Progress Report: FY2009

Atmospheric Modeling, Assimilation and Source-Sink Estimation for the Carbon Cycle (NASA MAP/04-0085-0081)

CSU Denning SubProject

Summary:

We have deveoped a predictive, mechanistic model (the Simple Biosphere Model, SiB) of land-surface CO2 fluxes intended to provide surface forcing for assimilation of CO2 mixing ratios from in-situ and orbital platforms into the GEOS-5 atmosphere. The model will be capable of capturing most of the high-frequency variability (e.g., diurnal cycles of photosynthesis, synoptic variations associated with weather, seasonal cycles of leaf-on and leaf-off) that produce strong “nuisance” variability when trying to retrieve sources and sinks. Recent improvements include prediction of seasonal cycles and spatial gradients by assimilation of MODIS imagery, treatment of croplands, and soil hydrology in tropical forests.

The model has been tested against local and regional observations, and was used to develop synthetic CO2 flux and mixing ratio data for observing system simulation experiments (OSSEs). The OSSE data have been distributed via the Oak Ridge DAAC to a large community of atmospheric transport modelers, who have used them for an intercomparison experiment to evaluate diurnal and synoptic variations of CO2 mixing ratios against tower observations around the world, leading to a series of papers.

Finally, we are also developing and testing a system for source/sink estimation on a relatively fine spatial grid from high-frequency in-situ data and GOSAT data as they become available. The ensemble data assimilation system has been tested with synthetic data and described in a journal article which was published last year. It is capable of processing the very large observation vector anticipated from GOSAT, and shows excellent skill at recovering regional sources and sinks, both over land and ocean.

We have revised our modeling platforms to work with GEOS5 products rather than the GEOS4 analyses we have used to date. This will eventually allow seamless analyses from 1979 to the ongoing present. In addition, we have worked with Scott Doney and colleagues to incorporate their ocean flux model and with Denis O’Brien to prepare to assimilate the GOSAT Level2 data into GEOS5/PCTM for source/sink estimation.

Note that the work described here is much more ambitious than can be supported solely by the modest subaward from NASA-MAP. The research is jointly supported by NASA and the US Department of Energy, and papers describing it will acknowledge multiple funding sources.

Further detail on each component of the research is provided below.

Summary of Accomplishments for 2009

In our 2008 report, we identified the following priority tasks for 2009:

- Work with our GMAO colleagues (especially Pawson and Kawa) to obtain and process output files from the GEOS5 reanalysis;
- Use our ensemble data assimilation system to estimate gridded sources and sinks of CO2 over the period 2002-2007, and compare to other published results;
- Conduct a preliminary assimilation of GOSAT L1 and L2 products in collaboration with Denis O'Brien and the rest of our MAP-funded colleagues.

We have accomplished all of the above objectives. Since the tragic loss of the OCO mission, we have refocused our OSSE work to prepare to assimilate GOSAT data.

1. Observing System Simulation Experiments with GOSAT observations

We are analyzing GOSAT/Tanso data using a combination of existing models of CO2 exchanges due to hourly photosynthesis and respiration (Baker et al, 2008), daily air-sea gas exchange (Doney et al, 2009), biomass burning (GFED, Randerson et al, 2007), Fossil Fuel Emissions (Gurney et al, 2009), and atmospheric transport (PCTM, Kawa et al, 2004). This comprehensive system allows direct comparison to the observed record of both in-situ and remotely sensed atmospheric CO2 at hourly timescales. We have previously demonstrated that a lower-resolution version of the system has good skill at replicating diurnal, synoptic, and seasonal variations over vegetated land surfaces (Parazoo et al, 2008). The analysis system will be operated on a 0.5° x 0.67° grid ($\Delta x \sim$ 50 km), providing global mesoscale coverage. The system is driven by meteorological output from the NASA Goddard EOS Data Assimilation System, version 5. Surface weather from the system drives calculations of terrestrial ecosystem metabolism (radiation, precipitation, humidity, temperature) and air-sea gas exchange (wind), with other input data coming from satellite data products (e.g., fPAR and LAI from MODIS, and ocean color from SeaWiFS and MODIS).

