Constraining the CO2 Missing Sink (S. R. Kawa, P.I.) : CSU Contributions 2005-2007

Summary:

We developed, implemented, evaluated, and published results from a suite of numerical models of the terrestrial carbon cycle and its interaction with atmospheric constituents (CO2, COS). These efforts were part of a larger research program directed at NASA Goddard Space Flight Center led by S. Randall Kawa and colleagues. We report here on (1) work we did to couple the ecophysiology model SiB with a biogeochemical cycling model (CASA); (2) an investigation of the role of terrestrial ecosystems in the uptake of carbonyl sulfide (COS); (3) the mechanisms controlling synoptic variations of CO2; and (4) the development and evaluation of an ensemble data assimilation system for analyzing measured variations in atmospheric CO2. This report also lists graduate students supported, publications and conference presentations supported by the project.

Coupling of Physiology and Biogeochemistry (SiB-CASA) (Schaefer et al, 2008)

We combined the biogeochemistry from the Carnegie-Ames-Stanford Approach (CASA) model with the photosynthesis and biophysical calculations in the Simple Biosphere (SiB) model to create SibCasa, a hybrid capable of estimating terrestrial carbon fluxes from diurnal to decadal time scales (Fig 1). We added a carbohydrate storage pool to the CASA configuration to calculate fluxes on diurnal time scales and to explicitly calculate autotrophic respiration. The leaf biomass pool is prescribed by Leaf Area Index (LAI) derived from remotely sensed Normalized Difference Vegetation Index (NDVI). Simulated carbon fluxes and biomass compared well with observations at selected eddy covariance flux towers in the Ameriflux network. The largest sources of error in the modeled fluxes were the assumed initial wood biomass, the LAI derived from the NDVI, and ignoring shade leaf photosynthesis. Expanding to a Sun-shade leaf photosynthesis model and improving the representation of agriculture are the highest priority items for future model development.

An important advantage of the coupled SiB-CASA framework is the ability to evaluate the results against a new suite of observations: biomass measurements. When coupled to an atmospheric transport model such as PCTM, the modeling system now predicts variables that can be evaluated against three distinct types of data: (1) eddy covariance measurements of surface turbulent fluxes; (2) biomass data as estimated from forest inventory or other products; and (3) atmospheric constituent data collected in-situ or estimated from satellites.

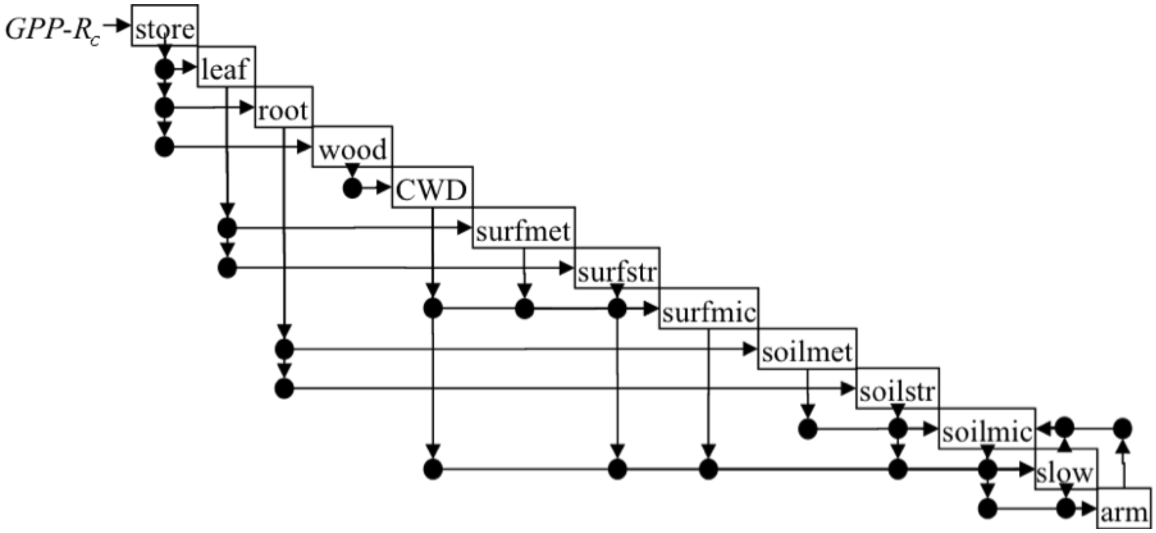


Figure 1: The SibCasa pool configuration. Dots are transfers between pools; the vertical arrows are losses from each pool; and horizontal arrows are inputs to each pool. The carbon generally flows from upper left to lower right. The primary input is canopy net assimilation (*GPP* – R_c, where *GPP* is Gross primary Productivity and R_c is canopy autotrophic respiration).

