NASA Carbon Monitoring System Scoping Study Workshop Report

13-14 July 2010 Boulder CO

Contents

Introduction and Vision

NASA's Contribution to a Carbon Monitoring System

The Fiscal Year 2010 Congressional Appropriation directed NASA to initiate work towards a Carbon Monitoring System (CMS), and provided specific guidance. Funding was made available for "*pre-phase A and pilot initiatives for the development of a carbon monitoring system. Any pilot developed shall replicate state and national carbon and biomass inventory processes that provide statistical precision and accuracy with geospatially explicit associated attribute data for aggregation at the project, county, state and federal level using a common dataset with complete market transparency, including extraction algorithms and correlation modeling.*"

The approach NASA developed in following these directions emphasizes exploitation of the satellite remote sensing resources, scientific knowledge, and end-to-end system expertise that are major strengths of the NASA Earth Science program. The approach takes into account data and expertise that are the domain or other U.S. government agencies, and anticipates close communications and/or partnerships with those agencies and their scientific and technical experts. Additionally, it lays the groundwork for CMS-related applications of future satellite sensors now in development (e.g., OCO-2) or from the Decadal Survey (e.g., Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI), Active Sensing of CO_2 Emissions Over Nights, Days, and Seasons (ASCENDS), Ice, Cloud, and Land Elevation Satellite-II (ICESat-II)).

NASA's initial Carbon Monitoring System activities will involve two pilot studies and a scoping effort. A brief description of each follows:

- *Biomass and Carbon Storage Pilot Product*: A biomass and carbon storage pilot product (to be hereafter referred to as the Biomass Product) will be developed. The focus will be on quantifying the terrestrial vegetation aboveground carbon stock using consistent approach(es) and performing uncertainty analysis on its magnitude and spatial distribution. The initial emphasis will be on production and evaluation of a U.S. biomass and carbon storage product, but a global product also will be planned.
- *Integrated Emission/Uptake ("Flux") Pilot Product*: A global product for integrated emission/uptake (to be hereafter referred to as the Flux Product) will be developed. This product will be created through a combination of space-based measurements of atmospheric carbon dioxide (from Japan's Greenhouse gases Observing Satellite (GOSAT), NASA's Tropospheric Emission Spectrometer (TES), and other instruments), carbon cycle models and assimilation systems, and observationally-constrained, but model-calculated, information about the processes that couple the surface to the atmosphere.
- *Scoping Study*: The scoping study will map NASA's evolving observational and modeling capability and the ability of the research and

applied science community to use this capability to enhance information products to meet policy and decision-making requirements. This effort will focus on streamlining the flow of information products to decision-makers from future research efforts and planned observation capabilities, allowing NASA to engage the carbon policy and decision-making community.

Further details on both pilot projects and the Scoping Study may be found at http://cce.nasa.gov/cms.

The June 2010 Climate Initiative[1] proposed by NASA's Earth Science Division, and included in the President's FY 2011 budget request for NASA, recognizes the need to strengthen and extend basic carbon cycle research for the purpose of addressing critical national needs related to energy and climate. The initiative called for: …*continuation and growth of the Carbon Monitoring System activity begun in FY2010 to provide an improving set of products on carbon storage and exchange between the surface and biosphere for regular delivery to policy and decision-makers, as well as for observing system simulation experiments designed to facilitate development of future carbon monitoring observational capability. This investment leverages the much larger underlying NASA program in Carbon Cycle science. Other agencies of the federal government will be undertaking related activities in coming years to support national policy objectives (e.g., treaty verification, quantitative analysis of cap-and-trade limits), policy development, and resource management. However, most other agencies will not have the capability of fully utilizing NASA's increasing set of satellite and airborne data, and may not fully utilize the observationally-based advances in carbon modeling and data assimilation that NASA will be creating in coming years. Thus, the continuation of the current effort should allow NASA to fulfill its necessary role in the growing interagency set of activities on carbon monitoring and thus generate better overall products in support of national needs.*

This document provides options for a for NASA to leverage its considerable current efforts in carbon cycle science towards the development of a NASA contribution to a national-level Carbon Monitoring System (CMS). The design of the NASA plan should target the following key features of an envisioned CMS:

- Responsive to the information needs of decision makers (including both policy makers and resource managers);
- Systematic, timely and relevant information;
- Easily accessible and useable information;
- Scientifically sound and thoroughly evaluated and documented; and,
- Sustained over an extended period (i.e., at least 10 years).

