Estimation of Regional CO2 Budgets and Biomass by Fusion of LandSat, MODIS, and Atmospheric Observations

P.I.: Scott Denning

Department of Atmospheric Science, Colorado State University

Summary

We have begun an analysis of the carbon fluxes and storage by synthesizing observations of weather, surface spectra, and high-resolution land-cover, and atmospheric CO2 with a suite of mechanistic models. The analysis will be performed globally, but many of the data products we will use are available only over the contiguous USA, so the quality of the estimation will be enhanced here and will contribute to NACP synthesis and integration. The synthesis of these data products will result in (1) global maps of time-varying sources and sinks of atmospheric CO2, wood biomass and soil carbon that are consistent with many kinds of observations; and (2) a self-consistent process-based model of these sources and sinks that can be extrapolated beyond this region of high data density. We have developed a robust data assimilation system (the Maximum Likelihood Ensemble Filter, MLEF) that can efficiently process very large volumes of data into a complex and nonlinear forward model. We have tested the system by assimilating weather and CO2 data into SiB-CASA, a global model of the interactions between ecosystems and the climate. The model has been updated to include carbon allocation, storage, and biogeochemical cycling through multiple ecosystem pools. Other recent improvements include explicit treatment of crops, high-resolution fossil fuel emissions estimates, and a prognostic phenology algorithm derived by assimilating 8 years of global MODIS data. The model simulates fluxes that result from both short-term (sub-diurnal physiology to seasonal phenology) and long-term (disturbance, succession, land management) processes, predicting carbon pools as well as hourly fluxes and high-frequency variations in atmospheric CO2.

The model will be initialized using climatology and historical land-use data, then run in forward mode for the satellite era using disturbance maps derived from LandSat-derived disturbance products obtained from the North American Forest Dynamics project. Finally, we will perform ensemble data assimilation during the period of rich continuous CO2 data from NACP (2007-2012), including GOSAT/Ibuki data. We will use GEOS-5 weather analyses on a 0.5° x 0.67° grid, NAFD disturbance data, GFED fire products, VULCAN fossil fuel emissions, and daily air-sea gas exchanges derived from the WHOI ocean model to predict vegetation and soil carbon pools, fluxes, and atmospheric CO2 on an hourly basis. Carbon pools will then be optimized by running ensemble assimilations of data from flux towers, atmospheric CO2 measurements. The final simulations will be made available through the NACP Modeling and Synthesis Thematic Data Center.

Our work received NASA support starting December 1, 2010. In the first seven months of this project hired two new scientific staff and lost one. We have begun an ambitious upgrade of the modeling system that brings together the various branches of code previously developed into a consistent, documented trunk that can be shared with the science community. We purchased a large compute cluster and disk array to perform the model/data analyses and began to port the assimilation system to the new hardware. We have used our MODIS-based phenology assimilation system to produce a global analysis of leaf area and FPAR, which we published in the peer-reviewed literature. Finally, we have conducted extensive testing of the Maximum Likelihood Ensemble Filter for GOSAT CO2

data (the latter work is also jointly supported by another NASA project).

1. Development and Testing of SiB4

A central element of this project is to produce a new version of the Simple Biosphere model (SiB4) which uses a single mathematical framework to predict self-consistent land-atmosphere exchanges of carbon, water, energy, radiation, and momentum as well as carbon storage in "cascading pools" of biomass. This work brings together prognostic phenology, plant physiology, and ecosystem biogeochemistry and transforms SiB from a model that has in the past relied on MODIS or AVHRR data as input to one whose output can be quantitatively compared to remotely-sensed estimates of leaf area, biomass, and chlorophyll fluorescence, as well as forest and agricultural inventories and other data as well. The goal is to use this model in a formal optimization framework (see section 2 below) to map gross carbon exchanges (GPP and ecosystem respiration) between the land surface and the atmosphere that are also consistent with net fluxes responsible for changes in atmospheric CO2.

We have combined algorithms from three previous models into a single modeling framework. Rather than relying on satellite data for model input, this new version of SiB (SiB4) includes prognostic phenology for natural vegetation types as well as specific crops (Stockli et al., 2011 and Lokupitiya et al., 2009). The model also simulates carbon pools (Schaefer et al., 2008 and 2009), including both above and below ground biomass estimates.

