Carbon and Climate

A response to the Request for Information from the Carbon and Climate workshop, Norman, Oklahoma
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David Schimel, Jet Propulsion Lab, California Institute of Technology
Piers Sellers, Goddard Space Flight Center
Berrien Moore III, University of Oklahoma
Norman Carbon and Climate Workshop Participants[1]
Full report: http://cce.nasa.gov/cce/pdfs/final_carbon_climate.pdf

1. ***What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?***

Changes in atmospheric radiative forcing arising from greenhouse gas emissions will be the most important driver of climate change in this century. 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) above a 280 ppm pre-industrial background and is growing at a rate of ~2 ppm/yr (± 0.1 ppm/yr). Similarly, CH_4 emissions have accelerated since 2007 and its concentration now exceeds 1800 parts per billion (ppb), roughly 2.5 times higher than pre-industrial levels. CO_2 concentrations would be dramatically higher, as would rates of climate change **if it were not for large compensating uptake by the terrestrial biosphere and oceans, offsetting more than 50% of anthropogenic CO_2 emissions per year (Figure 1).** This fraction, the atmospheric carbon fraction, or the percentage of fossil and deforestation emissions that remain in the atmosphere, defines the climate impact of any given level of GHG emission. Understanding how changes to emissions affect atmospheric concentrations and hence climate, and how the emission-concentration-climate relationship may change in the future, is a central grand challenge for Earth System Science.

Fate of Anthropogenic CO_2 Emissions (2004-2013 average)

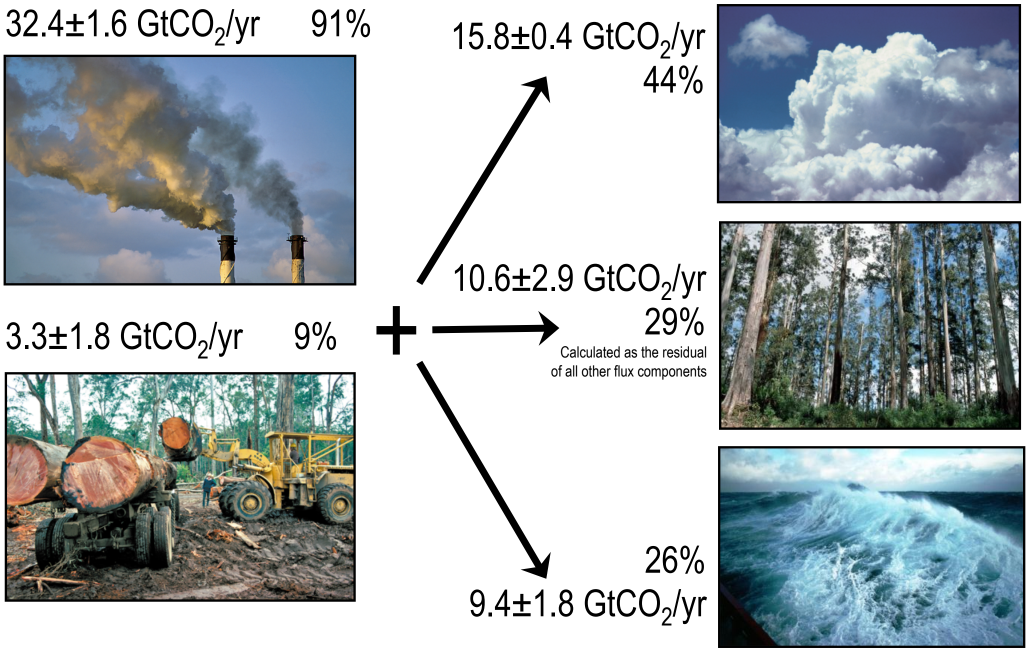

Figure 1: Carbon cycle feedbacks determine the "atmospheric carbon fraction" and climate-caused changes to CH_4 fluxes, and together affect the climate impact of human emissions. Source: Global Carbon Project (2014). More information, data sources and data files at http://www.globalcarbonproject.org/carbonbudget/.