NASA's contribution to a CMS must facilitate the critical research, analysis, product design, and delivery of carbon information from NASA Earth observations and science, all towards developing the capabilities for meeting national needs. A transformational improvement in interagency capabilities and coordination is required. Towards this goal, NASA will build on its program of record, the scientific and engineering expertise of its researchers and systems engineers, and its research assets, to develop carbon monitoring products. NASA will also collaborate with other US Government agencies to ensure that the design and implementation of a CMS complements the capabilities of other agencies (e.g. NOAA's in situ (flask, tower, and aircraft) observational networks, climate and carbon models; NSF's NEON and LTER programs; USDA's Forest Inventory and Analysis(FIA) and National Cooperative Soil Survey programs; USGS's geological and ecological carbon sequestration programs; and the interagency supported AmeriFlux program).

Towards a Prototype Carbon Monitoring System

The NASA plan should target initially, land carbon stocks, land-atmosphere carbon fluxes(particularly for regional and urban areas) and ocean carbon stocks and fluxes for integration into a CMS infrastructure. To ensure that the science information from these areas should be responsive to the needs of policy-makers, NASA should:

- *Organize and conduct periodic workshops, seminars and other appropriate events to acquire information from, and disseminate information to, resource managers and policy makers;*
- *Identify, and work with, potential users of the CMS products to design and implement carbon products and transfer responsibility for on-going production of useful products to the societal organizations that use can use these products for their decision making processes; and,*
- *Participate in national and international discussions relating to observation and information requirements for carbon monitoring systems.*

The design and test of a prototype system that achieves timely, useable data products that are easily accessible and scientifically sound will be accomplished by:

- *Integrating the carbon-related data and knowledge from NASA's Earth Science satellite and airborne missions and, research and applications studies to develop prototype CMS information products and distribution mechanisms and to transfer key products to operational users;*
- *Identifying the core capabilities at NASA Centers which can contribute to CMS and coordinating activities among NASA Centers;*
- *Identifying aspects of the CMS that can be provided by the national and international Earth science community; and*
- *Solicit research and applied science efforts that will enhance the CMS and incorporate research results into existing infrastructure for carbon monitoring in operational agencies and organizations.*

Initial development of a CMS architecture and example products will require three to five years of concerted effort. A clear metric of success will be the transition of key CMS products and processes from research to operations in agencies with mandates for carbon policy and management decisions.

Cross-cutting Earth Observation Priorities for the CMS

It is essential for NASA to draw upon the full range of its Earth science capabilities to meet the requirements of a CMS.

Engagement

A process to engage users of information related to carbon policy and resource management to control carbon fluxes is critical to ensure that the CMS serves users efficiently and effectively. The process should directly engage target-users of the CMS, such as state federal and international users, as well as policy-related legislative, regulatory, and voluntary carbon-related management groups local to international interests. Such engagement requires sustained communication and interaction to extract well-posed questions and requirements and ensure that the CMS accounts for, and satisfies, current and evolving user needs.

Products

Products from a CMS must be relevant to the end-users and science community. A systems engineering and science analysis approach to defining CMS product requirements, analyses, reports, and relevant protocols will result in products, founded on fully reviewed science, that meet users' needs. All CMS products should address, as equal priorities, the evolution of both scientific understanding and value-added services to CMS users. An iterative improvement and validation of CMS products and applications over time is essential. CMS products will include quantified uncertainties of any estimated or measured parameters and documentation of product attributes and appropriate uses. NASA will integrate CMS products with related products from existing or planned projects and satellite observations. Pilot projects, to explore the infrastructure, measurements, and techniques needed to create CMS products, may be a useful approach.

Coordination- Among Agencies

CMS development will be coordinated with other federal agency and inter-agency activities, such as the U.S. Carbon Cycle Science Program, to minimize overlap and duplication, identify key interfaces for the exchange of data products among agencies, and develop protocols for product validation. Partner agencies engaged in current regional, national and international reporting mechanisms may be well positioned to coordinate efforts and develop approaches for data sharing and validation. The coordination should seek to address the national climate strategy approach as a chain with a number of links: observations, models, decision-support, governance, socio-economic impacts, and adaptation and mitigation actions.