Phenology modules for sixteen plant functional types (PFTs) and three specific crops (corn, soybean and wheat) prognose the leaf area index (LAI). The timing of plant growth, including leaf out and senescence is determined using temperature, radiation, and water vapor pressure deficit functions. To test the prognostic phenology scheme, SiB4 was run globally for a single year (2000). We compared seasonal LAI from SiB4 to LAI from the original SiB3 model, which did not include prognostic phenology but instead relied on remotely sensed satellite data (Figure 1). SiB4 has lower LAI in the tropics year round, although it has an enhanced seasonal cycle compare to SiB3. SiB4 also has higher LAI in the sub-tropics, with considerably more seasonality in the southern hemisphere sub-tropics.

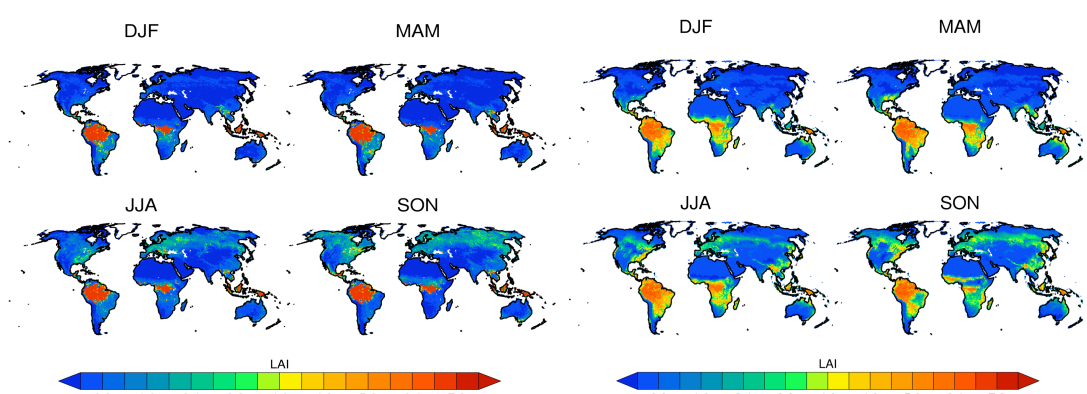

Figure 1: Seasonal mean LAI for SiB3 (left) and SiB-BGC (right). The SiB-BGC values are the weighted means from all PFT contributions in each grid cell.

The resulting carbon fluxes from SiB4 reflect the changes in the LAI (Figure 2). The seasonality of net primary production (NPP) is enhanced in the tropics and the sub-tropics in SiB4 compared to SiB3. Summertime carbon uptake is also more pronounced over heavily cultivated regions in SiB4 due to the inclusion of the crop modules and the high productivity of corn and soybeans compared to natural vegetation. Individual comparisons of carbon fluxes to flux towers revealed that the timing and magnitude of the fluxes is altered in SiB4 in comparison to SiB3, primarily due to the inclusion of crops in the mid-latitudes.

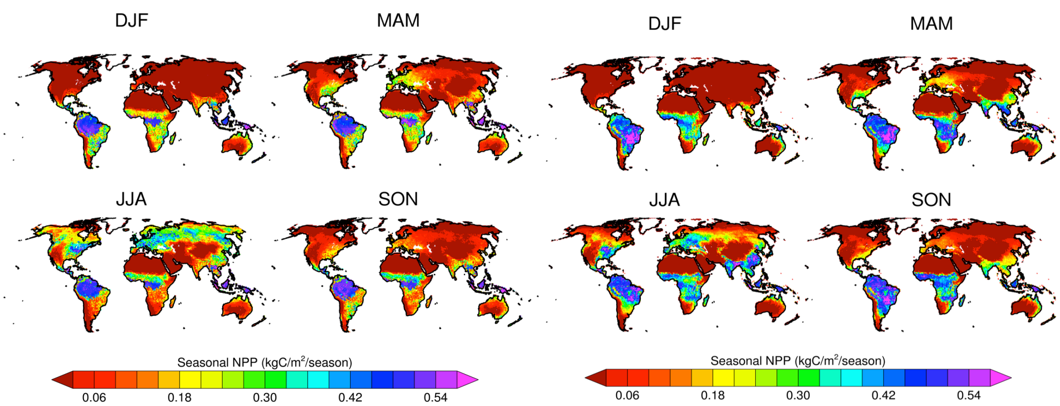

Figure 2: Seasonal total NPP for SiB3 (left) and SiB-BGC (right).

