A “Pre-Decadal Survey” Workshop: The Carbon-Climate System

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The Grand Challenge

The concentration of CO_2 in the planet’s atmosphere is now greater than 400 parts per million, an increase of more than 40% over the preindustrial value. Clearly, the need to understand future climate change, and thereby inform policy, is urgent. A central challenge is to understand how fossil fuel emissions will affect future climate, and this means that we must know how the airborne fraction of CO_2 will evolve. This requires knowledge of the behavior of anthropogenic carbon sources and natural land and ocean sinks. Developing this knowledge requires intellectual integration across land, ocean and atmospheric science, and integration of observations of multiple Earth System variables from multiple satellite missions and other sources.

Currently, the uncertainty in carbon cycle feedbacks roughly doubles the physical uncertainty in climate for any given climate target. Quantifying this feedback has been an important goal of CMIP5 and the AR5, and global observations are urgently needed to reduce model-derived uncertainty.

In addition, while current model ensembles provide a rough estimate of uncertainty, the inability to benchmark these models against directly relevant carbon measurements limits our ability to identify specific process failure or detect regions of growing model-data misfit indicative of imminent system change. This means our current knowledge is of limited use in identifying regions where abrupt changes or thresholds, not included in current models, may exist. Currently model performance is so uneven that errors in model skill are not informative, and data sets are so sparse we are often unable to diagnose systematic failure in any case.

Carbon cycle processes vary at high frequency in time and space, but the climate responds to the global atmospheric integral. Because of the high variability at small spatial and temporal scales, the ‘scaling-up” of local observations to global scales is difficult. Scientifically grounding local processes within a consistent global system is essential; therefore, making global observations is central to building and testing models; it is the “acid test”. Currently knowledge points to high sensitivity in areas of intense carbon sources (cities, tropical forests) or high carbon storage and exchange (e.g., tropical and high latitude ecosystems, Southern ocean), although others may exist.

Carbon science and the Decadal Survey

Remote sensing has always played a central role in carbon science, from early efforts exploiting the NDVI and ocean color to explain the season and spatial variations in atmospheric CO_2, the pioneering quantification of deforestation fluxes using LANDSAT to today's measurements of CO_2 itself from GOSAT and from OCO-2, following its successful launch on 1 July 2014.

NASA is uniquely poised to address the problem of integration, as a result of its global observing perspective, and accompanying Earth System models. The impacts of regional centers of action on atmospheric carbon concentration can only be understood in the context of the coupled global system, because of the way in which terrestrial and marine uptake respond to atmospheric CO_2 concentration, and this requires the global perspective the orbital vantage point provides.

Existing and new NASA missions will provide a global perspective on the carbon cycle, and key climate controls over its dynamics, including those linked to climate and the water cycle, the oceans, land use/land cover change, and human activities. Much carbon science is aligned with the traditional disciplines (land, atmosphere, oceans, human dimensions) or with specific missions; however, building upon the noted global perspective and the Earth System models there is great opportunity for expanded cross-disciplinary and cross-mission integration.

During the time period spanned by the next Decadal Survey, it will be essential for the community to:

- *Understand and Quantify the relationship between future fossil and land use emissions and resulting atmospheric concentrations by providing global observational constraints on the forcing and responses (feedbacks) of terrestrial and marine carbon cycle fluxes.*

NASA's existing program elements support this essential quantification, and include spaceborne missions, airborne systems, models, and science R&A and science applications. However, this goal requires close coordination and scientific integration between terrestrial, atmospheric, oceanic and human dimensions research.

This NASA foundation is essential. Carbon science relies on a wide variety of observations, both direct and ancillary. These include measurements of carbon in the atmosphere, ecosystem processes on land and in the ocean, carbon stocks (biomass), and key controls such as ocean circulation and sea surface temperature, light interception, soil moisture and air temperature. While the fossil+land use/land cover change, atmospheric, terrestrial and ocean communities conduct separate research, these communities also collaborate to produce global assessments such as the Global Carbon Project and Earth System models used in CMIP5 and now CMIP6.

We propose to bring these communities together in a Workshop, with participation from the Earth System Modeling community to review the current status and future requirements for global carbon cycle observations from space. These communities have always collaborated to address global carbon issues, but their collaboration will become increasingly close as the various domain-based estimates are increasingly knitted together through the spatially and temporally resolved concentration measurements provided by OCO-2 and GOSAT 1&2.

The workshop will not seek to identify mission concepts *per se*, and, in fact, we will ask the participants to “check their mission concepts at the door” rather, we will focus on science, observations and requirements that will help guide priorities for the upcoming decadal survey, and provide science targets that technology and hardware providers may use as guidance in developing mission concepts.

Workshop structure

The workshop will assemble teams from five groups, with the group balanced between modelers and observationalists:

- Earth system modeling: scientists involved in the development, application and analysis of coupled carbon-climate models.
- Atmospheric carbon dynamics: scientists involved in data collection, analysis and inverse modeling of atmospheric CO_2 and other constituents.
- Terrestrial ecosystems (including aquatic): researchers focusing on terrestrial carbon stocks and fluxes, and climate, land use, land management, nutrient and other controls over those stocks and fluxes.
- Ocean science: researchers focused on ocean carbon stocks and fluxes, controls over air-sea exchange and impacts on marine communities, including through acidification.
- Human systems: researchers focused on the estimation of fossil, cement and other direct anthropogenic fluxes, and their impacts on, and responses to changes in the environment.

These groups will not meet separately, but will rather work together to **identify three types of information**:

- Key ongoing and emerging science questions that frame carbon science for the decade and beyond. This includes both fundamental Earth System science and unknowns in the application of carbon science to societal benefit areas.
- Critical measurements required to address these questions in the atmosphere-land-ocean-human coupled system, including synergistic spaceborne and *in situ* measurements.

- Top-level requirements for these measurements. For example, the requirements for accuracy, precision, frequency and coverage often depend on the question motivating the observation.

The groups will meet in plenary. Initial presentations will level the playing field so that all participants are briefed on the current issues and unknowns across the science areas. Some background on current, planned and potential technology will be presented. After the minimal number of overview presentations, the group will focus on the three information-topics above with the goal of producing the three deliverables.

Deliverables

1) A short forum article for Science magazine on carbon cycle uncertainties and opportunities to reduce policy-relevant science uncertainties (carbon-climate feedbacks, precision of monitoring mitigation activity). This will be written by a writing team during the workshop
2) A longer article reviewing key science questions and current and future observing system requirements for BAMS, Frontiers in Ecology and the Environment or equivalent. The key ideas and content for this will be largely developed during the workshop.
3) Peer-reviewed papers summarizing key science uncertainties, modeling issues and emerging observational constraints. These may be integrative, or partially integrative but more tailored to specific disciplines. If discipline-oriented the papers will also address the impact of uncertainty in one domain on analyses in the others. Writing teams for these will be identified and leader's commitment secured at the workshop.