An Advance Planning "Pre-Decadal Survey" Workshop The Carbon-Climate System

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An Advance Planning "Pre-Decadal Survey" Workshop: The Carbon-Climate System

Workshop Summary

What we have: a sparse, exploratory carbon-observing framework.

What we need: a dense, robust and sustained carbon-observing system.

Changes in atmospheric radiative forcing arising from greenhouse gas emissions will likely be the most important driver of climate change in this century.

Primarily because of anthropogenic activities, the atmospheric concentrations of greenhouse gases, principally carbon dioxide (CO_2) and methane (CH_4) have increased substantially over the last century. The current atmospheric concentration of CO_2 exceeds 400 parts per million (ppm) and is growing at a rate of ~2 ppm/yr (± 0.1 ppm/yr). Similarly, CH_4 emissions have accelerated since 2007 and now exceed 1800 parts per billion (ppb), roughly 2.5 times increase over pre-industrial levels. In fact CO_2 concentrations would be even higher if it were not for large compensating uptake by the terrestrial biosphere and oceans, offsetting more than 50% of anthropogenic CO_2 emissions to date. Increasing CO_2 concentrations and surface temperature have direct carbon cycle feedback effects on the biospheric and oceanic uptake of CO_2; however, the magnitude and range of these feedbacks remain uncertain. Uncertainties in these carbon cycle feedbacks increase the physical uncertainty in climate projections by roughly 50% for any given emissions target, contributing significantly to uncertainty about future climate.

The goal for this science area – the Carbon-Climate System - is to significantly improve our understanding of, and our ability to predict, the likely future trajectory of the atmospheric carbon fraction.

Progress towards this goal is sure to be scientifically challenging, and such progress is of the utmost societal importance.

There is a clear need to better understand and predict future climate change, so that science can more confidently inform climate policy, including adaptation planning and future mitigation strategies. Understanding carbon cycle feedbacks, and the relationship between *emissions* (fossil and land use) and the resulting atmospheric CO_2 *concentrations* in a changing climate has been recognized as an important goal by the IPCC (5^{th} Assessment Report, 2013). To do this, the behavior of anthropogenic carbon sources and natural land and ocean sinks must be quantified (Schimel et al., 1995; U.S. Carbon Cycle Science Plan, ed. Michalak et al., 2011). There are also important uncertainties, both absolute and the relative uncertainties, *in current anthropogenic emissions*, and these uncertainties will likely continue to grow as the proportion of future

anthropogenic emissions shifts to developing countries (Marland et al., 2009; Guan et al., 2012; Andres et al., 2012).

The current *in situ* system of global atmospheric CO_2 and CH_4 measurements does not adequately constrain process-based carbon cycle models to allow diagnosis and/or attribution of the carbon fluxes with any confidence. Carbon cycle processes have high spatial and temporal variability at local scales, but the global climate forcing depends on the spatially- and temporally-integrated impact of these processes. Because of high variability at small spatial and temporal scales, the "scaling-up" of local observations to global scales is difficult, and requires a multi-scale measurement and modeling framework. The areas of largest uncertainty coincide with areas of poor *in situ* coverage and, unfortunately, with intense CO_2 and CH_4 flux (cities, wetlands, tropical forests) or high carbon storage (e.g., tropical and high latitude ecosystems, North Atlantic and Southern oceans). The existing surface greenhouse gas observing networks provide very accurate and precise measurements of background values but they are not configured to target the extended, complex and dynamic regions of the carbon budget.

Consequently, the models yield widely varying spatial and temporal patterns of land and ocean sources and sinks, which is clear evidence that the process level understanding and/or scaling is inadequate. The large differences between current model predictions, and our inability to *adequately* benchmark and test these models against the current suite of available carbon cycle measurements, severely limits their predictive capabilities, and usefulness for detecting important changes or improving our understanding of thresholds in the Earth's carbon cycle. Testing and improving the land-surface and ocean parameterizations in Earth System Models (ESMs) that calculate the surface-atmosphere fluxes of energy, water, and carbon, is essential for developing our capability to predict future climate, but this has proved to be a challenging task.