We originally planned to assimilate GOSAT/Tanso Level 1b spectra into this system by using the full-physics algorithm developed initially for OCO. Instead we have made arrangements to use the results of the full-physics retrieval algorithm obtained through the ACOS (Atmospheric Carbon dioxide Observations from Space) team at Colorado State University (Denis O'Brien and Chris O'Dell, PI's). For comparison, we will also assimilate the GOSAT/Tanso L2 products as they become available. The forward surface and atmospheric models provide a background field for the retrieval of column CO2 mixing ratio. The difference between the background fields and the CO2 estimated from the full-physics algorithm is be used to calculate a global cost function which is then minimized to obtain corrections to the surface models. Ensemble Data Assimilation (EnsDA) methods are employed to minimize the cost function.

The results of these calculations are estimates of time-varying surface sources and sinks of CO2 that are optimized with respect to GOSAT/Tanso observations, MODIS data, emissions inventories, and mechanistic models.

Component Model Descriptions:

Terrestrial Ecophysiology (SiB)

We use the Simple Biosphere model (SiB), which is based on a land-surface parameterization scheme originally used to compute biophysical exchanges in climate models (Sellers et al., 1986), but later adapted to include ecosystem metabolism (Sellers et al., 1996a; Denning et al., 1996a). The parameterization of photosynthetic carbon assimilation is based on enzyme kinetics originally developed by Farquhar et al. (1980), and is linked to stomatal conductance and thence to the surface energy budget and atmospheric climate (Collatz et al., 1991, 1992; Sellers et al., 1996a; Randall et al., 1996). The model has been updated to include prognostic calculation of temperature, moisture, and trace gases in the canopy air space, and the model has been evaluated against eddy covariance measurements at a number of sites (Baker et al., 2003; Hanan et al., 2004; Vidale and Stöckli, 2005). Revised treatment of root zone hydrology and physiological stress has resulted in improved simulation of the seasonality of transpiration, photosynthesis, and ecosystem respiration at tropical sites in the Amazon (Baker et al, 2008) and Africa (Williams et al, 2007). Other recent improvements include biogeochemical fractionation and recycling of stable carbon isotopes (Suits et al., 2005), improved treatment of soil hydrology and thermodynamics, and the introduction of a multilayer snow model based on the Community Land Model (Dai et al., 2003). Direct-beam and diffuse solar radiation are treated separately for calculations of photosynthesis and transpiration of sunlit and shaded canopy fractions, using algorithms similar to those of DePury and Farquhar (1997). The model is now referred to as SiB3.

Until recently, ecosystem respiration was treated in SiB by scaling a temperature and a moisture response to achieve net carbon balance at every grid cell in one year by prescribing the size of a single pool of organic matter. This approach has recently been replaced by a scheme for allocation, transformation, and decomposition based on the Carnegie/Ames/Stanford Approach (CASA, Randerson et al., 1997). Stored photosynthate is allocated to leaves, stems, and roots in fractions that are constrained by changes in satellite vegetation index (NDVI). Carbon is tracked through biomass pools and released to the surface as dead litter, woody debris, and root litter, where it interacts with a microbial pool to produce several pools of soil organic matter and CO2. The interactive biogeochemistry module has been tested at dozens of eddy-covariance sites and found to improve simulations of the seasonal cycle of net ecosystem exchange relative to the single-pool model it replaces (Schaefer et al, 2008). Following previous work with CASA (van der Werf et al, 2006), we also plan to add a fire module to this model. The incorporation of the fire module is partly supported by NASA through a subcontract from Goddard Space Flight Center.

Historically, SiB has used prescribed vegetation parameters derived by remote sensing (Sellers et al., 1996b). At global scales, this approach allows realistic simulation of spatial and temporal variations in vegetation cover and state (Denning et al., 1996; Schaefer et al., 2002, 2005). At the underlying pixel scale, however, phenology products derived from satellite data must be heavily smoothed to remove dropouts and artifacts introduced by frequent cloud cover. An inevitable trade-off between cloud-induced "noise" in the leaf area and time compositing systematically stretches the seasonal cycle by choosing data late in each compositing period in spring, and early in each composite in fall. We have addressed this problem by developing and testing a prognostic phenology module for SiB (Stockli et al, 2008). We have assimilated vegetation imagery into the prognostic phenology model to estimate its parameters (e.g., growing degree day thresholds), rather than forcing it with the satellite data.

We have developed and tested an explicit treatment of phenology and physiology of agricultural crops, and parameterized of the crop model using data from flux towers, experimental farms, and agricultural databases (Lokupitiya et al, 2009). The model represents fluxes from multiple sub-grid scale "tiles" (e.g., corn, soy, wheat, pasture), and the revised model matches observed fluxes, leaf-area, and grain yield much better than the control (Corbin, 2008).

