NASA CMS 2010, Pilot Study: Surface Carbon Fluxes

Summary:

There are no direct global-scale observations of carbon fluxes between the land and oceans and the overlying atmosphere. Understanding the carbon cycle requires estimates of these fluxes, which can be computed indirectly using models constrained with global space-based observations that provide information about the physical and biological state of the land, atmosphere or ocean. This pilot study will generate CO_2 flux maps for one year (July 2009-June 2010) using observational constraints in NASA's state-of-the-art models. Bottom-up surface flux estimates will be computed using data-constrained land (two variants of CASA) and ocean (ECCO2 and NOBM) models; comparison of the different techniques will provide some knowledge of uncertainty in these estimates. Ensembles of atmospheric carbon distributions will be computed using an atmospheric general circulation model (GEOS-5), with perturbations to the surface fluxes and to transport. Top-down flux estimates will be computed from observed atmospheric CO_2 distributions (ACOS/GOSAT retrievals) alongside the forward-model fields, in conjunction with an inverse approach based on the CO_2 adjoint of GEOS-Chem. The forward model ensembles will be used to build understanding of relationships among surface flux perturbations, transport uncertainty and atmospheric carbon concentration. This will help construct uncertainty estimates and information on the true spatial resolution of the top-down flux calculations. The agreement of the top-down and bottom-up flux distributions will be documented.

Scoping Team:

HQ: Ken Jucks, Diane Wickland, David Considine
JPL: Mike Gunson (coordinator), Kevin Bowman, Holger Brix, Joshua Fisher, Dimitris Menemenlis
GSFC: Steven Pawson (coordinator), Jim Collatz, Watson Gregg
ARC: Chris Potter (coordinator)

Objectives:

This project will combine NASA's observations and existing modeling tools to generate global maps of land-atmosphere and ocean-atmosphere carbon exchange. Two "bottom-up" flux maps over land will be produced using observation-constrained models of physical and biological parameters in land biophysical models. Correspondingly, "bottom-up" flux maps over oceans will use observations to constrain the physical state of the ocean surface and, in one case, to constrain ocean biology. Atmospheric carbon will be modeled using such bottom-up fluxes, as well as fossil-fuel emission inventories, as boundary conditions. Ensembles of atmospheric simulations will include a range of uncertainty in surface carbon fluxes and a set of different representations of atmospheric transport. These modeled atmospheric CO_2 concentrations will be compared to space-based observations of partial- and total-column CO_2 to evaluate the consistency between surface flux estimates and atmospheric observations, given the spread in the ensemble. A "top-down" inverse method will be used to derive new surface fluxes that are consistent with the atmospheric observations. This inverse approach will use the adjoint of GEOS-Chem, which is based on the same dynamical core as GEOS-5. An estimate of uncertainty in the fluxes will be given, given the spread among the bottom-up estimates, the range of values in the ensembles of forward model simulations, and the differences between the bottom-up and top-down flux estimates.

Deliverables:

The pilot project will produce carbon flux maps for the period July 2009-June 2010 using bottom-up and top-down approaches. Deliverables are:

- Two estimates of ocean-atmosphere carbon fluxes, produced using the ECCO2 and NOBM ocean models constrained with observations. The fluxes and their differences will be documented.

- Two estimates of land-atmosphere carbon fluxes, produced using different versions of the CASA model constrained with satellite observations. The fluxes and their differences will be documented.

- Ensembles of atmospheric CO_2 simulations will be produced using GEOS-5. One half degree resolution reference run will be accompanied by ten simulations with perturbed physical parameters. All runs will include fossil-fuel emissions and four representations (two ocean combined with two land estimates) of computed fluxes. The ensembles will show how surface flux uncertainty and transport error impact atmospheric CO_2 concentrations.

- Top-down estimates of surface carbon fluxes on a two-degree grid computed using ACOS/GOSAT CO_2 observations with the adjoint of GEOS-Chem.

Period of interest:

Carbon flux estimates will be computed for the period July 2009-June 2010. This is the first full year of GOSAT observations, which are deemed to be the most suitable atmospheric data for this pilot. It is expected that all other space-based observations (e.g., MODIS) will continue to be available in this period. The main caveat about this period is that it is unlikely that in-situ observations needed for evaluating the realism of the land- and ocean-atmosphere fluxes will be available before the end of the pilot. An alternate approach, of computing the fluxes for earlier years, was deemed to be less suitable because of the importance of total-column CO_2 observations for this project.

