer resolutions, better characterization of uncertainties, more quantitative approaches) is underway and likely to yield needed improvements in the near future (e.g., ESA's Biomass mission).

6.1.3 Need for Coordinated Satellite Observations

This report calls out needs for continuity of current time series data records of carbon pools and fluxes and provides compelling rationales for new measurements of carbon from space to begin new data records. Both are needed, and it would be impossible to prioritize one set of observations over the other – especially given the challenges of global climate change the world is facing and the need for an integrated approach to understanding and quantifying changes in Earth's carbon cycle and its interactions with climate.

This report points out that a long-term CEOS goal should be to foster the transition of the long time series data records into stable, operational environments and to strive for constellations of complementary satellite measurements. As was pointed out in the *GCOS Implementation Plan*, making observations more "operational" may be achieved in more than one way – by transitioning responsibilities from a research agency to an agency with an operational mandate or by a convergence of requirements and appropriate support.

It may be that the present is a time of transition where CEOS, GEO and the international carbon cycle science community are evolving from use of satellites developed for other purposes to provide information about carbon to deployment and utilization of satellites developed primarily to monitor, quantify, and/or understand carbon pools and fluxes. There is great excitement surrounding new missions optimized to make the quantitative measurements anticipated to be necessary for MRV and to understand changes in carbon cycling processes. In particular, there is intense interest in new measurements of carbon dioxide and methane in the atmosphere, already well demonstrated by GOSAT; and in new measurements of vegetation structure and/or canopy volume using lidar and radar approaches for estimating aboveground carbon pools, as demonstrated by ICESat and through the large body of work with ALOS PALSAR and other radar sensors. This report makes note of the compelling arguments for such new missions and emphasizes the need for coordination of CEOS members' plans in order to achieve the best coverage and continuity for the new data products – and to do so in a way that does not jeopardize the continuity of the existing time series observations everyone currently depends upon to document and understand change over time.

As has always been the case, many space agencies respond similarly to the priority needs of the day, planning and developing similar satellite missions both for continuity of indispensable, high priority time series data and for new measurements to enable more powerful science and applications. While CEOS coordination is unlikely to be able to deter most nations from implementing their own priorities, it may be able to use its considerable influence to maximize the scientific and societal returns from such missions. For missions with similar objectives and being developed to fly in the same timeframe, it should be possible to coordinate mission attributes so that complementary, rather than unnecessarily redundant, observations are made. For example, space agencies could coordinate orbits to increase temporal and spatial coverage or combine data from missions with differing technological approaches to a measurement to create a more useful data product. For missions with similar objectives that may follow one another in time, it should be possible to coordinate mission attributes such that the two data streams can be woven together to create a consistent time series to evaluate change over a longer time period than a single mission alone could achieve. Coordination of plans and schedules to allow for brief overlaps in time for each mission would greatly facilitate intercalibration of the satellite observations and is to be encouraged. The CEOS responses to the GCOS Implementation Plan (CEOS 2006; CEOS 2012) make these same points exceptionally well and they are as important and valid for observations of carbon from space as they still are today for climate.

6.1.4 Need for an Integrated Approach to Carbon Observations

Carbon cycling is an Earth system process, with intimate coupling among its land, oceans and inland waters, and atmosphere domains and with Earth's climate. This has already been elaborated throughout this report and, especially, in chapter 5, but it is important to emphasize again here that an Integrated Global Carbon Observing system (IGCO) must address all domains as well as the fluxes among them, must acknowledge the tight coupling with climate, and must pursue an end-to-end approach so that data are not just acquired, but relevant data products are produced in carbon units and used to advance understanding and meet societal needs. Considerable attention must be given to establishing priorities and coordinating with national and international CEOS partners so that priority needs are met efficiently and cost-effectively. Data must be of adequate quality to meet requirements, must be in understandable and useful forms (including for models), and must be openly and widely available. Data products must be transparently produced, validated, openly and widely available, and archived. Even if CEOS agencies do not have mandates this broad, they do have a responsibility to ensure the end-to-end work is done and the benefits of their missions are fully realized.

6.2 Overview of Recommendations: CEOS Elements of an Integrated Global Carbon Observation System

This section provides a brief, high-level summary of the contextual Challenges and CEOS Actions presented in this report. When possible, particular CEOS groups have been identified as a suitable responsible party for implementing the CEOS Actions. This was not possible in all cases and therefore the responsibility may rest with the CEOS SIT and/or Plenary to either oversee or refer to an appropriate group. The Challenges, CEOS Actions, and responsible and supporting CEOS entities are summarized in Table 6-1 (at the end of this chapter), sorted by type of recommendation (e.g., those related to: missions, products, calibration/validation, interactions/linkages/communications, and CEOS mechanisms and future planning). Table 6-1 also notes external organizations with which coordination is highly desirable, cites sections and pages in the *GEO Carbon Strategy* that call for the missions and products listed, and identifies relevant GCOS ECVs.

6.2.1 Challenges and Actions Focused on Missions

6.2.1.1 Data Continuity

This report calls for CEOS member agencies to accord high priority to continuing the following types of measurements for carbon:

- Moderate resolution (250m-1km) carbon-related properties of the land surface (e.g., land cover, disturbance, fire, LAI, FAPAR, wetlands, permafrost)
- Medium resolution (30-100m) carbon-related properties of the land surface (e.g., land cover, disturbance, LAI, FAPAR)
- Ocean color, sea surface temperature, and salinity with adequate calibration and sustained calibration/validation operations.
- Ocean color with resolution and frequency of coverage adequate for coastal waters
- Aquatic carbon constituents (e.g., CDOM, DOC, pCO_2) with sufficient spatial resolution and sensitivity for inland water bodies
- Atmospheric column measurements of CO_2 and CH_4

For the land and ocean domains, there is a clear understanding that multispectral optical sensors and microwave sensors with resolutions, coverage, and sensitivities similar to current, well-demonstrated systems can provide a wide diversity of data products highly useful for monitoring and understanding carbon cycle dynamics. The focus in these chapters is more on the data products, and how they can be improved, and on the potential to create valuable new products with current and expected capabilities in the continuity missions.

For the atmosphere domain, observations of carbon dioxide and methane in the atmosphere are fairly new, and the emphasis is on developing improved space-based observations while pursuing improved coverage and a continuous time series of increasingly capable missions.

6.2.1.2 New Missions

This report calls for the CEOS member agencies to deploy new missions to acquire high priority, new measurements of carbon. These missions have been conceived and designed with carbon cycle science and policy needs in mind and have the potential to revolutionize our ability to monitor and understand carbon cycle changes critical to addressing global climate change. These high priority new measurements are:

- Forest canopy height and aboveground biomass
- Ocean color with high temporal resolution for coastal waters (geostationary orbit)
- Ocean salinity with higher spatial resolution than current missions
- CO_2 and CH_4 with improved coverage and sensitivity (constellations of passive and active LEO and passive GEO observations)

The atmosphere domain chapter has put forward an ambitious long-term goal for CEOS of operational LEO and GEO constellations measuring greenhouse gases in the atmosphere. This new suite of observations has the potential to be an essential element for future MRV systems.

The land and ocean domain chapters focus on filling particular gaps in current satellite observations, noting the important contributions specific new measurements would make to the existing continuity time series suites of observations. Highly accurate measurements of forest height and vertical structure from a profiling lidar sensor would complement current and planned radar missions (e.g., ESA's Biomass mission) and greatly reduce uncertainties in their estimates of aboveground biomass. Geostationary ocean color would enable quantification of carbon dynamics in coastal waters, where high temporal resolution is essential. These new observations, in combination with the continuity measurements for these two domains can also be viewed as virtual constellations that may in the future also need to transition to a more operational status.

6.2.2 Challenges and Actions Focused on Data Products, Processing, and Availability

This report identifies a strong need for CEOS actions to encourage, improve, and enhance the utility of many remote sensing data products. In some cases, individual space agencies may be able to take the action, but most will require the international coordination, cooperation, and agreement that only CEOS can provide. Of particular note in this regard are:

- Development of protocols for the generation of particular products and enforcement of requirements for clarity and traceability in product generation
- Development of guidelines for the specification of errors and uncertainties
- Intercomparison of similar products from existing and new missions to ensure globally consistent products and enable integrated (i.e., multisensor) products
- Efforts to make remote sensing data products consistent within domains (so that different products can be used together), across domains (so that the same variable can be integrated globally, e.g., land and ocean productivity, PAR over land and ocean), and with the requirements of intended uses (e.g., for modeling, policy applications)
- Ensure long-term continuity, consistency, archive, and availability of their data and facilitate joint agency activities, where appropriate

This report also calls for CEOS to encourage the development of new data products from existing missions. These include:

- Maps of wetlands, inundated areas and small water bodies
- Ocean color-type products for inland water bodies
- Ocean carbon pool products
- River discharge and sediments
- Merged time series products (same variable from differing sensors and platforms), in a product-based approach
- Anthropogenic fossil fuel emissions, including those from large point sources such as cities, power plants, and other industrial sources

Full availability and easy access to carbon observations from space is essential for carbon cycle research and carbon policy. Both science and policy require transparent data and data products that are well-documented, widely available, and easy to obtain and comprehend. CEOS can facilitate this by encouraging free and open data access policies and promoting best practices among its member agencies with respect to providing complete information about sensor performance and calibration, data processing methods, data quality assessments, and the characteristics, limitations, and utility of particular data products. CEOS should also promote the use and/or establishment of long-term data archives that will ensure valuable data products remain readily available for science and policy long after the mission or data product development activity ends.

6.2.3 Challenges and Actions Focused on Calibration and Validation

This report calls for CEOS actions to ensure satellite data are well calibrated and data products are validated. The CEOS Working Group on Calibration and Validation (WGCV) has excelled over the years in coordinating essential calibration and validation activities among the member agencies. Yet there is still new work to be done, and several substantive actions have been referred to the WGCV and its subgroups. Specific challenges and actions called for include:

- Encourage national and international organizations with responsibilities for *in situ* data to provide ground reference data for calibration and validation; CEOS should be supportive of efforts to establish, coordinate, and maintain observational networks (land, oceans and inland waters, and atmosphere) for this purpose
- Assess the quality of validation and coverage for data products in each domain and devise a strategy for improvement
- Establish a subgroup for validation of ocean carbon products analogous to the land product validation group
- Expand the number of land variables being addressed by the land validation subgroup
- Coordinate the cross calibration of all current and future satellites to measure atmospheric CO_2 and CH_4

6.2.4 Challenges and Actions Focused on Institutional Arrangements and Infrastructure

This report contains several recommendations for CEOS and its member agencies to engage with other groups and the carbon science community in order to improve communications and optimally address actions. These include:

- Interactions with the GEO Carbon Community of Practice (CCoP) and the GEO Blue Planet initiative to advance work on new products and data product intercomparisons
- Interactions with the carbon and climate modeling communities and CEOS Working Group on Climate in support of data-model intercomparisons
- Interactions with the GEO CCoP and other relevant scientific organizations to understand science needs and priorities for missing carbon measurements that satellites could provide beyond 2020

Joint workshops, reports, or other such activities are suggested as productive means of advancing on these interactions.

It was noted that satellite programs are dependent on the provision of quality *in situ* observations for calibration and validation as well as for the creation of data assimilation products merging satellite and *in situ* data. It is important that CEOS and its member agencies acknowledge this need and develop productive relationships with the providers of those data. Closer interactions could improve both the quality and suitability of the *in situ* data for satellite calibration and validation purposes.

6.3 Implementation of CEOS Strategy for Carbon Observations from Space

CEOS will need to establish specific mechanisms and assign responsibilities for overseeing, coordinating the implementation of, and reporting on the actions recommended in this report. In the interest of not proliferating groups and subgroups, many actions have been directed toward established CEOS Working Groups and Virtual Constellations when the activity is clearly within the scope of their CEOS *Terms of Reference*. Strong relationships and substantive interactions across these groups will be important. However, it seems essential that there be some CEOS entity with overall responsibility for progress toward meeting the space-based observation needs of an IGCO.

6.3.1 CEOS Oversight and Coordination of Carbon Observations from Space

Options that have been considered for CEOS oversight and coordination of carbon observations from space and implementation of the actions in this report include:

- The CEOS Carbon Task Force is re-constituted as a new CEOS Working Group;
- The CEOS WG Climate is assigned responsibility for carbon observations, perhaps being re-named as the CEOS Working Group on Carbon and Climate; or
- A Carbon Subgroup is established under the CEOS WG Climate to focus on carbon observations and the recommendations of this report, reporting to and through the CEOS WG Climate.

In order to avoid undue expansion of CEOS Working Groups and Virtual Constellations while ensuring adequate effort and attention are devoted to carbon observations and growing societal needs for reliable information about carbon, it is recommended that a Carbon Subgroup be established under the CEOS WG Climate. A new Virtual Constellation is undesirable because there would be too much overlap with several of the existing constellations (i.e., Land Surface Imaging, Ocean Color Radiometry, Atmospheric Composition, Sea Surface Temperature). At this time, it is not clear how the recent merger to create the CEOS-CGMS Working Group on Climate may affect the viability of this recommendation or the timeframe in which it could be considered/adopted by the new group. It is imperative that whatever option CEOS selects, it be made clear that carbon observations are a major priority and an integrated perspective (e.g., land-oceans and inland waters-atmosphere; science and policy, etc.) is required.

6.3.2 CEOS Reporting and Tracking of Actions

CEOS will need to establish specific mechanisms for tracking and reporting on the actions recommended in this report. It recommended that the CEOS Actions in this report be tracked in a way similar that for the *CEOS Response to the GCOS Implementation Plan (IP)*. At a minimum, there should be annual reporting through the WG Climate to the CEOS SIT and Plenary.

6.3.3 CEOS Interactions with the Scientific Community, GEO, and Other Organizations with Carbon-Related Responsibilities

The primary beneficiaries (i.e., stakeholders) of the carbon observations that are the focus of this report are the international carbon cycle science community, GEO, the UNFCCC, and the many other organizations interested in information about changes in carbon pools and fluxes within the Earth system. In order to ensure that carbon observations from space are maximally useful to and well utilized by these end users, CEOS must establish strong and sustained interactions with these stakeholders.

Regular interactions with GEO, the GEO CCoP, the GEO Blue Planet initiative, the Global Forest Observation Initiative (GFOI), and the Global Carbon Project (GCP) of the Earth Systems Science Partnership (ESSP) will be especially important. Regular communications with these other programs and organizations will be highly beneficial: Food and Agriculture Organization (FAO), Global Climate Observing System (GCOS), Global Terrestrial Observing System (GTOS), Global Ocean Observing System (GOOS), World Meteorological Organization (WMO), Global Atmosphere Watch (GAW) of WMO, the World Climate Research Programme (WCRP), the International Geosphere Biosphere Programme (IGBP), and Future Earth. Also to be encouraged are regular interactions with national carbon cycle science programs through the auspices of CEOS agencies.

CEOS should continue to work closely with GEO and include regular reporting on the status of carbon-related actions in these interactions. CEOS and should continue to identify and work closely together with GEO on shared tasks for carbon (e.g., currently the GEO CL-02 Task). CEOS and GEO should also consider joint conceptualization and endorsement of relevant workshops, conferences, and special activities.

CEOS should act to ensure that space-based observations and the data products and information derived from them are made readily available in clear and understandable ways to the policy makers developing and implementing climate mitigation and adaptation policies. This could involve the facilitation of special reports, customized data products, or special meetings or side events at UNFCCC meetings.

6.4 Way Forward Recommendations and CEOS Actions

6.4.1 Mission-Related Recommendations

Overall Motivation/Rationale-16: In order to derive the maximum scientific and societal benefits from future satellite missions focused on carbon-relevant measurements, confirmed missions for continuity and new carbon data products must be launched as planned, and priority new missions should be confirmed as soon as required processes and resources permit. CEOS can identify any opportunities to develop additional items in support of these existing planned missions as joint activities and coordinate the planning of future satellite missions so as to optimize coverage, sampling, and utility of data products, adopting a virtual (or actual) constellation approach, when applicable.
Carbon-Challenge-15: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the timely confirmation and launch of carbon-related missions and provision of optimized carbon data products. For missions with similar objectives and being developed to fly in the same timeframe, CEOS will encourage coordination of mission attributes so that observations are made in ways that optimize areal coverage, time and space

sampling, and/or accuracy. For missions with similar objectives that may follow one another in time, CEOS will encourage coordination of mission and data attributes so that the multiple data streams are compatible and can be integrated to create a consistent time series over a longer time period than any single mission alone could achieve.

6.4.2 Calibration/Validation-Related Recommendations

Overall Motivation/Rationale-7: The *GEO Carbon Strategy* calls for robust carbon tracking and accurate carbon budgets, and these major products require quantitative analysis of changes in Earth system carbon properties over time. This in turn requires well-calibrated satellite sensors and well-validated data products. Development of specific remote sensing products often requires use of surface reference data sets. In some cases, land-based networks have been developed to provide *in situ* data for validation of specific products (e.g., soil moisture, atmospheric CO_2), where in others, networks either need expansion or considerable development (such as biomass dynamics). For the ocean, this requires global-scale validation of algorithms for estimating ocean carbon pools from satellite data, in carbon units, in close collaboration with *in situ* observation systems. It is also necessary to provide adequate error characterization of remote sensing variables and carbon products derived from satellite data, ideally on a pixel-by-pixel basis, to ensure their appropriate use in quantifying and modeling carbon dynamics. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure *in situ* data are accessible to the satellite community for validation of satellite data products. The CEOS WGCV and its relevant subgroups have conducted and coordinated much-needed calibration and validation work over the years, and this work needs to continue and be expanded. The CEOS VCs are also conducting valuable work in this area. There is a need to strengthen mechanisms within CEOS and at the individual space agency level, in particular investment as part of satellite development, for product validation to establish validation methodologies, protocols and benchmark datasets. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure *in situ* data are accessible to the satellite community.

Carbon-Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its individual space agency members, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.

6.4.3 CEOS Mechanisms- and Future Planning-Related Recommendations

Overall Motivation/Rationale-23: In order for CEOS to act effectively on the findings and recommendations of this report, a responsible CEOS entity must be identified. The responsible entity must establish strong working relationships with all relevant VCs and CEOS Working Groups, especially the WG Climate and WGCV.

Carbon-Action-38: CEOS will establish a group to be responsible for carbon activities within CEOS and for advancing the findings and recommendations of this report. This group will take responsibility for overseeing, coordinating, and reporting on the actions identified in this report. It is recommended that CEOS establish a Carbon Subgroup within the CEOS WG on Climate as a most efficient way of implementing this action (this recommended group will hereafter be referred to as the "Carbon Subgroup"). The Carbon Subgroup will report to (and through) the WG Climate. It will establish strong working relationships with all relevant VCs and CEOS WGs, especially the WGCV.

Overall Motivation and Rationale-25: In order for CEOS to act effectively on the findings and recommendations of its *Strategy for Carbon Observations from Space*, regular follow-up and reporting on progress made in implementation will be essential.
Carbon-Action-41: The CEOS Carbon Subgroup will report to the CEOS WG Climate. It will track and report upon progress in responding to the actions in the *CEOS Strategy for Carbon Observations from Space* in a manner similar to that for the *CEOS Response to the GCOS Implementation Plan (IP)*, which includes at a minimum annual reporting by the Carbon Subgroup through the WG Climate to the CEOS SIT and Plenary.

Overall Motivation/Rationale-24: There is a strong need for CEOS to better understand and further prioritize the needs of the carbon community for space-based measurements in the context of time (2015-2020-2025) and space (i.e., needs for increased resolution) and then to reinforce multi-agency planning and preparation for satellites, as coordinated through the CEOS Carbon Subgroup (recommended in Carbon-Action-38) and relevant VCs to ensure that these priority observations are made in the future. It will be important to identify the priority missing components for emissions/stock assessment that are capable of being addressed with satellite data sources. Also, the *GEO Carbon Strategy* does not provide the level of detail for measurement specifications or observation attributes necessary for a space agency to design a mission or verify if a current or planned sensor can provide adequate data. These specifications, custom for carbon -- and especially when they differ from those for the ECVs -- are urgently needed.
Carbon-Challenge-20: CEOS acknowledges this challenge and will engage the carbon science and policy communities to develop a more refined understanding of requirements and priorities for carbon-related measurements from space. CEOS recognizes this will require coordination with GEO, IGBP, Future Earth, and other relevant international organizations.
Carbon-Action-39: CEOS and individual CEOS Agencies will sponsor (or co-sponsor) work (e.g., one or more workshops, a written report) to 1) develop more specific measurement requirements for continuing and new carbon observations from space that will fulfill science and policy needs and 2) encourage further prioritization of these measurements.
Carbon-Action-40: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will lead in the planning for activities to 1) develop more specific measurement requirements for continuing and new carbon observations from space that will fulfill science and policy needs and 2) encourage further prioritization of these measurements. It will work, in consultation with the relevant VCs, to coordinate the incorporation of the refined requirements and priorities into multi-agency planning and preparation for future satellites.

Overall Motivation/Rationale-26: This report poses contextual Challenges that identify important missions, data products and activities necessary for a useful IGCO. While none of these are within CEOS' and/or CEOS Agencies' capacity to address wholly, it is desirable to maintain attention on these needs, periodically assess progress, and ask if there are things CEOS can do to facilitate further progress.
Carbon-Action-42: CEOS will periodically (approximately every 3-5 years) assess progress toward meeting the challenges identified in this report. This may be accomplished through a variety of means, including but not limited to workshops, *ad hoc* studies, or discussions within or among relevant CEOS WGs and VCs.

6.5 Conclusions

The *GEO Carbon Strategy* has detailed an ambitious set of requirements for observations of the global carbon cycle. CEOS is well-positioned to coordinate the response of the world's space agencies to meeting these requirements for space-based observations as well as emerging requirements in support of climate mitigation and carbon management policies. The challenges in doing so for carbon mirror those acknowledged in the 2006 CEOS response to the GCOS Implementation plan for climate, and the following articulation of findings for this report borrows from and echoes that of this earlier CEOS response.

CEOS recognizes that the GEO requirements for carbon observations from space are well-conceived and technically feasible, but challenging in terms of a complete, sustained, and coordinated response. They provide an incentive for the CEOS member agencies to improve the ways in which multi-agency coordination on carbon-related observations is prioritized, agreed-upon, funded, implemented, and tracked. In addition to coordination of existing and future satellite mission capabilities, CEOS agencies must devote additional attention to data processing; data quality and accessibility; development and production of new data products; improved, better coordinated, and transparent calibration and validation work; and securing long-term archival of valuable products for carbon and climate science and policy. Additional resources, and in some cases mandates, beyond current capacities will be needed. CEOS recognizes it will take time and political will to achieve these objectives and that they cannot be pursued in isolation from other Earth system science priorities (e.g., observations of natural hazards, water resources, other aspects of climate, etc.).

To address these challenges and actions, the following way forward is proposed:

- CEOS and its member agencies make note of the important and wide-ranging challenges and actions identified in this report. They will work within their own capacities and with their governing bodies to identify and secure the resources that are required to implement the actions and meet the long-term challenges.
- CEOS identifies a group to be responsible for carbon-related observations within CEOS and for advancing the findings of this report. This group will take responsibility for overseeing, coordinating, and reporting on the actions identified in this report and will establish strong working relationships with relevant CEOS Virtual Constellations and Working Groups.
- CEOS works with GEO, GCOS, UNFCCC and other relevant bodies to strengthen understanding, communications, and cooperation on carbon observations for science and policy.
- CEOS recognizes the importance of periodically assessing progress and reporting on actions and will establish internal (to CEOS) procedures for these purposes and will also report to relevant external bodies, as appropriate and when requested.

In summary, CEOS is pleased to offer this response to the *GEO Carbon Strategy* and thanks GEO and the Parties supporting the space agencies for this opportunity to respond to GEO's requirements. CEOS will work with GEO, the UNFCCC, and its sponsoring Parties to implement the actions called for in this report and to strengthen communications and cooperation in support of these shared objectives. CEOS welcomes feedback on this response.

Table 6-1. Summary of all Challenges and CEOS Actions. The columns of this table summarize, in order from left to right: the Challenges posed for CEOS, the CEOS Actions, when the action needs to occur (near-term (1-3 years), mid-term (4-6 years), far-term (7-10 years), or ongoing); the responsible CEOS entity; supporting CEOS entities, external organizations with which coordination is highly desirable; sections and pages in the *GEO Carbon Strategy* that call for the missions and products listed; and GCOS ECVs that are relevant. They are in order by type of recommendation, specifically, those related to: missions, products, calibration/validation, interactions/linkages/communications, and CEOS mechanisms and future planning. (Acronyms used in this table are defined in Appendix B.)

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
Mission-Related Challenges and Actions:							
Challenge-1: CEOS acknowledges the challenge to provide accurate measurements of forest canopy height and estimates of aboveground biomass and will influence and coordinate the activities of its Member Agencies toward this goal.CEOS Agencies will consider efforts to provide the needed lidar data and/or interferometric SAR data (i.e., by considering a new satellite mission and/or by cooperating to assemble existing airborne lidar data and making it available for validation of satellite SAR height and biomass data products).	Action-1: CEOS Member Agencies with interests in missions and data products for forest canopy height and aboveground biomass will sponsor or co-sponsor one or more workshops (and require a written report) to define the scientific and policy requirements to quantify aboveground carbon storage in vegetation. These meetings should involve the key international science, applications, and remote sensing communities in specifying the technical foundation and scientific requirements for as well as the societal benefits of future missions to quantify aboveground carbon storage in vegetation globally. The workshops should consider these requirements in the context of the added value to be derived from coordinated mission planning and associated data compilation activities both in the future and by exploiting archive data.	Near-Term	CEOS Member Agencies	Carbon Subgroup; WG Climate	GEO CCoP	Section 4.6, p. 24	Above-ground biomass
Challenge-2: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies so that high-quality, well-calibrated continuity satellite measurements of land cover, land cover change, disturbance, fires, LAI, FAPAR, wetlands, and permafrost are available to estimate carbon pools and fluxes, data gaps are avoided, and satellites flying at the same time, in constellations, and in time series are cross-calibrated and well-validated.	Action-2: The relevant CEOS VCs and CEOS WG Climate will act to include IGCO priorities for continuity carbon-related observations of the land surface from space in their respective activities to coordinate the VCs and climate-related measurements.	Ongoing	All relevant VCs and WG Climate	CEOS SIT and Plenary		Executive Summary, p.7; Section 3.2.4, p. 13	Land cover, FAPAR, LAI, Fire disturbance, Permafrost, Soil moisture (for wetlands)?, River discharge, Lakes, Snow cover

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
Challenge-9: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies so that high-quality, well-calibrated, moderate-resolution continuity measurements of ocean color, sea surface temperature, surface winds, salinity, sea state, currents and eddies, sea ice extent and ice edge structure are available, data gaps are avoided, and satellites flying at the same time, in constellations, and in time series are cross-calibrated and well-validated. CEOS notes that these requirements are commensurate with corresponding GCOS requirements.	Action-10: The relevant CEOS VCs and CEOS WG Climate will act to include IGCO priorities to extend the time series of moderate-resolution carbon-related observations of the open ocean from space into their respective activities to coordinate the VCs and climate-related measurements.	Ongoing	All relevant VCs (OCR, SST, OSVW); WG Climate; WGCV IVOS	CEOS Member Agencies	WMO; WCRP	Executive Summary, p.7; Section 3.2.4, p. 13	Ocean color, SST, SSS, pCO_2, Phytoplankton, Aerosol, Ocean acidity, Sea state, Sea ice, Surface current
Challenge-10: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Member Agencies so that high-quality continuity satellite measurements of coastal waters, with appropriate spatial, temporal and spectral sampling properties, are available for ocean carbon science.	Action-11: The relevant CEOS VCs and CEOS WG Climate will act to include IGCO priorities for continuity in high-resolution (better than 0.5 km) carbon-related observations of coastal waters from space in their respective activities to coordinate the VCs and climate-related measurements, noting the higher temporal and spatial resolutions and spectral coverage required, compared with open-ocean measurements.	Ongoing	Ocean-related VCs (OCR, SST, OSVW) and WG Climate	CEOS Member Agencies		Section 4.6, p. 24	Ocean color, SST, SSS, pCO_2, Phytoplankton, Aerosol, Ocean acidity, Sea state, Surface current *(note the additional spatial and temporal resolutions needed are finer than GCOS requirements)*

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
Challenge-11: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the development and deployment of new satellite mission types to provide new information on phytoplankton functional types, phytoplankton carbon by type, detritus, particulate carbon, and aerosols, and 2) provide higher spatial, temporal, and spectral resolution data for coastal and inland waters.	Action-12:CEOS Member Agencies with interests in and/or mandates for developing and deploying new types of satellite missions to provide 1) new information on phytoplankton functional types, phytoplankton carbon by type, detritus, particulate carbon, and aerosols, and/or 2) higher spatial, temporal, and spectral resolution data for coastal and inland waters will coordinate their efforts in consultation with relevant CEOS WGs and VCs.	Mid- to Far-Term	CEOS Member Agencies (especially Eumetsat, NOAA, JAXA, ISRO, NASA)	All relevant VCs (especially OCR); WGCV IVOS; and WG Climate	IOCCG	Section 4.6, p. 24	Ocean color, pCO_2, Phytoplankton, Aerosol, Ocean acidity *(note higher frequency of temporal coverage is more stringent that that of GCOS)*
Challenge-12: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the development and deployment satellites to extend the time series of measurements of sea surface salinity and to improve their spatial resolution in the future.	Action-13: CEOS Member Agencies with interests in and/or mandates for developing and deploying new satellites to measure ocean salinity will coordinate their efforts in consultation with relevant CEOS WGs and VCs.	Mid- to Far-Term	CEOS Member Agencies, especially ESA and NASA	All relevant VCs and WG Climate		Section 4.6, p. 24	SSS *(note need for higher spatial resolution)*
Challenge-13: CEOS acknowledges the challenge to achieve a LEO constellation of satellites to measure atmospheric CO_2 and CH_4, with appropriate coverage and sensitivity, and will influence and coordinate the activities of its Member Agencies toward this goal.	Action-16: CEOS Member Agencies with interests in CO_2- and CH_4-measuring LEO missions will sponsor or co-sponsor one or more workshops (and require a written report) to refine the scientific and policy requirements for quantitative data on atmospheric CO_2 and CH_4 from low Earth orbit. These meetings should involve the key international science and applications communities in specifying the technical foundation and scientific requirements for as well as the societal benefits of future missions to quantify atmospheric CO_2 and CH_4 from low earth orbit.	Near-Term	CEOS Member Agencies	Atmospheric Composition VC; WG Climate, especially the Carbon Subgroup	GEO CCoP; CGMS; WMO GAW	Section 4.5, p. 14-18; Section 5.1.4, p. 26	CO_2, CH_4 *(required accuracies differ from those of GCOS)*

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
Challenge-13: CEOS acknowledges the challenge to achieve a LEO constellation of satellites to measure atmospheric CO_2 and CH_4, with appropriate coverage and sensitivity, and will influence and coordinate the activities of its Member Agencies toward this goal.	Action-17: The CEOS Atmospheric Composition VC will coordinate the detailed planning and preparation for a constellation of passive and active remote sensing instruments to measure CO_2 and CH_4 from low Earth orbit with the higher spatial and temporal resolution and accuracy needed to monitor carbon sources and sinks.	Near- to Mid-Term	Atmospheric Composition VC	WG Climate, especially the Carbon Subgroup	GEO CCoP; CGMS; WMO GAW	Section 4.5, p. 14-18; Section 5.1.4, p. 26	CO_2, CH_4 *(required accuracies differ from those of GCOS)*
Challenge-14: CEOS acknowledges the challenge to achieve a geostationary constellation of satellites to measure atmospheric CO_2 and CH_4, with appropriate coverage and sensitivity, and will influence and coordinate the activities of its Member Agencies toward this goal.	Action-18: CEOS Member Agencies with interests in CO_2- and CH_4-measuring GEO missions will sponsor or co-sponsor one or more workshops (and require a written report) to refine the scientific and policy requirements for quantitative data on atmospheric CO_2 and CH_4 from geostationary Earth orbit. These meetings should involve the involve the broad, international science and applications communities in advancing the technical foundation and scientific requirements for as well as the societal benefits of future missions to quantify atmospheric CO_2 and CH_4 from geostationary orbit.	Mid-Term	CEOS Member Agencies	Atmospheric Composition VC; WG Climate, especially the Carbon Subgroup	GEO CCoP; CGMS; WMO GAW	Section 4.5, p. 14-18; Section 5.1.4, p. 26	CO_2, CH_4 *(required accuracies differ from those of GCOS)*
Challenge-14: CEOS acknowledges the challenge to achieve a geostationary constellation of satellites to measure atmospheric CO_2 and CH_4, with appropriate coverage and sensitivity, and will influence and coordinate the activities of its Member Agencies toward this goal.	Action-19: The CEOS Atmospheric Composition VC will coordinate the detailed planning and preparation for a constellation of passive remote sensing instruments to measure CO_2 and CH_4 from geostationary orbit covering all longitudes with the spatial and temporal resolution and accuracy needed to monitor carbon sources and sinks.	Mid- to Far-Term	Atmospheric Composition VC	WG Climate, especially the Carbon Subgroup	GEO CCoP; CGMS; WMO GAW	Section 4.5, p. 14-18; Section 5.1.4, p. 26	CO_2, CH_4 *(required accuracies differ from those of GCOS)*

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
Challenge-15: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the timely confirmation and launch of carbon-related missions and provision of optimized carbon data products. For missions with similar objectives and being developed to fly in the same timeframe, CEOS will encourage coordination of mission attributes so that observations are made in ways that optimize areal coverage, time and space sampling, and/or accuracy. For missions with similar objectives that may follow one another in time, CEOS will encourage coordination of mission and data attributes so that the multiple data streams are compatible and can be integrated to create a consistent time series over a longer time period than any single mission alone could achieve.			CEOS SIT and Plenary	CEOS Member Agencies; All relevant VCs	GEO		
Challenge-16: CEOS acknowledges this challenge and will encourage its Member Agencies to engage the carbon science and policy communities in their mission identification, review, selection, and implementation processes to the fullest extent possible.			CEOS SIT and Plenary	CEOS Member Agencies	GEO CCoP, IGBP, Future Earth		