Global Fire Emissions Database (GFED)

Emissions of CO2 due to biomass burning are specified using the Global Fire Emissions Database (GFED v2.1, Randerson et al, 2007). The 8-day emissions data set was compiled using satellite data and the Carnegie-Ames-Stanford Approach (CASA) biogeochemical model. Burned area from 2001-2004 was derived from active fire and 500-m burned area data from MODIS (Giglio et al., 2006). ATSR (Along Track Scanning Radiometer) and VIRS (Visible and Infrared Scanner) satellite data were used to extend the burned area time series back to 1997 (Arino et al., 1999; Giglio et al., 2003; Van der Werf et al., 2004). Fuel loads and net flux from terrestrial ecosystems were estimated as the balance between net primary production, heterotrophic respiration, and biomass burning, using time varying inputs of precipitation, temperature, solar radiation, and satellite-derived fractional absorbed photosynthetically active radiation. Tropical and boreal peatland emissions were also considered, using a global wetland cover map (Matthews and Fung, 1987) to modify surface and belowground fuel availability.

Ocean Circulation and Biogeochemistry

Air-sea gas exchange is derived from a multi-decade (1979–2004) hindcast experiment conducted with the Community Climate System Model (CCSM-3) ocean carbon model (Doney et al, 2009). The CCSM-3 ocean carbon model incorporates a multi-nutrient, multi-phytoplankton functional group ecosystem module coupled with a carbon, oxygen, nitrogen, phosphorus, silicon, and iron biogeochemistry module embedded in a global, three-dimensional ocean general circulation model. The model is forced with physical climate forcing from atmospheric reanalysis and satellite data products and time-varying atmospheric dust deposition. Data-based skill metrics have been used to evaluate the simulated time-mean spatial patterns, seasonal cycle amplitude and phase, and subannual to interannual variability. Evaluation data include: sea surface temperature and mixed layer depth; satellite-derived surface ocean chlorophyll, primary productivity, phytoplankton growth rate and carbon biomass; large-scale climatologies of surface nutrients, pCO2, and air–sea CO2 and O2 flux; and time-series data from the Joint Global Ocean Flux Study (JGOFS).

Atmospheric Tracer Transport (PCTM)

The Parameterized Chemistry Transport Model (PCTM) will be used for forward global simulations of CO2 transport (Kawa et al., 2004; Parazoo et al, 2008). This provides a diagnostic tool for studying synoptic interactions among weather and surface CO2 flux. Transport fields will be provided by the NASA Goddard EOS Data Assimilation System, version 5 and include 6-hourly analyzed winds, temperatures, and convective/diffusive parameters for off-line transport (Rienecker et al., 2008). The GEOS-5 atmospheric general circulation model maintains the finite-volume dynamics (Lin, 2004) used for GEOS-4 and found to be effective for transport in the stratosphere and troposphere. The physical parameterizations include four major groups of processes and their submodules: moist processes, radiation, turbulent mixing, and surface processes. Moist convective mass flux is calculated with a relaxed Arakawa-Schubert scheme (Moorthi and Suarez, 1992). Subgrid scale vertical processes also include a turbulent mixing scheme. GEOS-5 uses a new grid point statistical interpolation assimilation method that is a three-dimensional variational analysis applied in grid-point space.

Global Flux Estimation by Data Assimilation

We use the component models described above to obtain an improved analysis of global sources and sinks of CO2 at regional scales. For the first time, this analysis will include mechanistic treatment of all components of the carbon cycle (fossil fuels, air-sea gas exchange, biomass burning, photosynthesis, and respiration) and their error covariances, constrained by multiple data streams.