Analysis of Carbonyl Sulfide (COS) Uptake by the Land Surface (Denning et al, 2008)

Because photosynthesis, the process of cells containing chlorophyll using energy from sunlight to convert water and carbon dioxide into carbohydrates for growth and emitting oxygen as a by-product, and respiration, the process of oxidizing reduced organic compounds to yield energy and emitting carbon dioxide as a by-product, can act in concert as well as work in opposition, it is intractable to understand the controlling mechanisms through field and laboratory studies alone. Thus, we parameterize these processes separately in order to improve the tractability of the problem of understanding these processess. However, it is difficult to assess our parameterizations of these processes because we cannot separate observations of the photosynthetic processes from observations of the respiration processes.

To better assess our models and understand errors in the CO2 seasonal cycle we developed an algorithm to simulate the uptake of carbonyl sulfide (COS) in SiB3. We then compared the seasonal cycle of the COS exchange with the seasonal cycle calculated from recent measurements taken by the NOAA CMDL flask network. COS and CO2 have similar molecular diffusivities and enter the leaves of plants through the stomata. Within the leaves, both undergo reactions with the enzyme carbonic anhydrase (CA): CA catalyzes the hydrolysis of COS into H2S and CO2 and CA catalyzes the hydration of CO2 (an easily reversible process), the first of two reactions comprising photosynthesis (the second reaction converts aqueous CO2 into carbohydrate and O2 and is catalyzed by Rubisco (in C3 plants) and PEP-carboxylase (in C4 plants). Thus the pathways of COS and CO2 from their relatively inert states in the atmosphere to their destruction/assimilation within terrestrial vegetation, their dominant sink, are virtually identical (Fig 2).

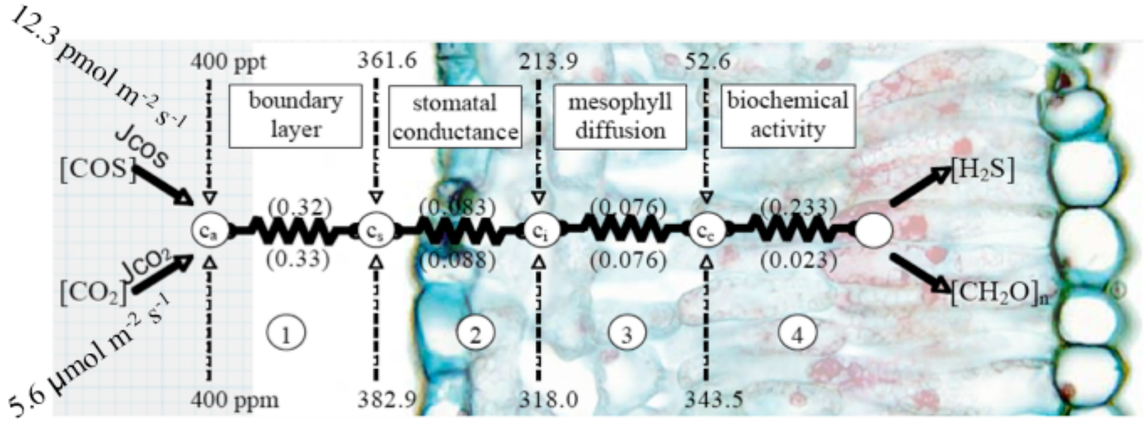


Figure 1: CO2 and COS take the same pathway for diffusion from the atmosphere to the site of reaction. Physiological mechanisms control the stomatal aperture so that the diffusion limitation changes in step with the capacity for photosynthesis. Therefore COS uptake by leaves can be solved for together with CO2 uptake and is closely linked to it.

When the COS model was coupled to PCTM, and used to simulated global distributions of the gas, we found improved agreement of seasonal cycles and vertical profiles of the gas over vegetated land areas compared with earlier published estimates of COS fluxes (Fig 3). The model driven by the fluxes of Kettle et al showed enhancement near the surface, whereas the SiB-derived fluxes produced approximately the correct amount of drawdown in comparison with airborne samples collected during INTEX-NA.