Product-Related Challenges and Actions:

Challenge-3: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the continuity and systematic improvement of moderate-resolution (~250 m - 1 km) satellite time series data products.	Action-3: CEOS Agencies with historical moderate-resolution (~250 m - 1 km) satellite data records will strive to ensure these data are publicly available and used to create the moderate-resolution (~250 m - 1 km) records of land properties over the historical satellite record that are useful for carbon science. They will coordinate their efforts with relevant CEOS WGs and VCs.	Ongoing	CEOS Agencies	All relevant VCs (especially LSI) and WGs; SDCG	GOFC-GOLD	Executive Summary, p.7; Section 3.2.4, p. 13	Land cover, FAPAR, LAI, Fire disturbance, Permafrost, Soil moisture (for wetlands)?, Snow cover

Contextual Challenge	**CEOS Action**	**Term for Action**	**Responsible CEOS Entity**	**Supporting CEOS Entity(ies)**	**Desirable External Coordination**	***GEO Carbon Strategy***	**Relevant GCOS ECV**
Challenge-4: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the continuity and systematic improvement of historic medium-resolution (~30 - 100 m) satellite time series data products.	Action-4: CEOS Agencies with historical medium-resolution (~30 m -100 m) satellite data records will strive to ensure these data are publicly available and used to create the medium-resolution records of land properties useful for carbon science over the historical satellite record. They will coordinate their efforts with relevant CEOS WGs and VCs.	Ongoing	CEOS Agencies	All relevant VCs (especially LSI) and WGs; SDCG	GOFC-GOLD	Executive Summary, p.7; Section 4.6, p. 23-24	Land cover, FAPAR, LAI, Fire disturbance, Permafrost
Challenge 5: CEOS acknowledges this challenge and will influence and coordinate the activities of the CEOS Member Agencies toward the continuity and systematic improvement of long time series of multi-sensor, multi-mission data products.	Action-5: CEOS Agencies with interests in and/or mandates for developing multi-sensor, multi-mission time series data products for the land and ocean will strive to ensure consistent, well-calibrated, bias-free satellite time-series carbon products are produced and continued into the future. They will coordinate their efforts in consultation with relevant CEOS WGs and VCs to ensure appropriate merging of data and products from multiple sensors.	Ongoing	CEOS Agencies	All relevant VCs (OCR, SST, LSI); WGCV IVOS; WG Climate; SDCG	IOCCG, GFOI	Executive Summary, p.7; Section 3.2.4, p. 13	Land cover, FAPAR, LAI, Fire disturbance, Permafrost, Soil moisture (for wetlands)?, Snow cover, Ocean color, SST, SSS, pCO_2, Phytoplankton, Sea state, Surface current, Sea ice, Aerosol, CO_2, CH_4

Contextual Challenge	**CEOS Action**	**Term for Action**	**Responsible CEOS Entity**	**Supporting CEOS Entity(ies)**	**Desirable External Coordination**	***GEO Carbon Strategy***	**Relevant GCOS ECV**
Challenge-6: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the continuing deployment of satellites and development of satellite data products for mapping wetlands, wetland types, wetland inundation, rivers, flooding, reservoirs, lakes, and ponds and estimating their associated carbon-related biophysical properties (e.g., dissolved and particulate carbon, river discharge) and biological productivity. CEOS will encourage its Member Agencies to coordinate the launch of satellites that meet requirements in a timely fashion and to avoid gaps. CEOS Agencies will strive to implement projects to develop these essential wetland and inland water data products at regional and global scales and with appropriate spatial and temporal resolutions and sensitivities to the carbon constituents in inland waters.	Action-6: Individual CEOS Agencies with interests in and/or mandates for developing 1) satellites to observe wetlands and inland waters and 2) wetland and inland water data products will coordinate their efforts in consultation with relevant CEOS WGs and VCs.	Near-Term	Individual CEOS Agencies	All relevant VCs (especially LSI)and WGs, especially Carbon Subgroup	GEO CCoP; GEO Water Strategy; GEO IGWCO theme	Section 3.2.3, p. 12-13; Section 5.5, p. 35-36	Lakes, river discharge, soil moisture (for wetlands)? *(note the higher spatial and spectral resolutions as compared with the GCOS requirements)*
Challenge-17: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies so that issues that transcend traditional scientific domains are not overlooked. CEOS will foster communications across CEOS in recognition of the need to support understanding of three-domain coupling of the carbon cycle and strong carbon-climate coupling in the Earth system.	Action-21: The CEOS Carbon Subgroup (recommended in Action-38) will coordinate with other relevant CEOS WGs and VCs to ensure that the carbon observations and data products that transcend traditional scientific domains (e.g. black carbon, nutrient fertilization) are accorded appropriate priority in CEOS activities and future plans and that key satellite products to permit scientific studies of these phenomena are produced and made available.	Mid-Term	Carbon Subgroup	WGs and VCs	GEO CCoP, IGBP		

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
	Action-22: CEOS Agencies engaged in development of carbon products will coordinate to achieve compatibility, comparability and consistency of carbon products across all relevant domains (land, oceans and inland waters, and atmosphere, as appropriate), in consultation with relevant CEOS VCs and WGs.	Ongoing	CEOS Agencies	WGs and All relevant VCs	GEO CCoP, IGOS, IOCCP, GHRSST, IOCCG, WCRP-SPARC, IGBP, IGAC, GTOS, National and international *in situ* networks	Section 3, p. 11	Land cover, FAPAR, LAI, Fire disturbance, Permafrost, Soil moisture (for wetlands)?, Snow cover, Ocean color, SST, SSS, pCO_2, Phytoplankton, Sea state, Sea ice, Surface current, Aerosol, CO_2, CH_4
Challenge-18: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies so that improved information on natural and anthropogenic emissions of carbon (CO_2, CH_4, but also CO and black carbon) is produced and made publicly available.	Action-23: Individual CEOS Agencies with interests in and/or mandates for providing improved information on natural and anthropogenic emissions of carbon (CO2, CH4, CO and black carbon) will coordinate their efforts in consultation with relevant CEOS WGs and the Atmospheric Composition VC.	Near- to Mid-Term	Individual CEOS Agencies	Atmospheric Composition and LSI VCs, WGs, especially Carbon Subgroup	GEO CCoP; National agencies responsible for emissions monitoring and reporting	Section 1, p. 8; Section 3.2.4, p. 13 and Section 5.4, p. 34-35	CO_2, CH_4
Challenge 5: CEOS acknowledges this challenge and will influence and coordinate the activities of the CEOS Member Agencies toward the continuity and systematic improvement of long time series of multi-sensor, multi-mission data products.	Action-24: The CEOS Carbon Subgroup (recommended in Action-38) will work to encourage the production and availability of high-quality, consistent long time series data products based on multiple sensors and missions for carbon and climate science and for model-data and data-data intercomparison exercises.	Ongoing	Carbon Subgroup	WGs and VCs; CEOS Agencies	GEO CCoP; IGBP	Executive Summary, p.7; section 3.2.4, p. 13	Land cover, FAPAR, LAI, Fire disturbance, Permafrost, Soil moisture (for wetlands)?, Snow cover, Ocean color, SST, SSS, pCO_2, Phytoplankton, Sea state, Sea ice, Surface current, Aerosol, CO_2, CH_4

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
Challenge 5: CEOS acknowledges this challenge and will influence and coordinate the activities of the CEOS Member Agencies toward the continuity and systematic improvement of long time series of multi-sensor, multi-mission data products.	Action-25: The CEOS Carbon Subgroup (recommended in Action-38) and relevant VCs will provide periodic technical information to the research and operational space agencies regarding readiness for and issues regarding transitions from research to operations for long-time series carbon observations.	Mid-Term, then ongoing	Carbon Subgroup; All relevant VCs	WG Climate, relevant VCs	GEO CCoP, CGMS	Executive Summary, p.7; section 3.2.4, p. 13	Land cover, FAPAR, LAI, Fire disturbance, Permafrost, Soil moisture (for wetlands)?, Snow cover, Ocean color, SST, SSS, pCO_2, Phytoplankton, Sea state, Sea ice, Surface current, Aerosol, CO_2, CH_4
Challenge-19: CEOS acknowledges the challenges to see that products derived from different satellite sensors to represent the same carbon-related property are consistent and compatible with each other and that requirements for clarity and traceability in products are followed. When there are differences in the products (whether it be in the methods used, in the underlying assumptions, or in the applicability of the results), the documentation provided must help users to understand them. CEOS will use its influence to encourage CEOS Agencies toward this goal.	Action-26: The CEOS Carbon Subgroup (recommended in Carbon-Action-38), in consultation with the CEOS WGCV, will encourage comparison of protocols for the generation of carbon products from satellite data and and recommend adoption of the best protocols by CEOS agencies to ensure long-term consistent datasets relevant to carbon cycle community needs. This work shall include accounting for ancillary data dependence (e.g., land cover, aerosol, cloud, DEM, reanalysis products, etc.) such that there is consistency across individual products and variables.	Near- to Mid-Term	Carbon Subgroup	WGCV; other WGs; all relevant VCs			Land cover, FAPAR, LAI, Fire disturbance, Permafrost, Soil moisture (for wetlands)?, Snow cover, Ocean color, SST, SSS, pCO_2, Phytoplankton, Sea state, Sea ice, Surface current, Aerosol, CO_2, CH_4

Contextual Challenge	**CEOS Action**	**Term for Action**	**Responsible CEOS Entity**	**Supporting CEOS Entity(ies)**	**Desirable External Coordination**	***GEO Carbon Strategy***	**Relevant GCOS ECV**
Challenge-19: CEOS acknowledges the challenges to see that products derived from different satellite sensors to represent the same carbon-related property are consistent and compatible with each other and that requirements for clarity and traceability in products are followed. When there are differences in the products (whether it be in the methods used, in the underlying assumptions, or in the applicability of the results), the documentation provided must help users to understand them. CEOS will use its influence to encourage CEOS Agencies toward this goal.	Action-27: CEOS Agencies will make publicly available all information necessary to document the accuracy, clarity, and traceability of the satellite data and data products they produce.	Ongoing	CEOS Agencies	WG Climate and WGCV			Land cover, FAPAR, LAI, Fire disturbance, Permafrost, Soil moisture (for wetlands)?, Snow cover, Ocean color, SST, SSS, pCO_2, Phytoplankton, Sea state, Sea ice, Surface current, Aerosol, CO_2, CH_4
Challenge-19: CEOS acknowledges the challenges to see that products derived from different satellite sensors to represent the same carbon-related property are consistent and compatible with each other and that requirements for clarity and traceability in products are followed. When there are differences in the products (whether it be in the methods used, in the underlying assumptions, or in the applicability of the results), the documentation provided must help users to understand them. CEOS will use its influence to encourage CEOS Agencies toward this goal.	Action-28: CEOS Agencies will coordinate their efforts to develop compatible (e.g., temporal and spatial resolution, grids, data formats, common auxiliary data, units) carbon data products from multiple missions, in consultation with relevant CEOS WGs and VCs.	Ongoing	CEOS Agencies	WGs and relevant CVs	GEO CCoP; IOCCG; GHRSST		Land cover, FAPAR, LAI, Fire disturbance, Permafrost, Soil moisture (for wetlands)?, Snow cover, Ocean color, SST, SSS, pCO_2, Phytoplankton, Sea state, Sea ice, Surface current, Aerosol, CO_2, CH_4

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
Challenge-19: CEOS acknowledges the challenges to see that products derived from different satellite sensors to represent the same carbon-related property are consistent and compatible with each other and that requirements for clarity and traceability in products are followed. When there are differences in the products (whether it be in the methods used, in the underlying assumptions, or in the applicability of the results), the documentation provided must help users to understand them. CEOS will use its influence to encourage CEOS Agencies toward this goal.	Action-29: The CEOS Carbon Subgroup (recommended in Action-38) will develop guidelines for the specification of uncertainty in products, from signal counts through the various CEOS Processing Levels.	Near- to Mid-term	Carbon Subgroup	WGCV	GEO CCoP; IOCCG; GHRSST		Land cover, FAPAR, LAI, Fire disturbance, Permafrost, Soil moisture (for wetlands)?, Snow cover, Ocean color, SST, SSS, pCO_2, Phytoplankton, Sea state, Sea ice, Surface current, Aerosol, CO_2, CH_4
Challenge-19: CEOS acknowledges the challenges to see that products derived from different satellite sensors to represent the same carbon-related property are consistent and compatible with each other and that requirements for clarity and traceability in products are followed. When there are differences in the products (whether it be in the methods used, in the underlying assumptions, or in the applicability of the results), the documentation provided must help users to understand them. CEOS will use its influence to encourage CEOS Agencies toward this goal.	Action 30: CEOS Agencies will ensure the long-term accessibility of satellite data and data products for carbon cycle science and policy. This must include arrangement for secure archives, documentation, and metadata as well as provisions for easy discovery and access by the carbon science and policy communities.	Ongoing	CEOS Agencies	WG Climate			Land cover, FAPAR, LAI, Fire disturbance, Permafrost, Soil moisture (for wetlands)?, Snow cover, Ocean color, SST, SSS, pCO_2, Phytoplankton, Sea state, Sea ice, Surface current, Aerosol, CO_2, CH_4

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
Calibration / Validation-Related Challenges and Actions:							
Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its Member Agencies, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.	Action-7: CEOS and CEOS Agencies will encourage national and international agencies to improve and expand upon the availability of the *in situ* observations needed for the calibration and validation of satellite land data products used for carbon science. This will include coordinating with national and international agencies collecting *in situ* data to 1) assess the quality and coverage (spatial and temporal) of validation data and 2) employ design features that entice data sharing and provide safeguards.	Ongoing	CEOS and CEOS Agencies	WGCV; IVOS Subgroup; WG Climate, especially the Carbon Subgroup	GEO, National and international sponsors of relevant *in situ* measurement programs; GTOS	Section 3, p. 11	
Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its Member Agencies, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.	Action-8: The CEOS WGCV's Land Product Validation (LPV) Subgroup will continue its work to validate satellite land data products and expand the number of land variables addressed as priorities are identified and available resources permit, and where no other body takes responsibility (e.g., GOFC-GOLD).	Near-Term	LPV Subgroup of WGCV	WGCV; IVOS Subgroup; WG Climate, especially the Carbon Subgroup	GOFC-GOLD	Section 3, p. 11	
Challenge-8: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the systematic intercomparison of satellite data products of relevance to the carbon cycle. CEOS Agencies will participate, as appropriate, in major intercomparison activities, including model-data, data-data, and multiple data stream intercomparisons. CEOS recognizes that intercomparison activities will require coordination with relevant non-CEOS organizations and activities.	Action-9: CEOS WGCV and its relevant subgroups, in consultation with the CEOS Carbon Subgroup (recommended in Carbon-Action-38), will organize and coordinate carbon data product intercomparison activities as they are identified as priorities for CEOS action and in coordination with the wider carbon cycle science community.	Ongoing	WGCV; Carbon Subgroup	WG Climate; relevant VCs; CEOS Agencies	GEO, IPCC, IGBP, GOFC-GOLD	Section 3, p. 11	

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its Member Agencies, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.	Action-14: The CEOS WGCV, in close consultation with the relevant VCs (that are doing some of this work now), will establish a subgroup dealing with validation and error characterization of ocean carbon-relevant products analogous to the Land Product Validation Subgroup.	Near-Term	WGCV; CEOS SIT and Plenary	Ocean-related VCs (OCR, SST); WGCV IVOS; WG Climate	GEO Blue Planet initiative; IOCCG; GHRSST	Section 3, p. 11	
Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its Member Agencies, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.	Action-20: The CEOS Atmospheric Composition VC, in cooperation with the CEOS WGCV Atmospheric Composition Subgroup, will provide coordination and support for the cross calibration of all satellite CO2- and CH4-measuring sensors, coordinate their observations, and cross validate their CO2 and CH4 products against accepted international standards, so that they can be integrated into single continuous global climate record.	Ongoing	Atmospheric Composition VC and WGCV Atmospheric Composition Subgroup	CEOS Member Agencies, especially JAXA, NASA, and ESA; WG Climate	*In situ* atmospheric measurement networks (e.g., TCCON, CCGG Cooperative Air Sampling Network, WMO GAW)	Section 3, p. 11	
Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its individual space agency members, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.	Action-31: CEOS through its WGCV and relevant VCs will strengthen its mechanisms for product validation by establishing validation methodologies, protocols and benchmark datasets.	Near- to Mid-Term	CEOS SIT and Plenary	WGCV; relevant VCs	*In situ* measurement programs (e.g., GAW, Argo, FluxNet, CCGG Cooperative Air Sampling Network, TCCON)	Section 3, p. 11	

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its individual space agency members, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.	Action-32: For each of the relevant variables in each of the domains CEOS will work with the carbon science community to assess the current provision of validation data in terms of quality (defined by protocols (e.g., WGCV LAI protocol) and or maturity matrices (e.g., WG Climate)) and spatial and temporal coverage. This work should identify potential additional sources and develop a strategy to improve global in situ data distributions in relation to satellite validation and model parameterization. It should also exploit existing infrastructures to develop key intensive collection sites.	Ongoing	CEOS SIT and Plenary	WG Climate, especially its Carbon Subgroup; WGCV	GEO CCoP; *In situ* measurement programs (e.g., GAW, Argo, FluxNet, CCGG Cooperative Air Sampling Network, TCCON)	Section 3, p. 11	
Challenge-8: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the systematic intercomparison of satellite data products of relevance to the carbon cycle. CEOS Agencies will participate, as appropriate, in major intercomparison activities, including model-data, data-data, and multiple data stream intercomparisons. CEOS recognizes that intercomparison activities will require coordination with relevant non-CEOS organizations and activities.	Action-33: CEOS will reinforce the mechanisms already in place in CEOS for all domains (WGCV, and VCs, and WG Climate) and clarify their responsibilities to ensure intercomparison activities are well-coordinated and effective.	Near-Term	CEOS SIT and Plenary	WGCV; WG Climate, and relevant CVs	GEO, IGBP, IPCC	Section 3, p. 11	
Challenge-8: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the systematic intercomparison of satellite data products of relevance to the carbon cycle. CEOS Agencies will participate, as appropriate, in major intercomparison activities, including model-data, data-data, and multiple data stream intercomparisons. CEOS recognizes that intercomparison activities will require coordination with relevant non-CEOS organizations and activities.	Action-34: Individual CEOS Agencies producing the same (or similar) carbon data products will cooperate to ensure that their products are compared to the other relevant products and, if technically feasible, ensure efforts are made so that their products can be used quantitatively with these other products.	Ongoing	Individual CEOS Agencies	WG Climate, especially its Carbon Subgroup; WGCV	CCoP, IGBP, GHRSST, IOCCP, GOFC-GOLD	Section 3, p. 11	

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
	Action-35: The CEOS Carbon Subgroup (recommended in Action-38) will develop guidelines for appropriate data use of satellite data and data products. This will require improved interactions between the carbon cycle community and the satellite community; comprehensive review of the current use of data products, including current data limitations; and reconciliation of methodological differences and spatial compatibility. Such interactions may include co-sponsorship of joint workshops targeting specific data needs and investment in community product assessments, especially for key intercomparison exercises.	Near- to Mid-Term	Carbon Subgroup; CEOS Agencies	CESO SIT and Plenary; WG Climate; All relevant VCs	GEO CCoP, IPCC		

Interactions / Linkages / Communications-Related Challenges and Actions:

	Action-15: CEOS Agencies will maintain and/or act to strengthen their linkages with the Blue Planet initiative and support of GEO Task SB-01, which brings together the ocean communities engaged in satellite as well as *in situ* observations, to ensure that user requirements are taken into account and products are produced in carbon units.	Near-Term	CEOS Agencies	CEOS SIT and Plenary; Ocean-related VCs (OCR, SST, OSVW); WG Climate	GEO Blue Planet initiative; IOCCG	Section 3, p. 11	
	Action-36: CEOS will strengthen linkages with relevant carbon communities and organizations to facilitate the communications and coordination necessary to ensure that the satellite data products provided by CEOS Agencies meet needs and are utilized appropriately.	Ongoing	CEOS SIT and Plenary	WG Climate, especially its Carbon Subgroup	GEO CCoP; MAREMIP; GODAE		

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
	Action-37: The CEOS Carbon Subgroup (recommended in Action-38) will serve as a point-of-contact for appropriate satellite products for major model-data intercomparison exercises related to the carbon cycle.	Ongoing	Carbon Subgroup	WGCV; CEOS Agencies	GEO CCoP, IGBP, IPCC, ESGF		

CEOS Mechanisms- and Future Planning-Related Challenges and Actions:

	Action-38: CEOS will establish a group to be responsible for carbon activities within CEOS and for advancing the findings and recommendations of this report. This group will take responsibility for overseeing, coordinating, and reporting on the actions identified in this report. It is recommended that CEOS establish a Carbon Subgroup within the CEOS WG on Climate as a most efficient way of implementing this action (this recommended group will hereafter be referred to as the "Carbon Subgroup"). The Carbon Subgroup will report to (and through) the WG Climate. It will establish strong working relationships with all relevant VCs and CEOS WGs, especially the WGCV.	Near-Term	CEOS SIT and Plenary	WG Climate; also all other relevant WGs and VCs	GEO CCoP		
Challenge-20: CEOS acknowledges this challenge and will engage the carbon science and policy communities to develop a more refined understanding of requirements and priorities for carbon-related measurements from space. CEOS recognizes this will require coordination with GEO, IGBP, Future Earth, and other relevant international organizations.	Action-39: CEOS and individual CEOS Agencies will sponsor (or co-sponsor) work (e.g., one or more workshops, a written report) to 1) develop more specific measurement requirements for continuing and new carbon observations from space that will fulfill science and policy needs and 2) encourage further prioritization of these measurements.	Near-Term	CEOS SIT and Plenary	WG Climate, especially its Carbon Subgroup; CEOS Agencies	GEO CCoP, UNFCCC		

Contextual Challenge	CEOS Action	Term for Action	Responsible CEOS Entity	Supporting CEOS Entity(ies)	Desirable External Coordination	*GEO Carbon Strategy*	Relevant GCOS ECV
Challenge-20: CEOS acknowledges this challenge and will engage the carbon science and policy communities to develop a more refined understanding of requirements and priorities for carbon-related measurements from space. CEOS recognizes this will require coordination with GEO, IGBP, Future Earth, and other relevant international organizations.	Action-40: The CEOS Carbon Subgroup (recommended in Action-38) will lead in the planning for activities to 1) develop more specific measurement requirements for continuing and new carbon observations from space that will fulfill science and policy needs and 2) encourage further prioritization of these measurements. It will work, in consultation with the relevant VCs, to coordinate the incorporation of the refined requirements and priorities into multi-agency planning and preparation for future satellites.	Near-Term	Carbon Subgroup	WG Climate, All relevant VCs; CEOS Agencies	GEO CCoP, UNFCCC		
	Action-41: The CEOS Carbon Subgroup (recommended in Action-38) will report to the CEOS WG Climate. It will track and report upon progress in responding to the actions in the *Strategy for Carbon Observations from Space* in a manner similar to that for the *CEOS Response to the GCOS Implementation Plan (IP)*, which includes at a minimum annual reporting by the Carbon Subgroup through the WG Climate to the CEOS SIT and Plenary.	Ongoing	Carbon Subgroup	WG Climate; CEOS SIT and Plenary; CEO	GEO, GCOS, UNFCCC, SBSTA,		
	Action-42: CEOS will periodically (approximately every 3-5 years) assess progress toward meeting the challenges identified in this report. This may be accomplished through a variety of means, including but not limited to workshops, ad hoc studies, or discussions within or among relevant CEOS WGs and VCs	Mid-Term	CEOS SIT and Plenary	WGs and relevant VCs	GEO		

ACKNOWLEDGEMENTS

This report has been prepared under the direction of the CEOS Carbon Task Force (CTF) co-chaired by Masakatsu Nakajima of the Japan Aerospace Exploration Agency (JAXA) and Diane E. Wickland of the U.S. National Aeronautics and Space Administration (NASA). The CTF recruited chapter authors from the broad scientific community – each chapter was led by one or two Domain Leads and included members from academia and CEOS agencies. The Executive Team that oversaw the development of the report and integrated the final document consisted of: Masakatsu Nakajima, Diane E. Wickland, Osamu Ochiai, Stephen Ward, George Dyke, Berrien Moore (lead, atmosphere domain), Shubha Saythendranath (lead, oceans and inland waters domain), Ralph Dubayah (co-lead, land domain), Christiane Schmullius (co-lead, land domain), and Stephen Plummer (lead, integration chapter). Appreciation is extended to all of the domain chapter co-authors, who are listed at the beginning of their respective chapters. The valuable contributions from the full membership of the CEOS CTF (listed in Appendix C) and CEOS member agency representatives who participated in side meetings at SIT-27 and SIT-28 are very gratefully acknowledged. Special thanks are extended to the following individuals for support in moving the report forward at various stages: Shelly Stover, Matthew Steventon, Joanne Nightingale, Kei Shiomi, Elisabeth Larson, Brian Killough, Venetia Stuart, Jamie Shutler, Martin Lindner, and Takashi Moriyama (former CTF co-chair). Financial, in-kind, and moral support from NASA, JAXA, and ESA is also gratefully acknowledged. This report could not have been completed without their strong support!

The CTF thanks the many reviewers of this report for their time and insights in commenting on drafts. The depth and detail of their comments, suggestions for improvements and corrections were invaluable. The following people provided helpful comments during the open review period in October-November 2013: John J. Bates, Kevin Bowman, Michael Buchwitz, James Butler, Raymond Byrnes, Thomas Cecere, Selma Cherchali, Ishida Chu, Yves Crevier (on behalf of colleagues from the Canadian Forest Service), Mark Dowell, Riley Duren, John Dwyer, Richard Eckman, Christian Frankenberg, Kevin Gurney, Paul Ingmann, Shoken Ishii, Daniel Jacob, Stephan R. Kawa, Michio Kawamiya, Kim Keith, Rosemary Munro, Ray Nassar, Jim Penman, Ivan Petiteville, Coleen Roehl, Miguel Roman (on behalf of WGCV LPV Subgroup), Katherine Saad, Kerry Sawyer, Frank Martin Seifert, Brent Smith, Pieter Tans, Oksana A. Tarasova, Albrecht von Bargen, Paul Wennberg, Debra Wunch, Claus Zehner, and Zhiliang Zhu.

REFERENCES

Achard, F., Eva, H. D., Mayaux, P., Stibig, H. J., & Belward, A. (2004). Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. *Global Biogeochemical Cycles*, *18*(2). doi:10.1029/2003GB002142

Achard, F., Eva, H. D., Stibig, H. J., Mayaux, P., Gallego, J., Richards, T., & Malingreau, J. P. (2002). Determination of deforestation rates of the world's humid tropical forests. *Science*, *297*(5583), 999–1002. doi:10.1126/science.1070656

Achard, F., Stibig, H.-J., Eva, H. D., Lindquist, E. J., Bouvet, A., Arino, O., & Mayaux, P. (2010). Estimating tropical deforestation from Earth observation data. *Carbon Management*, *1*(2), 271–287. doi:10.4155/CMT.10.30

Alencar, A., Asner, G. P., Knapp, D., & Zarin, D. (2011). Temporal variability of forest fires in eastern Amazonia. *Ecological Applications*, *21*(7), 2397–2412.

Almeida-Filho, R., Shimabukuro, Y. E., Rosenqvist, A., & Sanchez, G. A. (2009). Using dual-polarized ALOS PALSAR data for detecting new fronts of deforestation in the Brazilian Amazonia. *International Journal of Remote Sensing*, *30*(14), 3735–3743.

Amekudzi, A. (2011). Placing carbon reduction in the context of sustainable development priorities: a global perspective. *Carbon Management*, *2*(4), 413–423. doi:10.4155/CMT.11.43

Amiro, B. D., Barr, A. G., Barr, J. G., Black, T. A., Bracho, R., Brown, M., … Xiao, J. (2010). Ecosystem carbon dioxide fluxes after disturbance in forests of North America. *Journal of Geophysical Research-Biogeosciences*, *115*. doi:10.1029/2010JG001390

Andres, R. J., Boden, T. A., Bréon, F.-M., Ciais, P., Davis, S., Erickson, D., … Treanton, K. (2012). A synthesis of carbon dioxide emissions from fossil-fuel combustion. *Biogeosciences*, *9*(5), 1845–1871. doi:10.5194/bg-9-1845-2012

Andres, R. J., Gregg, J. S., Losey, L., Marland, G., & Boden, T. A. (2011). Monthly, global emissions of carbon dioxide from fossil fuel consumption. *Tellus B*, *63*(3), 309–327. doi:10.1111/j.1600-0889.2011.00530.x

Antoine, D., & Morel, A. (1996). Oceanic primary production .1. Adaptation of a spectral light-photosynthesis model in view of application to satellite chlorophyll observations. *Global Biogeochemical Cycles*, *10*(1), 43–55. doi:10.1029/95GB02831

Antonarakis, A. S., Saatchi, S. S., Chazdon, R. L., & Moorcroft, P. R. (2011). Using Lidar and Radar measurements to constrain predictions of forest ecosystem structure and function. *Ecological Applications*, *21*(4), 1120–1137. doi:10.1890/10-0274.1

Arino, O., Bicheron, P., Achard, F., Latham, J., Witt, R., & Weber, J. L. (2008). GLOBCOVER - The most detailed portrait of Earth. *ESA Bulletin*, *136*, 25–31.

Asner, G. P., Powell, G. V. N., Mascaro, J., Knapp, D. E., Clark, J. K., Jacobson, J., … Hughes, R. F. (2010). High-resolution forest carbon stocks and emissions in the Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(38), 16738–16742. doi:10.1073/pnas.1004875107

Aufdenkampe, A. K., Mayorga, E., Raymond, P. A., Melack, J. M., Doney, S. C., Alin, S. R., … Yoo, K. (2011). Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Frontiers in Ecology and the Environment*, *9*(1), 53–60. doi:10.1890/100014

Baccini, A., Goetz, S. J., Walker, W. S., Laporte, N. T., Sun, M., Sulla-Menashe, D., … Houghton, R. A. (2012). Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change*, *2*(3), 182–185. doi:10.1038/NCLIMATE1354

Baccini, A., Laporte, N., Goetz, S. J., Sun, M., & Dong, H. (2008). A first map of tropical Africa's above-ground biomass derived from satellite imagery. *Environmental Research Letters*, *3*(4). doi:10.1088/1748-9326/3/4/045011

Baker, D. F., Law, R. M., Gurney, K. R., Rayner, P., Peylin, P., Denning, A. S., … Zhu, Z. (2006). TransCom 3 inversion intercomparison: Impact of transport model errors on the interannual variability of regional CO2 fluxes, 1988-2003. *Global Biogeochemical Cycles*, *20*(1). doi:10.1029/2004GB002439

Balch, W. M., Gordon, H. R., Bowler, B. C., Drapeau, D. T., & Booth, E. S. (2005). Calcium carbonate measurements in the surface global ocean based on Moderate-Resolution Imaging Spectroradiometer data. *Journal of Geophysical Research-Oceans*, *110*(C7). doi:10.1029/2004JC002560

Ballantyne, A. P., Alden, C. B., Miller, J. B., Tans, P. P., & White, J. W. C. (2012). Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. *Nature*, *488*(7409), 70–+. doi:10.1038/nature11299

Baret, F., Hagolle, O., Geiger, B., Bicheron, P., Miras, B., Huc, M., … Leroy, M. (2007). LAI, fAPAR and fCover CYCLOPES global products derived from VEGETATION - Part 1: Principles of the algorithm. *Remote Sensing of Environment*, *110*(3), 275–286. doi:10.1016/j.rse.2007.02.018

Barichivich, J., Briffa, K. R., Myneni, R. B., Osborn, T. J., Melvin, T. M., Ciais, P., … Tucker, C. (2013). Large-scale variations in the vegetation growing season and annual cycle of atmospheric CO2 at high northern latitudes from 1950 to 2011. *Global Change Biology*, *19*(10), 3167–3183. doi:10.1111/gcb.12283

Bartalev, S. A., Belward, A. S., Erchov, D. V., & Isaev, A. S. (2003). A new SPOT4-VEGETATION derived land cover map of Northern Eurasia. *International Journal of Remote Sensing*, *24*(9), 1977–1982. doi:10.1080/0143116031000066297

Bartsch, A. (2010). Ten Years of Sea Winds on QuikSCAT for Snow Applications. *Remote Sensing*, *2*(4), 1142–1156. doi:10.3390/rs2041142

Bartsch, A., Trofaier, A. M., Hayman, G., Sabel, D., Schlaffer, S., Clark, D. B., & Blyth, E. (2012). Detection of open water dynamics with ENVISAT ASAR in support of land surface modeling at high latitudes. *Biogeosciences*, *9*(2), 703–714. doi:10.5194/bg-9-703-2012

Bartsch, A., Wagner, W., Scipal, K., Pathe, C., Sabel, D., & Wolski, P. (2009). Global monitoring of wetlands - the value of ENVISAT ASAR Global mode. *Journal of Environmental Management*, *90*(7), 2226–2233. doi:10.1016/j.jenvman.2007.06.023

Bastviken, D., Cole, J., Pace, M., & Tranvik, L. (2004). Methane emissions from lakes: Dependence of lake characteristics, two regional assessments, and a global estimate. *Global Biogeochemical Cycles*, *18*(4). doi:10.1029/2004GB002238

Bates, B., Kundzewicz, Z. W., Wu, S., & Palutikof, J. (2008). Climate Change and Water - IPCC Technical Paper VI. *Intergovernmental Panel on Climate Change.*

Bates, J. J., & Privette, J. L. (2012). A maturity model for assessing the completeness of climate data records. *Eos, Transactions American Geophysical Union*, *93*(44), 441–441. doi:10.1029/2012EO440006

Battin, T. J., Kaplan, L. A., Findlay, S., Hopkinson, C. S., Marti, E., Packman, A. I., … Sabater, F. (2008). Biophysical controls on organic carbon fluxes in fluvial networks. *Nature Geoscience*, *1*(2), 95–100. doi:10.1038/ngeo101

Battin, T. J., Luyssaert, S., Kaplan, L. A., Aufdenkampe, A. K., Richter, A., & Tranvik, L. J. (2009). The boundless carbon cycle. *Nature Geoscience*, *2*(9), 598–600. doi:10.1038/ngeo618

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., … Papale, D. (2010). Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate. *Science*, *329*(5993), 834–838. doi:10.1126/science.1184984

Behrenfeld, M. J., & Falkowski, P. G. (1997). Photosynthetic rates derived from satellite-based chlorophyll concentration. *Limnology and Oceanography*, *42*(1), 1–20.