Instead of requiring a balanced carbon cycle, SiB4 calculates terrestrial carbon pools using the strategy from the Carnegie-Ames-Stanford Approach (CASA) model. SiB4 updates thirteen carbon pools daily, including the prognostic leaf pool that utilizes the phenology routines for the carbon allocation. Compared to remotely-sensed above ground biomass estimates from Saatchi et al. (2011), SiB4 overestimates the biomass throughout South America (Figure 3). The simulated biomass is too high for both tropical forest and savannah regions; however, the pattern of spatial variability between the two maps is similar.

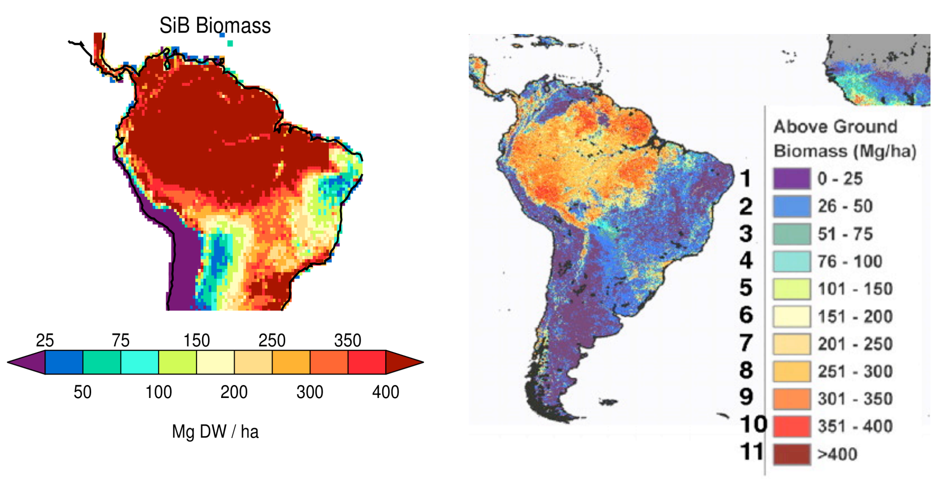

Figure 3: Left) SiB-BGC simulated above ground biomass (AGB; Mg dry weight per hectare). Right) AGB from Saatchi et al. (2011), using a combination of in situ inventory plots and satellite data.

In addition to evaluating the model against satellite data, we also compared SiB4 results to field campaign measurements. Looking at three sites in South America, both carbon fluxes and carbon stocks can be compared to field data collected in the Large-Scale Biosphere-Atmosphere Experiment in the

Amazon (LBA). The carbon flux results vary between the three sites. At two of the sites, the gross primary productivity (GPP) and respiration is overestimated, while GPP and respiration at one site is simulated by SiB4 reasonably well. Despite errors in carbon uptake and respiration, the simulated net primary productivity (NPP) is relatively close to the observations. Looking at the carbon pools, SiB4 simulates the carbon in the canopy reasonably well; however, it overestimates the wood and coarse roots and underestimates the soil organic carbon. With a self-consistent model that calculates both carbon fluxes and carbon pools, the next step of this research will be to further improve SiB4 by evaluating against field data and NASA Biomass Pilot Products, in addition to comparing simulated concentrations from both in situ data and satellite measurements.