One way to improve the coverage and resolution of these measurements is to collect high-resolution observations of CO_2 and CH_4 concentrations[1] from space-based measurement platforms. Emerging measurement systems, including the Japanese Greenhouse gases Observing SATellite (GOSAT), the NASA Orbiting Carbon Observatory-2 (OCO-2), and other new sources of data will improve the situation. However, these pioneering missions neither provide the spatial/temporal coverage to answer the key carbon-climate feedback questions at process-relevant scales nor do they address the distribution and quantification of anthropogenic sources at urban scales. They do demonstrate, nevertheless, that a well-planned future system integrating space-based and *in situ* observations and measurements could provide the accuracy, spatial resolution, and coverage needed to address these issues (Ciais et al., 2014).

Enhancing and improving satellite observations of CO_2, CH_4, and CO is necessary to advance our understanding of the carbon cycle, including necessary improvements in process-based models and their ability to predict future atmospheric CO_2 and CH_4 levels.

[1] Specifically column-based average, dry air mole fraction of CO_2 and CH_4, denoted X_{CO2} and X_{CH4}

The goal should be to provide "top-down" estimates of the surface fluxes of CO_2 and CH_4 at 100 km (~1°x1°) monthly scales by combining satellite data with atmospheric inversion models over several annual cycles. For major urban areas, and for estimation of anthropogenic emissions, the flux determinations need to be at spatial scales on the order of 10 km. Measurement of CO would help significantly on the issue of anthropogenic source attribution (fossil fuel and biomass combustion, in particular). These top-down flux products could be directly compared with bottom-up estimates of the fluxes generated from carbon cycle models forced by local environmental and remotely sensed data (see Figure 1) to precisely define the attribution of sinks and sources, and thereby resolve model ambiguities. Independent carbon flux estimates with associated uncertainties will provide rigorous metrics for evaluating anthropogenic, land biosphere and ocean process models; moreover, this process will help us in refining poorly understood model parameterizations and structures, and will improve our predictive capability for the carbon-climate system, supporting both basic geophysical understanding and policy-relevant applications.

In summary, the measurement objectives include:

- *Developing and sustaining a time series of global atmospheric CO_2, CH_4, and CO concentrations with sufficiently small and understood biases at spatial and temporal resolutions that allow rigorous evaluation and improvement of models needed to reduce uncertainty in future predictions/projections.*
- *Improving attribution and quantification of patterns of carbon emissions, thereby reducing the growing uncertainty of anthropogenic emissions of carbon.*
- *Acquiring the critical measurements that allow attribution of fluxes to specific mechanisms and processes within terrestrial and marine carbon cycles. Many of these measurements are expected to be priorities for disciplines such as terrestrial ecosystems, ocean biology, biogeochemistry, and climate.*
- *Addressing how the natural dynamics of the carbon cycle and human activities feedback to influence future trajectory of the atmospheric carbon fraction.*

These measurement objectives need to be taken together; they define what is needed for an integrated and coordinated carbon-observing system. A system that includes a combination of satellite measurements and other remote and *in situ* measurements, together with land, ocean, and atmospheric models and data assimilation systems. Addressing the critical uncertainties in the global carbon cycle requires a coordinated effort rather than the current fragmented approach. Sustaining current observational capacity and improving the spatial and temporal resolution of measurements is essential to understanding how the airborne fractions of CO_2 and CH_4 will evolve; in other words how anthropogenic emissions and carbon cycle feedbacks will continue to affect future climate.

There are several space-borne measurement techniques for observing atmospheric CO_2, CH_4 and CO concentrations that are likely to be available to us during the next decade, but the relative strengths and weaknesses of these techniques have not yet been thoroughly examined. In addition, it is not clear what combination of techniques and platform configurations would yield the best science results for a given resource profile. It is therefore essential to explore the

measurement trade space rigorously prior to any detailed discussions about mission specification, including the potential contributions of surface networks and airborne measurements. This task will require further investment in analyses specifically in conducting a wide array of Observing System Simulation Experiments (OSSEs). The following items, among others, need to be studied:

- The impact of potential future observing systems, including changes to swath, spatial resolution, and revisit regularity and vantage point (e.g., Low Earth Orbit (LEO), GEostationary Orbit (GEO), Highly Elliptical Orbit (HEO)) on the scale and frequency of resolvable fluxes.
- The impact of using advanced technologies (e.g., active and/or multichannel systems) to improve resolution of the lower atmosphere concentrations, particularly the Planetary Boundary Layer (PBL), and to provide night-time and high-latitude (low illumination) observations, and reduce bias.
- The utility of high resolution observations to quantify strong sources, including megacities, power infrastructure and wildfires, contrasting orbital vantage points and their associated revisit frequencies and spatial resolutions.
- The potential for combined systems, where passive imaging sensors and active systems are mounted on the same spacecraft, to obtain wide-area coverage enhanced with localized calibration, vertical resolution and bias correction.
- Finally, the combination of satellite sensors that best complements existing and planned long-term ground- and aircraft-based greenhouse gas observing systems.

We note that there are certain key Earth System properties that cannot be observed from space with any known technology, but are critical and synergistic with the space-based program, beyond basic calibration/validation requirements (Schimel et al., 2015a). We highlight a few of these below, such as the ARGO floats characterizing the interior oceans, terrestrial and airborne eddy-covariance observations, expanded surface-based measurements of CO_2 and CH_4 concentrations, and soil measurements. While this report does not set forth a program for these types of observational networks specifically, we highlight their contribution for future studies.

Observing the Global Carbon Cycle

Currently, the anthropogenic combustion of fossil fuels is releasing 10 billion metric tons of carbon per year (or Gigatons of carbon as CO_2 per year or GtC/yr) while land use change is adding an additional 1 GtC/yr to the atmosphere. Respiration by terrestrial vegetation and soil adds approximately 120 GtC/yr to the atmosphere (IPCC AR5, 2013). However, photosynthesis balances respiration, removing a nearly equal amount of CO_2 from the atmosphere, along with about one quarter of the anthropogenic CO_2 emissions. Similarly, the oceans emit nearly 80 GtC/yr (IPCC AR5, 2013) and reabsorb this amount plus another quarter of the anthropogenic emissions. On average, this results in slightly less than 50% of anthropogenic CO_2 emissions staying in the atmosphere, leading to a contemporary global CO_2 growth rate of ~2 ppm/yr ($\pm$ 0.1 ppm/yr).

Global emissions of CO_2 from fossil fuel combustion (and cement manufacture) currently have an uncertainty of ~10%. The uncertainty on fossil-fuel emission from many developed countries is typically less than 5%, while the uncertainty on fossil-fuel emissions from recently developed countries (such as China, India, Brazil and Russia) is 10-20%; whereas, in much of the developing world the larger uncertainties are offset by the emissions being smaller (Marland et al., 2009; Guan et al., 2012; Andres et al., 2012). As the fraction of global emissions originating from rapidly expanding and newly developed economies, as well as from lesser-developed nations, has grown, so has the uncertainty in global fossil fuel emissions. A major reason for reducing this uncertainty is that it propagates through the inferred fluxes in atmospheric inversion calculations (see again Figure 1). At sub-national scales, the consequences of such uncertainty on inflow into the domain of interest can have a critical impact on the estimates of local emissions and uptake.

Along with CO_2, quantifying the emissions of CH_4 is critical for projecting and mitigating changes to climate. After a period of rapid increase in the 1980's, atmospheric CH_4 concentrations stabilized for almost a decade between the mid-1990s and the mid-2000s (Kai et al., 2011), and have begun to increase rapidly since 2007 (Rigby et al., 2008; Dlugokencky et al. 2009; Nisbet et al., 2014). Wetland emissions represent the largest and most uncertain natural source of CH_4, with published estimates ranging from 140 to 280 million tons CH_4 per year (Bloom et al., 2010; Kirschke et al., 2013). Emissions from other, smaller sources, such as termites, permafrost, and freshwaters are documented by only a handful of studies. Anthropogenic sources including wet (rice paddy) agriculture, biomass burning, and CH_4 leaks from the coal, oil and gas extraction and transport, landfills, waste-water processing, are also poorly known. At present, they are mainly estimated from statistical data on energy use and emission factors, both of which vary greatly. These and other human activities have multiplied the atmospheric CH_4 concentration by nearly 2.5 since the beginning of the industrial age. Our inability to explain current trends or allocate them to anthropogenic versus natural causes is one of the main rationales for continuously measuring methane at high-resolution and with high precision.