We separate the well-understood "fast" processes driven by environmental forcing (temperature, solar radiation, precipitation, wind speed) from "slow" processes driven by less-understood biases in biogeochemistry and emissions. The total flux of CO2 to the atmosphere from any grid cell at any time can be written as:

$$\begin{aligned} F_T(x,y,t) = {} & \beta_{FF}(x,y)FF(x,y,t) + \beta_{Fire}(x,y)Fire(x,y,t) \\ & + \beta_{RESP}(x,y)RESP(x,y,t) - \beta_{GPP}(x,y)GPP(x,y,t) \\ & + \beta_{Ocean}(x,y)Ocean(x,y,t) \end{aligned}$$

where x and y denote the spatial coordinates and t represents the time, which is at hourly resolution. Here *FF*, *Fire*, *RESP*, *GPP*, and *Ocean* refer to the hourly gridded flux estimates described above. The β's represent persistent multiplicative biases in the grid-scale component fluxes. A persistent bias in photosynthesis might result (for example) from underestimation of available nitrogen, forest management, or agricultural land-use, whereas a persistent bias in respiration might result from overestimation of soil carbon or coarse woody debris. Sub-daily variations in the simulated component fluxes respiration and GPP are primarily controlled by the weather (especially changes in radiation due to clouds and the diurnal cycle of solar forcing), whereas seasonal changes are derived from phenological calculations parameterized from satellite imagery. Fine scale spatial variations are driven by changes in vegetation cover, soil texture, and soil moisture. It is reasonable to assume that the biases vary much more slowly than the fluxes themselves. Our method allows for component fluxes to vary on hourly, synoptic, and seasonal time scales, but assumes that biases in these fluxes persist for a period of approximately 2 months.

Optimization of the bias vector is accomplished using the Maximum Likelihood Ensemble Filter (MLEF, Zupanski, 2005; Zupanski et al, 2007; Lokupitiya et al, 2008). Important advantages of the MLEF are (1) that it can operate on fully mechanistic forward models of the component fluxes without requiring the derivation of their adjoints, and (2) it can be efficiently integrated in parallel on large computer clusters. The outcome of this calculation will be time-resolved maps of CO2 sources and sinks at grid scale with mechanistic attribution that also optimally match observations of many kinds. Additionally, the MLEF allows us to quantify uncertainty in sources and sinks.

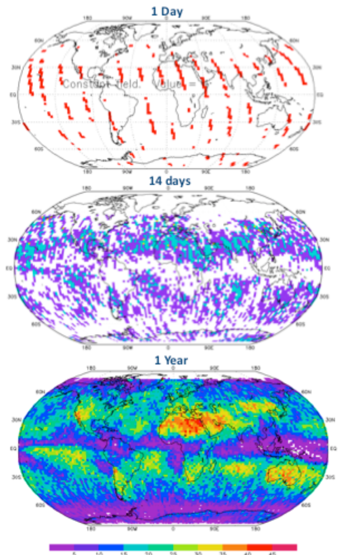


Figure 1: Sampling density for OSSE

We have tested the ensemble assimilation system using synthetic GOSAT data. Multiplicative biases (b) were specified to represent reasonable spatial patterns associated with CO2 fertilization, atmospheric nitrogen deposition, forest regrowth, boreal growing season changes, and a saturating sink in the Southern Ocean. Random grid-scale perturbations were added to each of these biases in each month, and synthetic CO2 data were created. Atmospheric columns were then sampled along the GOSAT orbit and masked for subgrid-scale clouds using NCEP-2 reanalyses. The resulting observation density is shown in Fig 1.