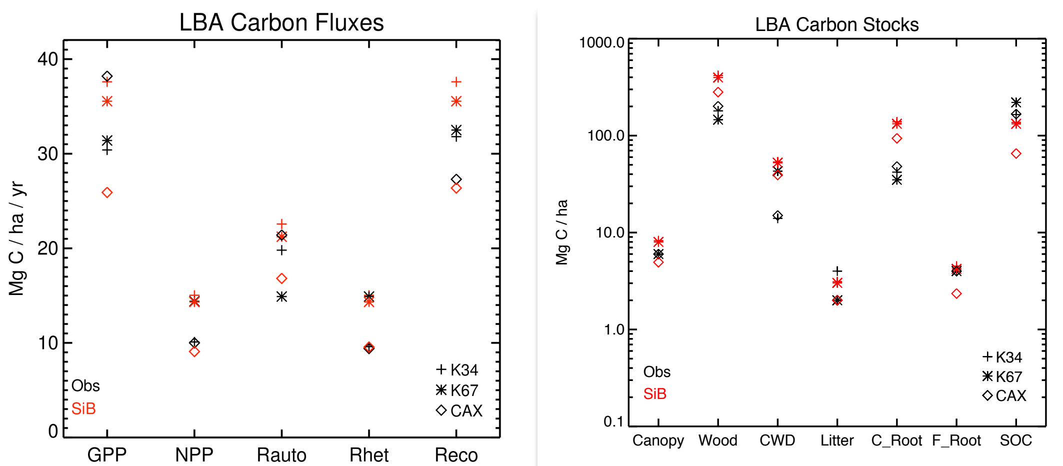

Figure 4: Left) Annual carbon fluxes (gross primary production, GPP; net primary production, NPP; autotrophic respiration, Rauto; heterotrophic respiration, Rhet; and ecosystem respiration, Reco) at three LBA sites (K34, K67, and CAX). Right) Carbon stocks. Black symbols show field measurements and red symbols show SiB4 results.

Following on work we previously conducted for LBA, we have also explored the sensitivity of the new model to drought stress across the Amazon Basin by evaluating seasonal cycles of simulated photosynthesis, ecosystem respiration, evapotranspiration, and sensible heat flux to observations made at eddy covariance sites in the region. These sites span a huge range of annual mean precipitation and experience dry seasons of very different lengths and severity, so they provide a difficult test of SiB4's representation of drought stress.

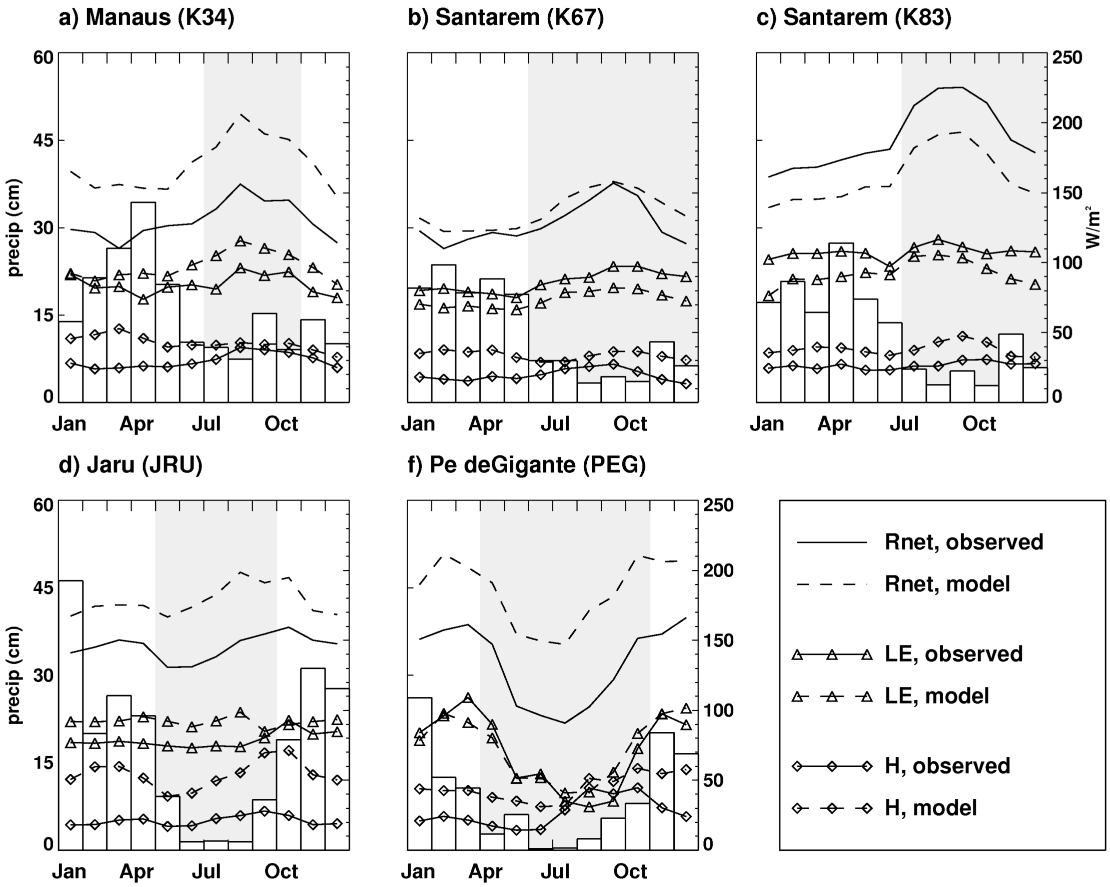

Figure 5: Mean annual cycles of net radiation, latent, and sensible heat simulated and observed at each of five stations in the Amazon Basin. Superimposed histograms indicate monthly rainfall, and the dry season is shaded in each plot.