Attribution

The CMS should develop and implement techniques to attribute surface carbon fluxes to anthropogenic, natural, or biogenic sources within specific spatial domains. This task is a priority both for fundamental research and product development and validation (including pilot projects focused on anthropogenic attribution). NASA should explore with other agencies, the needs and options for a joint synthesis analysis capability that identifies and reconciles differences between top-down and bottom-up estimates of anthropogenic carbon emissions and sequestration, including propagation of uncertainties.

Modeling and Tools

The functionality, performance and reliability of models and data assimilation systems can be improved to meet fundamental CMS objectives. The current suite of research models and assimilation systems needs to be transformed into a set of robust, operational, production tools. A critical element in this transformation is quantification of performance requirements for land, ocean, and atmospheric models and data assimilation systems needed to meet the specifications of CMS products. NASA should develop analysis tools such as flexible Observing System Simulation Experiments (OSSEs) to enable rapid architectural trades, optimal system design, and performance prediction for different sensor technologies, sensor placement, observing strategy, and end-to-end data system design. Current OSSEs and related design tools typically require several months to prepare and execute for each unique sensor and observing scheme. To help the broader science community improve models, NASA should develop a sustained framework for comparing carbon observations with associated models (with appropriate connectivity to other agency observations and models).

Leverages, Synergies and Technology Transfer

The CMS products must be driven by user needs. As products are developed, it is imperative to facilitate technology transfer and utilization in existing applications and monitoring programs by U.S. national agencies and international organizations. Applications of an urgent nature should be identified, with a priority mandate, and for which the use of remote sensing technology is both essential and practical to satisfy the mandate. It is critical that CMS coordinate with existing carbon programs such as USGCRP’s Carbon Cycle Interagency Working Group, among many others

Monitoring Terrestrial Carbon Stocks and Dynamics

Improved information on terrestrial carbon stocks and dynamics is essential to serve current and future climate mitigation policies and applications needs. As the spatial/temporal resolution and accuracy of these records are improved, the information will be used increasingly to support reporting and verification, both nationally and internationally. NASA's observational archives, as well as existing and planned airborne and spaceborne assets, may be useful for that purpose in two ways. First, CMS activities could accelerate the development and use of existing data products in support of national carbon assessments (e.g. those of USGS, EPA, and USDA) and international efforts in the realm of climate treaty verification. Second, CMS activities could pioneer the development and use of new remote sensing technology, new methodological frameworks, and new models using disparate data sources that improve CMS products. Accordingly, NASA should consider focused activities in three primary areas over the next decade: (1) creation of historical and current maps of annual carbon stocks and main drivers of change (e.g. wall-to-wall maps of land cover change/disturbance, canopy properties and structure, forest age, and carbon accumulation rates), with measures of uncertainty at fine resolution; (2) development of airborne sensors (such as lidar, radar and multi-angle passive optical instruments) for cal/val and demonstration projects, and (3) transfer of key technology, model and framework developments to domestic and international partners.

The following are critical elements for CMS observational and modeling activities:

Spatial and Temporal Resolutions. Carbon stocks and their changes vary across the landscape annually and inter-annually at small scales (1 hectare and finer). It is critical that remote sensing techniques and other capabilities improve to map annual and decadal variability in carbon stocks and changes at relevant spatial and temporal scales commensurate with policy and applications needs.

Remote Sensing. The NASA CMS should utilize existing, and develop new carbon-related products that map two-dimensional landscape properties and changes. These products should be used while developing the next generation of airborne and spaceborne active remote sensing technologies to enable the observation of the third, or vertical, dimension of forest structure

Modeling. Ecosystem and carbon accounting models, parameterized with remotely sensed data, and adhering to international reporting standards, will provide consistent estimation frameworks and allow for future scenario evaluation (prognosis). NASA should encourage the development and validation of carbon-related models, and, as appropriate, global access and usability.

Integration. Dedicated demonstration projects that integrate existing and spaceborne and airborne observations and their associated algorithms with field data and new classes of ecosystem models should be a priority. Some demonstration projects may be developed into operational prototypes.

The following activities are critical to evaluating terrestrial carbon stocks monitoring processes and tools (in addition to the current CMS terrestrial biomass pilot project).