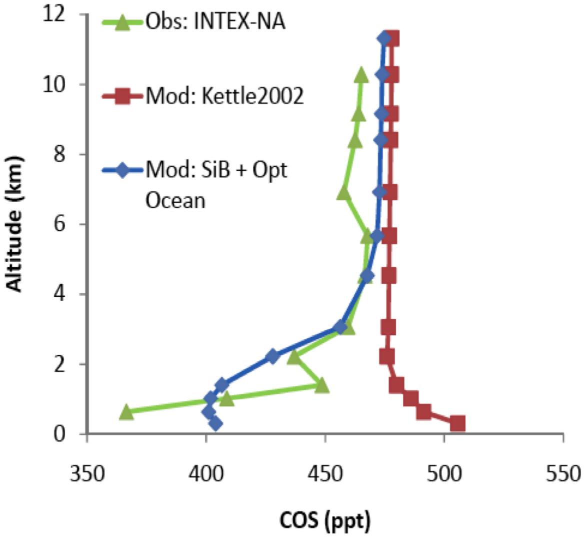


Figure 3: Observed and simulated Vertical profiles of COS over the midcontinent USA in summer 2004.

Mechanisms for synoptic variations of CO2 in SiB-PCTM (Parazoo et al, 2008)

The affect of interactions between weather and surface fluxes on synoptic CO2 variations is investigated mechanistically and quantitatively in midlatitude and tropical regions using continuous in-situ CO2 observations in North America, South America and Europe (Fig 4) and forward global chemical transport model simulations with the Parameterized Chemistry Transport Model (PCTM). Observed and simulated frontal CO2 climatologies suggest persistence of strong frontal CO2 signals throughout midlatitudes of North

America and Europe. Either replacement of synoptically unique CO2 air masses or transient spikes along the frontal boundary characterize these signals (Fig 5).

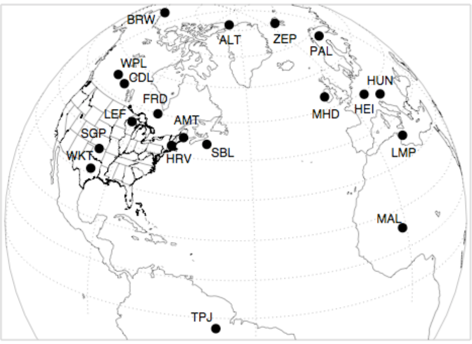


Figure 4: Stations used in synoptic CO$_2$ study for comparison to SiB-PCTM.

One case study of a summer cold front finds that CO2 gradients can organize with deformational flow along fronts and cause strong and spatially coherent variations. A boundary layer budget equation was constructed in order to determine contributions to boundary layer CO2 tendencies by horizontal and vertical advection, moist convection, and biological and anthropogenic surface fluxes. Analysis of this equation suggests that advection is responsible for 50-90% of frontal variations in the summer, depending on local and non-local influences, and therefore much of the total CO2 variance. Cloud and surface flux sensitivity simulations further suggest that horizontal advection is a major source for synoptic CO2 variability in midlatitudes and also that coupling between convective transport and surface CO2 flux is most important in the tropics. With more continuous CO2 observations becoming available in the tropics, future work should extend the mechanistic analysis to additional tropical locations.