Methods:

There are four steps in the flux estimation: (i) computing fluxes using observation-constrained land and ocean models; (ii) production of ensembles of atmospheric concentrations that span uncertainty in surface fluxes and transport; (iii) assessment of agreement between these forward-model computations and the atmospheric observations; (iv) "inverse" modeling using the differences between observations and simulations of atmospheric carbon concentrations to optimally estimate the distribution of surface fluxes that would best agree with the atmospheric observations. A fifth step (v) in the process is to document the consistency of the bottom-flux estimates from step (i) with the top-down estimates from step (iv); quantification of the reasons for any discrepancies and improvement of the underlying models will be a research theme which is likely to extend beyond the timescale of this pilot.

This section describes the five steps. Details of the models and data used in them are left to the appendix. The project will place substantial demands on NASA's computing resources, but it is anticipated that adequate capacity exists in NASA's High-Performance Computing environment to meet these demands.

Step (i): Bottom-up surface flux estimates.

Two independently computed "bottom-up" estimates of land-atmosphere carbon fluxes by biological activity. The first will be from the ARC group using their latest CASA model, and the second will be from the GSFC group, using a different version of the CASA model, CASA-GFED, that includes estimates of biomass-burning fluxes. Both models use MODIS data as observational constraints. Estimates of fossil-fuel emissions from inventories will be provided alongside both land flux datasets.

Two independently computed "bottom-up" estimates of ocean-atmosphere carbon fluxes. The first will be from the ECCO2 group, using assimilation of space-based observations of the physical ocean state into the Massachusetts Institute of Technology general circulation model (MITgcm). The second will be from the GSFC/GMAO NOBM model, which uses meteorological analyses to constrain the physical ocean state and space-based observations (e.g., ocean color) to constrain biological activity.

Step (ii): Production of forward model ensembles.

Atmospheric estimates of surface carbon fluxes will be computed using the GEOS-5 general circulation model constrained by observations. Forward model simulations will use surface-flux estimates from Step (i) as boundary conditions. The ensemble will include four distinct representations of CO_2 obtained from the separate estimates of two land- and two ocean-atmosphere fluxes. Additionally, for each of these combinations, an ensemble of simulations which represent transport in different ways will be included, using an established set of results from GEOS-5.

Step (iii): Assessment of modeled versus observed concentrations.

These model estimates will be used alongside NASA's ACOS total-column CO_2 retrievals from the GOSAT instrument radiance measurements, and partial-column CO_2 retrievals from thermal infrared radiances (e.g., TES). An important part of this task is completion of the ACOS/GOSAT retrievals in a timely manner for the project – this work is not to be funded by the present pilot study, but will be coordinated by Dr. Gunson (PI for ACOS) in a way that this pilot project can proceed in a timely way. Evaluation of the agreement between the model-produced CO_2 distributions with the retrievals will provide deductions about the consistency between the "bottom-up" flux estimates with the observation-derived atmospheric concentrations.

Step (iv): Top-down flux estimates.

An inverse technique, based on the adjoint of the GEOS-Chem trace-gas transport module, will be used to infer surface fluxes that are consistent with the atmospheric CO_2. This adjoint technique uses atmospheric observations alongside the forward-model predictions to optimize the surface fluxes, given knowledge of the priors. The ensemble of simulations will be used to estimate "error" (spread) in the forward model computations arising from both surface-source uncertainty and atmospheric transport uncertainty.