Atmospheric inversions can provide carbon flux estimates over large areas (the "top-down" approach), but reflect complex physical and biological processes that can only be understood using the "bottom-up" approach (see Figure 1). The basic premise of the top-down or inverse modeling approach is that using a set of atmospheric CO_2 and CH_4 observations along with an atmospheric transport model, it is possible to infer information on the distribution of fluxes of CO_2 and CH_4 at the Earth's surface (e.g., Enting, 2002). The bottom-up approach takes advantage of scientific understanding of plant physiology, ocean dynamics and other biogeochemical processes associated with the carbon cycle. Because the bottom-up modeling can capture process information, reconciliation of the two approaches offers the potential to advance understanding of the underlying processes and their parameterizations in ESMs) and enable fundamental advances and increases in predictive capacity (Schimel et al., 2015b). Recognizing the merit of such activities, recently community-wide inter-comparison efforts are being

undertaken as part of the REgional Carbon Cycle Assessment and Processes (Canadell et al., 2012-2014) project. Results from these studies highlight that reconciling the carbon flux estimates not only minimizes the uncertainty within each approach but also increases confidence in the results from these approaches.

For methane, the primary uncertainty is the source fluxes as sketched above. For carbon dioxide it is both the sources and the sinks; as noted at the outset, CO_2 concentrations would be even higher if it were not for large compensating uptakes by the terrestrial biosphere and the oceans.

Ocean carbon uptake is a critical feedback to atmospheric CO_2, responding to both changing concentrations and climate. Carbon fluxes between the ocean and atmosphere are regulated primarily by the gradient between atmospheric and oceanic pCO_2. Ocean pCO_2 is set primarily by circulation and two main oceanic processes: the solubility and the biological pumps. The solubility pump is the largest regulator, and is directly affected by changes in physical circulation, surface winds and stratification of the water column. Increasing temperatures and dissolved inorganic carbon (DIC) concentrations in oceanic surface waters are expected to decrease the efficiency of the solubility pump thereby slowing down the uptake of atmospheric CO_2. Satellite measurements of physical ocean variables are essential to computing CO_2 exchange, but chemical and biological measurements made *in situ* are also required, and increasingly come from the ARGO floats, autonomous drifting buoys with multiple sensors. ARGO floats with pCO_2 sensors are currently under development and will provide an additional constraint on the net ocean flux (Fiedler et al., 2013). Measurements of pCO_2 from ships and CO_2 fluxes from eddy covariance towers are important for validation of ocean fluxes as inferred from atmospheric concentration measurements using transport models.

The biological pump also affects pCO_2 and hence plays a role in the carbon fluxes. Phytoplankton absorb carbon dioxide during photosynthesis, which converts inorganic carbon into organic carbon. The phytoplankton concentration therefore directly affects the biological pump by absorbing CO_2 and potentially sinking it into the deep oceans. Current and planned measurements of ocean color, a proxy for phytoplankton concentration, provide a good constraint on phytoplankton productivity as well as other key ocean processes. Coastal-zone carbon fluxes are poorly quantified and mechanistic understanding is limited, but current estimates suggest that they may represent 25% of the total ocean CO_2 absorption (Landschützer et al., 2014, Laruelle et al., 2014). It is reasonable to expect that future climate and land-use changes could significantly impact these fluxes.

The terrestrial biosphere plays a major role in moderating atmospheric CO_2 increase; however again we lack the observational coverage needed to determine the spatial and temporal patterns of land-atmosphere carbon exchange on global scales: observations of carbon uptake, losses, and associated changes in stocks in the terrestrial biosphere are all critically needed for assessing the current status of the coupled carbon-climate system. *In situ* observation networks have provided valuable insight into these processes, but sampling is at its most sparse where feedbacks are anticipated to be strongest, in particular the Arctic-Boreal Zone and Tropics.