Behrenfeld, M. J., Westberry, T. K., Boss, E. S., O'Malley, R. T., Siegel, D. A., Wiggert, J. D., … Mahowald, N. (2009). Satellite-detected fluorescence reveals global physiology of ocean phytoplankton. *Biogeosciences*, *6*(5), 779–794. doi:10.5194/bg-6-779-2009

Bergamaschi, P., Frankenberg, C., Meirink, J. F., Krol, M., Dentener, F., Wagner, T., … Goede, A. (2007). Satellite chartography of atmospheric methane from SCIAMACHY on board ENVISAT: 2. Evaluation based on inverse model simulations. *Journal of Geophysical Research*, *112*(D2). doi:10.1029/2006JD007268

Blackard, J. A., Finco, M. V., Helmer, E. H., Holden, G. R., Hoppus, M. L., Jacobs, D. M., … Tymcio, R. P. (2008). Mapping US forest biomass using nationwide forest inventory data and moderate resolution information. *Remote Sensing of Environment*, *112*(4), 1658–1677. doi:10.1016/j.rse.2007.08.021

Boden, T. A., Andres, R. J., & Marland, G. (2013). Global CO2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2010. Retrieved from http://cdiac.ornl.gov/trends/emis/meth_reg.html

Bontemps, S., Defourny, P., Brockmann, C., Herold, M., Kalogirou, V., & Arino, O. (2012). New Global Land Cover Mapping Exercise in the Framework of the Esa Climate Change Initiative. In *2012 Ieee International Geoscience and Remote Sensing Symposium (igarss)* (pp. 44–47). New York: Ieee.

Boudreau, J., Nelson, R. F., Margolis, H. A., Beaudoin, A., Guindon, L., & Kimes, D. S. (2008). Regional aboveground forest biomass using airborne and spaceborne LiDAR in Quebec. *Remote Sensing of Environment*, *112*(10), 3876–3890. doi:10.1016/j.rse.2008.06.003

Bouman, H. A., Platt, T., Sathyendranath, S., Li, W. K. W., Stuart, V., Fuentes-Yaco, C., … Kyewalyanga, M. (2003). Temperature as indicator of optical properties and community structure of marine phytoplankton: implications for remote sensing. *Marine Ecology Progress Series*, *258*, 19–30. doi:10.3354/meps258019

Bourgeau-Chavez, L. L., Kasischke, E. S., Brunzell, S., Mudd, J. P., & Tukman, M. (2002). Mapping fire scars in global boreal forests using imaging radar data. *International Journal of Remote Sensing*, *23*(20), 4211–4234. doi:10.1080/01431160110109589

Bourgeau-Chavez, L. L., Smith, K. B., Brunzell, S. M., Kasischke, E. S., Romanowicz, E. A., & Richardson, C. J. (2005). Remote monitoring of regional inundation patterns and hydroperiod in the greater everglades using synthetic aperture radar. *Wetlands*, *25*(1), 176–191. doi:10.1672/0277-5212(2005)025[0176:RMORIP]2.0.CO;2

Boutin, J., Etcheto, J., Dandonneau, Y., Bakker, D. C. E., Feely, R. A., Inoue, H. Y., … Wanninkhof, R. (1999). Satellite sea surface temperature: a powerful tool for interpreting in situ pCO2 measurements in the equatorial Pacific Ocean. *Tellus Series B-Chemical and Physical Meteorology*, *51*(2), 490–508. doi:10.1034/j.1600-0889.1999.00025.x

Brandt, J. S., Kuemmerle, T., Li, H., Ren, G., Zhu, J., & Radeloff, V. C. (2012). Using Landsat imagery to map forest change in southwest China in response to the national logging ban and ecotourism development. *Remote Sensing of Environment*, *121*, 358–369. doi:10.1016/j.rse.2012.02.010

Brenninkmeijer, C. a. M., Crutzen, P., Boumard, F., Dauer, T., Dix, B., Ebinghaus, R., … Ziereis, H. (2007). Civil Aircraft for the regular investigation of the atmosphere based on an instrumented container: The new CARIBIC system. *Atmospheric Chemistry and Physics*, *7*(18), 4953–4976.

Brewin, R. J. W., Devred, E., Sathyendranath, S., Lavender, S. J., & Hardman-Mountford, N. J. (2011). Model of phytoplankton absorption based on three size classes. *Applied Optics*, *50*(22), 4535–4549. doi:10.1364/AO.50.004535

Brewin, R. J. W., Hardman-Mountford, N. J., Lavender, S. J., Raitsos, D. E., Hirata, T., Uitz, J., … Gentili, B. (2011). An intercomparison of bio-optical techniques for detecting dominant phytoplankton size class from satellite remote sensing. *Remote Sensing of Environment*, *115*(2), 325–339. doi:10.1016/j.rse.2010.09.004

Brewin, R. J. W., Sathyendranath, S., Hirata, T., Lavender, S. J., Barciela, R. M., & Hardman-Mountford, N. J. (2010). A three-component model of phytoplankton size class for the Atlantic Ocean. *Ecological Modeling*, *221*(11), 1472–1483. doi:10.1016/j.ecolmodel.2010.02.014

Brown, C., & Yoder, J. (1994). Coccolithophorid Blooms in the Global Ocean. *Journal of Geophysical Research-Oceans*, *99*(C4), 7467–7482. doi:10.1029/93JC02156

Brown, R., Derksen, C., & Wang, L. (2010). A multi-data set analysis of variability and change in Arctic spring snow cover extent, 1967-2008. *Journal of Geophysical Research-Atmospheres*, *115*. doi:10.1029/2010JD013975

Buckley, J., Gammelsrod, T., Johannessen, J., Johannessen, O., & Roed, L. (1979). Upwelling - Oceanic Structure at Edge of Arctic Ice Pack in Winter. *Science*, *203*(4376), 165–167. doi:10.1126/science.203.4376.165

Burrows, J., Holzle, E., Goede, A., Visser, H., & Fricke, W. (1995). Sciamachy - Scanning Imaging Absorption Spectrometer for Atmospheric Chartography. *Acta Astronautica*, *35*(7), 445–451. doi:10.1016/0094-5765(94)00278-T

Butz, A., Guerlet, S., Hasekamp, O., Schepers, D., Galli, A., Aben, I., … Warneke, T. (2011). Toward accurate CO2 and CH4 observations from GOSAT. *Geophysical Research Letters*, *38*. doi:10.1029/2011GL047888

Cambaliza, M. O., Shepson, P. B., Caulton, D., Stirm, B., Samarov, D., Gurney, K. R., … Richardson, S. J. (2013). Assessment of uncertainties of an aircraft-based mass-balance approach for quantifying urban greenhouse gas emissions. *Atmos. Chem. Phys. Discuss.*, *13*(11), 29895–29945. doi:10.5194/acpd-13-29895-2013

Canadell, J. G., Ciais, P., Cox, P., & Heimann, M. (2004). Quantifying, Understanding and Managing the Carbon Cycle in the Next Decades. *Climatic Change*, *67*(2-3), 147–160. doi:10.1007/s10584-004-3765-y

Carr, M.-E., Friedrichs, M. A. M., Schmeltz, M., Aita, M. N., Antoine, D., Arrigo, K. R., … Yamanaka, Y. (2006). A comparison of global estimates of marine primary production from ocean color. *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, *53*(5-7), 741–770. doi:10.1016/j.dsr2.2006.01.028

Carroll, M. L., Townshend, J. R., DiMiceli, C. M., Noojipady, P., & Sohlberg, R. A. (2009). A new global raster water mask at 250 m resolution. *International Journal of Digital Earth*, *2*(4), 291–308. doi:10.1080/17538940902951401

Carroll, M. L., Townshend, J. R. G., DiMiceli, C. M., Loboda, T., & Sohlberg, R. A. (2011). Shrinking lakes of the Arctic: Spatial relationships and trajectory of change. *Geophysical Research Letters*, *38*. doi:10.1029/2011GL049427

Casadio, S., Arino, O., & Serpe, D. (2012). Gas flaring monitoring from space using the ATSR instrument series. *Remote Sensing of Environment*, *116*, 239–249. doi:10.1016/j.rse.2010.11.022

CEOS. (2006). *Satellite observation of the climate system* (No. The Committee on Earth Observation Satellites (CEOS) Response to the Global Climate Observing System (GCOS) Implementation Plan (IP)) (p. 54).

CEOS. (2012). *The Response of the Committee on Earth Observation Satellites (CEOS) to the Global Climate Observing System Implementation Plan 2010 (GCOS IP - 10)* (p. 111). Retrieved from http://www.ceos.org/images/WGClimate/ceos_response_to_gcos_ip-10_24_september_2012_formatted.pdf

Chahine, M. T., Chen, L., Dimotakis, P., Jiang, X., Li, Q., Olsen, E. T., … Yung, Y. L. (2008). Satellite remote sounding of mid-tropospheric CO2. *Geophysical Research Letters*, *35*(17), n/a–n/a. doi:10.1029/2008GL035022

Chambers, J. Q., Asner, G. P., Morton, D. C., Anderson, L. O., Saatch, S. S., Espirito-Santo, F. D. B., … Souza, C. (2007). Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. *Trends in Ecology & Evolution*, *22*(8), 414–423. doi:10.1016/j.tree.2007.05.001

Chapron, B., Collard, F., & Ardhuin, F. (2005). Direct measurements of ocean surface velocity from space: Interpretation and validation. *Journal of Geophysical Research-Oceans*, *110*(C7).

doi:10.1029/2004JC002809

Chelton, D. B., Schlax, M. G., Freilich, M. H., & Milliff, R. F. (2004). Satellite measurements reveal persistent small-scale features in ocean winds. *Science*, *303*(5660), 978–983. doi:10.1126/science.1091901

Chen, J., & Black, T. (1992). Defining Leaf-Area Index for Non-Flat Leaves. *Plant Cell and Environment*, *15*(4), 421–429. doi:10.1111/j.1365-3040.1992.tb00992.x

Chen, J. M., Pavlic, G., Brown, L., Cihlar, J., Leblanc, S. G., White, H. P., … Pellikka, P. K. E. (2002). Derivation and validation of Canada-wide coarse-resolution leaf area index maps using high-resolution satellite imagery and ground measurements. *Remote Sensing of Environment*, *80*(1), 165–184. doi:10.1016/S0034-4257(01)00300-5

Chopping, M., Moisen, G. G., Su, L., Laliberte, A., Rango, A., Martonchik, J. V., & Peters, D. P. C. (2008). Large area mapping of southwestern forest crown cover, canopy height, and biomass using the NASA Multiangle Imaging Spectro-Radiometer. *Remote Sensing of Environment*, *112*(5), 2051–2063. doi:10.1016/j.rse.2007.07.024

Ciais, P., Dolman, A. J., Bombelli, A., Duren, R., Peregon, A., Rayner, P. J., … Zehner, C. (2013). Current systematic carbon cycle observations and needs for implementing a policy-relevant carbon observing system. *Biogeosciences Discuss.*, *10*(7), 11447–11581. doi:10.5194/bgd-10-11447-2013

Ciais, P., Dolman, A. J., Dargaville, R., Barrie, L., Butler, J., Canadell, J., & Moriyama, T. (2010). *GEO Carbon Strategy*. Rome: GEO Secretariat, Geneva / FAO.

Ciais, P., Moore, B., Steffen, W., Hood, M., Quegan, S., Cihlar, J., … Wickland, D. (2004). *Integrated Global Carbon Observation Theme: A Strategy to Realize a Coodinated System of Integrated Global Carbon Cycle Observations*. Rome: GEO Secretariat, Geneva / FAO.

Ciais, P., Schelhaas, M. J., Zaehle, S., Piao, S. L., Cescatti, A., Liski, J., … Nabuurs, G. J. (2008). Carbon accumulation in European forests. *Nature Geoscience*, *1*(7), 425–429. doi:10.1038/ngeo233

Cihlar, J. (2000). Land cover mapping of large areas from satellites: status and research priorities. *International Journal of Remote Sensing*, *21*(6-7), 1093–1114. doi:10.1080/014311600210092

Cihlar, J., Chen, J., & Li, Z. (1997). Seasonal AVHRR multichannel data sets and products for studies of surface-atmosphere interactions. *Journal of Geophysical Research-Atmospheres*, *102*(D24), 29625–29640. doi:10.1029/97JD01195

Ciotti, A. M., & Bricaud, A. (2006). Retrievals of a size parameter for phytoplankton and spectral light absorption by colored detrital matter from water-leaving radiances at SeaWiFS channels in a continental shelf region off Brazil. *Limnology and Oceanography-Methods*, *4*, 237–253.

Cogan, A. J., Boesch, H., Parker, R. J., Feng, L., Palmer, P. I., Blavier, J.-F. L., … Wunch, D. (2012). Atmospheric carbon dioxide retrieved from the Greenhouse gases Observing SATellite (GOSAT): Comparison with ground-based TCCON observations and GEOS-Chem model calculations. *Journal of Geophysical Research: Atmospheres*, *117*(D21), n/a–n/a. doi:10.1029/2012JD018087

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., … Melack, J. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems*, *10*(1), 171–184. doi:10.1007/s10021-006-9013-8

Coll, C., Hook, S. J., & Galve, J. M. (2009). Land Surface Temperature From the Advanced Along-Track Scanning Radiometer: Validation Over Inland Waters and Vegetated Surfaces. *Ieee Transactions on Geoscience and Remote Sensing*, *47*(1), 350–360. doi:10.1109/TGRS.2008.2002912

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., & Totterdell, I. J. (2000). Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, *408*(6809), 184–187. doi:10.1038/35041539

Crevoisier, C., Chédin, A., Matsueda, H., Machida, T., Armante, R., & Scott, N. A. (2009). First year of upper tropospheric integrated content of CO2 from IASI hyperspectral infrared observations. *Atmospheric Chemistry and Physics Discussions*, *9*(2), 8187–8222. doi:10.5194/acpd-9-8187-2009

Crisp, D., Fisher, B. M., O'Dell, C., Frankenberg, C., Basilio, R., Boesch, H., … Yung, Y. L. (2012). The ACOS CO2 retrieval algorithm - Part II: Global X-CO2 data characterization. *Atmospheric Measurement Techniques*, *5*(4), 687–707. doi:10.5194/amt-5-687-2012

Dash, J., Jeganathan, C., & Atkinson, P. M. (2010). The use of MERIS Terrestrial Chlorophyll Index to study spatio-temporal variation in vegetation phenology over India. *Remote Sensing of Environment*, *114*(7), 1388–1402. doi:10.1016/j.rse.2010.01.021

de Beurs, K. M., & Townsend, P. A. (2008). Estimating the effect of gypsy moth defoliation using MODIS. *Remote Sensing of Environment*, *112*(10), 3983–3990. doi:10.1016/j.rse.2008.07.008

de Groot, W. J., Landry, R., Kurz, W. A., Anderson, K. R., Englefield, P., Fraser, R. H., … Pritchard, J. M. (2007). Estimating direct carbon emissions from Canadian wildland fires1. *International Journal of Wildland Fire*, *16*(5), 593–606. doi:10.1071/WF06150

De Mazière, M., Vigouroux, C., Bernath, P. F., Baron, P., Blumenstock, T., Boone, C., … Wood, S. (2008). Validation of ACE-FTS v2.2 methane profiles from the upper troposphere to the lower mesosphere. *Atmos. Chem. Phys.*, *8*(9), 2421–2435. doi:10.5194/acp-8-2421-2008

Defourny, P., Mayaux, P., Herold, M., & Bontemps, S. (2012). Global Land-Cover Map Validation Experiences: Toward the Characterization of Quantitative Uncertainty. In *Remote Sensing of Land Use and Land Cover* (Vol. 20120991, pp. 207–224). CRC Press. Retrieved from http://www.crcnetbase.com/doi/abs/10.1201/b11964-17

DeFries, R. S., Hansen, M., Townshend, J. R. G., & Sohlberg, R. (1998). Global land cover classifications at 8 km spatial resolution: The use of training data derived from Landsat imagery in decision tree classifiers. *International Journal of Remote Sensing*, *19*(16), 3141–3168. doi:10.1080/014311698214235

DeFries, R. S., Houghton, R. A., Hansen, M. C., Field, C. B., Skole, D., & Townshend, J. (2002). Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. *Proceedings of the National Academy of Sciences of the United States of America*, *99*(22), 14256–14261. doi:10.1073/pnas.182560099

DeFries, R. S., Townshend, J. R. G., & Hansen, M. C. (1999). Continuous fields of vegetation characteristics at the global scale at 1-km resolution. *Journal of Geophysical Research-Atmospheres*, *104*(D14), 16911–16923. doi:10.1029/1999JD900057

Delbart, N., Le Toan, T., Kergoat, L., & Fedotova, V. (2006). Remote sensing of spring phenology in boreal regions: A free of snow-effect method using NOAA-AVHRR and SPOT-VGT data (1982-2004). *Remote Sensing of Environment*, *101*(1), 52–62. doi:10.1016/j.rse.2005.11.012

Devred, E., Sathyendranath, S., Stuart, V., & Platt, T. (2011). A three component classification of phytoplankton absorption spectra: Application to ocean-color data. *Remote Sensing of Environment*, *115*(9), 2255–2266. doi:10.1016/j.rse.2011.04.025

Dhakal, S. (2010). GHG emissions from urbanization and opportunities for urban carbon mitigation. *Current Opinion in Environmental Sustainability*, *2*(4), 277–283. doi:10.1016/j.cosust.2010.05.007

Di Gregorio, A. (2005). Land Cover Classification System (LCCS), version 2: Classification Concepts and User Manual (Version 2). Rome: FAO Environment and Natural Resources Service Series.

Dobson, M., Ulaby, F., Letoan, T., Beaudoin, A., Kasischke, E., & Christensen, N. (1992). Dependence of Radar Backscatter on Coniferous Forest Biomass. *Ieee Transactions on Geoscience and Remote Sensing*, *30*(2), 412–415. doi:10.1109/36.134090

Dolan, K. A., Hurtt, G. C., Chambers, J. Q., Dubayah, R. O., Frolking, S., & Masek, J. G. (2011). Using ICESat's Geoscience Laser Altimeter System (GLAS) to assess large-scale forest disturbance caused by hurricane Katrina. *Remote Sensing of Environment*, *115*(1), 86–96. doi:10.1016/j.rse.2010.08.007

Doll, C. N. H. (2008). *CIESIN Thematic Guide to Night-Time Light Remote Sensing and its Applications.* Palisades, NY: Center for International Earth Science Information Network.

Doubkova, M., van Dijk, A. I. J. M., Sabel, D., Wagner, W., & Bloeschl, G. (2012). Evaluation of the predicted error of the soil moisture retrieval from C-band SAR by comparison against modelled soil moisture estimates over Australia. *Remote Sensing of Environment*, *120*, 188–196. doi:10.1016/j.rse.2011.09.031

Drake, J. B., Dubayah, R. O., Clark, D. B., Knox, R. G., Blair, J. B., Hofton, M. A., … Prince, S. D. (2002). Estimation of tropical forest structural characteristics using large-footprint lidar. *Remote Sensing of Environment*, *79*(2-3), 305–319. doi:10.1016/S0034-4257(01)00281-4

Dubayah, R. O., Sheldon, S. L., Clark, D. B., Hofton, M. A., Blair, J. B., Hurtt, G. C., & Chazdon, R. L. (2010). Estimation of tropical forest height and biomass dynamics using lidar remote sensing at La Selva, Costa Rica. *Journal of Geophysical Research-Biogeosciences*, *115*. doi:10.1029/2009JG000933

Duggen, S., Croot, P., Schacht, U., & Hoffmann, L. (2007). Subduction zone volcanic ash can fertilize the surface ocean and stimulate phytoplankton growth: Evidence from biogeochemical experiments and satellite data. *Geophysical Research Letters*, *34*(1). doi:10.1029/2006GL027522

Edburg, S. L., Hicke, J. A., Lawrence, D. M., & Thornton, P. E. (2011). Simulating coupled carbon and nitrogen dynamics following mountain pine beetle outbreaks in the western United States. *Journal of Geophysical Research-Biogeosciences*, *116*. doi:10.1029/2011JG001786

Eidenshink, J., Schwind, B., Brewer, K., Zhu, Z.-L., Quayle, B., & Howard, S. (2007). A Project for Monitoring Trends in Burn Severity. *Fire Ecology*, *3*(1), 3–21. doi:10.4996/fireecology.0301003

Eklundh, L., Johansson, T., & Solberg, S. (2009). Mapping insect defoliation in Scots pine with MODIS time-series data. *Remote Sensing of Environment*, *113*(7), 1566–1573. doi:10.1016/j.rse.2009.03.008

Ellicott, E., Vermote, E., Giglio, L., & Roberts, G. (2009). Estimating biomass consumed from fire using MODIS FRE. *Geophysical Research Letters*, *36*. doi:10.1029/2009GL038581

Elvidge, C. D., Cinzano, P., Pettit, D. R., Arvesen, J., Sutton, P., Small, C., … Ebener, S. (2007). The Nightsat mission concept. *International Journal of Remote Sensing*, *28*(12), 2645–2670. doi:10.1080/01431160600981525

Elvidge, D. E., Baugh, K., Hus, F., & Zhizhin, M. (2013). Nightime VIIRS Data Application. Presented at the International Workshop on INventory, Modeling and Climate IMpacts on Greenhouse GAs Emissions and Aerosols in the Asian Region, Jun 26-28, Tsukuba, Japan.

Entekhabi, D., Njoku, E. G., O'Neill, P. E., Kellogg, K. H., Crow, W. T., Edelstein, W. N., … Van Zyl, J. (2010). The Soil Moisture Active Passive (SMAP) Mission. *Proceedings of the Ieee*, *98*(5), 704–716. doi:10.1109/JPROC.2010.2043918

Enting, I. (1993). Inverse Problems in Atmospheric Constituent Studies .3. Estimating Errors in Surface Sources. *Inverse Problems*, *9*(6), 649–665. doi:10.1088/0266-5611/9/6/004

Etheridge, D. M., Steele, L. P., Langenfelds, R. L., Francey, R. J., Barnola, J. M., & Morgan, V. I. (1996). Natural and anthropogenic changes in atmospheric CO2 over the last 1000 years from air in Antarctic ice and firn. *Journal of Geophysical Research-Atmospheres*, *101*(D2), 4115–4128. doi:10.1029/95JD03410

Eva, H., Carboni, S., Achard, F., Stach, N., Durieux, L., Faure, J.-F., & Mollicone, D. (2010). Monitoring forest areas from continental to territorial levels using a sample of medium spatial resolution satellite imagery. *Isprs Journal of Photogrammetry and Remote Sensing*, *65*(2), 191–197. doi:10.1016/j.isprsjprs.2009.10.008

Falkowski, P., Behrenfeld, M., & Kolber, Z. (1995). *Variations in photochemical energy conversion efficiency in oceanic phytoplankton: Scaling from reaction centers to the global ocean.* (P. Mathis, Ed.). Dordrecht: Kluwer Academic Publ.

Fan, S. M., Moxim, W. J., & Levy, H. (2006). Aeolian input of bioavailable iron to the ocean. *Geophysical Research Letters*, *33*(7). doi:10.1029/2005GL024852

Fang, H., Jiang, C., Li, W., Wei, S., Baret, F., Chen, J. M., … Zhu, Z. (2013). Characterization and intercomparison of global moderate resolution leaf area index (LAI) products: Analysis of climatologies and theoretical uncertainties. *Journal of Geophysical Research: Biogeosciences*, *118*(2), 529–548. doi:10.1002/jgrg.20051

Fernandes, R., Butson, C., Leblanc, S., & Latifovic, R. (2003). Landsat-5 TM and Landsat-7 ETM+ based accuracy assessment of leaf area index products for Canada derived from SPOT-4 VEGETATION data. *Canadian Journal of Remote Sensing*, *29*(2), 241–258.

Field, C., Randerson, J., & Malmstrom, C. (1995). Global Net Primary Production - Combining Ecology and Remote-Sensing. *Remote Sensing of Environment*, *51*(1), 74–88. doi:10.1016/0034-4257(94)00066-V

Foody, G. M. (2002). Status of land cover classification accuracy assessment. *Remote Sensing of Environment*, *80*(1), 185–201. doi:10.1016/S0034-4257(01)00295-4

Foody, G. M., Lucas, R. M., Curran, P. J., & Honzak, M. (1997). Mapping tropical forest fractional cover from coarse spatial resolution remote sensing imagery. *Plant Ecology*, *131*(2), 143–154. doi:10.1023/A:1009775619936

Forkel, M., Thonicke, K., Beer, C., Cramer, W., Bartalev, S., & Schmullius, C. (2012). Extreme fire events are related to previous-year surface moisture conditions in permafrost-underlain larch forests of Siberia. *Environmental Research Letters*, *7*(4), 044021. doi:10.1088/1748-9326/7/4/044021

Foucher, P. Y., Chédin, A., Armante, R., Boone, C., Crevoisier, C., & Bernath, P. (2011). Carbon dioxide atmospheric vertical profiles retrieved from space observation using ACE-FTS solar occultation instrument. *Atmos. Chem. Phys.*, *11*(6), 2455–2470. doi:10.5194/acp-11-2455-2011

Fragkias, M., Lobo, J., Strumsky, D., & Seto, K. C. (2013). Does Size Matter? Scaling of CO2 Emissions and U.S. Urban Areas. *PLoS ONE*, *8*(6), e64727. doi:10.1371/journal.pone.0064727

Francois, C. (2002). The potential of directional radiometric temperatures for monitoring soil and leaf temperature and soil moisture status. *Remote Sensing of Environment*, *80*(1), 122–133. doi:10.1016/S0034-4257(01)00293-0

Frankenberg, C., Fisher, J. B., Worden, J., Badgley, G., Saatchi, S. S., Lee, J.-E., … Yokota, T. (2011). New global observations of the terrestrial carbon cycle from GOSAT: Patterns of plant fluorescence with gross primary productivity. *Geophysical Research Letters*, *38*(17), n/a–n/a. doi:10.1029/2011GL048738

Franklin, S. E., Wulder, M. A., Skakun, R. S., & Carroll, A. L. (2003). Mountain pine beetle red-attack forest damage classification using stratified Landsat TM data in British Columbia, Canada. *Photogrammetric Engineering and Remote Sensing*, *69*(3), 283–288.

Fraser, R. H. (2004). Validation and calibration of Canada-wide coarse-resolution satellite burned area maps. *Photogrammetric Engineering & Remote Sensing*, *70*, 451–459.

Fraser, R. H., & Latifovic, R. (2005). Mapping insect-induced tree defoliation and mortality using coarse spatial resolution satellite imagery. *International Journal of Remote Sensing*, *26*(1), 193–200. doi:10.1080/01431160410001716923

French, A. N., Jacob, F., Anderson, M. C., Kustas, W. P., Timmermans, W., Gieske, A., … Brunsell, N. (2005). Surface energy fluxes with the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) at the Iowa 2002 SMACEX site (USA). *Remote Sensing of Environment*, *99*(1-2), 55–65. doi:10.1016/j.rse.2005.05.015

Friedl, M. A., McIver, D. K., Hodges, J. C. F., Zhang, X. Y., Muchoney, D., Strahler, A. H., … Schaaf, C. (2002). Global land cover mapping from MODIS: algorithms and early results. *Remote Sensing of Environment*, *83*(1-2), 287–302. doi:10.1016/S0034-4257(02)00078-0

Friedlingstein, P., Bopp, L., Ciais, P., Dufresne, J. L., Fairhead, L., LeTreut, H., … Orr, J. (2001). Positive feedback between future climate change and the carbon cycle. *Geophysical Research Letters*, *28*(8), 1543–1546. doi:10.1029/2000GL012015

Friedrichs, M. A. M., Carr, M.-E., Barber, R. T., Scardi, M., Antoine, D., Armstrong, R. A., … Winguth, A. (2009). Assessing the uncertainties of model estimates of primary productivity in the tropical Pacific Ocean. *Journal of Marine Systems*, *76*(1-2), 113–133. doi:10.1016/j.jmarsys.2008.05.010

Frouin, R., & Wang, M. (2000). *Algorithm to estimate PAR from SeaWiFS data, NASA SeaWiFs technical report, version 1.2* (p. 15). Greenbelt, MD: NASA Goddard Space Flight Center. Retrieved from fttp://daac.gsfc.nasa.gov/oceancolor/documentation/OB_Documentation.shtml

Fu, D., Sung, K., Boone, C. D., Walker, K. A., & Bernath, P. F. (2008). Ground-based solar absorption studies for the Carbon Cycle science by Fourier Transform Spectroscopy (CC-FTS) mission. *Journal of Quantitative Spectroscopy & Radiative Transfer*, *109*(12-13), 2219–2243. doi:10.1016/j.jqsrt.2008.02.003

Fujiwara, A., Hirawake, T., Suzuki, K., & Saitoh, S.-I. (2011). Remote sensing of size structure of phytoplankton communities using optical properties of the Chukchi and Bering Sea shelf region. *Biogeosciences*, *8*(12), 3567–3580. doi:10.5194/bg-8-3567-2011

Gallego, J., & Bamps, C. (2008). Using CORINE land cover and the point survey LUCAS for area estimation. *International Journal of Applied Earth Observation and Geoinformation*, *10*(4), 467–475. doi:10.1016/j.jag.2007.11.001

Ganguly, S., Friedl, M. A., Tan, B., Zhang, X., & Verma, M. (2010). Land surface phenology from MODIS: Characterization of the Collection 5 global land cover dynamics product. *Remote Sensing of Environment*, *114*(8), 1805–1816. doi:10.1016/j.rse.2010.04.005

Ganguly, S., Nemani, R. R., Baret, F., Bi, B., Weiss, M., Zhang, G., … Myneni, R. B. (2014). Green Leaf Area and Fraction of Photosynthetically Active Radiation Absorbed by Vegetation. In J. M. Hanes (Ed.), *Biophysical Applications of Satellite Remote Sensing* (pp. 43–61). Springer - Verlag.

Ganguly, S., Nemani, R. R., Zhang, G., Hashimoto, H., Milesi, C., Michaelis, A., … Myneni, R. B. (2012). Generating global Leaf Area Index from Landsat: Algorithm formulation and demonstration. *Remote Sensing of Environment*, *122*, 185–202. doi:10.1016/j.rse.2011.10.032

Ganguly, S., Schull, M. A., Samanta, A., Shabanov, N. V., Milesi, C., Nemani, R. R., … Myneni, R. B. (2008). Generating vegetation leaf area index earth system data record from multiple sensors. Part 1: Theory. *Remote Sensing of Environment*, *112*(12), 4333–4343. doi:10.1016/j.rse.2008.07.014

Gao, B. C. (1996). NDWI - A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, *58*(3), 257–266. doi:10.1016/S0034-4257(96)00067-3

Gao, Y., Fan, S. M., & Sarmiento, J. L. (2003). Aeolian iron input to the ocean through precipitation scavenging: A modeling perspective and its implication for natural iron fertilization in the ocean. *Journal of Geophysical Research-Atmospheres*, *108*(D7). doi:10.1029/2002JD002420

Gardner, W. D., Mishonov, A. V., & Richardson, M. J. (2006). Global POC concentrations from in-situ and satellite data. *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, *53*(5-7), 718–740. doi:10.1016/j.dsr2.2006.01.029

Garrigues, S., Lacaze, R., Baret, F., Morisette, J. T., Weiss, M., Nickeson, J. E., … Yang, W. (2008). Validation and intercomparison of global Leaf Area Index products derived from remote sensing data. *Journal of Geophysical Research: Biogeosciences*, *113*(G2), n/a–n/a. doi:10.1029/2007JG000635

GCOS. (2010a). *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC* (No. GCOS-92, WMO/TD-No 1219). Retrieved from http://www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf

GCOS. (2010b). *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC* (No. GCOS-92, WMO/TD-No 1219). Retrieved from http://www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf

Geibel, M. C., Messerschmidt, J., Gerbig, C., Blumenstock, T., Chen, H., Hase, F., … Feist, D. G. (2012). Calibration of column-averaged CH4 over European TCCON FTS sites with airborne in-situ measurements. *Atmospheric Chemistry and Physics*, *12*(18), 8763–8775. doi:10.5194/acp-12-8763-2012

GEOGLAM Work Plan. (n.d.). *The GEO Agricultural Monitoring Initiative* (p. 19). Retrieved from http://www.ceos.org/images/sit27/GEOGLAM%20WORK%20PLAN-G20%5B1%5D.pdf

Ghimire, B., Williams, C. A., Collatz, G. J., & Vanderhoof, M. (2012). Fire-induced carbon emissions and regrowth uptake in western U.S. forests: Documenting variation across forest types, fire severity, and climate regions. *Journal of Geophysical Research-Biogeosciences*, *117*. doi:10.1029/2011JG001935

Ghosh, T., Elvidge, C. D., Sutton, P. C., Baugh, K. E., Ziskin, D., & Tuttle, B. T. (2010). Creating a Global Grid of Distributed Fossil Fuel CO2 Emissions from Nighttime Satellite Imagery. *Energies*, *3*(12), 1895–1913. doi:10.3390/en3121895

Giglio, L., Csiszar, I., & Justice, C. O. (2006). Global distribution and seasonality of active fires as observed with the Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) sensors. *Journal of Geophysical Research-Biogeosciences*, *111*(G2). doi:10.1029/2005JG000142

Giglio, L., Randerson, J. T., van der Werf, G. R., Kasibhatla, P. S., Collatz, G. J., Morton, D. C., & DeFries, R. S. (2010). Assessing variability and long-term trends in burned area by merging multiple satellite fire products. *Biogeosciences*, *7*(3), 1171–1186.