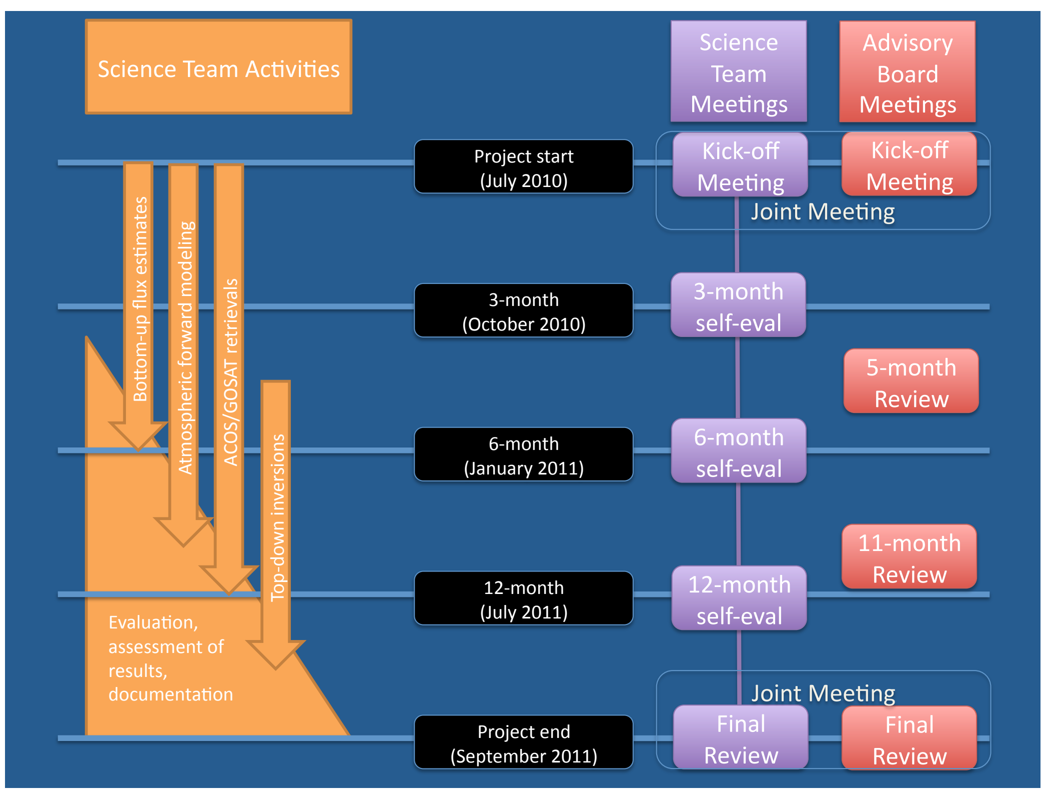
Step (v): Evaluation.

The flux maps produced in this pilot project will be accompanied by estimates of error terms in the individual computations. A collaborative assessment of the results, performed by all team members, will focus on (a) the agreement among the fluxes computed using the various methods and (b) evaluation of whether the agreement or disagreement among the different methods is consistent with the error estimates from the individual methods. Comparisons of the two representations of land-atmosphere and ocean-atmosphere results can begin once these estimates are computed; inclusion of the "top-down" estimates into the evaluation will begin later, and part of that uncertainty will be impacted by the uncertainty among the "bottom-up" flux models. As an independent comparison against direct measurements of CO_2 fluxes at the land surface, we will use data from FLUXNET scaled appropriately to match the coarser products (following Jung et al. 2009). The results of the evaluations will be documented and provided to the community, along with the flux maps.

Management and Oversight Plan

The schematic includes a set of activities for the science team and for an advisory board. The science-team activities, with staged delivery of tasks and evaluation of results, are designed to provide results in a sequential manner, with pre-production testing and post-production evaluation of products. The Advisory Board, which is anticipated to be a small body consisting of NASA HQ Project Scientists and independent external scientists, will provide a critical overview of the project. We expect to have joint Science Team/Advisory Board meetings at the beginning and end of the projects, with different schedules in the intermediate period.

Schematic of the production schedule, Science Team meetings and Advisory Board Meetings of the Pilot Project. The project has an 18-month duration and the dates given correspond to an anticipated start date of July 1, 2010.



NASA Data Usage

This Pilot Project will use a range of NASA (and other) observation-based data, as outlined in the table.

Component	*Data input*
CASA (Ames)	GEOS-5 or NCEP Reanalysis meteorological parameters (surface temperature, precipitation) TRMM/Terra/Aqua-CERES surface solar radiation flux Terra/Aqua-MODIS – enhanced vegetation index and leaf Area Index
CASA-GFED (GSFC)	GEOS-5 meteorological parameters (surface temperature, precipitation, , photosynthetically active radiation,.) Terra/Aqua-MODIS Products: FPAR, Veg Continuous Fields, Active Fire, 500m Surface Reflectance.
ECCO2 (JPL)	Jason and Envisat-RA-2 (EUMetsat) Altimetry Aqua-AMSR-E sea-surface temperature (SST) ARGO buoy (NOAA) temperature and salinity XBT (expendable bathythermograph) (NOAA) temperature (QuickSCAT, GRACE, and sea ice data constraints being added)
NOBM (GSFC)	Constraints from above: • GEOS-5 meteorological analyses (surface wind speeds and stress) • Specified ice fields, consistent with GEOS-5 • Atmospheric CO_2 observations (presently NOAA) • Dust deposition from GOCART model, computed using GEOS-5 meteorology • OASIM – radiation transfer model Assimilated in ocean model: • SeaWifs and Aqua-MODIS chlorophyll • water-leaving radiances
GEOS-5	Meteorological observations from operational network, including Aqua-AIRS etc. Surface constraints (SSTs, land parameters)
GEOS-Chem v8	Meteorological parameters from GEOS-5 ACOS CO_2 retrievals using GOSAT observations
Evaluation	Aqua-AIRS CO_2 retrievals Aura-TES CO_2 retrievals FLUXNET: CO_2 flux tower and surface fluxes TCCON (Total Carbon Column Observing Network) CO_2 ...