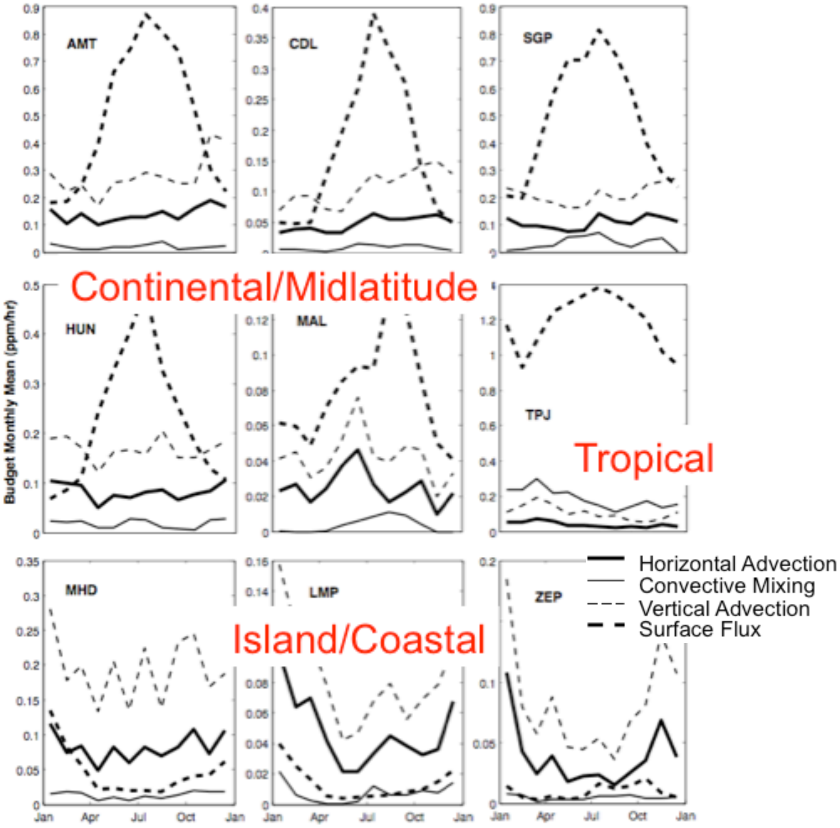


Figure 5: Fraction of variation of synoptic CO2 at each station due to horizontal and vertical advection, convective mixing, and surface biology.

Impacts of Potential Clearsky Bias in Satellite CO2 retrievals (Corbin et al, 2008)

The Orbiting Carbon Observatory (OCO) and the Greenhouse gases Observing SATellite (GOSAT) will make global observations of the total column dry-air mole fraction of atmospheric CO2 (XCO2) starting in 2009. Although satellites have global coverage, X_{CO2} retrieval will be made only a few times each month over a given location and will only be sampled in clear conditions. Modelers will use X_{CO2} in atmospheric inversions to estimate carbon sources and sinks; however, if satellite measurements are used to represent temporal averages, modelers may incur temporal sampling errors.

We investigated these errors using a SiB-PCTM also forced by fossil fuel emissions and air-sea gas exchange fluxes. Hourly global simulations of atmospheric column X_{CO2} were sampled along the OCO orbit and masked for cloudy conditions, obtaining an OCO subset which was then compared to actual monthly, seasonal, and annual estimates of temporal sampling errors associated with spaceborne CO_2 measurements. Temporal sampling errors vary with time and location, exhibit spatially coherent patterns, and are greatest over land and during summer. These errors often exceed 1 ppm (Figs 6-7) and must be addressed in a data assimilation system by correct simulation of synoptic CO_2 variations associated with cloud systems.

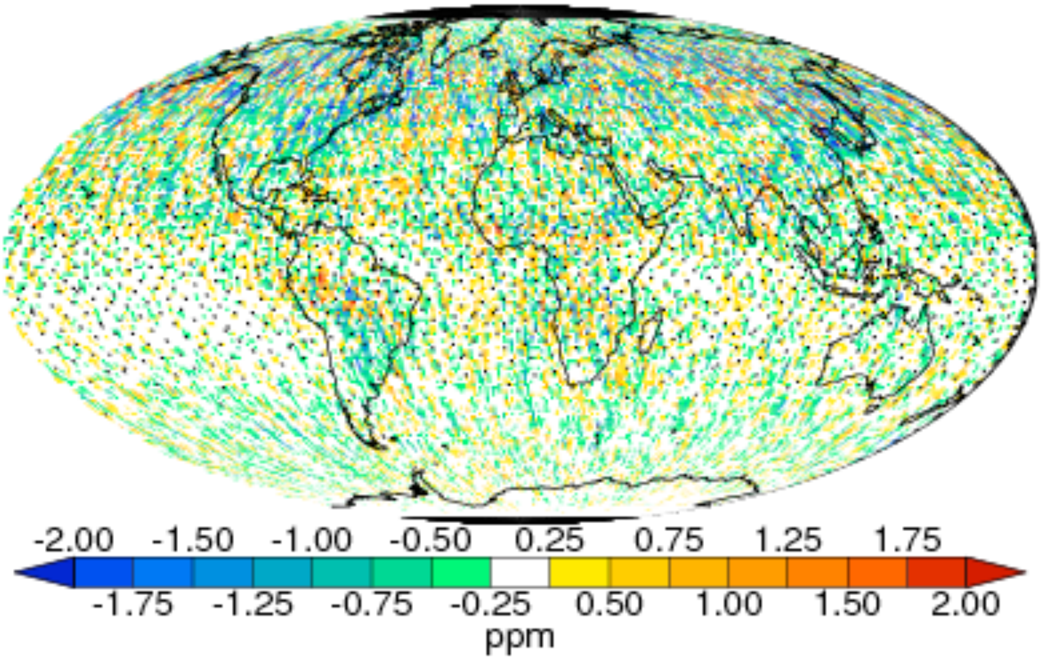


Figure 6: Annual mean temporal sampling errors, obtained by subtracting the annual mean at each grid cell from the annual mean in the OCO subset.