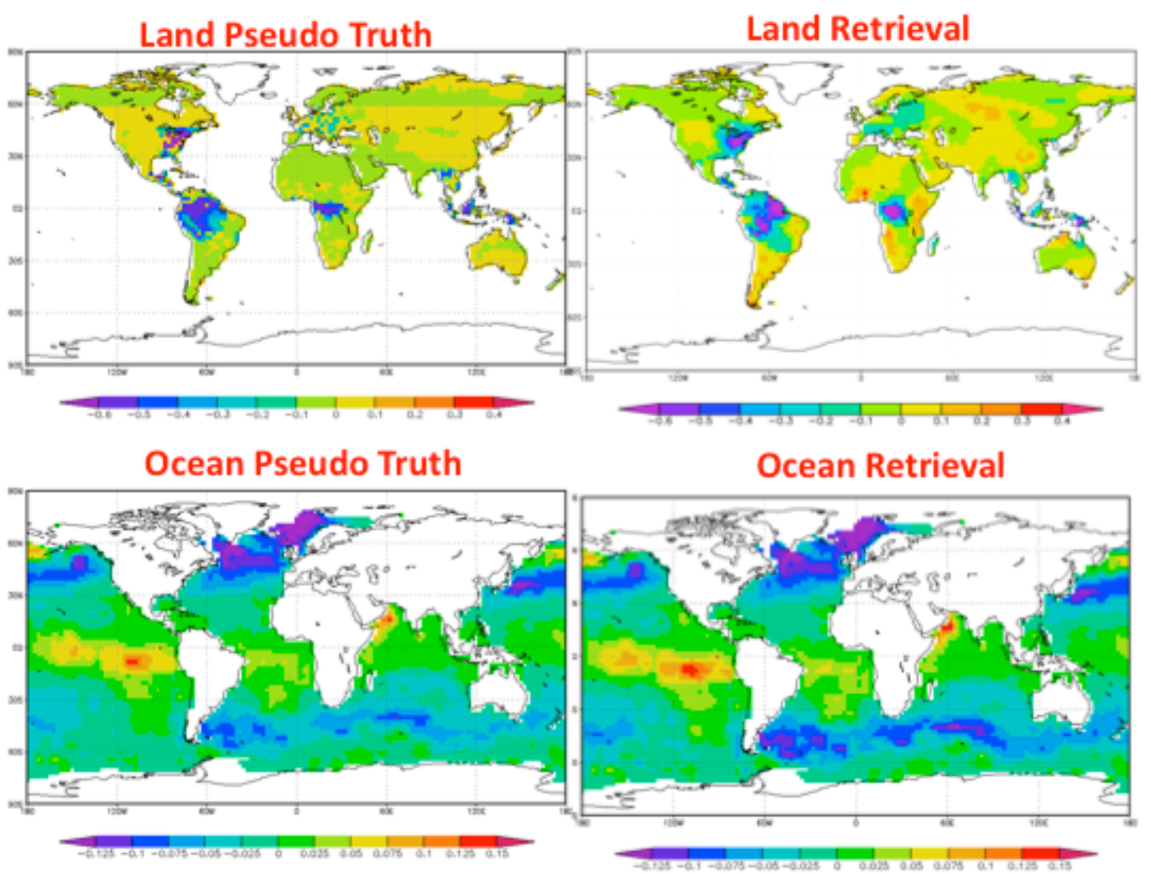


Figure 2: Results of OSSE assimilation of GOSAT observations for one year. "True" and estimated fluxes (μMol CO_2 m^{-2} s^{-1}) recovered by Ensemble Data Assimilation.

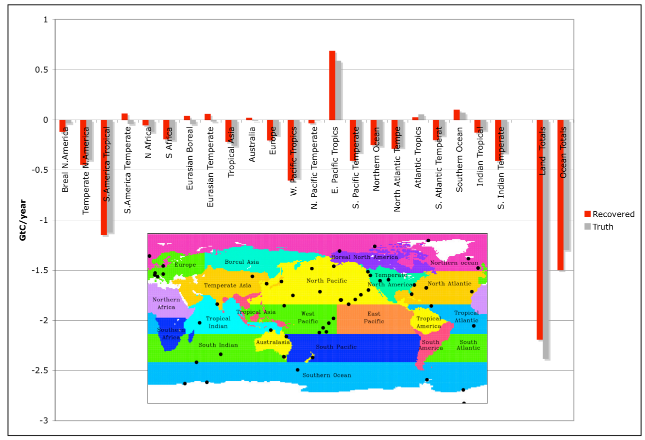


Figure 4: Post-aggregated flux estimates by TransCom region for OSSE compared to pseudo-truth (inset shows regions). Note that all land (but not ocean) priors were zero.