Gross uptake of carbon by photosynthesis ("gross primary production" or GPP) is a primary driver of the carbon cycle and a major point of interaction with climate change. Carbon loss through respiration from plants and microbes, together with uptake via GPP defines the carbon balance of an undisturbed ecosystem. Respiration is perhaps the least well understood of the terrestrial biological fluxes. Improved direct estimates of GPP from satellite measurements, coupled with measurements of Net Ecosystem Exchange (NEE) or Production (NEP) inferred from satellite-derived X_{CO2}, will provide a key constraint on model formulations of respiration. A potentially effective approach for separating GPP from respiration is through a strategically coordinated suite of measurements of solar-induced chlorophyll fluorescence plus chlorophyll concentration, possibly complemented with photochemical reflectance index measurements.

Biomass measurements provide a long-term integral constraint on land carbon fluxes. Repeated measurements of biomass provide a decadal scale constraint on land-atmosphere models. Contemporary (e.g. ALOS-PALSAR, NISAR) and planned (e.g., GEDI, BIOMASS) missions provide measurements of carbon stocks in the current era over largely tropical regions. Repeat measurements on a five- to ten-year cycle, and with coverage at all latitudes, could monitor disturbance and land-use impacts (Schimel et al., 2015a), provide information about the response of terrestrial biomass to climate change and increasing atmospheric CO_2, and disentangle the impacts of climate and direct CO_2 effect.

While the land biosphere is currently a net sink for CO_2, it is a net source of CH_4. Methane fluxes arise from fossil fuel production and distribution, agriculture, wetlands, and fire. The contributions of each of these are poorly understood and consequently ecosystem process models show very little agreement in their estimates of CH_4 fluxes (Melton et al., 2013). While process models will continue to rely on bottom-up parameterizations based on inventories and fire emission data, existing remote sensing products such as soil moisture, inundation by surface water, gravity anomalies and land use, provide an opportunity to refine model estimates of CH_4 emissions. A step-change in understanding could be obtained by collecting new, systematic atmospheric measurements of CH_4 concentrations.

The atmosphere has a central and integrating role in the global carbon cycle as the primary medium for carbon exchange between the larger land and ocean carbon reservoirs, and this role, as noted earlier, implies that atmospheric measurements of X_{CO2} and X_{CH4} can constrain CO_2 and CH_4 flux calculations. Consequently, having robust techniques for incorporating these observations into carbon cycle data assimilation frameworks is essential for connecting top-down flux estimates to improvements in the structure and parameterizations of process-based models.

Measurements of X_{CO2} and X_{CH4} can be retrieved from high-resolution spectroscopic observations of reflected sunlight in near infrared CO_2 and CH_4 bands by dividing by the total column of air that is similarly obtained from O_2 measurements. Space-based remote sensing observations of these gases are challenging because these gases are so long-lived that even strong sources or sinks produce changes of small magnitude relative to the background concentrations. Consequently, for these measurements to be useful for deriving information about surface fluxes, they need to be made with a very high precision and high accuracy (or low biases). GOSAT for

X_{CO2} and X_{CH4} and OCO-2 for X_{CO2} have pioneered this capability, but a much denser grid of observations is needed to retrieve estimates of surface fluxes at the desired spatial and temporal resolution (100 km. or ~1°x1°, and monthly).

An important ancillary space measurement would be carbon monoxide (CO), which helps to separate emissions from various combustion sources and other processes such as biospheric respiration. *In situ* studies of CO/CO_2 ratios from different types of burning (liquid, gas or solid fossil fuels or biomass) show promise in disentangling emissions from different sectors. When the atmospheric CO_2 information is combined with the information from CO as an additional trace gas species significant improvement in CO_2 surface flux attribution can be obtained (Wang et al., 2009). Furthermore, tropospheric CO eventually oxidizes to CO_2, a chemical source of CO_2 that is inadequately dealt with in most carbon budgets, and is a factor in the detailed 3D spatial distribution of CO_2 (Nassar et al., 2010).

The need now is for an extensive set of Observing System Simulation Experiments (OSSEs) to best define an observing strategy for X_{CO2}, X_{CH4}, and X_{CO}.