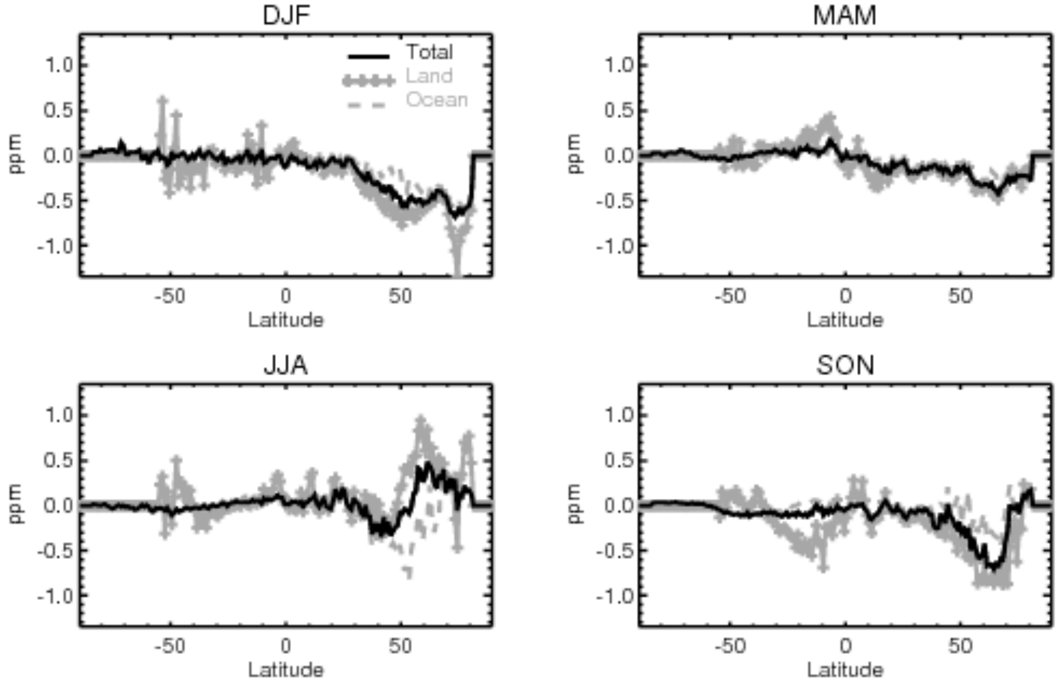
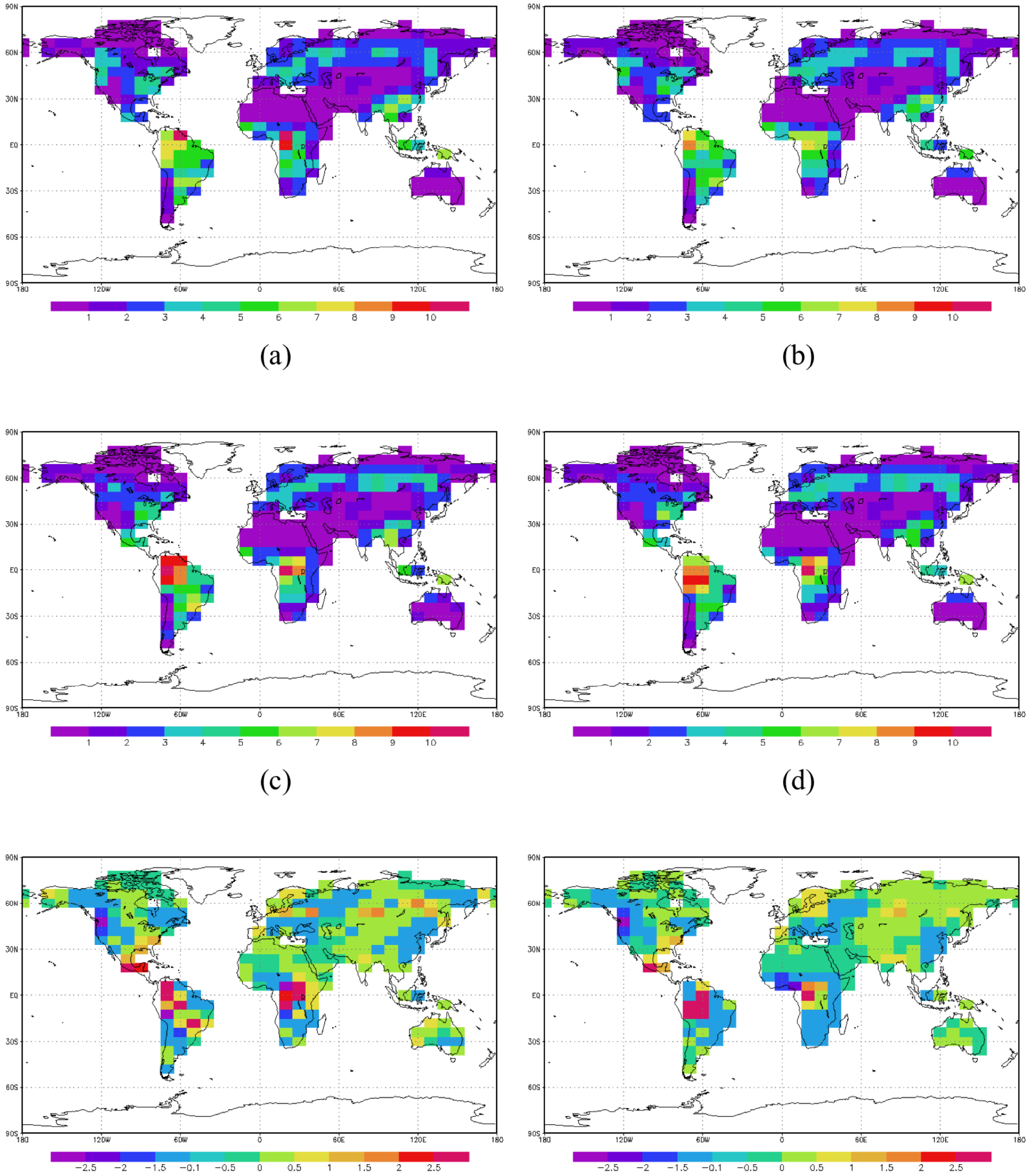