Gloor, M., Fan, S. M., Pacala, S., & Sarmiento, J. (2000). Optimal sampling of the atmosphere for purpose of inverse modeling: A model study. *Global Biogeochemical Cycles*, *14*(1), 407–428. doi:10.1029/1999GB900052

Gobron, N., Pinty, B., Aussedat, O., Chen, J. M., Cohen, W. B., Fensholt, R., … Widlowski, J.-L. (2006). Evaluation of fraction of absorbed photosynthetically active radiation products for different canopy radiation transfer regimes: Methodology and results using Joint Research Center products derived from SeaWiFS against ground-based estimations. *Journal of Geophysical Research: Atmospheres*, *111*(D13), n/a–n/a. doi:10.1029/2005JD006511

Gobron, N., Pinty, B., Verstraete, M., & Govaerts, Y. (1999). The MERIS Global Vegetation Index (MGVI): description and preliminary application. *International Journal of Remote Sensing*, *20*(9), 1917–1927. doi:10.1080/014311699212542

Godo, O. R., Samuelsen, A., Macaulay, G. J., Patel, R., Hjollo, S. S., Horne, J., … Johannessen, J. A. (2012). Mesoscale Eddies Are Oases for Higher Trophic Marine Life. *Plos One*, *7*(1). doi:10.1371/journal.pone.0030161

Goes, J. I., Saino, T., Oaku, H., Ishizaka, J., Wong, C. S., & Nojiri, Y. (2000). Basin scale estimates of Sea Surface Nitrate and New Production from remotely sensed Sea Surface Temperature and Chlorophyll. *Geophysical Research Letters*, *27*(9), 1263–1266. doi:10.1029/1999GL002353

Goetz, S. J., Bunn, A. G., Fiske, G. J., & Houghton, R. A. (2005). Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(38), 13521–13525. doi:10.1073/pnas.0506179102

Goetz, S. J., Prince, S. D., Goward, S. N., Thawley, M. M., & Small, J. (1999). Satellite remote sensing of primary production: an improved production efficiency modeling approach. *Ecological Modeling*, *122*(3), 239–255. doi:10.1016/S0304-3800(99)00140-4

Gong, P., Wang, J., Yu, L., Zhao, Y., Zhao, Y., Liang, L., … Chen, J. (2013). Finer resolution observation and monitoring of global land cover: first mapping results with Landsat TM and ETM+ data. *International Journal of Remote Sensing*, *34*(7), 2607–2654. doi:10.1080/01431161.2012.748992

Gourdji, S. M., Mueller, K. L., Schaefer, K., & Michalak, A. M. (2008). Global monthly averaged CO_2 fluxes recovered using a geostatistical inverse modeling approach: 2. Results including auxiliary environmental data. *Journal of Geophysical Research-Atmospheres*, *113*(D21). doi:10.1029/2007JD009733

Goward, S. N., Masek, J. G., Cohen, W., Moisen, G., Collatz, G. J., Healey, S., … Wulder, M. A. (2008). Forest disturbance and North American carbon flux. *EOS, Transactions, American Geophysical Union*, *89*(11), 105–116.

Gower, J., & Borstad, G. (1990). Mapping of Phytoplankton by Solar-Stimulated Fluorescence Using an Imaging Spectrometer. *International Journal of Remote Sensing*, *11*(2), 313–320.

Gregg, J. S., Andres, R. J., & Marland, G. (2008). China: Emissions pattern of the world leader in CO2 emissions from fossil fuel consumption and cement production. *Geophysical Research Letters*, *35*(8). doi:10.1029/2007GL032887

Gregg, W. W., Casey, N. W., O'Reilly, J. E., & Esaias, W. E. (2009). An empirical approach to ocean color data: Reducing bias and the need for post-launch radiometric re-calibration. *Remote Sensing of Environment*, *113*(8), 1598–1612. doi:10.1016/j.rse.2009.03.005

Grosse, G., Harden, J., Turetsky, M., McGuire, A. D., Camill, P., Tarnocai, C., … Striegl, R. G. (2011). Vulnerability of high-latitude soil organic carbon in North America to disturbance. *Journal of Geophysical Research*, *116*(G4), G00K06. doi:10.1029/2010JG001507

Guan, D., Liu, Z., Geng, Y., Lindner, S., & Hubacek, K. (2012). The gigatonne gap in China/'s carbon dioxide inventories. *Nature Climate Change*, *2*(9), 672–675. doi:10.1038/nclimate1560

Guerlet, S., Basu, S., Butz, A., Krol, M., Hahne, P., Houweling, S., … Aben, I. (2013). Reduced carbon uptake during the 2010 Northern Hemisphere summer from GOSAT. *Geophysical Research Letters*, *40*(10), 2378–2383. doi:10.1002/grl.50402

Guillevic, P. C., Privette, J. L., Coudert, B., Palecki, M. A., Demarty, J., Ottle, C., & Augustine, J. A. (2012). Land Surface Temperature product validation using NOAA's surface climate observation networks-Scaling methodology for the Visible Infrared Imager Radiometer Suite (VIIRS). *Remote Sensing of Environment*, *124*, 282–298. doi:10.1016/j.rse.2012.05.004

Gurney, K., & O'Keeffe, D. (2013). Crowdsourcing Power Plant Carbon Dioxide Emissions Data. *Eos, Transactions American Geophysical Union*, *94*(43), 385–386. doi:10.1002/2013EO430001

Gurney, K. R., Law, R. M., Denning, A. S., Rayner, P. J., Baker, D., Bousquet, P., … Yuen, C. W. (2002). Towards robust regional estimates of CO2 sources and sinks using atmospheric transport models. *Nature*, *415*(6872), 626–630. doi:10.1038/415626a

Gurney, K. R., Mendoza, D. L., Zhou, Y., Fischer, M. L., Miller, C. C., Geethakumar, S., & de la Rue du Can, S. (2009). High Resolution Fossil Fuel Combustion CO2 Emission Fluxes for the United States. *Environmental Science & Technology*, *43*(14), 5535–5541. doi:10.1021/es900806c

Gurney, K. R., Razlivanov, I., Song, Y., Zhou, Y., Benes, B., & Abdul-Massih, M. (2012). Quantification of Fossil Fuel CO2 Emissions on the Building/Street Scale for a Large U.S. City. *Environmental Science & Technology*, *46*(21), 12194–12202. doi:10.1021/es3011282

Gusso, A., Fontana, D. C., & Goncalves, G. A. (2007). Mapping land surface temperature using AVHRR/NOAA sensor. *Pesquisa Agropecuaria Brasileira*, *42*(2), 231–237.

Hall, D. K., Kelly, R. E., Foster, J. L., & Chang, A. T. (2006). Estimation of Snow Extent and Snow Properties. In *Encyclopedia of Hydrological Sciences*. John Wiley & Sons, Ltd. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/0470848944.hsa062/abstract

Hall, R. J., Fernandes, R. A., Hogg, E. H., Brandt, J. P., Butson, C., Case, B. S., & Leblanc, S. G. (2003). Relating aspen defoliation to changes in leaf area derived from field and satellite remote sensing data. *Canadian Journal of Remote Sensing*, *29*(3), 299–313.

Hammes, K., Schmidt, M. W. I., Smernik, R. J., Currie, L. A., Ball, W. P., Nguyen, T. H., … Ding, L. (2007). Comparison of quantification methods to measure fire-derived (black/elemental) carbon in soils and sediments using reference materials from soil, water, sediment and the atmosphere. *Global Biogeochemical Cycles*, *21*(3), n/a–n/a. doi:10.1029/2006GB002914

Hansen, M. C., DeFries, R. S., Townshend, J. R. G., Carroll, M., Dimiceli, C., & Sohlberg, R. A. (2003). Global Percent Tree Cover at a Spatial Resolution of 500 Meters: First Results of the MODIS Vegetation Continuous Fields Algorithm. *Earth Interactions*, *7*.

Hansen, M. C., Defries, R. S., Townshend, J. R. G., & Sohlberg, R. (2000). Global land cover classification at 1km spatial resolution using a classification tree approach. *International Journal of Remote Sensing*, *21*(6-7), 1331–1364. doi:10.1080/014311600210209

Hansen, M. C., DeFries, R. S., Townshend, J. R. G., Sohlberg, R., Dimiceli, C., & Carroll, M. (2002). Towards an operational MODIS continuous field of percent tree cover algorithm: examples using

AVHRR and MODIS data. *Remote Sensing of Environment*, *83*(1-2), 303–319. doi:10.1016/S0034-4257(02)00079-2

Hansen, M. C., Egorov, A., Roy, D. P., Potapov, P., Ju, J., Turubanova, S., … Loveland, T. R. (2011). Continuous fields of land cover for the conterminous United States using Landsat data: first results from the Web-Enabled Landsat Data (WELD) project. *Remote Sensing Letters*, *2*(4), 279–288. doi:10.1080/01431161.2010.519002

Hansen, M. C., & Loveland, T. R. (2012). A review of large area monitoring of land cover change using Landsat data. *Remote Sensing of Environment*, *122*, 66–74. doi:10.1016/j.rse.2011.08.024

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., … Townshend, J. R. G. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, *342*(6160), 850–853. doi:10.1126/science.1244693

Hansen, M. C., Stehman, S. V., & Potapov, P. V. (2010). Quantification of global gross forest cover loss. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(19), 8650–8655. doi:10.1073/pnas.0912668107

Harden, J. W., Koven, C. D., Ping, C.-L., Hugelius, G., McGuire, A. D., Camill, P., … Grosse, G. (2012). Field information links permafrost carbon to physical vulnerabilities of thawing. *Geophysical Research Letters*, *39*. doi:10.1029/2012GL051958

Harding, D. J., & Carabajal, C. C. (2005). ICESat waveform measurements of within-footprint topographic relief and vegetation vertical structure. *Geophysical Research Letters*, *32*(21). doi:10.1029/2005GL023471

Harmon, M. E., Bond-Lamberty, B., Tang, J., & Vargas, R. (2011). Heterotrophic respiration in disturbed forests: A review with examples from North America. *Journal of Geophysical Research-Biogeosciences*, *116*. doi:10.1029/2010JG001495

Harris, N. L., Brown, S., Hagen, S. C., Saatchi, S. S., Petrova, S., Salas, W., … Lotsch, A. (2012). Baseline Map of Carbon Emissions from Deforestation in Tropical Regions. *Science*, *336*(6088), 1573–1576. doi:10.1126/science.1217962

Haruyama, S., & Shida, K. (2008). Geomorphologic land classification map of the Mekong Delta utilizing JERS-1 SAR images. *Hydrological Processes*, *22*(9), 1373–1381. doi:10.1002/hyp.6946

Hatala, J. A., Crabtree, R. L., Halligan, K. Q., & Moorcroft, P. R. (2010). Landscape-scale patterns of forest pest and pathogen damage in the Greater Yellowstone Ecosystem. *Remote Sensing of Environment*, *114*(2), 375–384. doi:10.1016/j.rse.2009.09.008

Hayes, D. J., Turner, D. P., Stinson, G., McGuire, A. D., Wei, Y., West, T. O., … Cook, R. B. (2012). Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions, and a new approach for estimating net ecosystem exchange from inventory-based data. *Global Change Biology*, *18*(4), 1282–1299. doi:10.1111/j.1365-2486.2011.02627.x

Herold, M., Woodcock, C., Cihlar, J., Wulder, M., Arino, O., Achard, F., … Sessa, R. (2009). *Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables: T9 Land Cover* (No. Global Terrestrial Observing System Report 64) (p. 25). Rome: FAO.

Hess, L., Melack, J., Filoso, S., & Wang, Y. (1995). Delineation of Inundated Area and Vegetation Along the Amazon Floodplain with the Sir-C Synthetic-Aperture Radar. *Ieee Transactions on Geoscience and Remote Sensing*, *33*(4), 896–904. doi:10.1109/36.406675

Hicke, J. A., Allen, C. D., Desai, A. R., Dietze, M. C., Hall, R. J., (Ted) Hogg, E. H., … Vogelmann, J. (2012). Effects of biotic disturbances on forest carbon cycling in the United States and Canada. *Global Change Biology*, *18*(1), 7–34. doi:10.1111/j.1365-2486.2011.02543.x

Hooijer, A., Page, S., Canadell, J. G., Silvius, M., Kwadijk, J., Wosten, H., & Jauhiainen, J. (2010). Current and future CO2 emissions from drained peatlands in Southeast Asia. *Biogeosciences*, *7*(5), 1505–1514. doi:10.5194/bg-7-1505-2010

Hornacek, M., Wagner, W., Sabel, D., Truong, H.-L., Snoeij, P., Hahmann, T., … Doubkova, M. (2012). Potential for High Resolution Systematic Global Surface Soil Moisture Retrieval via Change Detection Using Sentinel-1. *Ieee Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *5*(4), 1303–1311. doi:10.1109/JSTARS.2012.2190136

Houghton, R. A. (2007). Balancing the global carbon budget. *Annual Review of Earth and Planetary Sciences*, *35*, 313–347. doi:10.1146/annurev.earth.35.031306.140057

Houghton, R. A. (2012). Carbon emissions and the drivers of deforestation and forest degradation in the tropics. *Current Opinion in Environmental Sustainability*, *4*(6), 597–603. doi:10.1016/j.cosust.2012.06.006

Houghton, R. A., Hall, F., & Goetz, S. J. (2009). Importance of biomass in the global carbon cycle. *Journal of Geophysical Research-Biogeosciences*, *114*. doi:10.1029/2009JG000935

Houghton, R. A., Skole, D. L., Nobre, C. A., Hackler, J. L., Lawrence, K. T., & Chomentowski, W. H. (2000). Annual fluxes or carbon from deforestation and regrowth in the Brazilian Amazon. *Nature*, *403*(6767), 301–304. doi:10.1038/35002062

Huang, C., Coward, S. N., Masek, J. G., Thomas, N., Zhu, Z., & Vogelmann, J. E. (2010). An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks. *Remote Sensing of Environment*, *114*(1), 183–198. doi:10.1016/j.rse.2009.08.017

Huang, C., Goward, S. N., Schleeweis, K., Thomas, N., Masek, J. G., & Zhu, Z. (2009). Dynamics of national forests assessed using the Landsat record: Case studies in eastern United States. *Remote Sensing of Environment*, *113*(7), 1430–1442. doi:10.1016/j.rse.2008.06.016

Huang, C., Li, X., & Lu, L. (2008). Retrieving soil temperature profile by assimilating MODIS LST products with ensemble Kalman filter. *Remote Sensing of Environment*, *112*(4), 1320–1336. doi:10.1016/j.rse.2007.03.028

Huang, M., & Asner, G. P. (2010). Long-term carbon loss and recovery following selective logging in Amazon forests. *Global Biogeochemical Cycles*, *24*(3), n/a–n/a. doi:10.1029/2009GB003727

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, *83*(1-2), 195–213. doi:10.1016/S0034-4257(02)00096-2

Hulley, G. C., & Hook, S. J. (2009). The North American ASTER Land Surface Emissivity Database (NAALSED) Version 2.0. *Remote Sensing of Environment*, *113*(9), 1967–1975. doi:10.1016/j.rse.2009.05.005

Hurtt, G. C., Dubayah, R., Drake, J., Moorcroft, P. R., Pacala, S. W., Blair, J. B., & Fearon, M. G. (2004). Beyond potential vegetation: combining lidar data and a height-structured model for carbon studies. *Ecological Applications*, *14*(3), 873–883. doi:10.1890/02-5317

Hurtt, G. C., Fisk, J., Thomas, R. Q., Dubayah, R., Moorcroft, P. R., & Shugart, H. H. (2010). Linking models and data on vegetation structure. *Journal of Geophysical Research-Biogeosciences*, *115*. doi:10.1029/2009JG000937

IGACO. (2004). *The Changing Atmosphere: An Integrated Global Atmospheric Chemistry Observation Theme for the Igos Partnership* (No. ESA SP-1282, WMO TD No. 1235). WMO.

IGOS-P. (2003). *Integrated Global Carbon Observation Theme: A Strategy to Realize a Coordinated System of Integrated Global Carbon Cycle Observations*. Retrieved from http://www.eohandbook.com/igosp/Carbon.htm

IOCCG. (2008). *Why Ocean Colour? The Societal Benefits of Ocean-Colour Technology* (No. Reports of the International Ocean-Colour Coordinating Group, No. 7). Dartmouth, Canada: IOCCG.

IOCCG. (2009a). *Partition of the Ocean into Ecological Provinces: Role of Ocean-Colour Radiometry* (No. Reports of the International Ocean-Colour Coordinating Group, No. 9). Dartmouth, Canada: IOCCG.

IOCCG. (2009b). *Remote Sensing in Fisheries and Aquaculture* (No. Reports of the International Ocean-Colour Coordinating Group, No. 8). Dartmouth, Canada: IOCCG.

IOCCG. (2012). *Mission Requirements for Future Ocean-Colour Sensors* (No. Reports of the International Ocean-Colour Coordinating Group, No. 13, IOCC). Dartmouth, Canada.

IPCC. (2007). *Climate Change 2007: Synthesis Report. Contribution Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* (R. Pachauri & A. Reisinger, Eds.). Geneva, Switzerland: IPCC.

IPCC. (2013). *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* (T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, … P. M. Midgley, Eds.). Cambridge, UK: Cambridge University Press.

Ippoliti-Ramilo, G. A., Epiphanio, J. C. N., & Shimabukuro, Y. E. (2003). Landsat-5 Thematic Mapper data for pre-planting crop area evaluation in tropical countries. *International Journal of Remote Sensing*, *24*(7), 1521–1534. doi:10.1080/01431160010007105

Ishimura, A., Shimizu, Y., Rahimzadeh-Bajgiran, P., & Omasa, K. (2011). Remote sensing of Japanese beech forest decline using an improved Temperature Vegetation Dryness Index (iTVDI). *Iforest-Biogeosciences and Forestry*, *4*, 195–199. doi:10.3832/ifor0592-004

Jackson, T. J., Bindlish, R., Cosh, M. H., Zhao, T., Starks, P. J., Bosch, D. D., … Leroux, D. (2012). Validation of Soil Moisture and Ocean Salinity (SMOS) Soil Moisture Over Watershed Networks in the U.S. *IEEE Transactions on Geoscience and Remote Sensing*, *50*(5), 1530–1543. doi:10.1109/TGRS.2011.2168533

Jaffe, R., Ding, Y., Niggemann, J., Vahatalo, A. V., Stubbins, A., Spencer, R. G. M., … Dittmar, T. (2013). Global Charcoal Mobilization from Soils via Dissolution and Riverine Transport to the Oceans. *Science*, *340*(6130), 345–347. doi:10.1126/science.1231476

Jain, N., Pathak, H., Mitra, S., & Bhatia, A. (2004). Emission of methane from rice fields - A review. *Journal of Scientific & Industrial Research*, *63*(2), 101–115.

Jamet, C., Moulin, C., & Lefevre, N. (2007). Estimation of the oceanic pCO2 in the North Atlantic from VOS lines in-situ measurements: parameters needed to generate seasonally mean maps. *Annales Geophysicae*, *25*(11), 2247–2257.

JASON. (2011). *Methods for remote determination of CO2 emissions.* (JSR-10-300). McLean, VA. http://www.fas.org/irp/agency/dod/jason/emissions.pdf: MITRE Corp. Retrieved from http://www.fas.org/irp/agency/dod/jason/emissions.pdf

Jiao, Z., Woodcock, C., Schaaf, C. B., Tan, B., Liu, J., Gao, F., … Wang, J. (2011). Improving MODIS land cover classification by combining MODIS spectral and angular signatures in a Canadian boreal forest. *Canadian Journal of Remote Sensing*, *37*(2), 184–203.

Johannessen, S. C., Potentier, G., Wright, C. A., Masson, D., & Macdonald, R. W. (2008). Water column organic carbon in a Pacific marginal sea (Strait of Georgia, Canada). *Marine Environmental Research*, *66*, S49–S61. doi:10.1016/j.marenvres.2008.07.008

Johnson, D. M. (2013). A 2010 map estimate of annually tilled cropland within the conterminous United States. *Agricultural Systems*, *114*, 95–105. doi:10.1016/j.agsy.2012.08.004

Joiner, J., Yoshida, Y., Vasilkov, A. P., Yoshida, Y., Corp, L. A., & Middleton, E. M. (2011). First observations of global and seasonal terrestrial chlorophyll fluorescence from space. *Biogeosciences*, *8*(3), 637–651. doi:10.5194/bg-8-637-2011

Jones, C. T., Sikora, T. D., Vachon, P. W., & Buckley, J. R. (2013). Ocean feature analysis using automated detection and classification of sea-surface temperature front signatures in RADARSAT-2 images. *Bulletin of the American Meteorological Society*, 130906094626000. doi:10.1175/BAMS-D-12-00174.1

Jones, L. A., Ferguson, C. R., Kimball, J. S., Zhang, K., Chan, S. T. K., McDonald, K. C., … Wood, E. F.

(2010). Satellite Microwave Remote Sensing of Daily Land Surface Air Temperature Minima and Maxima From AMSR-E. *Ieee Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *3*(1), 111–123. doi:10.1109/JSTARS.2010.2041530

Jones, M. O., Kimball, J. S., Jones, L. A., & McDonald, K. C. (2012). Satellite passive microwave detection of North America start of season. *Remote Sensing of Environment*, *123*, 324–333. doi:10.1016/j.rse.2012.03.025

Justice, C. O., Townshend, J. R. G., Vermote, E. F., Masuoka, E., Wolfe, R. E., Saleous, N., … Morisette, J. T. (2002). An overview of MODIS Land data processing and product status. *Remote Sensing of Environment*, *83*(1-2), 3–15. doi:10.1016/S0034-4257(02)00084-6

Justice, C. O., Vermote, E., Townshend, J. R. G., Defries, R., Roy, D. P., Hall, D. K., … Barnsley, M. J. (1998). The Moderate Resolution Imaging Spectroradiometer (MODIS): Land remote sensing for global change research. *Ieee Transactions on Geoscience and Remote Sensing*, *36*(4), 1228–1249. doi:10.1109/36.701075

Kaiser, J. W., Heil, A., Andreae, M. O., Benedetti, A., Chubarova, N., Jones, L., … van der Werf, G. R. (2012). Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. *Biogeosciences*, *9*(1), 527–554. doi:10.5194/bg-9-527-2012

Kallio, K., Attila, J., Harma, P., Koponen, S., Pulliainen, J., Hyytiainen, U.-M., & Pyhalahti, T. (2008). Landsat ETM+ images in the estimation of seasonal lake water quality in boreal river basins. *Environmental Management*, *42*(3), 511–522. doi:10.1007/s00267-008-9146-y

Kallio, K., Kutser, T., Hannonen, T., Koponen, S., Pulliainen, J., Vepsalainen, J., & Pyhalahti, T. (2001). Retrieval of water quality from airborne imaging spectrometry of various lake types in different seasons. *Science of the Total Environment*, *268*(1-3), 59–77. doi:10.1016/S0048-9697(00)00685-9

Kalogirou, V., Ramos Perez, J., & Arino, O. (2013). A first analysis on the Culture-MERIS products. *Remote Sensing Letters*, *4*(3), 211–218. doi:10.1080/2150704X.2012.719087

Kaptue Tchuente, A. T., Roujean, J.-L., & De Jong, S. M. (2011). Comparison and relative quality assessment of the GLC2000, GLOBCOVER, MODIS and ECOCLIMAP land cover data sets at the African continental scale. *International Journal of Applied Earth Observation and Geoinformation*, *13*(2), 207–219. doi:10.1016/j.jag.2010.11.005

Kasischke, E. S., Amiro, B. D., Barger, N. N., French, N. H. F., Goetz, S. J., Grosse, G., … Masek, J. G. (2013). Impacts of disturbance on the terrestrial carbon budget of North America: Disturbance and Carbon Cycling. *Journal of Geophysical Research: Biogeosciences*, *118*(1), 303–316. doi:10.1002/jgrg.20027

Kasischke, E. S., Bourgeau-Chavez, L. L., & Johnstone, J. F. (2007). Assessing spatial and temporal variations in surface soil moisture in fire-disturbed black spruce forests in Interior Alaska using spaceborne synthetic aperture radar imagery - Implications for post-fire tree recruitment. *Remote Sensing of Environment*, *108*(1), 42–58. doi:10.1016/j.rse.2006.10.020

Kasischke, E. S., & Hoy, E. E. (2012). Controls on carbon consumption during Alaskan wildland fires. *Global Change Biology*, *18*(2), 685–699. doi:10.1111/j.1365-2486.2011.02573.x

Kasischke, E. S., Loboda, T., Giglio, L., French, N. H. F., Hoy, E. E., de Jong, B., & Riano, D. (2011). Quantifying burned area for North American forests: Implications for direct reduction of carbon stocks. *Journal of Geophysical Research*, *116*(G4). doi:10.1029/2011JG001707

Keeling, C. D. (1960). The Concentration and Isotopic Abundances of Carbon Dioxide in the Atmosphere. *Tellus*, *12*(2), 200–203. doi:10.1111/j.2153-3490.1960.tb01300.x

Keeling, R. F., & Severinghaus, J. (2000). Atmospheric Oxygen Measurements and the Carbon Cycle. In *The Carbon Cycle*. Cambridge University Press. Retrieved from http://dx.doi.org/10.1017/CBO9780511573095.012

Keenan, T. F., Baker, I., Barr, A., Ciais, P., Davis, K., Dietze, M., … Richardson, A. D. (2012). Terrestrial biosphere model performance for inter-annual variability of land-atmosphere CO2 exchange.

Global Change Biology, *18*(6), 1971–1987. doi:10.1111/j.1365-2486.2012.02678.x

Kennedy, R. E., Cohen, W. B., & Schroeder, T. A. (2007). Trajectory-based change detection for automated characterization of forest disturbance dynamics. *Remote Sensing of Environment*, *110*(3), 370–386. doi:10.1016/j.rse.2007.03.010

Kennedy, R. E., Yang, Z., Cohen, W. B., Pfaff, E., Braaten, J., & Nelson, P. (2012). Spatial and temporal patterns of forest disturbance and regrowth within the area of the Northwest Forest Plan. *Remote Sensing of Environment*, *122*, 117–133. doi:10.1016/j.rse.2011.09.024

Kerr, Y. H., Waldteufel, P., Wigneron, J.-P., Delwart, S., Cabot, F., Boutin, J., … Mecklenburg, S. (2010). The SMOS Mission: New Tool for Monitoring Key Elements of the Global Water Cycle. *Proceedings of the Ieee*, *98*(5), 666–687. doi:10.1109/JPROC.2010.2043032

Kharuk, V. I., Ranson, K. J., & Im, S. T. (2009). Siberian silkmoth outbreak pattern analysis based on SPOT VEGETATION data. *International Journal of Remote Sensing*, *30*(9), 2377–2388. doi:10.1080/01431160802549419

Kharuk, V. I., Ranson, K. J., Kozuhovskaya, A. G., Kondakov, Y. P., & Pestunov, I. A. (2004). NOAA/AVHRR satellite detection of Siberian silkmoth outbreaks in eastern Siberia. *International Journal of Remote Sensing*, *25*(24), 5543–5555. doi:10.1080/01431160410001719858

Kiemle, C., Quatrevalet, M., Ehret, G., Amediek, A., Fix, A., & Wirth, M. (2011). Sensitivity studies for a space-based methane lidar mission. *Atmospheric Measurement Techniques*, *4*(10), 2195–2211. doi:10.5194/amt-4-2195-2011

Kim, Y., Kimball, J. S., McDonald, K. C., & Glassy, J. (2011). Developing a Global Data Record of Daily Landscape Freeze/Thaw Status Using Satellite Passive Microwave Remote Sensing. *Ieee Transactions on Geoscience and Remote Sensing*, *49*(3), 949–960. doi:10.1109/TGRS.2010.2070515

Kim, Y., Kimball, J. S., Zhang, K., & McDonald, K. C. (2012). Satellite detection of increasing Northern Hemisphere non-frozen seasons from 1979 to 2008: Implications for regional vegetation growth. *Remote Sensing of Environment*, *121*, 472–487. doi:10.1016/j.rse.2012.02.014

Kimball, J. S., McDonald, K. C., Frolking, S., & Running, S. W. (2004). Radar remote sensing of the spring thaw transition across a boreal landscape. *Remote Sensing of Environment*, *89*(2), 163–175. doi:10.1016/j.rse.2002.06.004

Kimball, J. S., McDonald, K. C., & Zhao, M. (2006). Terrestrial vegetation productivity in the western arctic observed from satellite microwave and optical remote sensing. *Earth Interactions*, *10*.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J. G., Dlugokencky, E. J., … Zeng, G. (2013). Three decades of global methane sources and sinks. *Nature Geoscience*, *advance online publication*. doi:10.1038/ngeo1955

Knyazikhin, Y., Martonchik, J. V., Myneni, R. B., Diner, D. J., & Running, S. W. (1998). Synergistic algorithm for estimating vegetation canopy leaf area index and fraction of absorbed photosynthetically active radiation from MODIS and MISR data. *Journal of Geophysical Research-Atmospheres*, *103*(D24), 32257–32275. doi:10.1029/98JD02462

Kogler, C., Pinnock, S., Arino, O., Casadio, S., Corlett, G., Prata, F., & Bras, T. (2012). Note on the quality of the (A)ATSR land surface temperature record from 1991 to 2009. *International Journal of Remote Sensing*, *33*(13), 4178–4192. doi:10.1080/01431161.2011.645085

Kort, E. A., Frankenberg, C., Miller, C. E., & Oda, T. (2012). Space-based observations of megacity carbon dioxide. *Geophysical Research Letters*, *39*, L17806. doi:10.1029/2012GL052738

Kostadinov, T. S., Siegel, D. A., & Maritorena, S. (2009). Retrieval of the particle size distribution from satellite ocean color observations. *Journal of Geophysical Research-Oceans*, *114*. doi:10.1029/2009JC005303

Kostadinov, T. S., Siegel, D. A., & Maritorena, S. (2010). Global variability of phytoplankton functional types from space: assessment via the particle size distribution. *Biogeosciences*, *7*(10), 3239–3257. doi:10.5194/bg-7-3239-2010

Kowalewski, M., & Ostrowski, M. (2005). Coastal up- and downwelling in the southern Baltic. *Oceanologia*, *47*(4), 453–475.

Kozlov, I. E., Kudryavtsev, V. N., Johannessen, J. A., Chapron, B., Dailidienė, I., & Myasoedov, A. G. (2012). ASAR imaging for coastal upwelling in the Baltic Sea. *Advances in Space Research*, *50*(8), 1125–1137. doi:10.1016/j.asr.2011.08.017

Kudryavtsev, V., Myasoedov, A., Chapron, B., Johannessen, J. A., & Collard, F. (2012). Imaging mesoscale upper ocean dynamics using synthetic aperture radar and optical data. *Journal of Geophysical Research-Oceans*, *117*. doi:10.1029/2011JC007492

Kuenzer, C., & Knauer, K. (2013). Remote sensing of rice crop areas. *International Journal of Remote Sensing*, *34*(6), 2101–2139. doi:10.1080/01431161.2012.738946

Kulawik, S. S., Jones, D. B. A., Nassar, R., Irion, F. W., Worden, J. R., Bowman, K. W., … Jacobson, A. R. (2010). Characterization of Tropospheric Emission Spectrometer (TES) CO2 for carbon cycle science. *Atmospheric Chemistry and Physics*, *10*(12), 5601–5623. doi:10.5194/acp-10-5601-2010

Kumar, S., Ramesh, R., Dwivedi, R. M., Raman, M., Sheshshayee, M. S., D&#39, & Souza, W. (2010). Nitrogen Uptake in the Northeastern Arabian Sea during Winter Cooling. *International Journal of Oceanography*, *2010*. doi:10.1155/2010/819029

Kustas, W. P., Norman, J. M., Anderson, M. C., & French, A. N. (2003). Estimating subpixel surface temperatures and energy fluxes from the vegetation index-radiometric temperature relationship. *Remote Sensing of Environment*, *85*(4), 429–440. doi:10.1016/S0034-4257(03)00036-1

Kutser, T., Pierson, D. C., Kallio, K. Y., Reinart, A., & Sobek, S. (2005). Mapping lake CDOM by satellite remote sensing. *Remote Sensing of Environment*, *94*(4), 535–540. doi:10.1016/j.rse.2004.11.009

Kutser, T., Pierson, D., Tranvik, L., Reinart, A., Sobek, S., & Kallio, K. (2005). Using satellite remote sensing to estimate the colored dissolved organic matter absorption coefficient in lakes. *Ecosystems*, *8*(6), 709–720. doi:10.1007/s10021-003-0148-6

Kutser, T., Tranvik, L., & Pierson, D. C. (2009). Variations in colored dissolved organic matter between boreal lakes studied by satellite remote sensing. *Journal of Applied Remote Sensing*, *3*. doi:10.1117/1.3184437

Kuze, A., Suto, H., Nakajima, M., & Hamazaki, T. (2009). Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the Greenhouse Gases Observing Satellite for greenhouse gases monitoring. *Applied Optics*, *48*(35), 6716–6733.