In order to detect changes to carbon-climate feedbacks, and attribute them to specific regions and processes, estimates of the surface fluxes of CO_2 and CH_4 targeting 100 km (~1°x1°) and monthly scales are needed. Globally, "top-down" flux estimates are obtained by combining satellite data with atmospheric inversion models. For major urban and land use land cover change (LULCC) areas, and to reduce growing uncertainty in estimation of anthropogenic emissions, flux determinations need to be at spatial scales on the order of 10 km. Measurement of CO is required for anthropogenic source attribution (fossil fuel and biomass combustion). Flux estimates with associated uncertainties will provide rigorous metrics for evaluating anthropogenic, land biosphere and ocean process models; moreover, this evaluation process will help us refine and assess 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 for addressing the outstanding questions concerning carbon-climate science include:

- *Developing and sustaining a space-based time series of global atmospheric CO_2, CH_4, and CO concentrations 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 the critical diagnostic measurements such as productivity, biomass, the water cycle, and ecosystem composition are priorities for disciplines such as terrestrial ecosystems, ocean biology and biogeochemistry, and climate.*
- *Modeling and data assimilation of atmospheric composition at appropriate resolution within the context of the Earth System is required to bring all of these threads together to understand the carbon cycle as a whole.*
- *Addressing how the natural dynamics of the carbon cycle and human activities feedback to influence future trajectory of the atmospheric carbon fraction.*

2. ***Why are these challenge/questions timely to address now especially with respect to readiness?***

Global measurements of trace gases in the atmosphere are required to estimate fluxes of these globally and constrain models of feedbacks. Measurements of total column CO_2 and CH_4 (referred to as 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 or surface pressure 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 small changes (~ +/- 1% for CO_2) 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 measurements of X_{CO2} and X_{CH4} and OCO-2 measurements of X_{CO2} have pioneered this capability, demonstrating readiness and establishing the basis for the required decadal, sustained observations needed to diagnose feedbacks in the carbon system, particularly against the background of significant year-to-year variability.

There are several space-borne measurement techniques for observing atmospheric CO_2, CH_4 and CO concentrations likely to be available to us during the next decade, but the strengths and weaknesses of these techniques have not 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 contributions of surface and airborne in situ measurement networks. This task will require investment in conducting a wide array of Observing System Simulation Experiments (OSSEs).

3. ***Why are space-based observations fundamental to addressing these challenges/questions?***

Gaps exist in our observations of the terrestrial and marine carbon cycles, resulting from sparse *in situ* sampling of high flux and high storage regions. New space-based observations can strongly complement *in situ* observations in providing required quantitative ecosystem and anthropogenic information globally. In situ atmospheric sampling is sparse in the highest flux and biomass regions of the world. Networks or data sets assembled post-hoc will almost always contain sampling biases that will limit, or at least influence the inferences that may be drawn. *In situ* studies in critical regions, such as the Southern Ocean, tropics and Arctic-Boreal Zone (ABZ) face serious challenges. Installing carbon flux towers is expensive and may be in conflict with conservation objectives in intact forest. The darkness and rough seas of the Southern Ocean, incessant biological activity of tropical plants and animals and mechanical effects of ABZ temperatures, freezing and wind create severe operational constraints.

While spaceborne measurements have uncertainty and errors of their own, only they provide global estimates of fluxes and key controls at the required time and space resolutions. In addition, space-borne measurements are probably the only way forward to obtain required data in large and critical regions of the world.