Annual Terrestrial Biomass Maps

The existing CMS assessment frameworks (current pilot project) should be rigorously evaluated and, if appropriate, continued and expanded to achieve a more mature technology readiness level that is responsive to evolving policy needs. Annual maps, with measures of uncertainty, of U.S. terrestrial biomass at spatial scales appropriate for decision making, using existing data sets (pre-DESDynI) should be produced and expanded to other geographic regions worldwide.

Preparation for DESDynI Observations

As NASA enters the DESDynI (Deformation, Ecosystem Structure and Dynamics of Ice)-era, annual high-resolution observations of global carbon inventories and dynamics will become available (starting in 2017). Prior to the launch of DESDynI, NASA should develop collaborative regional CMS demonstration projects, informed by the CMS pilot studies, which utilize US and international remote sensing and field data collection capabilities (from joint field campaigns). Data from DESDynI should then be merged into these ongoing regional projects for assessment and evaluation of how space-based lidar and radar observations can support policy decisions. These tasks will lead to CMS products, with documented uncertainties, that meet national and international carbon policy needs.

Atmospheric Regional Fluxes and Urban Domes

Disentangling the anthropogenic and natural components of the carbon cycle on policy-relevant spatio-temporal scales with acceptable levels of uncertainty is the driving technical barrier to independent, measurements of anthropogenic emissions. While accurate, global average estimates of CO_2 and other gas concentrations are available today, there currently is no observational system capable of providing accurate estimates of national or regional scale anthropogenic emissions. Nor has the community yet demonstrated the ability to measure emissions from urban “domes” (large, localized enhancements of CO_2 relative to background concentrations) and large power plants, collectively responsible for over half of the current 100 year anthropogenic global warming potential (Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), 2007). A recent NRC study (Pacala, 2010) described the potential near-term utility of monitoring the CO_2 emission trends of the urban domes from a statistically representative sample of cities as a proxy for national emission trends. There is no independent, systematic, observationally-based method for verifying greenhouse gas emissions inventories on local, regional, or national scales.

The first studies designed to determine anthropogenic fluxes have been undertaken. The North American Carbon Program’s Mid-Continent Intensive provided a valuable testbed for evaluating large-scale observations of the carbon cycle on a regional scale. Analyses of these data for 2000-2005 and 2007 are in progress. The Indianapolis Carbon Footprint Experiment (Mays, 2009) used high precision aircraft in situ measurements of CO_2 and CH_4 to quantify the footprints of these gases in the Indianapolis metro area with high spatial resolution. The emissions estimated from these data were compared to a high space/time resolution emissions data product calculated using the methods of the Vulcan project (Gurney, 2009). The National Institute of Science and Technology (NIST) has funded a second phase of this experiment which will incorporate more intensive aircraft measurements, as well as a deployment of a ‘ring of towers’ as was successfully used during the NACP MCI (Corbin, et.al., 2010). A building/street-level process-oriented emissions data product has been generated for the Indianapolis spatial domain and it is also currently being improved with fuel, transportation, utility, and activity data (Zhou and Gurney, 2010). A common feature of all existing CO_2 emission pilot studies is the absence of remote-sensing data in the inverse flux estimates. The growing capability within NASA and the international community to provide high-density, near-global observations of atmospheric CO_2 and other greenhouse gases and many other parameters relevant to reducing errors in atmospheric transport and land/ocean carbon models (and hence errors in inverse modeled fluxes) will be critical to addressing the above issues.

The following activities will develop the scientific and technical expertise needed to disentangle anthropogenic and natural components of the carbon cycle in order to quantify accurately the anthropogenic signal and its change over time:

Mid Continent Intensive "Follow-On"

A Mid Continent Intensive Follow-On in coordination with the National Aero-Space Plane (NASP) Program, applied to a region where integration with socio-economic data, land use change, etc. is possible. The southeastern US is a strong candidate location. Additionally, intensive measurements in and around Atlanta could serve to integrate this pilot activity with expertise gained in the Indianapolis Carbon Footprint experiment. The coupled regional/urban flux experiment would yield the following benefits:

- Comprehensive, detailed bottom-up/top-down reconciliation results (with a given level of uncertainty), as well as evaluation of types of data (e.g. remote sensing data which are the only data that would be available for urban areas in many countries).
- Quantification of the differences in the emissions estimates obtained using ALL available data and inventories with the estimates obtained using only the subset of information that would be available for non-instrumented areas and/or areas with poorer inventories. Quantification of the uncertainties in both cases.
- Identification of the most critical in situ observations.
- Quantification of how the information degrades (i.e. uncertainty increases) as data are removed from the analysis. Identification of the maximum benefit resource levels.