Comparisons of simulated and observed latent heat flux follow net radiation trends at K34, K83, and RJA (Fig. 5). At K67 observed LE is slightly larger than simulated, and at PEG modeled and simulated LE are very similar in magnitude and annual cycle. At K34, K67 and K83 the annual cycles are similar as well. At RJA there is very little amplitude in the annual cycle of LE, but simulations show a slight decrease at the end of the dry season where observations show a slight increase.

There is a positive bias in simulated sensible heat flux at all stations. This has been noted in SiB simulations before (Baker et al., 2003), and is believe to be related to the leaf-to-canopy scaling scheme outlined in Sellers (1985). This bias is most notable in simulations of forests, such as are simulated in this study. Simulated annual cycles generally follow observed, and Bowen ratio, or relative magnitude of sensible to latent heat is consistent between model and observations.

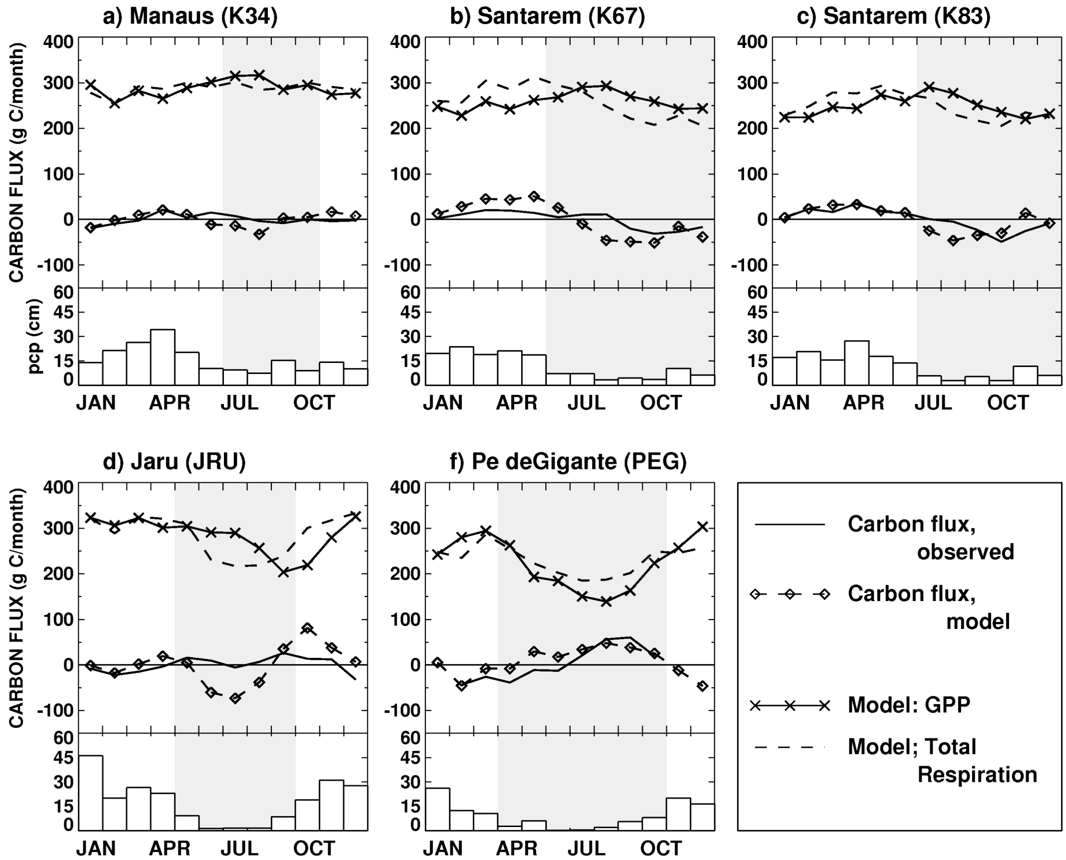

Figure 6: Mean annual cycles of modeled and observed carbon flux for the 5 stations, superimposed on a histogram of monthly-mean precipitation.