- ***Do existing and planned U.S. and international programs provide the capabilities necessary to make substantial progress on the identified challenge and associated questions. If not, what additional investments are needed?***

Today's XCO_2 measurements provide a necessary but not sufficient basis for understanding carbon and climate. The long time scales of terrestrial and ocean carbon processes generate a need for sustained observations for at least a decade or more, especially given high variability on the ENSO time scale. In fact, techniques that rely on variability to estimate sensitivity to climate require a relatively long time series and ideally several ENSO cycles. Thus, new investments should sustain time series through the 2020s, while working towards the capability to estimate fluxes at the targeted $\sim 1^{o}$ and 1 month resolutions. The long time scales of the carbon system require continuity of the critical CO_2 data record; attributing to fluxes to underlying mechanisms requires transformational advances in spatio-temporal sample density for CO_2, CH_4 and CO measurements from space

- ***How will space-based observations be linked with other observations to increase the value of data for addressing key scientific questions and societal needs;***

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 (Figure 2). These include ARGO floats and ship-based hydrography that, together, can monitor changes in the interior oceans, terrestrial and airborne eddy-covariance observations, expanded surface-based measurements of CO_2 and CH_4 concentrations, measurements of low abundance process tracers like $^{14}CO_2$ (fossil fuels) and COS (plant productivity) and soil carbon sticks and fluxes. Using remote sensing for key properties of the biosphere may allow redirection of *in situ* emphasis to equally-important measurements and experiments, on soil properties, microbial processes, genomics, and trophic processes that cannot be sensed remotely and that are equally important to prediction. This may be particularly important at high latitudes where soil processes dominate potential tipping element processes. Coordination of *in situ* and remote observations is critical for calibration and validation.