The relative values of a number of measurement strategies should be explored via OSSEs. Such investigations can provide quantitative assessments of the information needed to adequately estimate the quantity of interest (say global distributions of surface fluxes), taking into consideration a number of likely errors (including ranges of measurement uncertainty and transport uncertainty). It is likely that a carefully selected combination of CO_2, CH_4 and CO measurements from both LEO and GEO missions may be needed since they observe complementary time and space scales.

Only LEO can give global sampling with a single mission. CarbonSat (an ESA Earth Explorer 8 candidate mission to launch no earlier than 2022, Bovensmann et al., 2010) could contribute importantly to meeting the LEO requirements for CO_2 and CH_4, if selected (see also CEOS Strategy for Carbon Observations from Space, 2014). Active LEO systems offer significant advantages in terms of vertical information, reduced bias and low-illumination coverage, especially over high-latitudes.[2]

GEO platforms provide complementary information over large but fixed regions, allowing fluxes to be determined on shorter time scales and over finer spatial scales and providing detail not available from the LEO vantage point. A constellation of GEO platforms could provide passive observations at higher frequency over all land between ~55ºS and 55ºN latitudes.

The oceanic, terrestrial and atmospheric considerations stated above assume the continuation of a wide range of ancillary and supporting measurements for calibration/validation and retrieval algorithm development activities. For example, *in situ* vertical profiles of trace gases are required to calibrate ground-based remote sensing sites to the WMO CO_2, CH_4 and CO scales used in the surface networks, which enables calibration of the space-based measurements according to the same absolute scale. Cross-calibration between planned domestic and international missions will ensure high quality, complementary and consistent data records of atmospheric carbon species.

[2] e.g., http://cce.nasa.gov/ascends_2015/ASCENDS_FinalDraft_4_27_15.pdf

Refinements to existing retrieval algorithms need to focus on improvement of CO_2, CH_4 and CO spectroscopy and treatment of clouds, aerosols and other sources of bias. Along with the above, continuation of existing *in situ* observational data streams is needed to provide a long-term stable context to interpret the space-based measurements of greenhouse gases. These improve the accuracy and range of validity of remote sensing retrieval algorithms and facilitate the attribution of the estimated fluxes to specific natural and anthropogenic processes.

Alongside improved measurements of atmospheric carbon fraction, vigorous model advancement, benchmarking, and inter-comparison activities need to be continued and expanded. For example, a larger sustained, community-wide effort continues to be necessary to improve atmospheric transport modeling capabilities, for example improving the vertical mixing, terrain effects, and our understanding of the diurnal cycle. Coordination with ongoing and planned air quality observations may help capture some of the high-resolution transport features: in fact integrating air quality with carbon cycle science can advance both areas. Continuing advances in prototyping a diverse set of carbon monitoring system algorithms and models through NASA-CMS and other efforts will also be critical (Hurtt et al., 2014). Such improved integration and coordination of interdisciplinary observation and modeling tools are critical for meeting the overarching science priorities laid out earlier.

Conclusions

There is an urgent need to better understand and predict the future role of the carbon cycle in the climate system. Changes in the global pattern of sinks and sources of CO_2 and CH_4 will directly affect future climate through the time-trajectory of the airborne carbon fraction. This understanding is needed to more confidently inform climate policy and guide future adaptation and mitigation strategies. Developing this knowledge requires integration of observations and models for the land, ocean and atmosphere, with multiple observing platforms and modeling frameworks.

The goal for this science area – the Carbon-Climate System - is to significantly improve our understanding of, and our ability to predict, the likely future trajectory of the atmospheric carbon fraction.

While the spread between current model predictions of future CO_2 fluxes and concentrations provides an estimate of carbon cycle uncertainties, our inability to adequately benchmark and test these models against measurements, limits our ability to meaningfully reduce uncertainty among the models and/or improve them. This further limits our ability to detect and attribute abrupt changes or thresholds that might emerge: such as regime or ecotone shifts are either not included or are misrepresented in current models.