Add Remote Sensing to the Indianapolis Carbon Footprint Experiment

The NIST-sponsored Indianapolis Carbon Footprint Experiment scheduled for 2011-2012 is based on a combination of in situ measurements and the construction of a building/street-level emissions data product using the methods of the Hestia project (Zhou and Gurney 2010). An added remote sensing effort would coordinate intensive satellite sensor measurements (e.g. MODIS, GOSAT, TES) of the Indianapolis region, especially in conjunction with aircraft measurements. NASA's aircraft remote sensing assets (e.g. AVIRIS, AES, PALS, etc.) would be deployed to augment and enhance the planned observations. The multi-decade Landsat observational record, as well as the pending LDCM measurements, should be utilized to define or enhance for land cover and land use change variables. The effort would help exploit the information content of remote sensing measurements in the analyses and flux estimates. See the INFLUX Whitepaper at http://www.nacarbon.org/nacp/documents/INFLUX_white_paper_v4.pdf

Sustained Measurement of Complex Megacity GHG Emissions

Global trends in urbanization will concentrate a majority of anthropogenic GHG emissions in megacities (cities with populations > 10 million) in the coming decades. Although changes in the spatial extent of urban areas are currently mapped using moderate and fine resolution satellite data, there is no infrastructure to validate remote sensing measurements of GHGs from megacities. This activity would establish the sub-orbital observing network and analysis technology to reconcile emissions inventories and observations on spatial scales of 1 km^2. 2011 and 2012 experiments would use GOSAT targeted observations from space to prepare the system for validating OCO-2 measurements after its 2013 launch. Deploying this system in Los Angeles would leverage NASA ground-based remote sensing assets at Caltech, JPL, and on Mt. Wilson. Furthermore, multiple universities could provide contributions from NASA-sponsored measurement and modeling efforts.

Inverse Modeling / Data Assimilation

Develop inverse modeling / data assimilation tools that are tailored to estimating anthropogenic emissions with a focus on quantifying uncertainties and can incorporate in situ and remote sensing observations. For example, disentangling fossil fuel emissions from biogenic area fluxes will likely require fusion of remotely sensed CO_2, CO, NO_2 and other species with in-situ sampling and radio-isotope analysis (using assets from NASA, NOAA, and DOE). The new tools will enable reduction in inverse modeled flux uncertainties through the use of new GHG observations from satellites, GHG transport tracers and vertical profiles. NASA should begin development of inverse modeling systems immediately and test them with simulated data to ensure rapid delivery of flux products from OCO-2, OCO-3 and the carbon relevant Decadal Survey missions.

CMS products should focus on how decision makers will use atmospheric flux or concentration information. Two potential high-impact applications for this information are (i) verification / evaluation and (ii) guide emissions reductions for specific geographic or thematic areas that have the ability to deploy a wider array of instrumentation. In the former case (i) the activity will inform how much independent information could be gleaned WITHOUT intensive measurements. In the latter case (ii), the activity would serve as a model for what could be done in other areas and would guide the design of an optimized emissions monitoring network, including data on instrumentation to deployment.

Ocean Carbon Fluxes and Inventories

Any carbon monitoring program must include the open and coastal oceans and the Great Lakes, because the Earth's oceans contain more than 90% of global non-geologic active carbon pool and account for about 50% of global primary production. One quarter to nearly one half of the carbon emitted by fossil fuel burning is sequestered in the oceans. Furthermore, an unknown portion of the terrestrial carbon sink may be exported to the coastal ocean or to the atmosphere through rivers.
The CMS should provide continuous estimates of the state of ocean carbon fluxes and inventories. Three approaches should be considered:

1. Systematic observations of ocean color, SST, winds, and salinity with algorithms to globally estimate fluxes and inventories of ocean carbon:

Fluxes	**Inventories**
Air-sea fluxes of CO_2	Ocean pCO_2 and DIC
Ocean primary production	Ocean phytoplankton biomass
	Ocean CDOM
	Ocean PIC
	Ocean POC
	Ocean Alkalinity
	Coastal ocean DOC

2. Coupled Earth system models forced by transient atmospheric data sets to globally estimate:

All of the above ocean components related to carbon, plus

Fluxes	**Inventories**
Lateral fluxes	Open ocean DOC
(land/coastal, coastal/open ocean)	
DIC, DOC, POC, PIC, and alkalinity	

3. Integrated Earth system data assimilation using all relevant remote sensing Earth science data sets, and coupled interactively to refine the global estimates of ocean carbon components and fluxes.

Annual, monthly, and weekly output products would be useful from each approach.

Over the next 3-5 years, progress on the approaches described is essential for improving estimates of open ocean fluxes and estimates of US coastal fluxes derived from regional models. Over the longer term, 5-10 years, new sensors will help further improve estimates of open ocean fluxes, and estimates of coastal ocean fluxes and land-sea exchanges. In both the near- and long-term scenarios, the biases and uncertainties of the estimates will be fully characterized to the extent possible.

The following two activities are critical to evaluating ocean flux monitoring processes and tools in the context of global carbon budgets (in addition to the current flux pilot project).

Ocean CO_2 Flux Maps

Combine NASA satellite remote sensing observations, in situ ocean carbon dioxide measurements, and complementary data collection efforts with global ocean biogeochemistry models and data assimilation activities to produce global maps of monthly and, possibly, weekly global air-sea CO_2 fluxes. Remote sensing data products will include ocean color and sea surface temperature (SST) (for data assimilation), and wind products and, eventually, ocean salinity measurements from Aquarius (for model forcing). Initial estimates will utilize atmospheric data from the Global Modeling and Assimilation Office (GMAO) Modern Era Retrospective-Analysis for Research and Applications (MERRA) project to force the ocean biogeochemistry models. However, global estimates of air-sea CO_2 fluxes will evolve using fully coupled global atmospheric/ocean models and eventually utilize data assimilation of all available and applicable satellite products. Ocean carbon inventories and primary production using models and satellite data, such as those described above, will be included in the project because of their importance in refining air-sea CO_2 fluxes and because they reflect the state and variability of the ocean carbon cycle. Uncertainties in CO_2 fluxes will be characterized using available in situ data and multiple model outputs. In situ data include the Aquarius validation project in the mid-Atlantic enhanced with sensors to measure carbon components and fluxes. This project will enable us to quantify the state and variability of ocean carbon fluxes and clarify the ocean's role in the global carbon cycle, with enhanced understanding of uncertainties. NASA CMS activities should coordinate with NOAA's global moored and underway carbon observatories, which measured CO_2 only prior to 2010, and starting in 2010 also include pH at many locations, making it possible to calculate DIC and alkalinity values for any locations with both variables. NOAA has also played a leading role in generating algorithms to predict surface ocean pCO_2 from remotely sensed SST in many regions of the world's oceans, based in large part upon the large data set of surface ocean pCO_2 values collected by the moored and underway CO_2 sensors in this global network.

Land-Ocean Exchange/Flux Assessments

The quantity of carbon exchanged between the land and ocean remains an unknown in the global carbon budget. Using focused, in situ field programs, characterization of the magnitude and uncertainty of the land-ocean carbon fluxes can be achieved. Existing and planned regional monitoring and short term field sampling sites around the US coasts will maximize the data acquisition with reduced costs and improved efficiency. The information can be fed into regional and global models to improve parameterizations and land-ocean process characterization. Areas that should be emphasized include the Mississippi River plume, US Mid-Atlantic Bight, and other coastal regions now active and involved in the North American Carbon Program's coastal synthesis effort. Observations to be utilized include carbon flux measurements derived from satellite estimates of ocean color, SST, winds and salinity; satellite-estimated and in situ measured pCO_2; and in situ radiometry, air-sea CO_2 fluxes, POC, DOC, PIC, DIC and alkalinity.

Summary

This report summarizes the recommendations from the 1st Carbon Monitoring System Scoping Study workshop held on July 13-14, 2010 in Boulder, Colorado. Experts in carbon and Earth observation and familiar with the NASA Earth Science Division participated in the workshop and provided the content for this report.