Annual cycles of carbon fluxes are shown in Fig. 6. At K34 modeled and observed carbon flux has low amplitude and no obvious seasonality. At the Tapajos National Forest sites (K67, K83) the model captures the general form of the annual cycle (wet season efflux, dry season uptake), but precedes the time of uptake by one to 3 months. At RJA the model reproduces the basic form of the observed annual cycle, but with a larger amplitude, and at PEG SiB3 reproduces the observed carbon flux with reasonable fidelity.

Given the historical performance of land surface models in South America (cf. Fig. 2 in Saleska et al., 2003), we find these results to be very encouraging. We have simulated, with a minimum of localized tuning, the general form of annual cycles of energy, moisture, and carbon flux at several sites across Brazil.

2. Data Assimilation System Development

Last year we identified a number of issues with the overall usability of the MLEF-PCTM linked system. The complexity of the MLEF system and the lack of documentation and support for both MLEF and PCTM made the system unwieldy and necessary alterations to the framework too time consuming. In response to ongoing problems we converted our transport assimilation system to

GEOS-Chem with a simple square root Ensemble Kalman Filter written in ***R*** by Dr. Andrew Schuh. GEOS-Chem has a large user community and is well designed, scrupulously supported, and documented making it easy to use and extend. Dr. Schuh's Ensemble Kalman Filter (EnKF) is simple and well designed. It takes advantage of the extensive library of ***R*** packages and has effectively eliminated difficulties we were unable to resolve with our version MLEF since Dr. Dusanka Zupanski left CSU. This new assimilation framework (Fig 7) has proven to be extensible and computationally efficient.

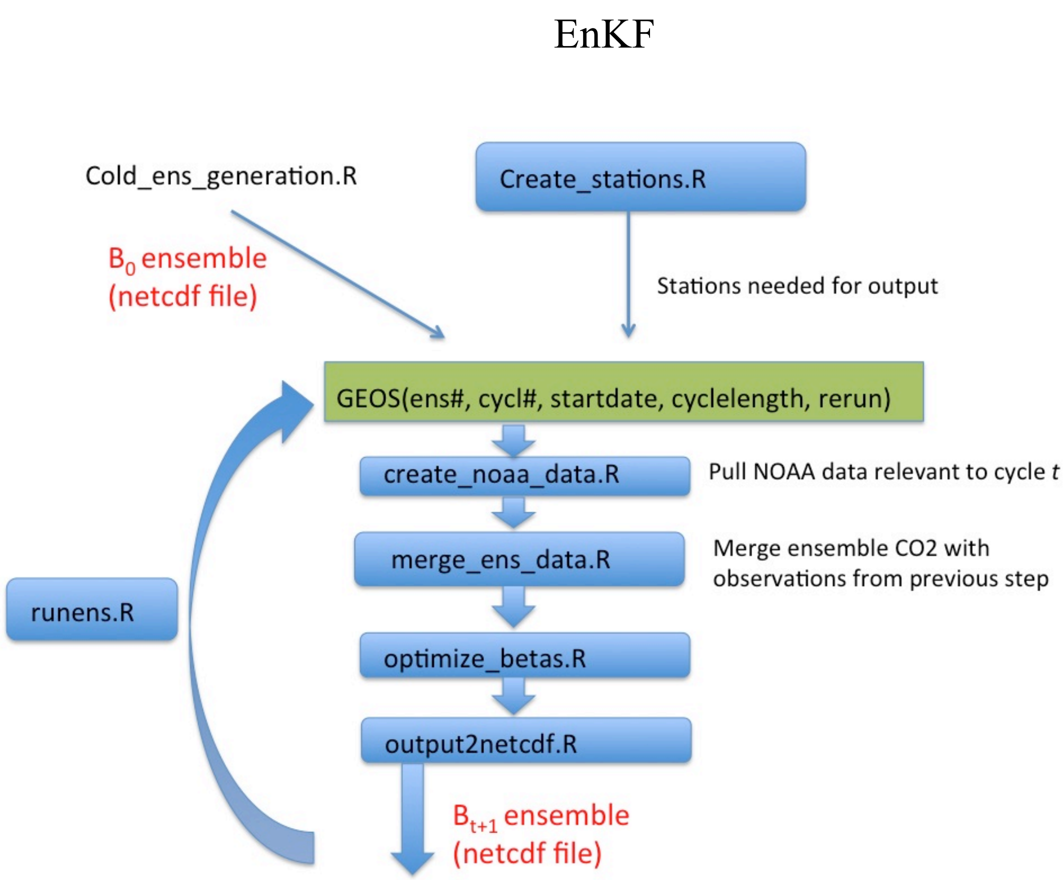

Figure 7: Algorithm and code structure for processing GOSAT retrievals in the Ensemble Kalman Filter using GEOS-Chem with SiB4, Doney Oceans, and ODIAC fossil fuel emissions.