Potential Future Activities

This Pilot Project will provide a basis for future research projects, developments and applications.

- The methodology will transfer, with minimal change, to the inclusion of OCO-II data. It thus provides NASA with a ready-to-go, in-house system for flux estimation using OCO-2 observations.

- In this project, the differences among various methods for flux estimation will be documented. Research projects beyond the scope of this pilot study could delve deeper into the models to examine why these differences arise and to improve the representation of processes in the models. This could include, among other activities, improved parameter estimates in land and ocean models and more detailed assessments of the error terms and spatial smoothing inherent in the top-down inversion computation. A framework would also be in place to include computations from other models developed nationally and internationally.

- Limitations in the computed fluxes can arise from uncertainty in the models and can also be impacted by limitations in either the type or the accuracy of observations available. Research studies directed at isolating requirements on future observing systems and at assessing likely impacts of planned future missions could follow this pilot study. Such "Observing System Simulation Experiments" are potentially valuable commodities, yet they are expensive to develop and to run.

- "Operational hardening" of this research-based system could lead to a viable system for "near-real-time" carbon monitoring. This would impose stringent demands on the availability of all necessary observations in a timely manner (which, for greenhouse gas monitoring is likely to be within several weeks of acquisition). It would also require development of a robust computational infrastructure to run, monitor and evaluate the end-to-end system in an operational environment.

Appendix: Model Descriptions

Land model 1: CASA (Ames Implementation)

The NASA Carnegie-Ames-Stanford (CASA) model is run with constraints on vegetation greenness from MODIS data and climate station reanalysis records to constrain productivity of vegetation and to allocate productivity to woody and herbaceous biomass. The turnover of biomass into detrital pools and subsequent release of CO_2 through respiration is included. CASA can compute global land cover changes and associated net carbon emissions. This includes the capability to monitor carbon emissions from deforestation, other forest disturbances, seasonal warming of high-latitude (tundra) ecosystems, droughts and crop failures, and other changes in agricultural land uses. Potter et al. (2009) describes the unique features of the Ames implementation of CASA.

Land Model 2: GFED-CASA (GSFC implementation)

A variant of the CASA model is used that is supported at GSFC, University of California Irvine, and Amsterdam Free University (see van der Werf et al., 2006). CASA-GFED includes the combustion of biomass from fires and accounts in a consistent way for the partitioning of CO_2 efflux between combustion and respiration. Absorption of solar radiation for productivity and the allocation of productivity to vegetation components are prescribed from MODIS products (see Table). Burned Area is derived from satellite observations (Giglio et al., 2006, 2010). GEOS-5 meteorological analyses (Rienecker et al., 2008) are used as meteorological forcing in the CASA-GFED model, following Olsen and Randerson (2004). Carbon uptake and emissions from this model have been used extensively in atmospheric transport modeling activities including TransCom (e.g., Baker et al., 2006), CarbonTracker (Peters et al., 2007), activities by the CASA-GFED team (e.g., van der Werf et al., 2004, 2008), and others (e.g., Campbell et al., 2008).

Ocean Model 1: MITgcm-ECCO2 (JPL/MIT implementation)

The MITgcm-ECCO2 solution will be based on physical ocean state estimates provided by the Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2) project (Menemenlis et al., 2005, 2008). ECCO2 aims to demonstrate the feasibility and utility of global, eddying ocean and sea ice state estimation. What sets apart ECCO2 estimates from operational atmospheric and oceanic data assimilation products is their physical consistency: ECCO2 estimates do not contain discontinuities when and where data are ingested and the estimated state satisfies conservation principles as described by the model equations. These properties make ECCO2 estimates particularly suitable for application to ocean tracer problems (e.g., Krakauer et al., 2006; Fletcher et al., 2006; 2007; Gruber et al., 2009; Manizza et al., 2009). Ocean carbon cycle computations will combine a carbonate chemistry and air-sea gas-exchange module (Dutkiewicz et al., 2006; Bennington et al., 2009) with parameterization of biological processes following the ecosystem model of Follows et al. (2007) in which regional and seasonal patterns of ecosystem structure, function and diversity (Barton et al., 2010) are emergent properties of a complex, "self-organizing" virtual ecosystem. This approach will yield a novel scheme for estimating present-day fluxes with the potential for a flexible ecosystem response to climate shifts not captured in more tightly prescribed formulations (Dutkiewicz et al., 2010).