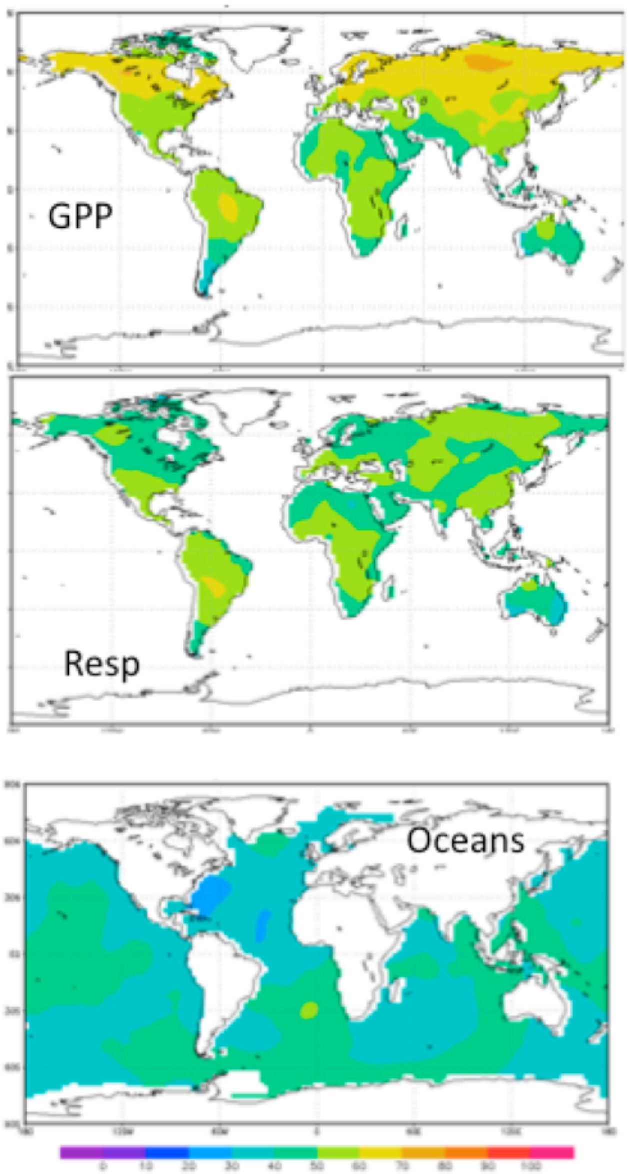


Figure 3: Uncertainty reduction (percent) relative to prior fluxes

A constant prior bias of $\beta(x,y,t)$=0.0 was assumed for all flux components, and new biases were estimated every month, with covariance propagation. Resulting fluxes were well-estimated (Fig 2) with excellent reduction of uncertainty over land. Ocean fluxes were somewhat less well-determined, due to the weaker fluxes there. (Fig 3)

An important advantage of the MLEF system is that we are able to “post-aggregate” fluxes and their uncertainties a posteriori using the error covariance statistics that result from the optimization. Doing this shows excellent retrieval of annual fluxes over TransCom regions (Fig 4). Note that prior fluxes over all land regions were precisely zero due to the net annual balance architecture of SiB.

2. Global Simulations of Atmospheric CO2 using GEOS-5 Products

We have updated the SiB-PCTM simulation experiments to the latest version of GEOS-DAS, version 5.1.0 of the GEOS general circulation model (GEOS5). GEOS5 is a new global reanalysis product from Goddard that resolves atmospheric processes at the mesoscale, using horizontal resolution of 0.5 latitude x 0.67 longitude (including 72 vertical levels), making possible global mesoscale simulations of atmospheric carbon. In the poster, we tested sensitivity of carbon flux calculations in SiB and synoptic variations of atmospheric CO2 in PCTM to GEOS4 (1.0 latitude x 1.25 longitude x 25 vertical levels) and GEOS5, to demonstrate: 1) the influence of spatial resolution on atmospheric CO2 and, 2) the influence of surface meteorology on GPP.

On the land surface side, with regard to GPP, owing to the strong sensitivity of SiB GPP to environmental factors such as atmospheric moisture, precipitation, and temperature, we find global, regional, and annual changes in GPP between reanalysis products. Enhanced moisture (in the atmosphere and soil) and decreased surface temperature in GEOS5 in Northern Hemisphere upper latitudes promotes more favorable environments for photosynthesis. Overall, global GPP increases from 111 GtC/yr using GEOS4 to 122 GtC/yr in GEOS5, which is consistent with estimates from the MODIS algorithm (Zhao et al., 2005).

On the atmospheric side, we performed experiments to determine whether day-to-day variations in atmospheric CO2 are more sensitive to land surface flux (based on SiB GPP calculated using GEOS4 and GEOS5, assuming constant transport) or changes in transport resolution (based on transport by GEOS4 and GEOS5, assuming constant GPP). Using time lag correlations of model output to surface observations over North America, Europe, and several remote sites, we find in general stronger correlations at zero time lag when moving the transport driver from GEOS4 to GEOS5. Changes in SiB GPP seem to have negligible impact on these correlations.