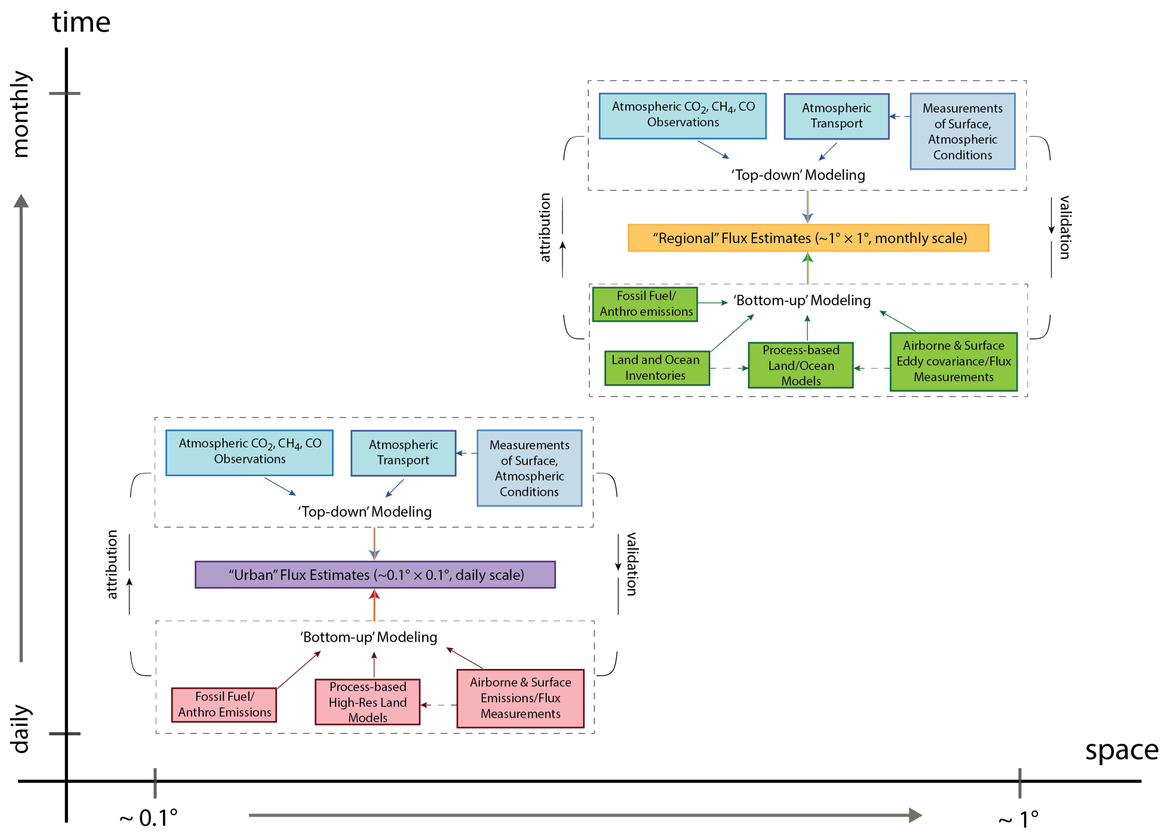

Figure 2: Conceptual approach for integrating surface and spaceborne measurements to detect and attribute fluxes to mechanisms in regional (biosphere and ocean) and high resolution (urban or similarly, land use change) cases, together the required scales of resolution. Data integration can lead to the knowledge products required for effective use to address societal benefit areas.

Finally, even with effective investment in a space-based program, certain issues remain very challenging. Gradients of CO_2 in the southern hemisphere are so gradual that current anticipated active and passive technologies cannot resolve them. The high latitude winter, increasingly critical with warming temperatures, is invisible to passive sensors, which are limited to the sunlit portion of the year, although active sensors may work there. Critical regions of the world are so cloudy that a single LEO sensor—based on the MODIS experience—may not obtain sufficient data to meet the 1^{o} target.

- ***The science communities that would be involved.***

As Peter Tans famously said "The carbon cycle is one" but research programs on the carbon cycle have historically been many, with land, atmosphere, ocean, fossil, policy and management components, supported by diverse programs within NASA NOAA, the USGS and at many other agencies. Since the atmosphere integrates all of these components, sensors like OCO-2 produce data that together with integrated, Earth-system modeling and data assimilation systems will serve to bring these diverse activities back together. Studying carbon and climate, and translating that information for policy and management requires as much interdisciplinary collaboration as any topic tackled by the Earth Sciences, and requires participation from outside the Earth Sciences, for example on energy production and use. At the heart of carbon science is the collaboration between atmospheric scientists, ecologists, oceanographers, energy analysts and human geographers studying land use and deforestation. The carbon science community is enabled by integrative data and systems (such as NASA's Carbon Monitoring System and the Global Modeling and Assimilation Office) to increasingly function as "one" and the structure and outcomes of the Decadal Survey can enhance this.

1) Norman Participants:
David Baker, Colorado State University
Joe Berry, Carnegie Institution for Science
Kevin Bowman, NASA, JPL
Abhishek Chatterjee, NASA, GSFC
David Crisp, NASA, JPL
Sean Crowell, University of Oklahoma
Scott Denning, Colorado State University
Riley Duren, NASA, JPL
Michelle Geirach, NASA, JPL
Kevin Gurney, Arizona State University
Kathy Hibbard, NASA, TE
Richard A. Houghton, Woods Hole Research Ctr.
Debbie Huntzinger, Northern Arizona University
George Hurtt, University of Maryland
Ken Jucks, NASA, UARP
Randy Kawa, NASA, GSFC
Randy Koster, NASA, GSFC
Charlie Koven, Lawrence Berkeley National Lab
Yiqi Luo, University of Oklahoma

Jeff Masek, NASA, GSFC
Galen McKinley, Univ. of Wisconsin-Madison
Chip Miller, NASA, JPL
John B. Miller, NOAA, ESRLBerrien Moore III, University of Oklahoma
Paul Moorcroft, Harvard University
Ray Nassar, Environment Canada
Chris O'Dell, Colorado State University
Leslie Ott, NASA, GSFC
Steven Pawson, NASA, GSFC
Michael Puma, Columbia University
Tris Quaife, University of Reading
Haris Riris, NASA, GSFC
Natasha Romanou, NASA, GISS
Cecile Rousseaux, NASA, GSFC
David Schimel, NASA, JPL
Andrew Schuh, Colorado State University
Piers Sellers, NASA, GSFC
Elena Shevliakova, GFDL
Ying Ping Wang, Center for Australian Weather
Chris Williams, Clark University
Xiangming Xiao, University of Oklahoma
Tatsuya Yokota, NIES Japan