Critical points to note are:

- The report comments on potential NASA contributions to a carbon monitoring system but does not attempt to design such a system at the national or global levels.

- The report do not address non-carbon gases, soil carbon, or black carbon

- The report is intended to be one product in an on-going activity to facilitate community interaction and communications as carbon policies, science, and technology evolve.

As the NASA CMS initiative procedes forward this document will help advance carbon monitoring science and carbon policy support.

Works Cited

Anthes and Moore. (2007). *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond.* Washington: National Academies of Sciences.

Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability.* (e. Parry, Ed.) New York, NY: Cambridge University Press.

Corbin, et.al. (2010). Assessing the Impact of Crops on Regional CO2 Fluxes and Atmospheric Concentrations. *(DOI: 10.111/j.1600-0889.2010.00485.x)* . (B. Tellus, Ed.) Department of Interior.

Gurney, e. (2009). High Resolution Fossil Fuel Combustion CO2 Emission Fluxes for the United States. *Environomental Science and Technology* (43), 5535-5541.

Mays, e. (2009). Aircraft-Based Measurements of the Carbon Footprint of Indianapolis. *Environmental Science and Technology* (43), 7816-7823.

NASA. (2010). *Responding to the Challenge of Climate and Evnrionmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space.*

Pacala. (2010). *Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements.* Washington, DC: National Academies of Sciences.

Zhou, Y. and K.R. Gurney (2010) A New Methodology for Quantifying Residential and Commercial Fossil Fuel CO_2 Emissions at the Building Spatial Scale and Hourly Time Scale, *Carbon Management,* 1(1), 45-56.

INFLUX Whitepaper (2010) http://www.nacarbon.org/nacp/documents/INFLUX_white_paper_v4.pdf

Further CMS documents may be found on the NASA Carbon Cycle & Ecosystems Focus Area website at http://cce.nasa.gov/cms

Acronym List

ACE: Advanced Composition Explorer spacecraft
AES: Airborne Emissions Spectrometer
AGAGE: Advanced Global Atmospheric Gases Experiment
AIRS: Atmospheric Infrared Sounder
ASCENDS: Active Sensing of CO_2 Emission over Nights, Days, and Seasons.
AVIRIS: Airborne Visible/Infrared Imaging Spectrometer
CASA: Carneggie Ames Stanford Approach – a global ecosystem model
CDOM: Chromophoric dissolved organic matter
CMS: Carbon Monitoring System
CZCS: Coastal Zone Color Scanner
DESDynI: Deformation, Ecosystem Structure and Dynamics of Ice
DIC: Dissolved inorganic carbon
DOC: Dissolved organic carbon
DoE: US Department of Energy
GEOS-Chem: Goddard Earth Observing System Chem model – a global 3-D chemical transport model
GHG: Greenhouse gas
GMAO: Global Modeling and Assimilation Office
GOSAT: Greenhouse gas Observing Satellite
ICESat: Ice, Cloud and land Elevation Satellite
LDCM: Landsat Data Continuity Mission
LVIS: Laser Vegetation Imaging Sensor
MERRA: Modern Era Retrospective-Analysis for Research and Applications
MODIS: Moderate Resolution Imaging Spectroradiometer
NACP: North American Carbon Program
NEON: National Ecological Observatory Network
NOAA: National Oceanic and Atmospheric Administration
NPOESS: National Polar-orbiting Operational Environmental Satellite System
NPP: Net Primary Productivity
NSF: National Science Foundation
OCO: Orbiting Carbon Observatory
pCTM: Parametrized Chemical Transport Model
PACE: Preliminary Advanced Colloids Experiments
PALS: Passive Active L and S Band microwave sensor
PIC: Particulate inorganic carbon
POC: Particulate organic carbon
SeaWiFS: Sea viewing Wide Field of view Sensor
SMAP: Soil Moisture Activeand Passive mission
SST: sea surface temperature
TCCON: Total Carbon Column Observing Network
TES: Tropospheric Emission Spectrometer
UAVSAR: Uninhabited Aerial Vehicle Synthetic Aperture Radar

USDA: Unites States Department of Agriculture
USGCRP: United States Global Change Research Program
USGS: United States Geological Survey (Department of the Interior)