Pioneering missions (such as GOSAT and OCO-2) are laying the groundwork for understanding the carbon cycle in an integrated unified way, but they offer neither the duration nor the spatio-temporal resolution that are essential to inform understanding of the processes relevant to surface fluxes and to answer the key carbon-climate feedback questions.

To confront and improve model parameterizations and reduce uncertainty in future climate projections, regional scale flux estimates of CO_2 and CH_4, at monthly time-scales and spatial scales of roughly 100 km (~1°x1°), with global coverage and over multiple annual cycles are critical. For major urban areas, and for estimation of anthropogenic emissions, the flux determinations need to be at spatial scales on the order of 10 km.

A coordinated observing system will require a suite of different types of measurements (multiple satellites, aircraft, ground-based *in situ* and remote sensing) and different types of model systems, linked together in a variety of ways. The system should be built around four measurement objectives:

- *Developing and sustaining a time series of global atmospheric CO_2, CH_4, and CO concentrations with sufficiently small and understood biases at spatial and temporal resolutions that allow rigorous evaluation and improvement of models needed to reduce uncertainty in future predictions/projections.*
- *Improving attribution and quantification of patterns of carbon emissions, thereby reducing the growing uncertainty of anthropogenic emissions of carbon.*
- *Acquiring the critical measurements that allow attribution of fluxes to specific mechanisms and processes within terrestrial and marine carbon cycles. Many of these measurements are expected to be priorities for disciplines such as terrestrial ecosystems, ocean biology, biogeochemistry, and climate.*
- *Addressing how the natural dynamics of the carbon cycle and human activities feedback to influence future trajectory of the atmospheric carbon fraction.*

An integrated and coordinated approach is needed. Specification of the optimal, most cost-effective satellite observing configuration will require significant investments in modeling analyses, principally OSSEs, to determine the best mix of observing system vantage points, sensor technologies, and *in situ* networks. Addressing the critical uncertainties in the global carbon cycle will require a coordinated observation effort over the land, atmosphere, ocean and anthropogenic domains, together with coupled carbon-climate models and data assimilation systems.