Figure 7: Seasonal zonally-averaged temporal sampling errors in simulated satellite retrievals frequently exceed 0.5 ppm compared to "actual" values simulated under all conditions.

Development of Ensemble Data Assimilation Framework in SiB-PCTM (Lokupitiya et al, 2008)

In this study, we used an ensemble-based data assimilation method, known as the Maximum Likelihood Ensemble Filter (MLEF), which has been coupled with a global atmospheric transport model to estimate biases of carbon surface fluxes. Carbon fluxes for this test consist of gross primary production and ecosystem, respiration over land, and air-sea gas exchange. Biases were estimated for one year at 10° longitude by 6° latitude spatial resolution and with an 8-week time window. We tested the model using a pseudo data experiment with an existing observation network that includes flasks, aircraft profiles, and continuous measurements. Due to the under constrained nature of the problem, strong covariance smoothing was applied in the first data assimilation cycle and localization schemes have been introduced. Error covariance was propagated in subsequent cycles. The coupled model satisfactorily recovered the land biases in densely observed areas (Fig 8). Ocean biases, however, were poorly constrained by the atmospheric observations. Unlike in batch mode inversions, the MLEF has a capability of assimilating large observation vectors and hence is suitable for assimilating hourly continuous observations and satellite observations in the future. Uncertainty was reduced further in our pseudo-data experiment than by previous batch methods, due to the ability to assimilate a large observation vector. Propagation of spatial covariance and dynamic localization avoid the need for prescribed spatial patterns of error covariance centered at observation sites as in previous grid-scale methods.



(a) (b)

(c) (d)

Figure 8: Mean annual fluxes for (a) GPP truth, (b) GPP recovered, (c) respiration truth, (d) respiration recovered, (e) NEE truth, and (f) NEE recovered. Units are in 10^{-8} kgC/m^2/s.

Students Supported:

- **Kathy Corbin (Ph.D.)**
- **Nick Parazoo (M.S. and Ph.D.)**
- **Sheri Conner-Gausepohl (Ph.D.)**
- **Ravi Lokupitiya (PostDoctoral Fellow)**

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