We have altered GEOS-Chem to incorporate new CO2 tracers including SiB hourly NEE, Woods Hole monthly and daily air-sea exchange (c/o Dr. Doney), ODIAC fossil emissions, as well as a generic combined flux. All of the flux data we maintain is now CF/COARDS compliant NetCDF and our alterations to GEOS-Chem I/O support this format.

We have used this system to process one year of GOSAT data (ACOS version B2.10 provided by Chris O'Dell), by estimating optimum GPP and Ecosystem Respiration at every model grid cell in each month, along with the observation error along with the satellite track (Fig 8). For these experiments, transport was driven by MERRA 1 x 1.25 degree gridded to 2 x 2.5 degree, which is 10 times higher resolution than our previous 6 x 10 work. The inversion at 2 x 2.5 included 16,000 state variables run in 14-day cycles from the middle of 2009 through 2010. The prior had a balanced GPP and respiration over land and a non-zero ocean flux.

Several interesting regional patterns are apparent (Fig 9), such as the colocation of C sink regions with industrialized fossil emission zones as well as apparent biases in the northern latitudes (Siberia in particular). Our next steps include (1) a better "spinup" of the inversion via using a priori flux corrections based upon past in situ inversions conducted on NOAA surface data, (2) a longer integration, and (3) comparison of the seemingly spurious inversion results (such as Siberia and fossil fuel regions) with covariates in the retrieval (e.g.,aerosol optical depth) which could potentially bias it. The "dipole" behavior of temperature northern midlatitude fluxes and northern boreal fluxes where the sum is better constrained than the individual pieces seem to imply that one flux region is becoming biased and then the other is being forced to respond to it to maintain global CO2 constraints.