FIGURE 1

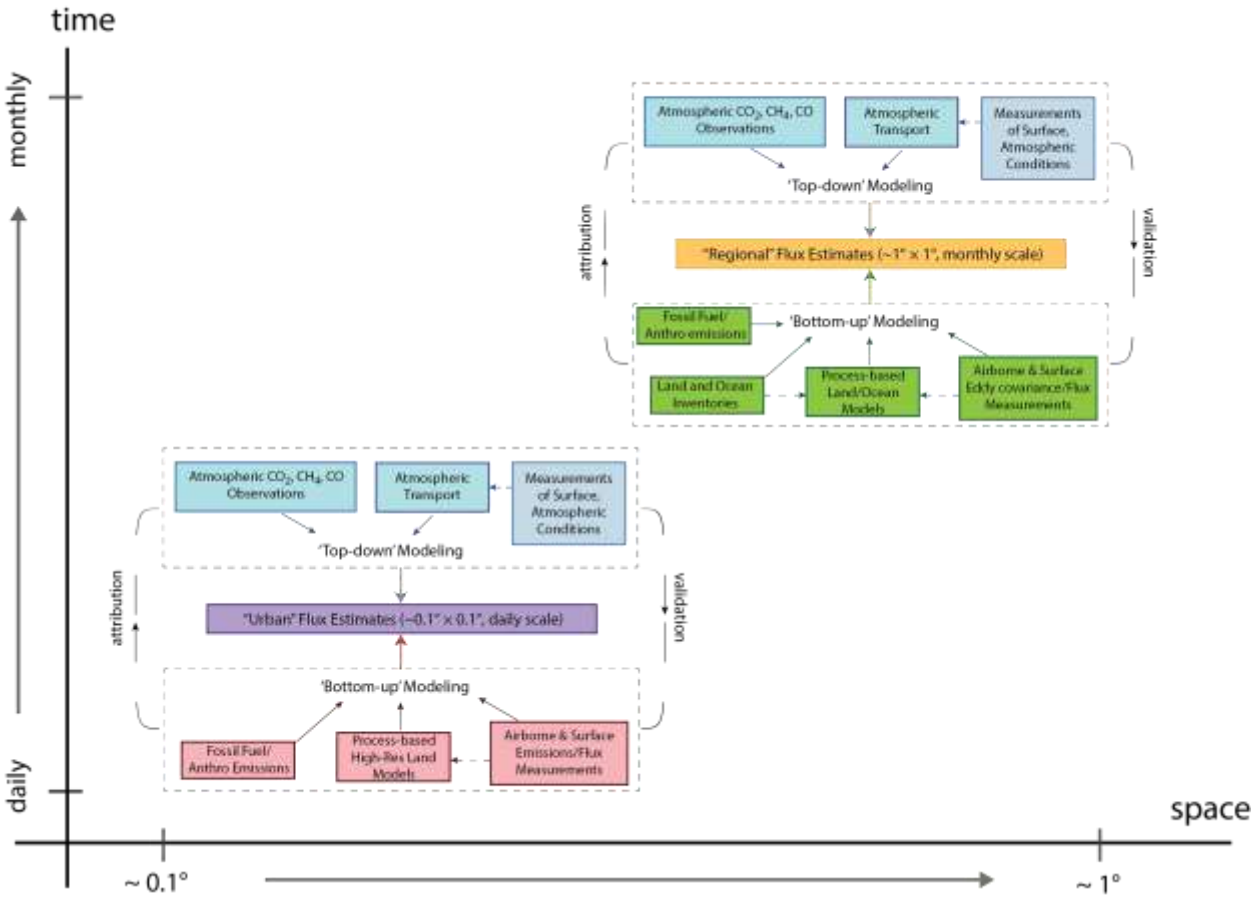

Figure 1. Estimates of surface carbon fluxes can be inferred via two main approaches - "bottom-up" (based on measurements in the land or ocean components, and process-based models) and "top-down" (based on measurements in the atmosphere). Being able to reconcile the estimates from these two approaches and combine them in an integrated framework allows for validation, attribution and prediction. Shown here are the desired estimation scales for obtaining the surface carbon fluxes – one focused on regional fluxes and another focused on urban anthropogenic emissions at finer spatial and temporal scales. For the urban flux estimates, we err on the side of parsimony and ignore some processes (e.g. coastal ocean fluxes) due to their small magnitude relative to the local anthropogenic emissions.

Table of abbreviations

ALOS	Advanced Land Observing Satellite
AOD	Aerosol Optical Depth
ASCENDS	Active Sensing of CO_2 Emissions over Nights, Days, and Seasons
CDOM	Colored Dissolved Organic Matter
CEOS	Committee of Earth Observation Satellites
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DIC	Dissolved Inorganic Carbon
DMS	Dimethyl Sulfide
ESM	Earth System Models
GEDI	Global Ecosystem Dynamics Investigation Lidar
GEO	Geostationary Orbit
GOSAT	Greenhouse gases Observing SATellite
GPP	Gross Primary Production
H_2S	Hydrogen Sulfide
HEO	Highly Elliptical Orbit
IPCC	Intergovernmental Panel on Climate Change
ISRO	Indian Space Research Organization
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
NISAR	NASA-ISRO Synthetic Aperture Radar

NO_2	Nitrogen Dioxide
NRC	National Research Council
O_2	Oxygen
O_3	Ozone
OCO-2	Orbiting Carbon Observatory-2
OCS	Carbonyl Sulfide
PALSAR	Phased Array L-band Synthetic Aperture Radar (Japan)
PAR	Photosynthetic Active Radiation
pCO_2	Partial pressure of carbon dioxide
PIC	Particulate Inorganic Carbon
ppb	Parts per billion
ppm	Part per million
SF_6	Sulfur hexafluoride
SOCCOM	Southern Ocean Carbon and Climate Observations and Modeling
TCCON	Total Carbon Column Observing Network
TECLUB	Terrestrial Ecology, Carbon Cycle, Land Use and Biodiversity
WMO	World Meteorological Organization
X_{CH4}	Column-averaged CH_4 dry-air mixing ratio (dry air mole fraction)
X_{CO2}	Column-averaged CO_2 dry-air mixing ratio (dry air mole fraction)

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