The adjoint-method-based ECCO2 ocean state estimate currently assimilates the following data sets: Jason altimetry, Envisat altimetry, AMSRE SST, ARGO temperature, ARGO salinity, and XBT temperature. Work is underway to add QuickSCAT, GRACE, and sea ice data constraints to the adjoint-method-based ECCO2 solution. An earlier ECCO2 solution, obtained using a Green's functions approach, already includes mean sea level and sea ice data constraints. The MIT biogeochemistry group uses ocean color data to test/evaluate/adjust their biogeochemical models.

Ocean Model 2: NOBM (GSFC implementation)

The NASA Ocean Biogeochemical Model is an explicit representation of global ocean ecosystem and biogeochemical processes, including carbon. It has been extensively validated against in situ and satellite data sets (e.g., Gregg and Casey, 2007; Gregg et al., 2003). It has been adapted for data assimilation using SeaWiFS and MODIS-Aqua data (Gregg, 2008; Nerger and Gregg, 2007, 2008). Meteorological forcing at the ocean surface comes from GEOS-5 analyses (Rienecker et al., 2008).

GEOS-5 atmospheric model

The GEOS-5 general circulation model (Rienecker et al., 2008) has been adapted to transport an arbitrary number of trace gases and chemical codes of varying complexity. For carbon work, it is most often used with a simple linear chemistry model for CO and CO_2, with specified surface emissions and uptake. Model output have been used by Wang et al. (2009) to compute CO:CO_2 correlations and their impact on inverse modeling. The model can be run with arbitrary datasets of emissions, interpolated to the correct grid – in “operational” data assimilation mode, resolution is typically 0.5°×0.66° globally, but this can be adapted readily. For this pilot study, a global 1.0°×1.25° resolution is proposed. The transport ensemble will be constructed using uncertainty in parameters that represent sub-grid transport: Ott et al. (2009) isolate several parameters in the convection code that impact vertical trace gas fluxes, and this has been extended to the three-dimensional state (Ott et al., 2010, in preparation). Additional sensitivity to the numerical treatment of cloud mass fluxes will also be included in the ensemble (Pawson and Zhu, 2010 in preparation). Each member of the transport ensemble will be computed with four combinations of the two ocean- and two land-carbon fluxes, including additional specified fluxes (fossil fuel inventories) from Law et al. (2008). The ensemble will include one reference member, run with the “default” version of GEOS-5 at

0.5°×0.67° resolution, plus ten perturbations (which may be run at lower resolution, for computational efficiency).

Transport Adjoint Inverse model (JPL implementation)

An adjoint approach, based on the GEOS-Chem chemistry transport model, will be used for the top-down surface flux estimation. The adjoint relates, in a computationally efficient manner, the sensitivity of an atmospheric CO_2 concentration at any time back to a surface flux at any location at an earlier time (see Giering and Kaminski, 1998) via the linearization of the transport model operator. GEOS-Chem uses analyzed meteorological fields from GEOS-5, mapped from the original resolution of 0.5°×0.67° to a coarser grid of 2°×2.5°. Transport in GEOS-Chem and in GEOS-5 is based on the flux-form semi-Lagrangian technique of Lin and Rood (1996), so that inverse computations made with GEOS-Chem will be consistent with the forward model computations using GEOS-5. Suntharalingam et al. (2003, 2004) described and analyzed the first forward CO_2 simulations with GEOS-Chem. The adjoint of GEOS-Chem was originally developed by Henze et al. (2007) and has been applied to optimize Asian CO sources using MOPITT data (Kopacz et al., 2009) and global CO sources using multi-sensor satellite (AIRS, MOPITT, TES and SCIAMACHY) data (Kopacz et al., 2010). The CO_2 adjoint is presently being used for TES data (Nassar et al., 2009) and will be adapted for this project by implementing spatial sampling patterns and observation operators that correspond to the ACOS/GOSAT data.

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