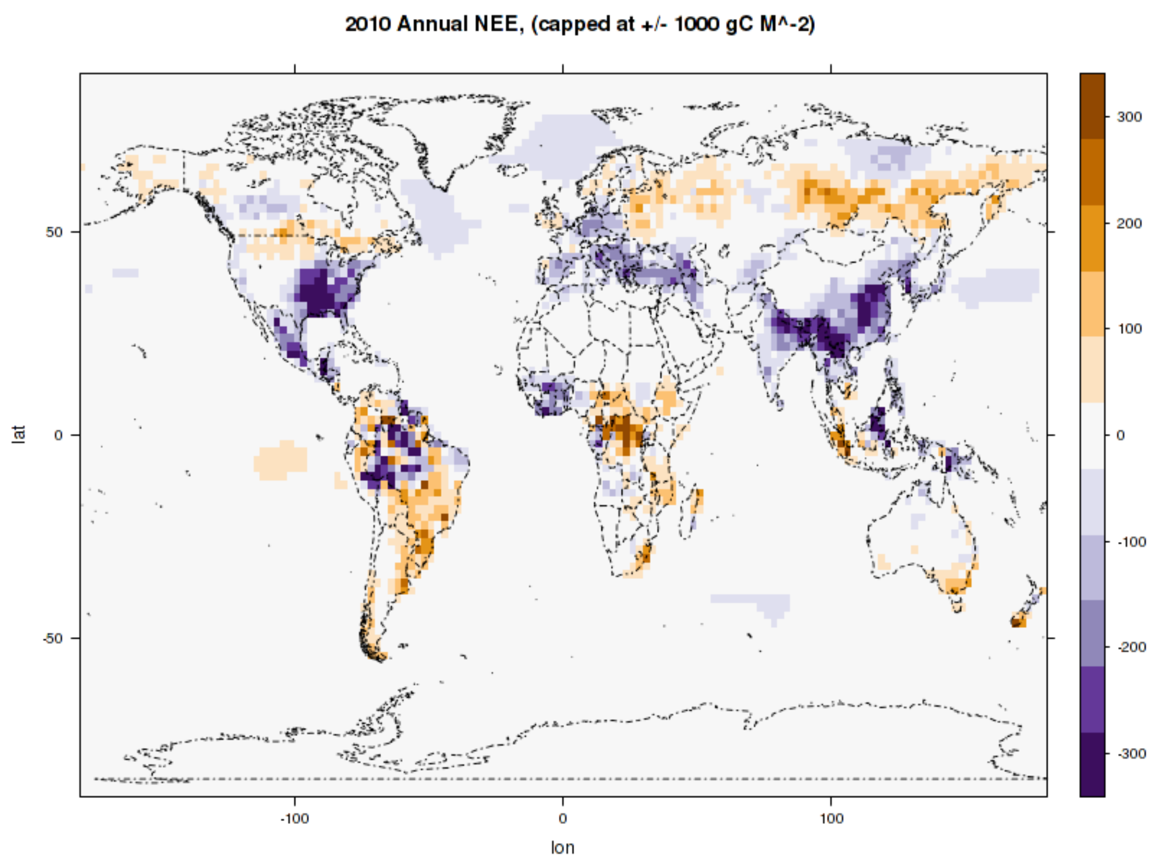

Figure 8: Global net terrestrial carbon fluxes for 2010 estimated from actual GOSAT retrievals using SiB4 and GEOS-Chem in the EnKF.

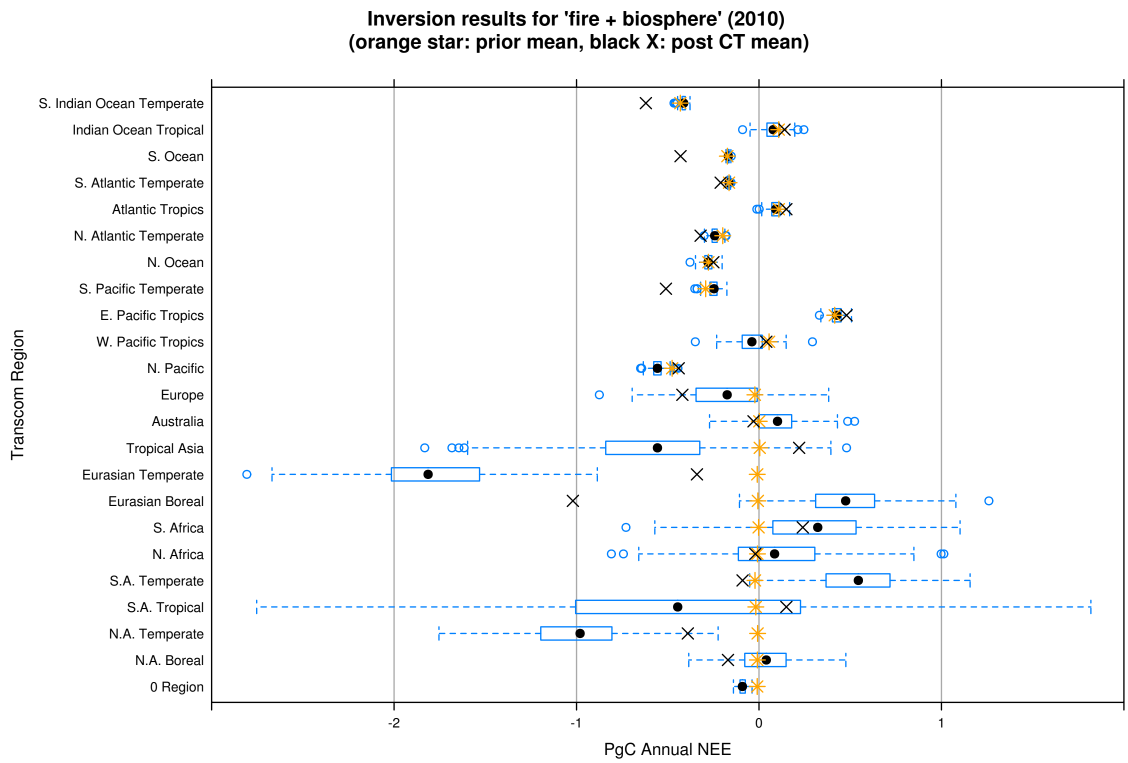

Figure 9: Regional aggregation of GOSAT inversion results from Fig 8 above. Priors are indicated by orange stars, and our flux estimates are shown in black circles with blue uncertainties. CarbonTracker estimates are shown for reference with black X symbols.