Laws, E. A., Falkowski, P. G., Smith, W. O., Ducklow, H., & McCarthy, J. J. (2000). Temperature effects on export production in the open ocean. *Global Biogeochemical Cycles*, *14*(4), 1231–1246. doi:10.1029/1999GB001229

Le Quéré, C. (2009). Closing the global budget for CO2. *Global Change*, *74*, 28–31.

Le Quéré, C., Andres, R. J., Boden, T., Conway, T., Houghton, R. A., House, J. I., … Zeng, N. (2013). The global carbon budget 1959–2011. *Earth System Science Data*, *5*(1), 165–185. doi:10.5194/essd-5-165-2013

Le Quéré, C., Takahashi, T., Buitenhuis, E. T., Rödenbeck, C., & Sutherland, S. C. (2010). Impact of climate change and variability on the global oceanic sink of CO2. *Global Biogeochemical Cycles*, *24*(4), n/a–n/a. doi:10.1029/2009GB003599

Le Toan, T., Beaudoin, A., Riom, J., & Guyon, D. (1992). Relating Forest Biomass to Sar Data. *Ieee Transactions on Geoscience and Remote Sensing*, *30*(2), 403–411. doi:10.1109/36.134089

Le Toan, T., Quegan, S., Davidson, M. W. J., Balzter, H., Paillou, P., Papathanassiou, K., … Ulander, L. (2011). The BIOMASS mission: Mapping global forest biomass to better understand the terrestrial carbon cycle. *Remote Sensing of Environment*, *115*(11), 2850–2860. doi:10.1016/j.rse.2011.03.020

Lee, K., Tong, L. T., Millero, F. J., Sabine, C. L., Dickson, A. G., Goyet, C., … Key, R. M. (2006). Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans.

Geophysical Research Letters, *33*(19). doi:10.1029/2006GL027207

Lefevre, N., & Taylor, A. (2002). Estimating pCO2 from sea surface temperatures in the Atlantic gyres. *Deep-Sea Research Part I-Oceanographic Research Papers*, *49*(3), 539–554. doi:10.1016/S0967-0637(01)00064-4

Lefsky, M. A. (2010). A global forest canopy height map from the Moderate Resolution Imaging Spectroradiometer and the Geoscience Laser Altimeter System. *Geophysical Research Letters*, *37*. doi:10.1029/2010GL043622

Lefsky, M. A., Harding, D. J., Keller, M., Cohen, W. B., Carabajal, C. C., Espirito-Santo, F. D., … de Oliveira, R. (2005). Estimates of forest canopy height and aboveground biomass using ICESat. *Geophysical Research Letters*, *32*(22). doi:10.1029/2005GL023971

Levin, N., & Heimowitz, A. (2012). Mapping spatial and temporal patterns of Mediterranean wildfires from MODIS. *Remote Sensing of Environment*, *126*, 12–26. doi:10.1016/j.rse.2012.08.003

Levy, M., Klein, P., & Treguier, A. M. (2001). Impact of sub-mesoscale physics on production and subduction of phytoplankton in an oligotrophic regime. *Journal of Marine Research*, *59*(4), 535–565. doi:10.1357/002224001762842181

Li, C. S., Frolking, S., Xiao, X. M., Moore, B., Boles, S., Qiu, J. J., … Sass, R. (2005). Modeling impacts of farming management alternatives on CO2, CH4, and N2O emissions: A case study for water management of rice agriculture of China. *Global Biogeochemical Cycles*, *19*(3). doi:10.1029/2004GB002341

Li, C. S., Mosier, A., Wassmann, R., Cai, Z. C., Zheng, X. H., Huang, Y., … Lantin, R. (2004). Modeling greenhouse gas emissions from rice-based production systems: Sensitivity and upscaling. *Global Biogeochemical Cycles*, *18*(1). doi:10.1029/2003GB002045

Li, L., Gaiser, P. W., Gao, B.-C., Bevilacqua, R. M., Jackson, T. J., Njoku, E. G., … Bindlish, R. (2010). WindSat Global Soil Moisture Retrieval and Validation. *Ieee Transactions on Geoscience and Remote Sensing*, *48*(5), 2224–2241. doi:10.1109/TGRS.2009.2037749

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., … Neves, E. G. (2006). Black Carbon Increases Cation Exchange Capacity in Soils. *Soil Science Society of America Journal*, *70*(5), 1719. doi:10.2136/sssaj2005.0383

Liang, L., Schwartz, M. D., & Fei, S. (2011). Validating satellite phenology through intensive ground observation and landscape scaling in a mixed seasonal forest. *Remote Sensing of Environment*, *115*(1), 143–157. doi:10.1016/j.rse.2010.08.013

Lindquist, E., D'Annunzio, R., Gerrand, A., MacDicken, K., Achard, F., Beuchle, R., … Stibig, H. J. (2012). *Global forest land-use change 1990–2005* (No. FAO Forestry Paper No. 169). Rome: FAO.

Liu, M.-M., Wang, H.-K., Wang, H.-M., Oda, T., Zhao, Y., Yang, X.-H., … Chen, J.-M. (2013). Refined estimate of China's CO2 emissions in spatiotemporal distributions. *Atmospheric Chemistry and Physics Discussions*, *13*(7), 17451–17478. doi:10.5194/acpd-13-17451-2013

Liu, Y., Hiyama, T., & Yamaguchi, Y. (2006). Scaling of land surface temperature using satellite data: A case examination on ASTER and MODIS products over a heterogeneous terrain area. *Remote Sensing of Environment*, *105*(2), 115–128. doi:10.1016/j.rse.2006.06.012

Loboda, T., O'Neal, K. J., & Csiszar, I. (2007). Regionally adaptable dNBR-based algorithm for burned area mapping from MODIS data. *Remote Sensing of Environment*, *109*(4), 429–442. doi:10.1016/j.rse.2007.01.017

Loboda, T. V., & Csiszar, I. A. (2007). Reconstruction of fire spread within wildland fire events in Northern Eurasia from the MODIS active fire product. *Global and Planetary Change*, *56*(3-4), 258–273. doi:10.1016/j.gloplacha.2006.07.015

Loisel, H., Nicolas, J. M., Deschamps, P. Y., & Frouin, R. (2002). Seasonal and inter-annual variability of particulate organic matter in the global ocean. *Geophysical Research Letters*, *29*(24). doi:10.1029/2002GL015948

Longhurst, A., Sathyendranath, S., Platt, T., & Caverhill, C. (1995). An Estimate of Global Primary Production in the Ocean from Satellite Radiometer Data. *Journal of Plankton Research*, *17*(6), 1245–1271. doi:10.1093/plankt/17.6.1245

Loveland, T. R., Reed, B. C., Brown, J. F., Ohlen, D. O., Zhu, Z., Yang, L., & Merchant, J. W. (2000). Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. *International Journal of Remote Sensing*, *21*(6-7), 1303–1330. doi:10.1080/014311600210191

Lu, D., & Weng, Q. (2006). Spectral mixture analysis of ASTER images for examining the relationship between urban thermal features and biophysical descriptors in Indianapolis, Indiana, USA. *Remote Sensing of Environment*, *104*(2), 157–167. doi:10.1016/j.rse.2005.11.015

Machida, T., Matsueda, H., Sawa, Y., Nakagawa, Y., Hirotani, K., Kondo, N., … Ogawa, T. (2008). Worldwide Measurements of Atmospheric CO2 and Other Trace Gas Species Using Commercial Airlines. *Journal of Atmospheric and Oceanic Technology*, *25*(10), 1744–1754. doi:10.1175/2008JTECHA1082.1

Mack, M. C., Bret-Harte, M. S., Hollingsworth, T. N., Jandt, R. R., Schuur, E. A. G., Shaver, G. R., & Verbyla, D. L. (2011). Carbon loss from an unprecedented Arctic tundra wildfire. *Nature*, *475*(7357), 489–492. doi:10.1038/nature10283

Mahecha, M. D., Reichstein, M., Jung, M., Seneviratne, S. I., Zaehle, S., Beer, C., … Moors, E. (2010). Comparing observations and process-based simulations of biosphere-atmosphere exchanges on multiple timescales. *Journal of Geophysical Research-Biogeosciences*, *115*. doi:10.1029/2009JG001016

Mangiarotti, S., Martinez, J.-M., Bonnet, M.-P., Buarque, D. C., Filizola, N., & Mazzega, P. (2013). Discharge and suspended sediment flux estimated along the mainstream of the Amazon and the Madeira Rivers (from in situ and MODIS Satellite Data). *International Journal of Applied Earth Observation and Geoinformation*, *21*, 341–355. doi:10.1016/j.jag.2012.07.015

Mannino, A., Russ, M. E., & Hooker, S. B. (2008). Algorithm development and validation for satellite-derived distributions of DOC and CDOM in the US Middle Atlantic Bight. *Journal of Geophysical Research-Oceans*, *113*(C7). doi:10.1029/2007JC004493

Marengo, J. A., Tomasella, J., Alves, L. M., Soares, W. R., & Rodriguez, D. A. (2011). The drought of 2010 in the context of historical droughts in the Amazon region. *Geophysical Research Letters*, *38*. doi:10.1029/2011GL047436

Margono, B. A., Turubanova, S., Zhuravleva, I., Potapov, P., Tyukavina, A., Baccini, A., … Hansen, M. C. (2012). Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010. *Environmental Research Letters*, *7*(3). doi:10.1088/1748-9326/7/3/034010

Maritorena, S., & Siegel, D. A. (2005). Consistent merging of satellite ocean color data sets using a bio-optical model. *Remote Sensing of Environment*, *94*(4), 429–440. doi:10.1016/j.rse.2004.08.014

Marland, G., Hamal, K., & Jonas, M. (2009). How Uncertain Are Estimates of CO2 Emissions ? *Journal of Industrial Ecology*, *13*(1), 4–7. doi:10.1111/j.1530-9290.2009.00108.x

Martin, M. E., & Aber, J. D. (1997). High spectral resolution remote sensing of forest canopy lignin, nitrogen, and ecosystem processes. *Ecological Applications*, *7*(2), 431–443. doi:10.1890/1051-0761(1997)007[0431:HSRRSO]2.0.CO;2

Martinez, J.-M., & Le Toan, T. (2007). Mapping of flood dynamics and spatial distribution of vegetation in the Amazon floodplain using multitemporal SAR data. *Remote Sensing of Environment*, *108*(3), 209–223. doi:10.1016/j.rse.2006.11.012

Masek, J. G., Huang, C., Wolfe, R., Cohen, W., Hall, F., Kutler, J., & Nelson, P. (2008). North American forest disturbance mapped from a decadal Landsat record. *Remote Sensing of Environment*, *112*(6), 2914–2926. doi:10.1016/j.rse.2008.02.010

Masiello, C. A., & Louchouarn, P. (2013). Fire in the Ocean. *Science*, *340*(6130), 287–288. doi:10.1126/science.1237688

Matricardi, E. A. T., Skole, D. L., Pedlowski, M. A., & Chomentowski, W. (2013). Assessment of forest disturbances by selective logging and forest fires in the Brazilian Amazon using Landsat data. *International Journal of Remote Sensing*, *34*(4), 1057–1086. doi:10.1080/01431161.2012.717182

Matricardi, E. A. T., Skole, D. L., Pedlowski, M. A., Chomentowski, W., & Fernandes, L. C. (2010). Assessment of tropical forest degradation by selective logging and fire using Landsat imagery. *Remote Sensing of Environment*, *114*(5), 1117–1129. doi:10.1016/j.rse.2010.01.001

Mayaux, P., Achard, F., & Malingreau, J. P. (1998). Global tropical forest area measurements derived from coarse resolution satellite imagery: a comparison with other approaches. *Environmental Conservation*, *25*(1), 37–52. doi:10.1017/S0376892998000083

Mayaux, P., & Lambin, E. F. (1997). Tropical forest area measured from global land-cover classifications: Inverse calibration models based on spatial textures. *Remote Sensing of Environment*, *59*(1), 29–43. doi:10.1016/S0034-4257(96)00077-6

McClain, C. R. (2009). A Decade of Satellite Ocean Color Observations. In *Annual Review of Marine Science* (Vol. 1, pp. 19–42). Palo Alto: Annual Reviews.

McDonald, K. C., Kimball, J. S., Zhao, M. S., Njoku, E., Zimmermann, R., & Running, S. W. (2004). Spaceborne microwave remote sensing of seasonal freeze-thaw processes in the terrestrial high latitudes: Relationships with land-atmosphere CO2 exchange. In G. S. Jackson & S. Uratsuka (Eds.), *Microwave Remote Sensing of the Atmosphere and Environment Iv* (Vol. 5654, pp. 167–178). Bellingham: Spie-Int Soc Optical Engineering.

McKain, K., Wofsy, S. C., Nehrkorn, T., Eluszkiewicz, J., Ehleringer, J. R., & Stephens, B. B. (2012a). Assessment of ground-based atmospheric observations for verification of greenhouse gas emissions from an urban region. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(22), 8423–8428. doi:10.1073/pnas.1116645109

McKain, K., Wofsy, S. C., Nehrkorn, T., Eluszkiewicz, J., Ehleringer, J. R., & Stephens, B. B. (2012b). Assessment of ground-based atmospheric observations for verification of greenhouse gas emissions from an urban region. *Proceedings of the National Academy of Sciences*. doi:10.1073/pnas.1116645109

Meddens, A. J. H., Hicke, J. A., & Vierling, L. A. (2011). Evaluating the potential of multispectral imagery to map multiple stages of tree mortality. *Remote Sensing of Environment*, *115*(7), 1632–1642. doi:10.1016/j.rse.2011.02.018

Melack, J. M., Hess, L. L., Gastil, M., Forsberg, B. R., Hamilton, S. K., Lima, I. B. T., & Novo, E. (2004). Regionalization of methane emissions in the Amazon Basin with microwave remote sensing. *Global Change Biology*, *10*(5), 530–544. doi:10.1111/j.1529-8817.2003.00763.x

Melis, M. T., & Pilloni, M. (2011). Analysis and validation of a methodology to evaluate land cover in the Mediterranean basin using multitemporal MODIS data. *Rivista Italiana Di Telerilevamento*, *43*(1), 19–31.

Messerschmidt, J., Geibel, M. C., Blumenstock, T., Chen, H., Deutscher, N. M., Engel, A., … Xueref-Remy, I. (2011). Calibration of TCCON column-averaged CO2: the first aircraft campaign over European TCCON sites. *Atmospheric Chemistry and Physics*, *11*(21), 10765–10777. doi:10.5194/acp-11-10765-2011

Michailovsky, C. I., McEnnis, S., Berry, P. A. M., Smith, R., & Bauer-Gottwein, P. (2012). River monitoring from satellite radar altimetry in the Zambezi River basin. *Hydrol. Earth Syst. Sci.*, *16*(7), 2181–2192. doi:10.5194/hess-16-2181-2012

Mildrexler, D. J., Zhao, M., & Running, S. W. (2009). Testing a MODIS Global Disturbance Index across North America. *Remote Sensing of Environment*, *113*(10), 2103–2117. doi:10.1016/j.rse.2009.05.016

Miller, C. E., Crisp, D., DeCola, P. L., Olsen, S. C., Randerson, J. T., Michalak, A. M., … Law, R. M. (2007). Precision requirements for space-based X-CO2 data. *Journal of Geophysical Research-Atmospheres*, *112*(D10). doi:10.1029/2006JD007659

Miller, C. E., & Dinardo, S. J. (2012). CARVE: The Carbon in Arctic Reservoirs Vulnerability Experiment. In *2012 Ieee Aerospace Conference*. New York: Ieee.

Milutinovic, S., Behrenfeld, M. J., Johannessen, J. A., & Johannessen, T. (2009). Sensitivity of remote sensing-derived phytoplankton productivity to mixed layer depth: Lessons from the carbon-based productivity model. *Global Biogeochemical Cycles*, *23*. doi:10.1029/2008GB003431

Mitchard, E. T. A., Saatchi, S. S., Woodhouse, I. H., Nangendo, G., Ribeiro, N. S., Williams, M., … Meir, P. (2009). Using satellite radar backscatter to predict above-ground woody biomass: A consistent relationship across four different African landscapes. *Geophysical Research Letters*, *36*. doi:10.1029/2009GL040692

Montes-Hugo, M. A., Vernet, M., Martinson, D., Smith, R., & Iannuzzi, R. (2008). Variability on phytoplankton size structure in the western Antarctic Peninsula (1997-2006). *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, *55*(18-19), 2106–2117. doi:10.1016/j.dsr2.2008.04.036

Moody, A., & Woodcock, C. E. (1996). Calibration-based models for correction of area estimates derived from coarse resolution land-cover data. *Remote Sensing of Environment*, *58*(3), 225–241. doi:10.1016/S0034-4257(96)00036-3

Morisette, J. T., Baret, F., Privette, J. L., Myneni, R. B., Nickeson, J. E., Garrigues, S., … Cook, R. (2006). Validation of global moderate-resolution LAI products: A framework proposed within the CEOS Land Product Validation subgroup. *Ieee Transactions on Geoscience and Remote Sensing*, *44*(7), 1804–1817. doi:10.1109/TGRS.2006.872529

Morrissey, L., Livingston, G., & Durden, S. (1994). Use of Sar in Regional Methane Exchange Studies. *International Journal of Remote Sensing*, *15*(6), 1337–1342.

Myint, S. W., Yuan, M., Cerveny, R. S., & Giri, C. P. (2008). Comparison of Remote Sensing Image Processing Techniques to Identify Tornado Damage Areas from Landsat TM Data. *Sensors*, *8*(2), 1128–1156. doi:10.3390/s8021128

Myneni, R. B., Hoffman, S., Knyazikhin, Y., Privette, J. L., Glassy, J., Tian, Y., … Running, S. W. (2002). Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data. *Remote Sensing of Environment*, *83*(1-2), 214–231. doi:10.1016/S0034-4257(02)00074-3

Myneni, R. B., Nemani, R. R., & Running, S. W. (1997). Estimation of global leaf area index and absorbed par using radiative transfer models. *Ieee Transactions on Geoscience and Remote Sensing*, *35*(6), 1380–1393. doi:10.1109/36.649788

Myneni, R. B., Yang, W., Nemani, R. R., Huete, A. R., Dickinson, R. E., Knyazikhin, Y., … Salomonson, V. V. (2007). Large seasonal swings in leaf area of Amazon rainforests. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(12), 4820–4823. doi:10.1073/pnas.0611338104

Naeimi, V., Paulik, C., Bartsch, A., Wagner, W., Kidd, R., Park, S.-E., … Boike, J. (2012). ASCAT Surface State Flag (SSF): Extracting Information on Surface Freeze/Thaw Conditions From Backscatter Data Using an Empirical Threshold-Analysis Algorithm. *Ieee Transactions on Geoscience and Remote Sensing*, *50*(7), 2566–2582. doi:10.1109/TGRS.2011.2177667

Naeimi, V., Scipal, K., Bartalis, Z., Hasenauer, S., & Wagner, W. (2009). An Improved Soil Moisture Retrieval Algorithm for ERS and METOP Scatterometer Observations. *Ieee Transactions on Geoscience and Remote Sensing*, *47*(7), 1999–2013. doi:10.1109/TGRS.2009.2011617

Nair, A., Sathyendranath, S., Platt, T., Morales, J., Stuart, V., Forget, M.-H., … Bouman, H. (2008). Remote sensing of phytoplankton functional types. *Remote Sensing of Environment*, *112*(8), 3366–3375. doi:10.1016/j.rse.2008.01.021

Nassar, R., Napier-Linton, L., Gurney, K. R., Andres, R. J., Oda, T., Vogel, F. R., & Deng, F. (2013). Improving the temporal and spatial distribution of CO2 emissions from global fossil fuel emission data sets. *Journal of Geophysical Research: Atmospheres*, *118*(2), 917–933. doi:10.1029/2012JD018196

Nassar, R., Sioris, C. E., Jones, D. B. A., & McConnell, J. C. (2014). Satellite observations of CO2 from a Highly Elliptical Orbit (HEO) for studies of the Arctic and boreal carbon cycle. *Journal of Geophysical Research: Atmospheres*, n/a–n/a. doi:10.1002/2013JD020337

National Research Council. (2007). *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. The National Academies Press. Retrieved from http://www.nap.edu/

openbook.php?record_id=11820

Negron-Juarez, R., Baker, D. B., Zeng, H., Henkel, T. K., & Chambers, J. Q. (2010). Assessing hurricane-induced tree mortality in U.S. Gulf Coast forest ecosystems. *Journal of Geophysical Research-Biogeosciences*, *115*. doi:10.1029/2009JG001221

Negron-Juarez, R. I., Chambers, J. Q., Marra, D. M., Ribeiro, G. H. P. M., Rifai, S. W., Higuchi, N., & Roberts, D. (2011). Detection of subpixel treefall gaps with Landsat imagery in Central Amazon forests. *Remote Sensing of Environment*, *115*(12), 3322–3328. doi:10.1016/j.rse.2011.07.015

Niu, Z., HaiYing, Z., XianWei, W., WenBo, Y., DeMin, Z., KuiYi, Z., … Peng, G. (2012). Mapping wetland changes in China between 1978 and 2008. *Chinese Science Bulletin*, *57*(22), 2813–2823. doi:10.1007/s11434-012-5093-3

O'Dell, C. W., Connor, B., Bösch, H., O'Brien, D., Frankenberg, C., Castano, R., … Wunch, D. (2011). The ACOS CO2 retrieval algorithm – Part 1: Description and validation against synthetic observations. *Atmospheric Measurement Techniques Discussions*, *4*(5), 6097–6158. doi:10.5194/amtd-4-6097-2011

Oda, T., & Maksyutov, S. (2011). A very high-resolution (1 km×1 km) global fossil fuel CO2 emission inventory derived using a point source database and satellite observations of nighttime lights. *Atmos. Chem. Phys.*, *11*(2), 543–556. doi:10.5194/acp-11-543-2011

Omta, A. W., Dutkiewicz, S., & Follows, M. J. (2011). Dependence of the ocean-atmosphere partitioning of carbon on temperature and alkalinity. *Global Biogeochemical Cycles*, *25*(1), n/a–n/a. doi:10.1029/2010GB003839

Ono, T., Saino, T., Kurita, N., & Sasaki, K. (2004). Basin-scale extrapolation of shipboard pCO(2) data by using satellite SST and Ch1a. *International Journal of Remote Sensing*, *25*(19), 3803–3815. doi:10.1080/01431160310001657515

Page, S. E., Siegert, F., Rieley, J. O., Boehm, H.-D. V., Jaya, A., & Limin, S. (2002). The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, *420*(6911), 61–65. doi:10.1038/nature01131

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., … Hayes, D. (2011). A Large and Persistent Carbon Sink in the World's Forests. *Science*, *333*(6045), 988–993. doi:10.1126/science.1201609

Parazoo, N. C., Bowman, K., Frankenberg, C., Lee, J.-E., Fisher, J. B., Worden, J., … Gerbig, C. (2013). Interpreting seasonal changes in the carbon balance of southern Amazonia using measurements of XCO2 and chlorophyll fluorescence from GOSAT. *Geophysical Research Letters*, *40*(11), 2829–2833. doi:10.1002/grl.50452

Parinussa, R. M., Meesters, A. G. C. A., Liu, Y. Y., Dorigo, W., Wagner, W., & de Jeu, R. A. M. (2011). Error Estimates for Near-Real-Time Satellite Soil Moisture as Derived From the Land Parameter Retrieval Model. *Ieee Geoscience and Remote Sensing Letters*, *8*(4), 779–783. doi:10.1109/LGRS.2011.2114872

Park, G.-H., & Wanninkhof, R. (2012). A large increase of the CO2 sink in the western tropical North Atlantic from 2002 to 2009. *Journal of Geophysical Research: Oceans*, *117*(C8), n/a–n/a. doi:10.1029/2011JC007803

Park, G.-H., Wanninkhof, R., Doney, S. C., Takahashi, T., Lee, K., Feely, R. A., … Lima, I. D. (2010). Variability of global net sea-air CO2 fluxes over the last three decades using empirical relationships. *Tellus Series B-Chemical and Physical Meteorology*, *62*(5), 352–368. doi:10.1111/j.1600-0889.2010.00498.x

Park, S.-E., Bartsch, A., Sabel, D., Wagner, W., Naeimi, V., & Yamaguchi, Y. (2011). Monitoring freeze/thaw cycles using ENVISAT ASAR Global Mode. *Remote Sensing of Environment*, *115*(12), 3457–3467. doi:10.1016/j.rse.2011.08.009

Pathak, H., Li, C., & Wassmann, R. (2005). Greenhouse gas emissions from Indian rice fields: calibration and upscaling using the DNDC model. *Biogeosciences*, *2*(2), 113–123.

Pathak, H., Prasad, S., Bhatia, A., Singh, S., Kumar, S., Singh, J., & Jain, M. C. (2003). Methane emission from rice-wheat cropping system in the Indo-Gangetic plain in relation to irrigation, farmyard manure and dicyandiamide application. *Agriculture Ecosystems & Environment*, *97*(1-3), 309–316. doi:10.1016/S0167-8809(03)00033-1

Pathe, C., Wagner, W., Sabel, D., Doubkova, M., & Basara, J. B. (2009). Using ENVISAT ASAR Global Mode Data for Surface Soil Moisture Retrieval Over Oklahoma, USA. *Ieee Transactions on Geoscience and Remote Sensing*, *47*(2), 468–480. doi:10.1109/TGRS.2008.2004711

Payne, V. H., Clough, S. A., Shephard, M. W., Nassar, R., & Logan, J. A. (2009). Information-centered representation of retrievals with limited degrees of freedom for signal: Application to methane from the Tropospheric Emission Spectrometer. *Journal of Geophysical Research: Atmospheres*, *114*(D10), n/a–n/a. doi:10.1029/2008JD010155

Pereira, H. M., Leadley, P. W., Proença, V., Alkemade, R., Scharlemann, J. P. W., Fernandez-Manjarrés, J. F., … Walpole, M. (2010). Scenarios for Global Biodiversity in the 21st Century. *Science*, *330*(6010), 1496–1501. doi:10.1126/science.1196624

Peters, G. P., Marland, G., Le Quéré, C., Boden, T., Canadell, J. G., & Raupach, M. R. (2012). Rapid growth in CO2 emissions after the 2008-2009 global financial crisis. *Nature Climate Change*, *2*(1), 2–4. doi:10.1038/nclimate1332

Petzold, A., Volz-Thomas, A., Gerbig, C., Thouret, V., Cammas, J.-P., Brenninkmeijer, C. A. M., & Iagos Team. (2013). The European Research Infrastructure IAGOS - From dedicated field studies to routine observations of the atmosphere by instrumented passenger aircraft (Vol. 15, p. 8644). Presented at the EGU General Assembly Conference Abstracts. Retrieved from http://adsabs.harvard.edu/abs/2013EGUGA..15.8644P

Pflugmacher, D., Cohen, W. B., & Kennedy, R. E. (2012). Using Landsat-derived disturbance history (1972-2010) to predict current forest structure. *Remote Sensing of Environment*, *122*, 146–165. doi:10.1016/j.rse.2011.09.025

Pinty, B., Lavergne, T., Vossbeck, M., Kaminski, T., Aussedat, O., Giering, R., … Widlowski, J.-L. (2007). Retrieving surface parameters for climate models from Moderate Resolution Imaging Spectroradiometer (MODIS)-Multiangle Imaging Spectroradiometer (MISR) albedo products. *Journal of Geophysical Research-Atmospheres*, *112*(D10). doi:10.1029/2006JD008105

Platt, T., & Sathyendranath, S. (2008). Ecological indicators for the pelagic zone of the ocean from remote sensing. *Remote Sensing of Environment*, *112*(8), 3426–3436. doi:10.1016/j.rse.2007.10.016

Platt, T., Sathyendranath, S., Forget, M.-H., White, G. N., Caverhill, C., Bouman, H., … Son, S. (2008). Operational estimation of primary production at large geographical scales. *Remote Sensing of Environment*, *112*(8), 3437–3448. doi:10.1016/j.rse.2007.11.018

Plummer, S., Arino, O., Simon, M., & Steffen, W. (2006). Establishing A Earth Observation Product Service For The Terrestrial Carbon Community: The Globcarbon Initiative. *Mitigation and Adaptation Strategies for Global Change*, *11*(1), 97–111. doi:10.1007/s11027-006-1012-8

Potter, C., Randerson, J., Field, C., Matson, P., Vitousek, P., Mooney, H., & Klooster, S. (1993). Terrestrial Ecosystem Production - a Process Model-Based on Global Satellite and Surface Data. *Global Biogeochemical Cycles*, *7*(4), 811–841. doi:10.1029/93GB02725

Potter, C., Tan, P. N., Kumar, V., Kucharik, C., Klooster, S., Genovese, V., … Healey, S. (2005). Recent history of large-scale ecosystem disturbances in North America derived from the AVHRR satellite record. *Ecosystems*, *8*(7), 808–824. doi:10.1007/s10021-005-0041-6

Potter, C., Tan, P. N., Steinbach, M., Klooster, S., Kumar, V., Myneni, R., & Genovese, V. (2003). Major disturbance events in terrestrial ecosystems detected using global satellite data sets. *Global Change Biology*, *9*(7), 1005–1021. doi:10.1046/j.1365-2486.2003.00648.x

Poulter, B., Ciais, P., Hodson, E., Lischke, H., Maignan, F., Plummer, S., & Zimmermann, N. E. (2011).

Plant functional type mapping for earth system models. *Geoscientific Model Development*, *4*(4), 993–1010. doi:10.5194/gmd-4-993-2011

Prakash, S., Ramesh, R., Sheshshayee, M. S., Dwivedi, R. M., & Raman, M. (2008). Quantification of new production during a winter Noctiluca scintillans bloom in the Arabian Sea. *Geophysical Research Letters*, *35*(8). doi:10.1029/2008GL033819

Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M., Heimann, M., Jaramillo, H. S., … Cramer, W. (2001). The Carbon Cycle and Atmospheric Carbon Dioxide. In *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (p. 881). Cambridge, UK and New York, NY USA: Cambridge University Press.

Prigent, C., Papa, F., Aires, F., Rossow, W. B., & Matthews, E. (2007). Global inundation dynamics inferred from multiple satellite observations, 1993-2000. *Journal of Geophysical Research-Atmospheres*, *112*(D12). doi:10.1029/2006JD007847

Ramsey, E. W., Hodgson, M. E., Sapkota, S. K., & Nelson, G. A. (2001). Forest impact estimated with NOAA AVHRR and Landsat TM data related to an empirical hurricane wind-field distribution. *Remote Sensing of Environment*, *77*(3), 279–292. doi:10.1016/S0034-4257(01)00217-6

Randerson, J. T., Chen, Y., van der Werf, G. R., Rogers, B. M., & Morton, D. C. (2012). Global burned area and biomass burning emissions from small fires. *Journal of Geophysical Research-Biogeosciences*, *117*. doi:10.1029/2012JG002128

Rath, A. K., Ramakrishnan, B., Rao, V. R., & Sethunathan, N. (2005). Effects of rice-straw and phosphorus application on production and emission of methane from tropical rice soil. *Journal of Plant Nutrition and Soil Science*, *168*(2), 248–254. doi:10.1002/jpln.200421604

Raupach, M. R. (2011). CARBON CYCLE Pinning down the land carbon sink. *Nature Climate Change*, *1*(3), 148–149.

Rautiainen, K., Lemmetyinen, J., Pulliainen, J., Vehvilainen, J., Drusch, M., Kontu, A., … Seppanen, J. (2012). L-Band Radiometer Observations of Soil Processes in Boreal and Subarctic Environments. *Ieee Transactions on Geoscience and Remote Sensing*, *50*(5), 1483–1497. doi:10.1109/TGRS.2011.2167755

Raymond, P. A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., … Guth, P. (2013). Global carbon dioxide emissions from inland waters. *Nature*, *503*(7476), 355–359. doi:10.1038/nature12760

Rayner, P. J., Law, R. M., O'Brien, D. M., Butler, T. M., & Dilley, A. C. (2002). Global observations of the carbon budget - 3. Initial assessment of the impact of satellite orbit, scan geometry, and cloud on measuring CO2 from space. *Journal of Geophysical Research-Atmospheres*, *107*(D21). doi:10.1029/2001JD000618

Rayner, P. J., & O'Brien, D. M. (2001). The utility of remotely sensed CO2 concentration data in surface source inversions. *Geophysical Research Letters*, *28*(1), 175–178. doi:10.1029/2000GL011912

Rayner, P. J., Raupach, M. R., Paget, M., Peylin, P., & Koffi, E. (2010). A new global gridded data set of CO2 emissions from fossil fuel combustion: Methodology and evaluation. *Journal of Geophysical Research: Atmospheres*, *115*(D19), n/a–n/a. doi:10.1029/2009JD013439

Rayner, P. J., Scholze, M., Knorr, W., Kaminski, T., Giering, R., & Widmann, H. (2005). Two decades of terrestrial carbon fluxes from a carbon cycle data assimilation system (CCDAS). *Global Biogeochemical Cycles*, *19*(2). doi:10.1029/2004GB002254

Razavi, A., Clerbaux, C., Wespes, C., Clarisse, L., Hurtmans, D., Payan, S., … Coheur, P. F. (2009). Characterization of methane retrievals from the IASI space-borne sounder. *Atmos. Chem. Phys.*, *9*(20), 7889–7899. doi:10.5194/acp-9-7889-2009

Rebelo, L.-M., Finlayson, C. M., & Nagabhatla, N. (2009). Remote sensing and GIS for wetland inventory, mapping and change analysis. *Journal of Environmental Management*, *90*(7), 2144–2153.

doi:10.1016/j.jenvman.2007.06.027

Reed, B. C., & Brown, J. F. (2005). *Trend analysis of time-series phenology derived from satellite data*. (R. L. King & N. H. Younan, Eds.). New York: Ieee.

Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. A., … Thullner, M. (2013). Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nature Geoscience*, *6*(8), 597–607. doi:10.1038/NGEO1830

Reul, N., Saux-Picart, S., Chapron, B., Vandemark, D., Tournadre, J., & Salisbury, J. (2009). Demonstration of ocean surface salinity microwave measurements from space using AMSR-E data over the Amazon plume. *Geophysical Research Letters*, *36*. doi:10.1029/2009GL038860

Richey, J. E., Melack, J. M., Aufdenkampe, A. K., Ballester, V. M., & Hess, L. L. (2002). Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO2. *Nature*, *416*(6881), 617–620. doi:10.1038/416617a

Roberts, G. J., & Wooster, M. J. (2008). Fire detection and fire characterization over Africa using Meteosat SEVIRI. *Ieee Transactions on Geoscience and Remote Sensing*, *46*(4), 1200–1218. doi:10.1109/TGRS.2008.915751

Rosa, I. M. D., Pereira, J. M. C., & Tarantola, S. (2011). Atmospheric emissions from vegetation fires in Portugal (1990-2008): estimates, uncertainty analysis, and sensitivity analysis. *Atmospheric Chemistry and Physics*, *11*(6), 2625–2640. doi:10.5194/acp-11-2625-2011

Rosenqvist, A., Forsberg, B. R., Pimentel, T., Rauste, Y. A., & Richey, J. E. (2002). The use of spaceborne radar data to model inundation patterns and trace gas emissions in the central Amazon floodplain. *International Journal of Remote Sensing*, *23*(7), 1303–1328. doi:10.1080/01430060110092911

Ross, A. N., Wooster, M. J., Boesch, H., & Parker, R. (2013). First satellite measurements of carbon dioxide and methane emission ratios in wildfire plumes. *Geophysical Research Letters*, *40*(15), 4098–4102. doi:10.1002/grl.50733

Roy, D. P., Boschetti, L., Justice, C. O., & Ju, J. (2008). The collection 5 MODIS burned area product - Global evaluation by comparison with the MODIS active fire product. *Remote Sensing of Environment*, *112*(9), 3690–3707. doi:10.1016/j.rse.2008.05.013

Russill, C., & Nyssa, Z. (2009). The tipping point trend in climate change communication. *Global Environmental Change*, *19*(3), 336–344. doi:10.1016/j.gloenvcha.2009.04.001

Ryan, C. M., Hill, T., Woollen, E., Ghee, C., Mitchard, E., Cassells, G., … Williams, M. (2012). Quantifying small-scale deforestation and forest degradation in African woodlands using radar imagery. *Global Change Biology*, *18*(1), 243–257. doi:10.1111/j.1365-2486.2011.02551.x

Saatchi, S., Marlier, M., Chazdon, R. L., Clark, D. B., & Russell, A. E. (2011). Impact of spatial variability of tropical forest structure on radar estimation of aboveground biomass. *Remote Sensing of Environment*, *115*(11), 2836–2849. doi:10.1016/j.rse.2010.07.015

Saatchi, S. S., Houghton, R. A., Alvala, R. C. D. S., Soares, J. V., & Yu, Y. (2007). Distribution of aboveground live biomass in the Amazon basin. *Global Change Biology*, *13*(4), 816–837. doi:10.1111/j.1365-2486.2007.01323.x

Sabel, D., & Bartsch, A. (2012). ESA DUE Permafrost - SAR Freeze/Thaw V2 product guide. *EPIC3Vienna, Vienna University of Technology (Institute of Photogrammetry and Remote Sensing)*. PANGAEA Documentation. Retrieved August 6, 2013, from http://epic.awi.de/30305/

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., … Rios, A. F. (2004). The Oceanic Sink for Anthropogenic CO2. *Science*, *305*(5682), 367–371. doi:10.1126/science.1097403

Santoro, M., Beer, C., Cartus, O., Schmullius, C., Shvidenko, A., McCallum, I., … Wiesmann, A. (2011). Retrieval of growing stock volume in boreal forest using hyper-temporal series of Envisat ASAR ScanSAR backscatter measurements. *Remote Sensing of Environment*, *115*(2), 490–507. doi:10.1016/j.rse.2010.09.018

Santoro, M., Cartus, O., Fransson, J. E. S., Shvidenko, A., McCallum, I., Hall, R. J., … Schmullius, C. (2013). Estimates of Forest Growing Stock Volume for Sweden, Central Siberia, and Québec Using Envisat Advanced Synthetic Aperture Radar Backscatter Data. *Remote Sensing*, *5*(9), 4503–4532. doi:10.3390/rs5094503

Santoro, M., Fransson, J. E. S., Eriksson, L. E. B., & Ulander, L. M. H. (2010). Clear-Cut Detection in Swedish Boreal Forest Using Multi-Temporal ALOS PALSAR Backscatter Data. *Ieee Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *3*(4), 618–631. doi:10.1109/JSTARS.2010.2048201

Sarma, V. V. S. S., Saino, T., Sasaoka, K., Nojiri, Y., Ono, T., Ishii, M., … Matsumoto, K. (2006). Basin-scale pCO(2) distribution using satellite sea surface temperature, Chla, and climatological salinity in the North Pacific in spring and summer. *Global Biogeochemical Cycles*, *20*(3). doi:10.1029/2005GB002594

Sathyendranath, S., & Platt, T. (1988). The Spectral Irradiance Field at the Surface and in the Interior of the Ocean - a Model for Applications in Oceanography and Remote-Sensing. *Journal of Geophysical Research-Oceans*, *93*(C8), 9270–9280. doi:10.1029/JC093iC08p09270

Sathyendranath, S., Platt, T., Horne, E. P. W., Harrison, W. G., Ulloa, O., Outerbridge, R., & Hoepffner, N. (1991). Estimation of new production in the ocean by compound remote sensing. *Nature*, *353*(6340), 129–133. doi:10.1038/353129a0

Sathyendranath, S., Stuart, V., Nair, A., Oka, K., Nakane, T., Bouman, H., … Platt, T. (2009). Carbon-to-chlorophyll ratio and growth rate of phytoplankton in the sea. *Marine Ecology Progress Series*, *383*, 73–84. doi:10.3354/meps07998

Schneider, A., Friedl, M. A., Mciver, D. K., & Woodcock, C. E. (2003). Mapping urban areas by fusing multiple sources of coarse resolution remotely sensed data. *Photogrammetric Engineering and Remote Sensing*, *69*(12), 1377–1386.

Schneider, J., Grosse, G., & Wagner, D. (2009). Land cover classification of tundra environments in the Arctic Lena Delta based on Landsat 7 ETM+ data and its application for upscaling of methane emissions. *Remote Sensing of Environment*, *113*(2), 380–391. doi:10.1016/j.rse.2008.10.013

Schneising, O., Heymann, J., Buchwitz, M., Reuter, M., Bovensmann, H., & Burrows, J. P. (2013). Anthropogenic carbon dioxide source areas observed from space: assessment of regional enhancements and trends. *Atmospheric Chemistry and Physics*, *13*(5), 2445–2454. doi:10.5194/acp-13-2445-2013

Schroeder, R., Rawlins, M. A., McDonald, K. C., Podest, E., Zimmermann, R., & Kueppers, M. (2010). Satellite microwave remote sensing of North Eurasian inundation dynamics: development of coarse-resolution products and comparison with high-resolution synthetic aperture radar data. *Environmental Research Letters*, *5*(1). doi:10.1088/1748-9326/5/1/015003

Schuur, E. A. G., & Abbott, B. (2011). High risk of permafrost thaw. *Nature*, *480*(7375), 32–33.

Schuur, E. A. G., Bockheim, J., Canadell, J. G., Euskirchen, E., Field, C. B., Goryachkin, S. V., … Zimov, S. A. (2008). Vulnerability of Permafrost Carbon to Climate Change: Implications for the Global Carbon Cycle. *BioScience*, *58*(8), 701–714. doi:10.1641/B580807

Shepherd, A., Ivins, E. R., Geruo, A., Barletta, V. R., Bentley, M. J., Bettadpur, S., … Zwally, H. J. (2012). A Reconciled Estimate of Ice-Sheet Mass Balance. *Science*, *338*(6111), 1183–1189. doi:10.1126/science.1228102

Shutler, J. D., Grant, M. G., Miller, P. I., Rushton, E., & Anderson, K. (2010). Coccolithophore bloom detection in the north east Atlantic using SeaWiFS: Algorithm description, application and sensitivity analysis. *Remote Sensing of Environment*, *114*(5), 1008–1016. doi:10.1016/j.rse.2009.12.024

Siegel, D. A., Maritorena, S., Nelson, N. B., & Behrenfeld, M. J. (2005). Independence and interdependencies among global ocean color properties: Reassessing the bio-optical assumption. *Journal of Geophysical Research-Oceans*, *110*(C7). doi:10.1029/2004JC002527

Siegel, D. A., Maritorena, S., Nelson, N. B., Hansell, D. A., & Lorenzi-Kayser, M. (2002). Global distribution and dynamics of colored dissolved and detrital organic materials. *Journal of Geophysical Research-Oceans*, *107*(C12). doi:10.1029/2001JC000965

Siegert, F., & Ruecker, G. (2000). Use of multitemporal ERS-2 SAR images for identification of burned scars in south-east Asian tropical rainforest. *International Journal of Remote Sensing*, *21*(4), 831–837. doi:10.1080/014311600210632

Silva, T. S. F., Costa, M. P. F., Melack, J. M., & Novo, E. M. L. M. (2008). Remote sensing of aquatic vegetation: theory and applications. *Environmental Monitoring and Assessment*, *140*(1-3), 131–145. doi:10.1007/s10661-007-9855-3

Simard, M., Hensley, S., Lavalle, M., Dubayah, R., Pinto, N., & Hofton, M. (2012). An Empirical Assessment of Temporal Decorrelation Using the Uninhabited Aerial Vehicle Synthetic Aperture Radar over Forested Landscapes. *Remote Sensing*, *4*(4), 975–986. doi:10.3390/rs4040975

Simard, M., Pinto, N., Fisher, J. B., & Baccini, A. (2011). Mapping forest canopy height globally with spaceborne lidar. *Journal of Geophysical Research-Biogeosciences*, *116*. doi:10.1029/2011JG001708

Simard, M., Saatchi, S. S., & De Grandi, G. (2000). The use of decision tree and multiscale texture for classification of JERS-1 SAR data over tropical forest. *Ieee Transactions on Geoscience and Remote Sensing*, *38*(5), 2310–2321. doi:10.1109/36.868888

Siqueira, P., Hensley, S., Shaffer, S., Hess, L., McGarragh, G., Chapman, B., & Freeman, A. (2000). A continental-scale mosaic of the Amazon Basin using JERS-1 SAR. *Ieee Transactions on Geoscience and Remote Sensing*, *38*(6), 2638–2644.

Sitch, S., McGuire, A. D., Kimball, J., Gedney, N., Gamon, J., Engstrom, R., … McDonald, K. C. (2007). Assessing the carbon balance of circumpolar Arctic tundra using remote sensing and process modeling. *Ecological Applications*, *17*(1), 213–234. doi:10.1890/1051-0761(2007)017[0213:ATCBOC]2.0.CO;2

Skole, D., & Tucker, C. (1993). Tropical Deforestation and Habitat Fragmentation in the Amazon: Satellite Data from 1978 to 1988. *Science*, *260*(5116), 1905–1910. doi:10.1126/science.260.5116.1905

Sobek, S., Algesten, G., Bergstrom, A. K., Jansson, M., & Tranvik, L. J. (2003). The catchment and climate regulation of pCO2 in boreal lakes. *Global Change Biology*, *9*(4), 630–641. doi:10.1046/j.1365-2486.2003.00619.x

SOCCR. (2008). *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.* Ashville, TN: National Oceanic and Atmospheric Administration, National Climatic Data Center.

Souza-Filho, P. W. M., Paradella, W. R., Rodrigues, S. W. P., Costa, F. R., Mura, J. C., & Goncalves, F. D. (2011). Discrimination of coastal wetland environments in the Amazon region based on multi-polarized L-band airborne Synthetic Aperture Radar imagery. *Estuarine Coastal and Shelf Science*, *95*(1), 88–98. doi:10.1016/j.ecss.2011.08.011

Stinson, G., Kurz, W. A., Smyth, C. E., Neilson, E. T., Dymond, C. C., Metsaranta, J. M., … Blain, D. (2011). An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Global Change Biology*, *17*(6), 2227–2244. doi:10.1111/j.1365-2486.2010.02369.x

Strahler, A. H., Boschetti, L., Foody, G. M., Friedl, M. A., Hansen, M. C., Herold, M., … Woodcock, C. E. (2006). *Global Land Cover Validation: Recommendations for Evaluation and Accuracy Assessment Of Global Land Cover Maps* (No. Report of Committee of Earth Observation Satellites (CEOS) - Working Group on Calibration and Validation (WGCV)).

Stramska, M. (2009). Particulate organic carbon in the global ocean derived from SeaWiFS ocean color. *Deep-Sea Research Part I-Oceanographic Research Papers*, *56*(9), 1459–1470. doi:10.1016/j.dsr.2009.04.009

Subramaniam, A., Brown, C. W., Hood, R. R., Carpenter, E. J., & Capone, D. G. (2002). Detecting

Trichodesmium blooms in SeaWiFS imagery. *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, *49*(1-3), 107–121.

Takala, M., Pulliainen, J., Metsamaki, S. J., & Koskinen, J. T. (2009). Detection of Snowmelt Using Spaceborne Microwave Radiometer Data in Eurasia From 1979 to 2007. *Ieee Transactions on Geoscience and Remote Sensing*, *47*(9), 2996–3007. doi:10.1109/TGRS.2009.2018442

Takeuchi, W., Tamura, M., & Yasuoka, Y. (2003). Estimation of methane emission from West Siberian wetland by scaling technique between NOAA AVHRR and SPOT HRV. *Remote Sensing of Environment*, *85*(1), 21–29. doi:10.1016/S0034-4257(02)00183-9

Tans, P., Berry, J., & Keeling, R. (1993). Oceanic C-13/C-12 Observations - a New Window on Ocean Co2 Uptake. *Global Biogeochemical Cycles*, *7*(2), 353–368. doi:10.1029/93GB00053

Tans, P., Conway, T., & Nakazawa, T. (1989). Latitudinal Distribution of the Sources and Sinks of Atmospheric Carbon-Dioxide Derived from Surface Observations and an Atmospheric Transport Model. *Journal of Geophysical Research-Atmospheres*, *94*(D4), 5151–5172. doi:10.1029/JD094iD04p05151

Tansey, K., Gregoire, J.-M., Defourny, P., Leigh, R., Pekel, J.-F., van Bogaert, E., & Bartholome, E. (2008). A new, global, multi-annual (2000-2007) burnt area product at 1 km resolution. *Geophysical Research Letters*, *35*(1). doi:10.1029/2007GL031567

Tarnocai, C., Canadell, J. G., Schuur, E. a. G., Kuhry, P., Mazhitova, G., & Zimov, S. (2009). Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*, *23*. doi:10.1029/2008GB003327

Thenkabail, P. S., Lyon, J. G., & Huete, A. (2011). *Hyperspectral remote sensing of vegetation*. Boca Raton, Fla: CRC Press.

Thomas, A. C., & Weatherbee, R. A. (2006). Satellite-measured temporal variability of the Columbia River plume. *Remote Sensing of Environment*, *100*(2), 167–178. doi:10.1016/j.rse.2005.10.018

Thomas, K. A., Denny, E. G., Miller-Rushing, A. J., Crimmins, T. M., & Weltzin, J. F. (2010). *The National Phenology Monitoring System v0.1* (No. USA-NPN Technical Series 2010-001) (p. 78). USA - National Phenology Network. Retrieved from http://www.usanpn.org/files/shared/files/Thomas_NPMSv0.1-FINAL.pdf

Thurner, M., Beer, C., Santoro, M., Carvalhais, N., Wutzler, T., Schepaschenko, D., … Schmullius, C. (2014). Carbon stock and density of northern boreal and temperate forests. *Global Ecology and Biogeography*, *23*(3), 297–310. doi:10.1111/geb.12125

Topliss, B., & Platt, T. (1986). Passive Fluorescence and Photosynthesis in the Ocean - Implications for Remote-Sensing. *Deep-Sea Research Part a-Oceanographic Research Papers*, *33*(7), 849–864. doi:10.1016/0198-0149(86)90001-4

Townsend, P. A., Singh, A., Foster, J. R., Rehberg, N. J., Kingdon, C. C., Eshleman, K. N., & Seagle, S. W. (2012). A general Landsat model to predict canopy defoliation in broadleaf deciduous forests. *Remote Sensing of Environment*, *119*, 255–265. doi:10.1016/j.rse.2011.12.023

Townshend, J. R. G., Justice, C. O., Skole, D., Malingreau, J.-P., Cihlar, J., Tellet, P., … Ruttenberg, S. (1994). The 1 km resolution global data set: needs of the International Geosphere Biosphere Programme†. *International Journal of Remote Sensing*, *15*(17), 3417–3441. doi:10.1080/01431169408954338

Townshend, J. R., Masek, J. G., Huang, C., Vermote, E. F., Gao, F., Channan, S., … Wolfe, R. E. (2012). Global characterization and monitoring of forest cover using Landsat data: opportunities and challenges. *International Journal of Digital Earth*, *5*(5), 373–397. doi:10.1080/17538947.2012.713190

Tranvik, L. (1990). Bacterioplankton Growth on Fractions of Dissolved Organic-Carbon of Different Molecular-Weights from Humic and Clear Waters. *Applied and Environmental Microbiology*, *56*(6), 1672–1677.

Tranvik, L. J., Downing, J. A., Cotner, J. B., Loiselle, S. A., Striegl, R. G., Ballatore, T. J., … Weyhenmeyer, G. A. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and*

Oceanography, *54*(6), 2298–2314. doi:10.4319/lo.2009.54.6_part_2.2298

Trigo, I. F., Peres, L. F., DaCarnara, C. C., & Freitas, S. C. (2008). Thermal land surface emissivity retrieved from SEVIRI/meteosat. *Ieee Transactions on Geoscience and Remote Sensing*, *46*(2), 307–315. doi:10.1109/TGRS.2007.905197

Trishchenko, A. P., & Garand, L. (2012). Observing polar regions from space: advantages of a satellite system on a highly elliptical orbit versus a constellation of low Earth polar orbiters. *Canadian Journal of Remote Sensing*, *38*(1), 12–24. doi:10.5589/m12-009

Tucker, C. J., Grant, D. M., & Dykstra, J. D. (2004). NASA's global orthorectified landsat data set. *Photogrammetric Engineering and Remote Sensing*, *70*(3), 313–322.

Turetsky, M. R., Donahue, W. F., & Benscoter, B. W. (2011). Experimental drying intensifies burning and carbon losses in a northern peatland. *Nature Communications*, *2*. doi:10.1038/ncomms1523

Turetsky, M. R., Kane, E. S., Harden, J. W., Ottmar, R. D., Manies, K. L., Hoy, E., & Kasischke, E. S. (2011). Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nature Geoscience*, *4*(1), 27–31. doi:10.1038/NGEO1027

Turner, D. P., Ritts, W. D., Cohen, W. B., Gower, S. T., Running, S. W., Zhao, M. S., … Ahl, D. E. (2006). Evaluation of MODIS NPP and GPP products across multiple biomes. *Remote Sensing of Environment*, *102*(3-4), 282–292. doi:10.1016/j.rse.2006.02.017

U.S. Defense Science Board. (2011). *Trends and Implications of Climate Change for National and International Security*. Washington, D.C.: Office of the Under Secretary of Defense.

Uitz, J., Claustre, H., Gentili, B., & Stramski, D. (2010). Phytoplankton class-specific primary production in the world's oceans: Seasonal and interannual variability from satellite observations. *Global Biogeochemical Cycles*, *24*. doi:10.1029/2009GB003680

Uitz, J., Claustre, H., Morel, A., & Hooker, S. B. (2006). Vertical distribution of phytoplankton communities in open ocean: An assessment based on surface chlorophyll. *Journal of Geophysical Research: Oceans*, *111*(C8), n/a–n/a. doi:10.1029/2005JC003207

Van der Werf, G. R., Morton, D. C., DeFries, R. S., Olivier, J. G. J., Kasibhatla, P. S., Jackson, R. B., … Randerson, J. T. (2009). CO2 emissions from forest loss. *Nature Geoscience*, *2*(11), 737–738. doi:10.1038/ngeo671

Van der Werf, G. R., Randerson, J. T., Collatz, G. J., & Giglio, L. (2003). Carbon emissions from fires in tropical and subtropical ecosystems. *Global Change Biology*, *9*(4), 547–562. doi:10.1046/j.1365-2486.2003.00604.x

Van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., … van Leeuwen, T. T. (2010). Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009). *Atmospheric Chemistry and Physics*, *10*(23), 11707–11735. doi:10.5194/acp-10-11707-2010

Vermote, E., Ellicott, E., Dubovik, O., Lapyonok, T., Chin, M., Giglio, L., & Roberts, G. J. (2009). An approach to estimate global biomass burning emissions of organic and black carbon from MODIS fire radiative power. *Journal of Geophysical Research-Atmospheres*, *114*. doi:10.1029/2008JD011188

Von Clarmann, T., Hoepfner, M., Kellmann, S., Linden, A., Chauhan, S., Funke, B., … Versick, S. (2009). Retrieval of temperature, H2O, O-3, HNO3, CH4, N2O, ClONO2 and ClO from MIPAS reduced resolution nominal mode limb emission measurements. *Atmospheric Measurement Techniques*, *2*(1), 159–175.

Walter, K. M., Zimov, S. A., Chanton, J. P., Verbyla, D., & Chapin, F. S. (2006). Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. *Nature*, *443*(7107), 71–75. doi:10.1038/nature05040

Wan, Z. (2008). New refinements and validation of the MODIS Land-Surface Temperature/Emissivity products. *Remote Sensing of Environment*, *112*(1), 59–74. doi:10.1016/j.rse.2006.06.026

Wan, Z., Zhang, Y., Zhang, Q., & Li, Z. L. (2004). Quality assessment and validation of the MODIS global land surface temperature. *International Journal of Remote Sensing*, *25*(1), 261–274. doi:10.1080/0143116031000116417

Wang, F., & Xu, Y. J. (2009). Hurricane Katrina-induced forest damage in relation to ecological factors at landscape scale. *Environmental Monitoring and Assessment*, *156*(1-4), 491–507. doi:10.1007/s10661-008-0500-6

Washenfelder, R. A., Toon, G. C., Blavier, J.-F., Yang, Z., Allen, N. T., Wennberg, P. O., … Daube, B. C. (2006). Carbon dioxide column abundances at the Wisconsin Tall Tower site. *Journal of Geophysical Research-Atmospheres*, *111*(D22), D22305. doi:10.1029/2006JD007154

Watson, A. J., Schuster, U., Bakker, D. C. E., Bates, N. R., Corbiere, A., Gonzalez-Davila, M., … Wanninkhof, R. (2009). Tracking the Variable North Atlantic Sink for Atmospheric CO2. *Science*, *326*(5958), 1391–1393. doi:10.1126/science.1177394

Watts, J. D., Kimball, J. S., Jones, L. A., Schroeder, R., & McDonald, K. C. (2012). Satellite Microwave remote sensing of contrasting surface water inundation changes within the Arctic-Boreal Region. *Remote Sensing of Environment*, *127*, 223–236. doi:10.1016/j.rse.2012.09.003

Westberry, T. K., Siegel, D. A., & Subramaniam, A. (2005). An improved bio-optical model for the remote sensing of Trichodesmium spp. blooms. *Journal of Geophysical Research-Oceans*, *110*(C6). doi:10.1029/2004JC002517

Whitcomb, J., Moghaddam, M., McDonald, K., Kellndorfer, J., & Podest, E. (2009). Mapping vegetated wetlands of Alaska using L-band radar satellite imagery. *Canadian Journal of Remote Sensing*, *35*(1), 54–72. doi:10.5589/m08-080

White, M. A., de Beurs, K. M., Didan, K., Inouye, D. W., Richardson, A. D., Jensen, O. P., … Lauenroth, W. K. (2009). Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982-2006. *Global Change Biology*, *15*(10), 2335–2359. doi:10.1111/j.1365-2486.2009.01910.x

Whittle, M., Quegan, S., Uryu, Y., Stueewe, M., & Yulianto, K. (2012). Detection of tropical deforestation using ALOS-PALSAR: A Sumatran case study. *Remote Sensing of Environment*, *124*, 83–98. doi:10.1016/j.rse.2012.04.027

Williams, C. A., Collatz, G. J., Masek, J., & Goward, S. N. (2012). Carbon consequences of forest disturbance and recovery across the conterminous United States. *Global Biogeochemical Cycles*, *26*. doi:10.1029/2010GB003947

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., … Edmonds, J. (2009). Implications of Limiting CO2 Concentrations for Land Use and Energy. *Science*, *324*(5931), 1183–1186. doi:10.1126/science.1168475

Wismann, V. (2000). Monitoring of seasonal thawing in Siberia with ERS scatterometer data. *Ieee Transactions on Geoscience and Remote Sensing*, *38*(4), 1804–1809. doi:10.1109/36.851764

Wofsy, S. C. (2011). HIAPER Pole-to-Pole Observations (HIPPO): fine-grained, global-scale measurements of climatically important atmospheric gases and aerosols. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, *369*(1943), 2073–2086. doi:10.1098/rsta.2010.0313

Wu, Q., Sun, L., Wang, F., & Jia, S. (2012). The Quantificational Evaluation of a Sampling Unit Error Derived from Main Crop Area Monitorings at National Scale Based 3S in China. *Sensor Letters*, *10*(1-2), 213–220. doi:10.1166/sl.2012.1824

Wulder, M. A., Dymond, C. C., White, J. C., Leckie, D. G., & Carroll, A. L. (2006). Surveying mountain pine beetle damage of forests: A review of remote sensing opportunities. *Forest Ecology and Management*, *221*(1-3), 27–41. doi:10.1016/j.foreco.2005.09.021

Wunch, D., Toon, G. C., Blavier, J.-F. L., Washenfelder, R. A., Notholt, J., Connor, B. J., … Wennberg, P. O. (2011). The Total Carbon Column Observing Network. *Philosophical Transactions of the Royal*

Society a-Mathematical Physical and Engineering Sciences, *369*(1943), 2087–2112. doi:10.1098/rsta.2010.0240

Xiao, X. M., Hollinger, D., Aber, J., Goltz, M., Davidson, E. A., Zhang, Q. Y., & Moore, B. (2004). Satellite-based modeling of gross primary production in an evergreen needleleaf forest. *Remote Sensing of Environment*, *89*(4), 519–534. doi:10.1016/j.rse.2003.11.008

Xiong, X., Barnet, C., Maddy, E., Sweeney, C., Liu, X., Zhou, L., & Goldberg, M. (2008). Characterization and validation of methane products from the Atmospheric Infrared Sounder (AIRS). *Journal of Geophysical Research: Biogeosciences*, *113*(G3), n/a–n/a. doi:10.1029/2007JG000500

Yan, X. Y., Cai, Z. C., Ohara, T., & Akimoto, H. (2003). Methane emission from rice fields in mainland China: Amount and seasonal and spatial distribution. *Journal of Geophysical Research-Atmospheres*, *108*(D16). doi:10.1029/2002JD003182

Yang, G., Pu, R., Zhao, C., Huang, W., & Wang, J. (2011). Estimation of subpixel land surface temperature using an endmember index based technique: A case examination on ASTER and MODIS temperature products over a heterogeneous area. *Remote Sensing of Environment*, *115*(5), 1202–1219. doi:10.1016/j.rse.2011.01.004

Yilmaz, M. T., Hunt, E. R., & Jackson, T. J. (2008). Remote sensing of vegetation water content from equivalent water thickness using satellite imagery. *Remote Sensing of Environment*, *112*(5), 2514–2522. doi:10.1016/j.rse.2007.11.014

Yoshida, Y., Kikuchi, N., Morino, I., Uchino, O., Oshchepkov, S., Bril, A., … Yokota, T. (2013). Improvement of the retrieval algorithm for GOSAT SWIR XCO2 and XCH4 and their validation using TCCON data. *Atmospheric Measurement Techniques*, *6*(6), 1533–1547. doi:10.5194/amt-6-1533-2013

Yoshida, Y., Ota, Y., Eguchi, N., Kikuchi, N., Nobuta, K., Tran, H., … Yokota, T. (2011). Retrieval algorithm for CO2 and CH4 column abundances from short-wavelength infrared spectral observations by the Greenhouse gases observing satellite. *Atmospheric Measurement Techniques*, *4*(4), 717–734. doi:10.5194/amt-4-717-2011

Yu, Y., Tarpley, D., Raja, M. K. R. V., Vinnikov, K., & Goldberg, M. D. (2008). Evaluation of Satellite Land Surface Temperatures Using Ground Measurements from Surface Radiation Budget Network. In M. D. Goldberg, H. J. Bloom, P. E. Ardanuy, & A. H. L. Huang (Eds.), *Atmospheric and Environmental Remote Sensing Data Processing and Utilization Iv: Readiness for Geoss Ii* (Vol. 7085). Bellingham: Spie-Int Soc Optical Engineering.

Zarco-Tejada, P. J., Rueda, C. A., & Ustin, S. L. (2003). Water content estimation in vegetation with MODIS reflectance data and model inversion methods. *Remote Sensing of Environment*, *85*(1), 109–124. doi:10.1016/S0034-4257(02)00197-9

Zhan, X., Sohlberg, R. A., Townshend, J. R. G., DiMiceli, C., Carroll, M. L., Eastman, J. C., … DeFries, R. S. (2002). Detection of land cover changes using MODIS 250 m data. *Remote Sensing of Environment*, *83*(1-2), 336–350. doi:10.1016/S0034-4257(02)00081-0

Zhang, F., Xu, M., Xie, C., Xia, Z., Li, K., & Wang, X. (2012). Forest and deforestation identification based on multitemporal polarimetric RADARSAT-2 images in Southwestern China. *Journal of Applied Remote Sensing*, *6*. doi:10.1117/1.JRS.6.063527

Zhao, M., & Running, S. W. (2010). Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009. *Science*, *329*(5994), 940–943. doi:10.1126/science.1192666

Zhu, Z., Bi, J., Pan, Y., Ganguly, S., Anav, A., Xu, L., … Myneni, R. B. (2013). Global Data Sets of Vegetation Leaf Area Index (LAI)3g and Fraction of Photosynthetically Active Radiation (FPAR)3g Derived from Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI3g) for the Period 1981 to 2011. *Remote Sensing*, *5*(2), 927–948. doi:10.3390/rs5020927

Zink, M., Bartusch, M., & Miller, D. (2010). TanDEM-X: Mission Overview and Status. In *Proceedings of* *the European Conference on Synthetic Aperture Radar* (pp. 132–135). VDE Verlag GmbH.

Zulkafli, Z., Buytaert, W., Onof, C., Lavado, W., & Guyot, J. L. (2013). A critical assessment of the JULES land surface model hydrology for humid tropical environments. *Hydrology and Earth System Sciences*, *17*(3), 1113–1132. doi:10.5194/hess-17-1113-2013

APPENDIX A: STAND-ALONE SUMMARY OF CHALLENGES AND CEOS ACTIONS RECOMMENDED IN RESPONSE TO THE GEO CARBON STRATEGY

Mission-Related:

Overall Motivation/Rationale-1: The *GEO Carbon Strategy* calls for quantification of carbon pools and their changes in response to human intervention and climate to meet the needs of science and policy (section 2.2, p. 10) and, specifically, estimates from space of vegetation aboveground biomass and carbon storage (section 4.6, p. 24). Satellites can provide global information about changes in carbon storage through accurate measurements of forest canopy height and/or estimates of aboveground biomass. Current and planned SAR missions, especially the P-band Biomass mission of ESA, will advance toward this goal. New space-based measurements using lidar, as envisioned to follow the ICESat mission (e.g., the Vegetation Canopy Lidar (VCL) and Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission concepts), and tandem PolInSAR (such as the Tandem-L concept) should have high priority and are recommended to provide complementary information on forest height and structure. Such missions would clearly support the needs of climate treaty frameworks as exemplified by the REDD+ component of the UNFCCC. Airborne lidar measurements to complement SAR missions, e.g., ESA's Biomass mission, are highly desirable in the near- and mid-term to improve accuracy.

Carbon-Challenge-1: CEOS acknowledges the challenge to provide accurate measurements of forest canopy height and estimates of aboveground biomass and will influence and coordinate the activities of its Member Agencies toward this goal. CEOS Agencies will consider efforts to provide the needed lidar data and/or interferometric SAR data (i.e., by considering a new satellite mission and/or by cooperating to assemble existing airborne lidar data and making it available for validation of satellite SAR height and biomass data products).

Carbon-Action-1: CEOS Member Agencies with interests in missions and data products for forest canopy height and aboveground biomass will sponsor or co-sponsor one or more workshops (and require a written report) to define the scientific and policy requirements to quantify aboveground carbon storage in vegetation. These meetings should involve the key international science, applications, and remote sensing communities in specifying the technical foundation and scientific requirements for as well as the societal benefits of future missions to quantify aboveground carbon storage in vegetation globally. The workshops should consider these requirements in the context of the added value to be derived from coordinated mission planning and associated data compilation activities both in the future and by exploiting archive data.

Overall Motivation/Rationale-2: The IGCO called for in the *GEO Carbon Strategy* requires continuous time series records from satellites of land surface properties (e.g., land cover, land cover change, disturbance, fires, LAI, FAPAR, wetlands, permafrost areas) at mid resolution (Executive Summary, p.7; section 3.2.4, p. 13). To document and analyze changes over time requires continuity of satellite measurements of land surface properties used to estimate carbon pools and fluxes. In order to meet this need, CEOS member agencies must develop and deploy satellites that can provide continuity measurements of land cover, land cover change, disturbance, fires, LAI, FAPAR, wetlands, and permafrost areas at moderate (~250 m - 1 km) and medium (~30 - 100 m) resolution with adequate on-board calibration and sustained calibration/validation operations. Some redundancy to cover contingencies and improve coverage should be part of the overall plan.

Carbon-Challenge-2: CEOS acknowledges this challenge and will influence and coordinate the

activities of its Member Agencies so that high-quality, well-calibrated continuity satellite measurements of land cover, land cover change, disturbance, fires, LAI, FAPAR, wetlands, and permafrost are available to estimate carbon pools and fluxes, data gaps are avoided, and satellites flying at the same time, in constellations, and in time series are cross-calibrated and well-validated.

Carbon-Action-2: The relevant CEOS VCs and CEOS WG Climate will act to include IGCO priorities for continuity carbon-related observations of the land surface from space in their respective activities to coordinate the VCs and climate-related measurements.

Overall Motivation/Rationale-9: The IGCO called for in the *GEO Carbon Strategy* requires continuous satellite time series records of ocean properties (e.g., ocean carbon state, ocean color and marine ecosystem composition, and ocean physical state) at mid resolution (Executive Summary, p.7; section 3.2.4, p. 13). These biological and physical properties of the ocean are needed to estimate ocean carbon pools and fluxes and document and analyze their changes over time. In order to meet this need, CEOS Member Agencies must develop and deploy satellites that can provide continuity moderate resolution (~0.5 km - 10 km) satellite measurements of ocean color, sea surface temperature, surface winds, salinity, sea state, currents and eddies, sea ice extent and ice edge structure with adequate on-board calibration and sustained calibration and validation operations. Some redundancy to cover contingencies and improve coverage should be part of the overall plan.

Carbon-Challenge-9: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies so that high-quality, well-calibrated, moderate-resolution continuity measurements of ocean color, sea surface temperature, surface winds, salinity, sea state, currents and eddies, sea ice extent and ice edge structure are available, data gaps are avoided, and satellites flying at the same time, in constellations, and in time series are cross-calibrated and well-validated. CEOS notes that these requirements are commensurate with corresponding GCOS requirements.

Carbon-Action-10: The relevant CEOS VCs and CEOS WG Climate will act to include IGCO priorities to extend the time series of moderate-resolution carbon-related observations of the open ocean from space into their respective activities to coordinate the VCs and climate-related measurements.

Overall Motivation/Rationale-10: The *GEO Carbon Strategy* points out that carbon fluxes in the coastal ocean are important, yet the coastal ocean is particularly challenging to observe from space (section 4.6, p. 24). The reasons range from the diurnal cycles of the biota to the complex optical properties of coastal waters. In contrast to the open ocean, the high spatio-temporal complexity of coastal regions requires a dedicated, oriented coverage rather than a global coverage. This requires continuity satellite ocean-color measurements with spatial resolution better than 0.5 km and/or repetition rate of less than a day and the capability to observe transitory events (e.g. unusual or transient algal blooms). In addition the challenging optical nature of coastal turbid waters requires more spectral channels in the visible spectrum (e.g., as are available on MERIS) on moderate and coarse resolution sensors than are necessarily required for the open ocean. To meet these needs, CEOS Member Agencies must coordinate the launch of satellites that meet these requirements in a timely fashion to avoid gaps.

Carbon-Challenge-10: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Member Agencies so that high-quality continuity satellite measurements of coastal waters, with appropriate spatial, temporal and spectral sampling properties, are available for ocean carbon science.

Carbon-Action-11: The relevant CEOS VCs and CEOS WG Climate will act to include IGCO priorities for continuity in high-resolution (better than 0.5 km) carbon-related observations of coastal waters from space in their respective activities to coordinate the VCs and climate-related measurements, noting the higher temporal and spatial resolutions and spectral coverage required, compared with open-ocean measurements.

Overall Motivation/Rationale-11: The *GEO Carbon Strategy* points out that carbon fluxes in the coastal ocean are important, yet the coastal ocean is particularly challenging to observe from space. The reasons range from the diurnal cycle of the biota to the complex optical properties of coastal waters. Future geostationary missions dedicated to the observation of the coastal ocean are likely to hold the key to solving this problem (section 4.6, p. 24). New missions and new types of missions are needed to provide higher resolution data than the continuity missions in order to further our understanding of the carbon cycle, especially with respect to phytoplankton functional types, phytoplankton carbon by type, detritus, particulate organic carbon, and aerosols for improved atmospheric corrections. Additionally, it is recognized that there are specific applications in coastal and inland-water bodies that require higher resolution in time, space, and spectral domains to further understanding of carbon cycling. Higher spatial resolution for certain coastal applications (of order 30 m, for applications including floods, tides, river discharge) is needed. Some of these requirements may be met through geostationary satellites. The Geostationary Ocean Color Imager (GOCI) launched by Korea has demonstrated the value of sensors capable of resolving the diurnal signal. Such high temporal resolution is particularly important for dealing with coastal waters because the temporal and spatial scales of relevance in coastal waters are typically smaller than those of the open ocean. Proposed high-spectral resolution polar-orbiting missions for global observations such as NASA's Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) should also be emphasized.

Carbon-Challenge-11: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the development and deployment of new satellite mission types to provide new information on phytoplankton functional types, phytoplankton carbon by type, detritus, particulate carbon, and aerosols, and 2) provide higher spatial, temporal, and spectral resolution data for coastal and inland waters.

Carbon-Action-12: CEOS Member Agencies with interests in and/or mandates for developing and deploying new types of satellite missions to provide 1) new information on phytoplankton functional types, phytoplankton carbon by type, detritus, particulate carbon, and aerosols, and/or 2) higher spatial, temporal, and spectral resolution data for coastal and inland waters will coordinate their efforts in consultation with relevant CEOS WGs and VCs.

Overall Motivation/Rationale-12: The *GEO Carbon Strategy* notes that satellite observations of sea surface salinity will benefit efforts to improve estimates of pCO_2 (section 4.6, p. 24). Continuity of measurements of sea surface salinity is needed in support this requirement. Improvements in spatial resolution over that of the current SMOS and Aquarius-type sensors will be needed, especially for coastal and inland water applications.

Carbon-Challenge-12: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the development and deployment satellites to extend the time series of measurements of sea surface salinity and to improve their spatial resolution in the future.

Carbon-Action-13: CEOS Member Agencies with interests in and/or mandates for developing and deploying new satellites to measure ocean salinity will coordinate their efforts in consultation with relevant CEOS WGs and VCs.

Overall Motivation/Rationale-14: The *GEO Carbon Strategy* emphasizes the importance of satellite observations of CO_2 and CH_4 in the global atmosphere for monitoring, assessing, and attributing carbon sources and sinks (section 4.5, p. 14-18) and calls for a next generation constellation of greenhouse gas satellite observations (section 5.1.4, p. 26). In addition, there are policy and management needs for this information to support monitoring and verification of CO_2 and CH_4 emissions for international purposes. A coordinated constellation of passive and active XCO2 and XCH4 remote sensing instruments in Low Earth Orbit (LEO) is needed, with retrieved, single-sounding measurement accuracy of 0.1 to 0.2% for XCO2 and XCH4, a spatial resolution of 1-2 km, and a temporal sampling yielding daily coverage of the entire globe. These missions should be considered in the context of the added value to be derived from coordinated mission planning and associated data compilation activities (spaceborne and in situ/aircraft) both in the future and by exploiting archive data.

Carbon-Challenge-13: CEOS acknowledges the challenge to achieve a LEO constellation of satellites to measure atmospheric CO_2 and CH_4, with appropriate coverage and sensitivity, and will influence and coordinate the activities of its Member Agencies toward this goal.

Carbon-Action-16: CEOS Member Agencies with interests in CO_2- and CH_4-measuring LEO missions will sponsor or co-sponsor one or more workshops (and require a written report) to refine the scientific and policy requirements for quantitative data on atmospheric CO_2 and CH_4 from low Earth orbit. These meetings should involve the key international science and applications communities in specifying the technical foundation and scientific requirements for as well as the societal benefits of future missions to quantify atmospheric CO_2 and CH_4 from low earth orbit.

Carbon-Action-17: The CEOS Atmospheric Composition VC will coordinate the detailed planning and preparation for a constellation of passive and active remote sensing instruments to measure CO_2 and CH_4 from low Earth orbit with the higher spatial and temporal resolution and accuracy needed to monitor carbon sources and sinks.

Overall Motivation/Rationale-15: The *GEO Carbon Strategy* emphasizes the importance of satellite observations of CO_2 and CH_4 in the global atmosphere for monitoring, assessing, and attributing carbon sources and sinks (section 4.5, p. 14-18) and calls for a next generation constellation of greenhouse gas satellite observations (section 5.1.4, p. 26). In addition there are policy and management needs for this information to support monitoring and verification of CO_2 and CH_4 emissions for international purposes. A coordinated constellation of passive XCO2 and XCH4 remote sensing instruments in geostationary orbit is needed to cover all longitudes at a spatial resolution of 1-2 km, with a retrieved, single-sounding measurement accuracy of 0.1 to 0.2% for XCO2 and XCH4 over continents, and a temporal sampling interval of 20 minutes to 1 hour.

Carbon-Challenge-14: CEOS acknowledges the challenge to achieve a geostationary constellation of satellites to measure atmospheric CO_2 and CH_4, with appropriate coverage and sensitivity, and will influence and coordinate the activities of its Member Agencies toward this goal.

Carbon-Action-18: CEOS Member Agencies with interests in CO_2- and CH_4-measuring GEO missions will sponsor or co-sponsor one or more workshops (and require a written report) to refine the scientific and policy requirements for quantitative data on atmospheric CO_2 and CH_4 from geostationary Earth orbit. These meetings should involve the involve the broad, international science and applications communities in advancing the technical foundation and scientific requirements for as well as the societal benefits of future missions to quantify atmospheric CO_2 and CH_4 from geostationary orbit.

Carbon-Action-19: The CEOS Atmospheric Composition VC will coordinate the detailed planning and preparation for a constellation of passive remote sensing instruments to measure CO_2 and CH_4 from geostationary orbit covering all longitudes with the spatial and temporal resolution and accuracy needed to monitor carbon sources and sinks.

Overall Motivation/Rationale-16: In order to derive the maximum scientific and societal benefits from future satellite missions focused on carbon-relevant measurements, confirmed missions for continuity and new carbon data products must be launched as planned, and priority new missions should be confirmed as soon as required processes and resources permit. CEOS can identify any opportunities to develop additional items in support of these existing planned missions as joint activities and coordinate the planning of future satellite missions so as to optimize coverage, sampling, and utility of data products, adopting a virtual (or actual) constellation approach, when applicable.

Carbon-Challenge-15: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the timely confirmation and launch of carbon-related missions and provision of optimized carbon data products. For missions with similar objectives and being developed to fly in the same timeframe, CEOS will encourage coordination of mission attributes so that observations are made in ways that optimize areal coverage, time and space sampling, and/or accuracy. For missions with similar objectives that may follow one another in time, CEOS will encourage coordination of mission and data attributes so that the multiple data streams are compatible and can be integrated to create a consistent time series over a longer time period than any single mission alone could achieve.

Overall Motivation/Rationale-17: To ensure that new missions yield the greatest scientific and societal benefits, there is a need for carbon science and policy information priorities to be factored into sensor selection decision-making for future space missions. Thus, it is important that space agencies and their sponsors engage the carbon science community in their mission identification, review, selection, and implementation processes. This will also help to ensure that choices made in response to technical or budget constraints do not compromise mission objectives.

Carbon-Challenge-16: CEOS acknowledges this challenge and will encourage its Member Agencies to engage the carbon science and policy communities in their mission identification, review, selection, and implementation processes to the fullest extent possible.

Product-Related:

Overall Motivation/Rationale-3: The *GEO Carbon Strategy* calls for a continuous supply of mid-resolution Earth observing satellite data (LAI, FAPAR, disturbance, land cover change; Executive Summary, p.7) and notes the extreme value of moderate resolution and high (i.e., referred to as “medium” in the land domain chapter) resolution satellite data for carbon science (section 4.6, p. 23-24). Data products that document the historical records of land surface properties (i.e., forest disturbed area, burned area, timing of burning, LAI, FAPAR, NDVI, land cover, snow cover) at moderate resolution (250 m - 1 km) are needed. Activities that need to be conducted include reprocessing of data to address cloud cover issues in a consistent fashion; merging data from different sensors (e.g., AVHRR, MODIS, (A)ATSR, MERIS, VIIRS, GCOM-C); and, when possible, developing finer spatial resolution products (e.g., 250 m compared to current products at resolutions of 1000 m and greater). The continuity of these moderate resolution records into the future must be assured.

Carbon-Challenge-3: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the continuity and systematic improvement of moderate-resolution (~250 m - 1 km) satellite time series data products.

Carbon-Action-3: CEOS Agencies with historical moderate-resolution (~250 m - 1 km) satellite data records will strive to ensure these data are publicly available and used to create the moderate-resolution (~250 m - 1 km) records of land properties over the historical satellite record that are useful for carbon science. They will coordinate their efforts with relevant CEOS WGs and VCs.

Overall Motivation/Rationale-4: The *GEO Carbon Strategy* calls for a continuous supply of mid-resolution Earth observing satellite data (LAI, FAPAR, disturbance, land cover change; Executive Summary, p.7) and notes the extreme value of moderate resolution and high (i.e., referred to as "medium" in the land domain chapter) resolution satellite data for carbon science (section 4.6, p. 23-24). Data products that document the historical records of land surface properties (e.g., land cover, land cover change, LAI, FAPAR, forest area disturbed, burned area, areas impacted by insects and storms, and fire severity) at medium resolution (30-100 m) are needed. The collection of global data sets using medium resolution satellite remote sensing systems (vis/IR sensors such as Landsat, SPOT, and IRS and radar sensors such as ERS-1, Radarsat, and JERS-1) has resulted in complete, global-scale data since the late 1990s, with data being available for some regions back to the mid-1970s. Improvement in computer processing speeds and data storage capacity makes processing remote sensing data at medium resolutions at continental and global scale feasible. A number of land remote sensing products listed in Table 2-2 have been developed from medium resolution data, and generation of these products at global scales would provide the ability to reduce uncertainties in terrestrial carbon cycle models. This activity should be extended to the radar archives of ESA, JAXA and CSA.

Carbon-Challenge-4: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the continuity and systematic improvement of historic medium-resolution (~30 - 100 m) satellite time series data products.

Carbon-Action-4: CEOS Agencies with historical medium-resolution (~30 m -100 m) satellite data records will strive to ensure these data are publicly available and used to create the medium-resolution records of land properties over the historical satellite record that are useful for carbon science. They will coordinate their efforts with relevant CEOS WGs and VCs.

Overall Motivation/Rationale-5: The IGCO called for in the *GEO Carbon Strategy* requires continuous time series records of land, ocean, and atmosphere properties (e.g., land cover, land cover change, wetland area, LAI, ocean color and marine ecosystem composition, wetlands, permafrost areas, CO_2 and CH_4) at mid resolution (Executive Summary, p.7; section 3.2.4, p. 13). It is now possible to develop data fusion and data assimilation algorithms using a combination of remote sensing data (vis/IR, SAR, Lidar) at medium to moderate resolutions to improve the accuracy of land and ocean products. Most of the currently available global remote sensing products are all based on a single instrument approach. To realize the full discrimination potential of the data collected by planned and future remote sensing systems and those currently in orbit, multi-sensor approaches must be developed and tested and a product-based (rather than mission-based) approach must be adopted. To ensure long-term continuity of time series data records, the satellite data provider may need to transition from a research satellite program to an operational satellite program; thus, there must be a continuous interface between the research agencies (e.g., ESA, NASA) and those with operational mandates (e.g., NOAA, Eumetsat) .

Carbon-Challenge-5: CEOS acknowledges this challenge and will influence and coordinate the

activities of the CEOS Member Agencies toward the continuity and systematic improvement of long time series of multi-sensor, multi-mission data products.

Carbon-Action-5: CEOS Agencies with interests in and/or mandates for developing multi-sensor, multi-mission time series data products for the land (and ocean) will strive to ensure consistent, well-calibrated, bias-free satellite time-series carbon products are produced and continued into the future. They will coordinate their efforts in consultation with relevant CEOS WGs and VCs to ensure appropriate merging of data and products from multiple sensors.

Carbon-Action-24: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will work to encourage the production and availability of high-quality, consistent long time series data products based on multiple sensors and missions for carbon and climate science and for model-data and data-data intercomparison exercises.

Carbon-Action-25: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) and relevant VCs will provide periodic technical information to the research and operational space agencies regarding readiness for and issues regarding transitions from research to operations for long-time series carbon observations.

Overall Motivation/Rationale-6: The IGCO called for in the *GEO Carbon Strategy* requires improved approaches for developing global land inventories and related data products of 1) the spatial distribution and extent of wetlands and peatlands and of changes in their organic carbon pools and 2) carbon content of reservoirs, lakes, ponds, and rivers. Satellite observations of inland waters must have appropriate spatial resolution and sensitivities. Lakes and reservoirs cover around 3% of the Earth's land surface, but the majority are small. Use of moderate to coarse resolution ocean-color sensors such as MODIS or MERIS is therefore fairly limited in lake carbon research. On the other hand, many medium to moderate resolution land remote sensing sensors (such as Landsat-7) do not have sufficient sensitivity to estimate lake content of colored dissolved organic matter (CDOM) and monitor long-term trends. At present there are only a few sensors (such as ALI on EO-1) that are suitable for mapping lake CDOM, dissolved organic carbon, and pCO2, but they do not provide full global coverage. Landsat-8 and Sentinel-2 will change the situation, as sensors on both these missions provide data with sufficient spatial and radiometric resolution as well as the global coverage needed for lake research. Space agencies must ensure the continuity of such measurements. Maps of lakes and ponds are needed annually and maps of flooding and inundation are needed seasonally. Estimates of associated carbon-related biophysical properties (e.g., dissolved and particulate carbon, river discharge) and biological productivity are needed as a contribution to terrestrial carbon budgeting. Research agencies must implement projects to develop these essential products at regional and global scales.

Carbon-Challenge-6: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the continuing deployment of satellites and development of satellite data products for mapping wetlands, wetland types, wetland inundation, rivers, flooding, reservoirs, lakes, and ponds and estimating their associated carbon-related biophysical properties (e.g., dissolved and particulate carbon, river discharge) and biological productivity. CEOS will encourage its Member Agencies to coordinate the launch of satellites that meet requirements in a timely fashion and to avoid gaps. CEOS Agencies will strive to implement projects to develop these essential wetland and inland water data products at regional and global scales and with appropriate spatial and temporal resolutions and sensitivities to the carbon constituents in inland waters.

Carbon-Action-6: CEOS Agencies with interests in and/or mandates for developing 1) satellites to observe wetlands and inland waters and 2) wetland and inland water data products will coordinate their efforts in consultation with relevant CEOS WGs and VCs.

Overall Motivation/Rationale-18: There are strong interdependencies among the atmosphere, oceans and inland waters, and land. The fluxes between domains are important, yet it is important to recognize that there is also three-domain coupling since the system under assessment is a cycle and there is strong carbon-climate coupling. Examples of this three-domain coupling include black carbon emissions from fire disturbance and industrial activities and ocean nutrient fertilization from dust aerosols.

Carbon-Challenge-17: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies so that issues that transcend traditional scientific domains are not overlooked. CEOS will foster communications across CEOS in recognition of the need to support understanding of three-domain coupling of the carbon cycle and strong carbon-climate coupling in the Earth system.

Carbon-Action-21: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will coordinate with other relevant CEOS WGs and VCs to ensure that the carbon observations and data products that transcend traditional scientific domains (e.g. black carbon, nutrient fertilization) are accorded appropriate priority in CEOS activities and future plans and that key satellite products to permit scientific studies of these phenomena are produced and made available.

Overall Motivation/Rationale-19: In order to achieve the integrated, global carbon budget analysis called for in the IGCO and meet the needs of the global carbon and climate modeling communities, satellite carbon data products must be consistent and compatible (i.e., temporal and spatial resolution, grids, data formats, units) across the land, oceans and inland waters, and atmosphere domains (e.g., estimates of terrestrial and oceanic primary production should be compatible; ocean products must be compatible, consistent and comparable with the satellite observations of key atmospheric properties (CO_2, CH_4, NO_x, aerosol)).

Carbon-Action-22: CEOS Agencies engaged in development of carbon products will coordinate to achieve compatibility, comparability and consistency of carbon products across all relevant domains (land, oceans and inland waters, and atmosphere, as appropriate), in consultation with relevant CEOS VCs and WGs.

Overall Motivation/Rationale-20: The IGCO called for in the *GEO Carbon Strategy* requires improved information on natural (section 1, p. 8 and section 3.2.4, p. 13) and anthropogenic (section 5.4, p. 34-35) emissions of carbon. In addition there are policy and management needs for this information to support monitoring and verification of CO_2 and CH_4 emissions for international purposes. CEOS member agencies must provide improved information from satellites on the spatial and temporal scale of anthropogenic emissions, in particular fossil fuel emissions from cities, gas flares and power plants and other industrial contributors through cumulation of existing satellite products and initiation of new projects and missions to tackle these issues at a global level. CEOS member agencies must improve the quality of satellite-derived information on emissions from biomass burning, coal mines, rice agriculture, livestock and landfills.

Carbon-Challenge-18: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies so that improved information on natural and anthropogenic emissions of carbon (CO_2, CH_4, but also CO and black carbon) is produced and made publicly available.

Carbon-Action-23: Individual CEOS Agencies with interests in and/or mandates for providing improved information on natural and anthropogenic emissions of carbon (CO_2, CH_4, CO and black carbon) will coordinate their efforts in consultation with relevant CEOS WGs and the Atmospheric Composition VC.

Overall Motivation/Rationale-21: In developing an IGCO it is important to ensure consistency of the products derived from satellite observations with, in so far as possible, emphasis on algorithm compatibility, clarity of documentation and, in particular, clarity in the assumptions used to create a given product. Satellite products should be appropriately validated using internationally agreed protocols and independently verified *in situ* data. Efforts are also needed to ensure that the best auxiliary data (e.g., land cover, aerosol, cloud, DEM, reanalysis products of clouds, ozone, surface pressure, winds, aerosols, etc.) are used consistently across sensors and agencies in processing satellite data in order to avoid inter-sensor differences in products arising from differences in use of auxiliary data. The role of CEOS in this regard extends to ensuring that product quality is a priority, independent verification mechanisms exist, there is continuity of the required data, products generated are effectively and traceably documented, intercomparison between products is undertaken in a collaborative manner, and the appropriate data products are taken and used downstream to both improve scientific understanding of the carbon cycle and establish effective mechanisms in support of policy requirements. CEOS also has an important role to play in promoting policies of free, open, and easy access to data, data products, and documentation for the carbon cycle information needed in support of national and international policies.

Carbon-Challenge-19: CEOS acknowledges the challenges to see that products derived from different satellite sensors to represent the same carbon-related property are consistent and compatible with each other and that requirements for clarity and traceability in products are followed. When there are differences in the products (whether it be in the methods used, in the underlying assumptions, or in the applicability of the results), the documentation provided must help users to understand them. CEOS will use its influence to encourage CEOS Agencies toward this goal.

Carbon-Action-26: The CEOS Carbon Subgroup (recommended in Carbon-Action-38), in consultation with the CEOS WGCV, will encourage comparison of protocols for the generation of carbon products from satellite data and and recommend adoption of the best protocols by CEOS agencies to ensure long-term consistent datasets relevant to carbon cycle community needs. This work shall include accounting for ancillary data dependence (e.g., land cover, aerosol, cloud, DEM, reanalysis products, etc.) such that there is consistency across individual products and variables.

Carbon-Action-27: CEOS Agencies will make publicly available all information necessary to document the accuracy, clarity, and traceability of the satellite data and data products they produce.

Carbon-Action-28: CEOS Agencies will coordinate their efforts to develop compatible (e.g., temporal and spatial resolution, grids, data formats, common auxiliary data, units) carbon data products from multiple missions, in consultation with relevant CEOS WGs and VCs.

Carbon-Action-29: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will develop guidelines for the specification of uncertainty in products, from signal counts through the various CEOS Processing Levels.

Carbon-Action-30: CEOS Agencies will ensure the long-term accessibility of satellite data and data products for carbon cycle science and policy. This must include arrangement for secure archives, documentation, and metadata as well as provisions for easy discovery and access by the carbon science and policy communities.

Calibration/Validation-Related:

Overall Motivation/Rationale-7: The *GEO Carbon Strategy* calls for robust carbon tracking and accurate carbon budgets (section 3, p. 11), and these major products require quantitative analysis of changes in Earth system carbon properties over time. This in turn requires well-calibrated satellite sensors and well-validated data products. Development of specific remote sensing products often requires use of surface reference data sets. In some cases, land-based networks have been developed to provide *in situ* data for validation of specific products (e.g., soil moisture, atmospheric CO_2), where in others, networks either need expansion or considerable development (such as biomass dynamics). For the ocean, this requires global-scale validation of algorithms for estimating ocean carbon pools from satellite data, in carbon units, in close collaboration with *in situ* observation systems. It is also necessary to provide adequate error characterization of remote sensing variables and carbon products derived from satellite data, ideally on a pixel-by-pixel basis, to ensure their appropriate use in quantifying and modeling carbon dynamics. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure *in situ* data are accessible to the satellite community for validation of satellite data products. The CEOS WGCV and its relevant subgroups have conducted and coordinated much-needed calibration and validation work over the years, and this work needs to continue and be expanded. The CEOS VCs are also conducting valuable work in this area. There is a need to strengthen mechanisms within CEOS and at the individual space agency level, in particular investment as part of satellite development, for product validation to establish validation methodologies, protocols and benchmark datasets. This must be guaranteed on timescales relevant for key science and policy problems and should be closely coordinated with the *in situ* observation community to ensure *in situ* data are accessible to the satellite community.

Carbon-Challenge-7: CEOS acknowledges this challenge and will influence and coordinate the activities of its Member Agencies toward the provision of well-calibrated and well-validated satellite data products with adequate error characterization. CEOS will encourage its Member Agencies, to include investment in calibration and validation as part of their satellite development activities. CEOS will promote use of accepted international standards. CEOS Agencies recognize the need to support the WGCV and VCs in these endeavors and to assist in prioritizing activities when resources are limited.

Carbon-Action-7: CEOS and CEOS Agencies will encourage national and international agencies to improve and expand upon the availability of the *in situ* observations needed for the calibration and validation of satellite land data products used for carbon science. This will include coordinating with national and international agencies collecting *in situ* data to 1) assess the quality and coverage (spatial and temporal) of validation data and 2) employ design features that entice data sharing and provide safeguards.

Carbon-Action-8: The CEOS WGCV's Land Product Validation (LPV) Subgroup will continue its work to validate satellite land data products and expand the number of land variables addressed as priorities are identified and available resources permit, and where no other body takes responsibility (e.g., GOFC-GOLD).

Carbon-Action-14: The CEOS WGCV, in close consultation with the relevant VCs (that are doing some of this work now), will establish a subgroup dealing with validation and error characterization of ocean carbon-relevant products analogous to the Land Product Validation Subgroup.

Carbon-Action-20: The CEOS Atmospheric Composition VC, in cooperation with the CEOS WGCV Atmospheric Composition Subgroup, will provide coordination and support for the cross calibration of all satellite CO_2- and CH_4-measuring sensors, coordinate their observations, and cross validate their CO_2 and CH_4 products against accepted international standards, so that they can be integrated into single continuous global climate record.

Carbon-Action-31: CEOS through its WGCV and relevant VCs will strengthen its mechanisms for product validation by establishing validation methodologies, protocols and benchmark datasets.

Carbon-Action-32: For each of the relevant variables in each of the domains CEOS will work with the carbon science community to assess the current provision of validation data in terms of quality (defined by protocols (e.g., WGCV LAI protocol) and or maturity matrices (e.g., WG Climate)) and spatial and temporal coverage. This work should identify potential additional sources and develop a strategy to improve global *in situ* data distributions in relation to satellite validation and model parameterization. It should also exploit existing infrastructures to develop key intensive collection sites.

Overall Motivation/Rationale-8: The two major products called for in the *GEO Carbon Strategy* (i.e., a robust and transparent carbon tracking system and accurate carbon budgets; section 3, p. 11) require quantitative analysis of changes in Earth system carbon properties over time. Desirable increases in spatial and temporal coverage can be achieved if data from two different, contemporaneous sensors can be combined seamlessly. To facilitate such data merger or fusion, data products acquired by differing sensors and satellites for each of these properties must be intercomparable, and systematic intercomparison activities must be conducted.

Carbon-Challenge-8: CEOS acknowledges this challenge and will influence and coordinate the activities of CEOS Agencies toward the systematic intercomparison of satellite data products of relevance to the carbon cycle. CEOS Agencies will participate, as appropriate, in major intercomparison activities, including model-data, data-data, and multiple data stream intercomparisons. CEOS recognizes that intercomparison activities will require coordination with relevant non-CEOS organizations and activities.

Carbon-Action-9: CEOS WGCV and its relevant subgroups, in consultation with the CEOS Carbon Subgroup (recommended in Carbon-Action-38), will organize and coordinate carbon data product intercomparison activities as they are identified as priorities for CEOS action and in coordination with the wider carbon cycle science community.

Carbon-Action-33: CEOS will reinforce the mechanisms already in place in CEOS for all domains (WGCV, and VCs, and WG Climate) and clarify their responsibilities to ensure intercomparison activities are well-coordinated and effective.

Carbon-Action-34: Individual CEOS Agencies producing the same (or similar) carbon data products will cooperate to ensure that their products are compared to the other relevant products and, if technically feasible, ensure efforts are made so that their products can be used quantitatively with these other products.

Overall Motivation/Rationale-22: In order for the satellite data and data products required for the IGCO to be identified, prioritized, developed, and utilized effectively, CEOS must establish effective linkages with the carbon science, applications, and policy communities. CEOS must work with organizations representing these communities to understand needs and priorities and to ensure satellite data products provided by CEOS Agencies meet needs and are utilized appropriately. CEOS should actively pursue a role within major model-data inter-comparison exercises dedicated to the carbon cycle (e.g., CxMIP, OCMIP, RECCAP) as the point of reference for appropriate satellite products. An effective way to proceed may be through the sponsorship of international workshops on the interface between models (land-oceans and inland waters-atmosphere) of the carbon cycle and satellite data products to reconcile methodological differences and spatial compatibility.

Carbon-Action-35: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will develop guidelines for appropriate data use of satellite data and data products. This will require improved interactions between the carbon cycle community and the satellite community; comprehensive review of the current use of data products, including current data limitations; and reconciliation of methodological differences and spatial compatibility. Such interactions may include co-sponsorship of joint workshops targeting specific data needs and investment in community product assessments, especially for key intercomparison exercises.

Interactions/Linkages/Communications-Related:

Overall Motivation/Rationale-13: The *GEO Carbon Strategy* calls for robust carbon tracking and accurate carbon budgets (section 3, p. 11). This requires global-scale validation of algorithms for estimating pools and fluxes of carbon from satellite data, in carbon units, in close collaboration with *in situ* observation systems. The Blue Planet Initiative brings together many ocean observation programs with a societal benefit angle, including all the existing ocean observation programs within GEO as well as new ones and fosters synergies among them. Its objectives, as stated on its Web page, are to *1) provide sustained ocean observations and information to underpin the development, and assess the efficacy, of global-change adaptation measures (such as those related to vulnerability of coastal zones, sea-level rise, and ocean acidification), 2) improve the global coverage and data accuracy of coastal and open-ocean observing systems (remote-sensing and in-situ), 3) coordinate and promote the gathering, processing, and analysis of ocean observations, 4) develop a global operational ocean forecasting network, 5) establish a global ocean information system by making observations and information, generated on a routine basis, available through the GEOSS Common Infrastructure, 6) provide advanced training in ocean observations, especially for developing countries, and 6) raise awareness of biodiversity issues in the ocean.* The GEO Task for "Oceans and Society: the Blue Planet" (Task SB-01) thus provides an excellent forum for CEOS and GEO to work together on these issues and CEOS should act to further strengthen and nurture this interaction.
Carbon-Action-15: CEOS Agencies will maintain and/or act to strengthen their linkages with the Blue Planet initiative and support of GEO Task SB-01, which brings together the ocean communities engaged in satellite as well as *in situ* observations, to ensure that user requirements are taken into account and products are produced in carbon units.

Overall Motivation/Rationale-22: In order for the satellite data and data products required for the IGCO to be identified, prioritized, developed, and utilized effectively, CEOS must establish effective linkages with the carbon science, applications, and policy communities. CEOS must work with organizations representing these communities to understand needs and priorities and to ensure satellite data products provided by CEOS Agencies meet needs and are utilized appropriately. CEOS should actively pursue a role within major model-data inter-comparison exercises dedicated to the carbon cycle (e.g., CxMIP, OCMIP, RECCAP) as the point of reference for appropriate satellite products. An effective way to proceed may be through the sponsorship of international workshops on the interface between models (land-oceans and inland waters-atmosphere) of the carbon cycle and satellite data products to reconcile methodological differences and spatial compatibility.
Carbon-Action-36: CEOS will strengthen linkages with relevant carbon communities and organizations to facilitate the communications and coordination necessary to ensure that the satellite data products provided by CEOS Agencies meet needs and are utilized appropriately.
Carbon-Action-37: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will serve as a point-of-contact for appropriate satellite products for major model-data intercomparison exercises related to the carbon cycle.

CEOS Mechanisms- and Future Planning-Related:

Overall Motivation/Rationale-23: In order for CEOS to act effectively on the findings and recommendations of this report, a responsible CEOS entity must be identified. The responsible entity must establish strong working relationships with all relevant VCs and CEOS Working Groups, especially the WG Climate and WGCV.

Carbon-Action-38: CEOS will establish a group to be responsible for carbon activities within CEOS and for advancing the findings and recommendations of this report. This group will take responsibility for overseeing, coordinating, and reporting on the actions identified in this report. It is recommended that CEOS establish a Carbon Subgroup within the CEOS WG on Climate as a most efficient way of implementing this action (this recommended group will hereafter be referred to as the "Carbon Subgroup"). The Carbon Subgroup will report to (and through) the WG Climate. It will establish strong working relationships with all relevant VCs and CEOS WGs, especially the WGCV.

Overall Motivation/Rationale-24: There is a strong need for CEOS to better understand and further prioritize the needs of the carbon community for space-based measurements in the context of time (2015-2020-2025) and space (i.e., needs for increased resolution) and then to reinforce multi-agency planning and preparation for satellites, as coordinated through the CEOS Carbon Subgroup (recommended in Carbon-Action-38) and relevant VCs to ensure that these priority observations are made in the future. It will be important to identify the priority missing components for emissions/stock assessment that are capable of being addressed with satellite data sources. Also, the *GEO Carbon Strategy* does not provide the level of detail for measurement specifications or observation attributes necessary for a space agency to design a mission or verify if a current or planned sensor can provide adequate data. These specifications, custom for carbon -- and especially when they differ from those for the ECVs -- are urgently needed.

Carbon-Challenge-20: CEOS acknowledges this challenge and will engage the carbon science and policy communities to develop a more refined understanding of requirements and priorities for carbon-related measurements from space. CEOS recognizes this will require coordination with GEO, IGBP, Future Earth, and other relevant international organizations.

Carbon-Action-39: CEOS and individual CEOS Agencies will sponsor (or co-sponsor) work (e.g., one or more workshops, a written report) to 1) develop more specific measurement requirements for continuing and new carbon observations from space that will fulfill science and policy needs and 2) encourage further prioritization of these measurements.

Carbon-Action-40: The CEOS Carbon Subgroup (recommended in Carbon-Action-38) will lead in the planning for activities to 1) develop more specific measurement requirements for continuing and new carbon observations from space that will fulfill science and policy needs and 2) encourage further prioritization of these measurements. It will work, in consultation with the relevant VCs, to coordinate the incorporation of the refined requirements and priorities into multi-agency planning and preparation for future satellites.

Overall Motivation and Rationale-25: In order for CEOS to act effectively on the findings and recommendations of its *Strategy for Carbon Observations from Space*, regular follow-up and reporting on progress made in implementation will be essential.

Carbon-Action-41: The CEOS Carbon Subgroup will report to the CEOS WG Climate. It will track and report upon progress in responding to the actions in the *CEOS Strategy for Carbon Observations from Space* in a manner similar to that for the *CEOS Response to the GCOS*

Implementation Plan (IP), which includes at a minimum annual reporting by the Carbon Subgroup through the WG Climate to the CEOS SIT and Plenary.

Overall Motivation/Rationale-26: This report poses contextual Challenges that identify important missions, data products and activities necessary for a useful IGCO. While none of these are within CEOS' and/or CEOS Agencies' capacity to address wholly, it is desirable to maintain attention on these needs, periodically assess progress, and ask if there are things CEOS can do to facilitate further progress.

Carbon-Action-42: CEOS will periodically (approximately every 3-5 years) assess progress toward meeting the challenges identified in this report. This may be accomplished through a variety of means, including but not limited to workshops, ad hoc studies, or discussions within or among relevant CEOS WGs and VCs.

APPENDIX B: ACRONYM LIST AND KEY DEFINITIONS

AATSR: Advanced Along-Track Scanning Radiometer (ESA)
ACE: Atmospheric Chemistry Experiment (on Canada's SCISAT)
ADEOS: Advanced Earth Observing Satellite (Japan)
AERONET: Aerosol Robotic Network
AIRS: Atmospheric Infrared Spectrometer (on NASA's Aqua satellite)
AMSR: Advanced Microwave Scanning Radiometer
Aqua: an Earth Observing System (EOS) satellite in an afternoon orbit (NASA)
AR: Assessment Report
Argo: Argo is a global array of 3,000 free-drifting profiling floats that measures the temperature and salinity of the upper 2000 m of the ocean
ASAR: Advanced Synthetic Aperture Radar
ASCAT: Advanced Scatterometer (on MetOp)
ASCENDS: Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (NASA)
ASF: Alaska Satellite Facility
A-Train: Afternoon Constellation of Earth observing satellites
ATSR: Along Track Scanning Radiometer (ESA)
Aura: an Earth Observing System (EOS) satellite (NASA)
AVHRR: Advanced Very High Resolution Radiometer
BC: black carbon
Bio-Argo: a bio-optical and biogeochemical component within the Argo program
BIOMASAR: an algorithm for retrieval of forest growing stock volume using stacks of multi-temporal SAR data
Biomass: Earth explorer 7 mission, carrying a P-band synthetic aperture polarimetric radar operating at 435 MHz and a 6 MHz bandwidth to measure forest biomass (ESA)
CAPI: Cloud and Aerosol Polarization Imager (on China's TanSat)
CarbonSat: Carbon Monitoring Satellite (ESA)
CARIBIC: Civil Aircraft for the Regular Investigation of the Atmosphere Based on an Instrument Container
CARVE: Carbon in Arctic Reservoirs Vulnerability Experiment (NASA)
CAS: Chinese Academy of Sciences
CASA: Carnegie Ames Stanford Approach model
CASS: Chemical and Aerosol Sounding Satellite (Canada)
CCGG: Carbon Cycle Greenhouse Gas
CCI: Climate Change Initiative (ESA)
CCoP: Carbon Community of Practice (CCoP)
CDIAC: Carbon Dioxide Information Analysis Center
CDOM: colored dissolved organic matter
CEOS: Committee on Earth Observation Satellites
CEOS Agencies: "CEOS Agencies" refers to the collective of all 55 CEOS Members and Associates
CEOS Member Agencies: "CEOS Member Agencies" refers to the government organizations that develop and operate civil Earth observation satellites and are full Members of CEOS
CGMS: Coordination Group for Meteorological Satellites
ChloroGIN: Chlorophyll Globally Integrated Network, an international network to assess the state of marine, coastal and inland-water ecosystems

CMA: National Satellite Meteorological Center (China)
CMIP: Coupled Model Intercomparison Project (CMIP)
CNES: Centre National d'Études Spatiales (France)
Coarse resolution: >1km spatial resolution
COCTS/CZI: Chinese Ocean Color and Temperature Scanner / Coastal Zone Imager
COMS: Communication, Ocean, and Meteorological Satellite (Korea)
CONTRAIL: Comprehensive Observation Network for Trace Gases by Airliner
CoP: Communities of Practice
Copernicus: new name for the Global Monitoring for Environment and Security programme, previously known as GMES (European Commission (EC) in partnership with the European Space Agency (ESA) and the European Environment Agency (EEA).
Coriolis: a U.S. Naval Research Laboratory and Air Force Research Laboratory earth and space observation satellite
COSMO-SkyMed: COnstellation of small Satellites for the Mediterranean basin Observation with X-band radar
CPR: Continuous Plankton Recorder
CRDS: cavity ring-down spectrometers
CSA: Canadian Space Agency
CSIRO: Commonwealth Scientific and Industrial Research Organisation (Australia)
CTF: Carbon Task Force
CxMIP: generic Coupled (or alternatively, Climate) Model Intercomparison Project (the "x" indicates the specific type of comparison is to be determined)
CZCS: Coastal Zone Color Scanner (NASA)
DAAC: Distributed Active Archive Center (NASA)
DEM: Digital Elevation Model
DESDynI: Deformation, Ecosystem Structure, and Dynamics of Ice (NASA; see also NI-SAR)
DGVM: Dynamic Global Vegetation Model
DIC: dissolved inorganic carbon
DLR: Deutsches Zentrum für Luft- und Raumfahrt
DMSP: Defense Meteorological Satellite Program (USA)
DOC: dissolved organic carbon
EASE-Grid: Northern Hemisphere Equal-Area Scalable Earth Grid
ECV: Essential Climate Variable
EDGAR: Emissions Database for Global Atmospheric Research
Envisat: Environmental Satellite (ESA)
EO: Earth Observation
EOS: Earth Observing System (NASA)
ERS: European Remote Sensing satellite
ESA: European Space Agency
ESGF: Earth System Grid Federation
ESRL: Earth System Research Laboratory (NOAA)
ESSP: Earth System Science Pathfinder (NASA)
ESSP: Earth System Science Partnership (ICSU)
ETM+: Enhanced Thematic Mapper
EU: European Union
EUMETSAT: European Organisation for the Exploitation of Meteorological Satellites
EVI: Enhanced Vegetation Index

FAO: Food and Agriculture Organization (UN)
FAPAR: Fraction of Absorbed Photosynthetically Active Radiation (also known as fAPAR or fPAR)
FCT: Forest Carbon Tracking
FLUXNET: a "network of regional networks," coordinating regional and global analysis of observations from micrometeorological tower sites (also known as FluxNet)
FOV: field of view
FT: Freeze-thaw
FTS: Fourier transform spectrometer
Future Earth: a new 10-year international research initiative that will develop the knowledge for responding effectively to the risks and opportunities of global environmental change and for supporting transformation towards global sustainability in the coming decades
FWHM: full width half maximum
GAW: Global Atmosphere Watch
GCM: General Circulation Model
GCOM-C: Global Change Observation Mission – Climate (Japan)
GCOS: Global Climate Observing System
GCP: Global Carbon Project
GEMS: Geostationary Environment Monitoring Spectrometer (Korea)
GEO: Group on Earth Observations
GEO: Geostationary Orbit
GEO-CAPE: Geostationary Coastal and Air Pollution Events (NASA)
GEOGLAM: GEO Global Agricultural Monitoring
GEOSS: Global Earth Observation System of Systems
GFED: Global Fire Emissions Database
GFOI: Global Forest Observation Initiative
GHG: Greenhouse Gas
GHRSST: Group for High Resolution Sea Surface Temperature
GLAS: Geoscience Laser Altimeter System (on NASA's ICESat)
GLC2000: Global Land Cover 2000
GLI: Global Imager (on Japan's ADEOS)
GLOBALVIEW: a cooperative effort to address issues of temporal discontinuity and data sparseness in atmospheric observations and is coordinated by NOAA/ESRL/GMD
GlobCarbon: Global Land Products for Carbon Model Assimilation
GlobCover: a project to develop a service capable of delivering global composites and land cover maps
GMD: Global Monitoring Division (NOAA ESRL)
GMES: Global Monitoring for Environment and Security (newly named Copernicus)
GOCI: Geostationary Ocean Color Imager (on Korea's COMS)
GODAE: Global Ocean Data Assimilation Experiment
GOES: Geostationary Operational Environmental Satellite (NOAA)
GOFC-GOLD: Global Observations of Forest and Land Cover Dynamics
GOME: Global Ozone Monitoring Experiment (on ESA's ERS-2)
GOOS: Global Ocean Observing System
GOSAT: Greenhouse gases Observing SATellite (Japan, also known as "Ibuki")
GPP: Gross Primary Production
GHRSST: Group for High Resolution Sea Surface Temperature
GTOS: Global Terrestrial Observing System

HEO: Highly Elliptical Orbit

HIAPER: High-performance Instrumented Airborne Platform for Environmental Research (NSF, USA)

High Resolution: spatial resolution modifiers are highly contextual and not used consistently across domains or sensor types; for the land domain chapter of this report, high resolution is defined to be 1-30 m spatial resolution

HIPPO: HIAPER Pole-to-Pole Observations

HY-1: Haiyang-1 or Ocean-1 satellite (China)

IAGOS: In-Service Aircraft for a Global Observing System

IASI: Infrared Atmospheric Sounding Interferometer (on Metop satellites)

ICESat: Ice, Cloud, and land Elevation Satellite

ICSU: International Council for Science

IFOV: instantaneous field of view

IGAC: International Global Atmospheric Chemistry

IGBP: International Geosphere-Biosphere Programme

IGCO: Integrated Global Carbon Observing system (see also IGCOAS)

IGCOAS: Integrated Global Carbon Observation and Analysis System (see also IGCO)

IGOS-P: Integrated Global Observing Strategy - Partnership

IGWCO: Integrated Global Water Cycle Observations theme (GEO)

ILTER: International Long-Term Ecological Research

IMBIE: Ice sheet Mass Balance Inter-comparison Exercise

INPE: Instituto Nacional de Pesquisas Espaciais (Brazil)

InSAR: Interferometric Synthetic Aperture Radar

IOC: Intergovernmental Oceanographic Commission of UNESCO

IOCCG: International Ocean-Colour Coordinating Group

IOCCP: International Ocean Carbon Coordination Project

IP: Implementation Plan

IPCC: Intergovernmental Panel on Climate Change

IR: infrared

IRS: Indian Remote Sensing satellite

IRS: thermal InfraRed Sounder (on ESA's Sentinel-4 satellite)

ISRO: Indian Space Research Organisation

ISS: International Space Station

IVOS: Infrared and Visible Optical Sensors subgroup

JASON: an independent scientific advisory group that provides consulting services to the U.S. government on matters of defense science and technology

JAXA: Japan Aerospace Exploration Agency

JEM-EF: Japanese Experiment Module Exposed Facility (on ISS)

JERS: Japanese Earth Resources Satellite

JPSS: Joint Polar-orbiting Satellite System (NOAA)

KOMPSAT: Korea Multipurpose Satellite

L3JRC: a global, multi-year, validated burnt area product derived from daily SPOT VEGETATION data

LAI: Leaf Area Index

Landsat: land satellite; longest series of space-based medium-resolution land remote sensing satellites

LEO: Low Earth Orbit

LGAC: Landsat Global Archive Consolidation

LP-DAAC: Land Processes Distributed Active Archive Center
LPV: Land Product Validation (subgroup of CEOS WGCV)
LST: Land Surface Temperature
LTER: Long-Term Ecological Research
LULCC: Land Use and Land Cover Change
MAREMIP: MARine Ecosystem Model Intercomparison Project
MEaSUREs: Making Earth System Data Records for Use in Research Environments (NASA)
Medium resolution: spatial resolution modifiers are highly contextual and not used consistently across domains or sensor types; for the land domain chapter of this report, medium resolution is defined to be 30-100 m spatial resolution
MERIS: Medium Resolution Imaging Spectrometer (ESA)
MERLin: Methane Remote sensing LIdar missioN (CNES and DLR)
Metop: Meteorological Operational satellite programme (ESA / EUMETSAT)
MicroCarb: a mission dedicated to the study of the greenhouse gas, and more particularly to carbon dioxide (CNES)
MIM: Mission, Instruments, and Measurements (a CEOS database)
MIPAS: Michelson Interferometer for Passive Atmospheric Sounding (on ESA's Envisat)
MIR: mid infrared
Moderate resolution: spatial resolution modifiers like "moderate" are highly contextual and not used consistently across domains or sensor types; for the land domain chapter of this report, moderate resolution is defined to be 250m-1km spatial resolution
MODIS: Moderate Resolution Imaging Spectroradiometer (NASA)
MoE: Ministry of the Environment (Japan)
MOS: Modular Optoelectronic Scanner (Germany)
MOST: Ministry of Science and Technology (China)
MRV: Measurement, Reporting, and Verification (also referred to as Monitoring, Reporting and Verification or Measuring, Reporting, and Verifying)
MTG-S: Meteosat Third Generation Sounding platform
NASA: National Aeronautics and Space Administration (USA)
NBP: Net Biome Production
NCAS: National Carbon Accounting System (Australia)
NDIR: non-dispersive infrared
NDVI: Normalized Distribution Vegetation Index
NEON: National Ecological Observatory Network (USA)
NEP: Net Ecosystem Production
NESDIS: National Environmental Satellite Data and Information Service (NOAA)
NIES: National Institute for Environmental Studies (Japan)
NIR: near infrared
NI-SAR: NASA - ISRO Synthetic Aperture Radar
NISE: Near-real-time Ice and Snow Extent
NOAA: National Oceanic and Atmospheric Administration (USA)
NPP: Net primary production
NSIDC: National Snow and Ice Data Center (USA)
NWP: numerical weather prediction
OBs4MIPS: Observations for Model Intercomparison Projects
OCEANSAT: Oceansat (India)
OceanSITES: a worldwide system of long-term, open-ocean reference stations

OCM: Ocean Colour Monitor (on India's Oceansat)
OCMIP: Ocean Carbon-Cycle Model Intercomparison Project
OCO: Orbiting Carbon Observatory (NASA)
OCR-VC: Ocean Color Radiometry Virtual Constellation
OCTS: Ocean Color and Temperature Scanner (Japan)
OCTS/POLDER: Ocean Color and Temperature Scanner / POLarization and Directionality of the Earth's Reflectances
ODIAC: Open source Data Inventory of Anthropogenic CO_2 emission
OLCI: Ocean and Land Color Instrument (on ESA's Sentinel-3)
OSMI: Ocean Scanning Multispectral Imager (on Korea's KOMPSAT)
OSSE: Observational System Simulation Experiment
OSVW-VC: Ocean Surface Vector Wind Virtual Constellation
PACE: Pre-Aerosol, Clouds, and ocean Ecosystem (NASA)
PALSAR: Phased Array type L-band Synthetic Aperture Radar
PAR: Photosynthetically Active Radiation
pCO_2: partial pressure of carbon dioxide
PCW: Polar Communications and Weather (Canada)
PFT: Plant Functional Type
PHEOS: Polar Highly Elliptical Orbit Science
POLDER: POLarization and Directionality of the Earth's Reflectances (CNES)
Pol-InSAR: Polarimetric and Interferometric SAR
PROBA: Project for On-Board Autonomy (ESA satellite series)
Proba-V: Project for On-Board Autonomy-Vegetation
PRODES: INPE's Amazon Deforestation Monitoring Project
QuikSCAT: Quick Scatterometer (NASA)
RADARSAT: a satellite series developed by Canada carrying C-band SAR sensors
RAINFOR: Amazon Forest Inventory Network
RAMI: Radiation transfer Model Intercomparison
RECCAP: Regional Carbon Cycle Assessment and Processes (of GCP)
REDD+: Reducing Emissions from Deforestation and Degradation
RFI: Radio Frequency Interference
RMSE: Root Mean Square Error
RS: Remote Sensing
SABIA/MAR: Satélite Argentino-Brasileño de Información en Alimento, Agua y Ambiente (Argentine-Brazilian Satellite for Information on Food, Water and Environment)
SAOCOM: SAtélite Argentino de Observación COn Microondas (Argentine Microwaves Observation Satellite)
SAR: Synthetic Aperture Radar
SARVI: Soil and Atmospherically Resistant Vegetation Index
SAVI: Soil Adjusted Vegetation Index
SCIA-ISS: SCanning Imaging Absorption spectrometer for the International Space Station.
SCIAMACHY : SCanning Imaging Absorption spectroMeter for Atmospheric ChartograpHY
SCISAT: a Canadian satellite designed to make observations of the Earth's atmosphere.
SDCG: Space Data Coordination Group
SeaWiFS: Sea-Viewing Wide Field-of-View Sensor
SeaWinds: a scatterometer that measures near-surface wind velocity (on Japan's ADEOS II)
Sentinel-1: C-band SAR mission (ESA)

Sentinal-2: a pair of satellites to deliver high-resolution optical images globally, providing enhanced continuity of SPOT- and Landsat-type data (ESA)

Sentinel-3: a mission to measure sea-surface topography, sea- and land-surface temperature and ocean- and land-surface color (ESA)

Sentinel-4: geostationary ESA mission to monitor the composition of the atmosphere (on Metosat)

Sentinel-5: polar orbiting ESA mission to monitor the composition of the atmosphere (on Metop)

SEO: System Engineering Office

SEVIRI: Spinning Enhanced Visible and Infrared Imager (on Meteosat)

SGLI: Second-Generation Global Imager (on Japan's GCOM-C satellite)

SIT: Strategic Implementation Team (CEOS)

SLC: Scan-Line Corrector (on Landsat)

SLSTR: Sea and Land Surface Temperature Radiometer (on Sentinel 3)

SMAP: Soil Moisture Active Passive mission (NASA)

SMOS: Soil Moisture Ocean Salinity mission (ESA)

SMMR: Scanning Multichannel Microwave Radiometer (on NASA's Nimbus-7 satellite)

SOCAT: Surface Ocean CO_2 Atlas

SOCCR: State of the Carbon Cycle Report

SPARC: Stratosphere-troposphere Processes And their Role in Climate

SPOT4-VEGETATION: Satellite Pour l'Observation de la Terre Vegetation sensor (see also SPOT-VGT)

SPOT-VGT: Satellite Pour l'Observation de la Terre Vegetation sensor (see also SPOT4-VEGETATION)

SSM/I: Special Sensor Microwave Imager (on U.S. DMSP satellites)

SSS: Sea Surface Salinity

SST: Sea Surface Temperature

Suomi-NPP: Suomi-National Polar-orbiting Partnership (NASA and NOAA)

SWIR: shortwave infrared

TanDEM-X: Terra-X SAR add-on for Digital Elevation Measurement

TanSat: The Chinese Carbon Dioxide Observing Satellite

TANSO: Thermal And Near infrared Sensor for carbon Observations

TANSO-CAI: Thermal And Near infrared Sensor for carbon Observations-Cloud and Aerosol Imager

TANSO-FTS: Thermal And Near infrared Sensor for carbon Observations-Fourier Transform Spectrometer

TCCON: Total Carbon Column Observing Network

TEMPO: Tropospheric Emissions: Monitoring of Pollution (NASA)

Terra: an Earth Observing System (EOS) satellite in a morning orbit (NASA)

TerraSAR-X: an X-band radar Earth observation satellite (a joint venture between DLR and EADS Astrium)

TES: Tropospheric Emission Spectrometer (on NASA's Aura satellite)

TIR: Thermal Infrared

TIROS: Television Infrared Observation Satellites (NOAA)

TM: Thematic Mapper

TMI: TRMM Microwave Imager (on TRMM)

TransCom: Atmospheric Tracer Transport Model Intercomparison Project

TRMM: Tropical Rainfall Measuring Mission

TropOMI: TROPOspheric Monitoring Instrument (on ESA's Sentinel-5 precursor satellite)

UN: United Nations
UNEP: United Nations Environment Programme
UNESCO: United Nations Educational Scientific and Cultural Organization
UNFCCC: United Nations Framework Convention on Climate Change
USGS: United States Geological Survey
UV: ultraviolet
VC: Virtual Constellation
VCL: Vegetation Canopy Lidar
VEGETATION: Vegetation sensor on the Satellite Pour l'Observation de la Terre
VIIRS: Visible Infrared Imaging Radiometer Suite (on Suomi NPP and JPSS)
VIRS: Visible and Infrared Scanner (on TRMM)
VIS/IR: Visible / Infrared
VOS: Voluntary Observing Ships (WMO)
WCRP: World Climate Research Programme
WG: Working Group
WGCV: Working Group on Calibration and Validation (CEOS)
WindSat: a demonstration project intended to measure ocean surface wind speed and wind direction from space using a polarimetric radiometer (on USA Coriolis satellite)
WMO: World Meteorological Organization
X_{CH4}: column-averaged dry air mole fraction of methane
X_{CO2}: column-averaged dry air mole fraction of carbon dioxide

APPENDIX C: CEOS CARBON TASK FORCE MEMBERS

Chris Barnet, National Oceanic and Atmospheric Administration (NOAA), USA
Christopher Blackerby, National Aeronautics and Space Administration (NASA), USA
Stephan Bojinski, Global Climate Observing System (GCOS)
Michael Buchwitz, Universität Bremen, Germany
John Burrows, Universität Bremen, Germany
Jim Butler, NOAA Earth System Research Laboratory (ESRL), USA
Pep Canadell, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia
Phillipe Ciais, Laboratoire des Sciences du Climat et de l'Environnement (LSCE), France
David Crisp, NASA Jet Propulsion Laboratory, USA
Carole Deniel, Centre National d'Etudes Spatiales (CNES), France
Scott Denning, University of Colorado, USA
Han Dolman, VU University Amsterdam, The Netherlands
Mark Dowell, European Commission (EC), Joint Research Centre (JRC)
George, Dyke, Japan Aerospace Exploration Agency (JAXA), Japan
Richard Eckman, National Aeronautics and Space Administration (NASA), USA
Azusa Fukuki, Remote Sensing Technology Center of Japan (RESTEC), Japan
Mitch Goldberg, National Oceanic and Atmospheric Administration (NOAA), USA
Yukio Haruyama, Remote Sensing Technology Center of Japan (RESTEC), Japan
Alex Held, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia
Nicolas Hoepffner, European Commission (EC), Joint Research Centre (JRC)
Shoken Ishii, National Institute of Information and Communication Technology (NICT), Japan
Masatoshi Kamei, Remote Sensing Technology Center of Japan (RESTEC), Japan
Michio Kawamiya, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan
Brian Killough, NASA Langley Research Center, USA
Christine McMahon-Bognar, National Aeronautics and Space Administration (NASA), USA
Dennis McSweeney, National Aeronautics and Space Administration (NASA), USA
Berrien Moore, University of Oklahoma, USA
Rosemary Munro, European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)
Masakatsu Nakajima, Japan Aerospace Exploration Agency (JAXA), Japan; Co-Chair
Osamu Ochiai, Japan Aerospace Exploration Agency (JAXA), Japan
Paul Palmer, The University of Edinburgh, UK
Philippe Peylin, Laboratoire des Sciences du Climat et de l'Environnement (LSCE), France
Stephen Plummer, European Space Agency (ESA)
Yasuhiro Sasano, National Institute for Environmental Studies (NIES), Japan
Shubha Sathyendranath, DAL / Plymouth Marine Laboratory, UK
Kerry Sawyer, National Oceanic and Atmospheric Administration (NOAA), USA
Christiane Schmullius, Friedrich-Schiller-Universität Jena, Germany
Kei Shiomi, Japan Aerospace Exploration Agency (JAXA), Japan
Brent Smith, National Oceanic and Atmospheric Administration (NOAA), USA
Jonathan Smith, United States Geological Survey (USGS), USA
Matthew Steventon, Japan Aerospace Exploration Agency (JAXA), Japan
Oksana Tarasova, World Meteorological Organisation (WMO)
Justin Tilman, National Aeronautics and Space Administration (NASA), USA

Kazuo Umezawa, Japan Aerospace Exploration Agency (JAXA), Japan
Espen Volden, Group on Earth Observations (GEO) Secretariat
Albrecht von Bargen, Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Germany
Stephen Ward, Japan Aerospace Exploration Agency (JAXA), Japan
Diane E. Wickland, National Aeronautics and Space Administration (NASA), USA; Co-Chair
Claus Zehner, European Space Agency (ESA)
Zhiliang Zhu, United States Geological Survey (USGS), USA

APPENDIX D: CHAPTER AUTHORS

Executive Summary:
Diane E. Wickland (National Aeronautics and Space Administration)
Stephen Plummer (European Space Agency)
Masakatsu Nakajima (Japan Aerospace Exploration Agency)
Stephen Ward (Japan Aerospace Exploration Agency)

Introduction:
Masakatsu Nakajima (Japan Aerospace Exploration Agency)
Diane E. Wickland (National Aeronautics and Space Administration)
Stephen Plummer (European Space Agency)
Stephen Ward (Japan Aerospace Exploration Agency)
Ralph Dubayah (University of Maryland)
Berrien Moore (University of Oklahoma)
Shubha Sathyendranath (Plymouth Marine Laboratory)

Land:
Ralph Dubayah (University of Maryland)
Chris Schmullius (Friedrich-Schiller University Jena)
Warren Cohen (USDA Forest Service)
Nadine Gobron (Joint Research Centre)
Eric Kasischke (University of Maryland)
Kyle McDonald (City College of New York)
Shaun Quegan (The University of Sheffield)
Jean Ometto (Instituto Nacional de Pesquisas Espaciais)
Stephen Plummer (European Space Agency)
Steven Running (University of Montana)
Sassan Saatchi (NASA Jet Propulsion Laboratory)
Masanobu Shimada (Japan Aerospace Exploration Agency)

Oceans and Inland Waters:
Shubha Sathyendranath (Plymouth Marine Laboratory)
Prakash Chauhan (Indian Space Research Organization)
Watson Gregg (NASA Goddard Space Flight Center)
Nicolas Hoepffner (Joint Research Centre)
Joji Ishizaka (Nagoya University)
Johnny Johannessen (Nansen Environmental and Remote Sensing Centre)
Milton Kampel (Instituto Nacional de Pesquisas Espaciais)
Tiit Kutser (University of Tartu)
Trevor Platt (Plymouth Marine Laboratory)
Joo-Hyung Ryu (Korea Institute of Ocean Science and Technology)
Atmosphere:

Berrien Moore (University of Oklahoma)
John Burrows (Universität Bremen)
David Crisp (NASA Jet Propulsion Laboratory)
Michio Kawamiya (Japan Agency for Marine-earth Science and Technology)
Martin Heimann (Max Plank Institute for Biogeochemistry, Jena)
Ray Nassar (Environment Canada)
Peter Rayner (University of Melbourne)

Integration:
Stephen Plummer (European Space Agency)
Warren Cohen (USDA Forest Service)
Martin Heimann (Max Plank Institute for Biogeochemistry, Jena)
Nicolas Hoepffner (Joint Research Centre)
Tiit Kutser (University of Tartu)
Peter Rayner (University of Melbourne)
Shubha Sathyendranath (Plymouth Marine Laboratory)
Masanobu Shimada (Japan Aerospace Exploration Agency)

The Way Forward:
Diane E. Wickland (National Aeronautics and Space Administration)
Masakatsu Nakajima (Japan Aerospace Exploration Agency)

APPENDIX E: LIST OF MEETINGS

In addition to monthly teleconference calls involving the Carbon Task Force (CTF) Executive team and lead chapter authors, the following meetings were held to advance the development, preparation, and review of the *CEOS Strategy for Carbon Observations from Space.* With the exception of the CTF meeting on 18 February 2011, none of these meetings had a majority the CTF members or report authors present. For the most part, participation at side meetings was limited to those CTF members and report authors who were attending the main meeting.

8 September 2010. Carbon from Space Workshop, Oxford, U.K. A consultative session regarding the scope and content of the CTF report was held on the final day of the Carbon from Space Workshop, followed by a short side meeting of CTF members present.

18 February 2011. CEOS-GEO Actions Workshop in Arlington, Virginia, USA. A full Carbon Task Force meeting was held immediately following the CEOS-GEO Actions Workshop. The CTF report was outlined, candidate domain chapter leads were identified, a list of candidate co-authors was developed, and a table of contents was created.

19 April 2011. Atmospheric Composition Constellation (ACC-8) meeting, Columbia, USA. CTF plans for the CEOS Carbon Strategy report were presented and discussed. The ACC agreed to review CTF report when ready.

18 May, 2011. International Workshop on Greenhouse Gas Measurements from Space (IWGGMS-7), Edinburgh, U.K. A consultative session and atmospheric domain working meeting were held with the atmospheric community as a side event at IWGGMS-7.

24-28 October 2011. WCRP Open Science Conference: Climate Research in Service to Society, Denver, Colorado, USA. The atmosphere domain writing team held a side meeting.

26 October 2011. GEO-Carbon Conference: Carbon in a Changing World, Rome, Italy. The CTF presented a progress report at the conference, and the land domain writing team held a side meeting.

7 November 2011. 25th CEOS Plenary, Lucca, Italy. A side meeting of the CTF Executive Team and interested CEOS Plenary participants was held to address report objectives and coordination.

6 December 2011. Fall American Geophysical Union (AGU) meeting, San Francisco, USA. A side meeting of land and atmosphere domain chapter authors was held to address domain chapter writing objectives and coordination.

20-24 February 2012. Ocean Sciences Meeting, Salt Lake City, Utah, USA. The ocean domain chapter authors held a side meeting to address domain chapter writing objectives and coordination.

29 March 2012. CEOS SIT-27 meeting, La Jolla, California, USA. CEOS agency representatives attending SIT-27 attended a consultative side meeting with the CTF report authors to provide feedback on the first draft CTF report.

30 March 2012. CTF Report Author Team meeting, La Jolla, California, USA. A meeting of CTF report authors was held to address domain chapter writing objectives and coordination as follow-up to the consultative meeting with CEOS SIT-27 participants.

April 2012. Global Carbon Project (GCP) meeting, Marrakech, Morocco. The GCP was apprised of CTF report plans and schedule and requested to provide advice and future review.

26 July 2012. International Geoscience and Remote Sensing Society (IGARSS) meeting in Munich, Germany. CTF report's land chapter author team held a side meeting.

8 October 2012. European Space Agency GlobBiomass meeting, Jena, Germany. A side meeting of members of the land domain chapter writing team was held.

16 October 2012. MERIS/AATSR and Sentinel-3 workshop, Frascati, Italy. A side meeting was held of members of the ocean and land domain chapter writing teams.

7 December 2012. Fall American Geophysical Union (AGU) meeting, San Francisco, USA. A side meeting of CTF report authors was held to coordinate report writing.

11 March 2013. CEOS SIT-28 meeting, Hampton, Virginia, USA. CEOS agency representatives attended a consultative side meeting with the CFT report authors to review the draft actions in the CTF report.

10 September 2013. CEOS SIT Technical Workshop, Pasadena, USA. CEOS agency representatives attending the SIT Technical Workshop attended a consultative side meeting with the CFT report authors to provide feedback on the second draft CTF report.

1 October 2013. GEO Carbon Conference, Geneva, Switzerland. *CEOS Strategy for Carbon Observations from Space* was presented in plenary session and participants at the meeting were invited to review the final draft report during the review open period which started on that day. (The GEO Carbon Office offered to communicate the request for review to their full mailing list and to make the final draft report directly available to the GEO Carbon Community of Practice. This offer was accepted.)

Recyclable Ⓐ