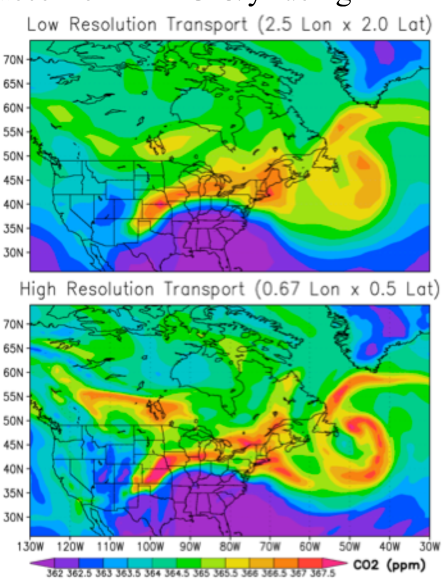
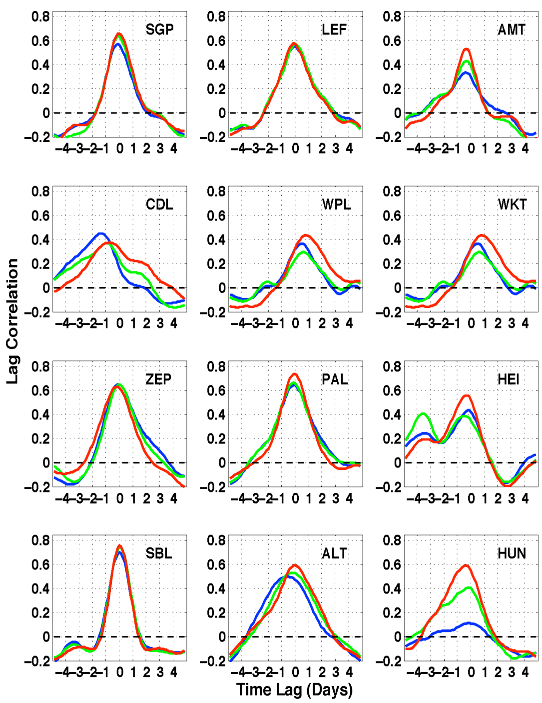


Figure 5: Simulated X_{CO2} for March 5, 2004 using two different grids

Figure 5 compares snapshots of column-integrated CO2 mixing ratio as simulated by SiB-PCTM using the 2x2.5 GEOS4 and the 0.5x0.67 GEOS5 transport. Much tighter gradients and spatial detail appear in the finer-scale simulation. To evaluate the realism of these simulations, we compared the timeseries of simulated surface CO2 with in-situ observations for 12 stations in the Northern Hemisphere (Fig 6). Autocorrelation with the observations is higher at almost all sites using the finer-resolution meteorology, and lags are improved at some sites.



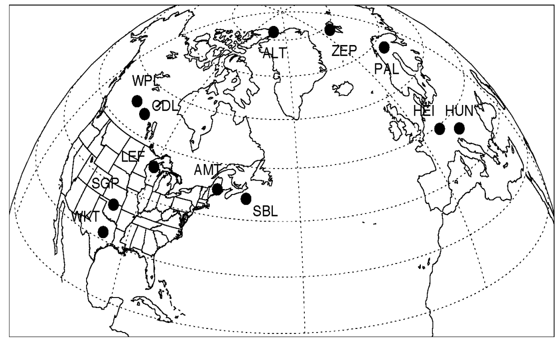


Figure 6: Lagged correlation analysis of synoptic variations of simulated and observed CO_2 at 12 in-situ stations (locations shown above). Abscissa is time lag (days). Blue is driven by GEOS-4 at 2°x2.5°, green uses GEOS4 at 1°x1°, and red uses GEOS-5 at 0.5°x0.67°

To interpret the sensitivity of day-to-day variations in atmospheric CO2 to transport, we use Eddy Decomposition of atmospheric transport to break down the meridional circulation into large scale transport by the mean meridional circulation (e.g., Hadley Cell), regional transport by stationary eddies (e.g., Bermuda High, Icelandic Low, etc), and regional transport by transient eddies (storm tracks). We believe it is transport along storm tracks that have the most influence on high frequency midlatitude variations. Using this analysis framework, we find sensitivity of transport by Transient Eddies to transport resolution. (Fig 7).

Using this method, we investigated the differences in transport mechanisms between the coarse (2x2.5) and fine (0.5x0.67) models (Fig 8). As expected, total meridional transport is not substantially different among the models, but there is a tradeoff among the strengths of different mechanisms. In the fine-scale transport model, meridional transport by the transient eddies (baroclinic waves) is stronger due to better resolution of both tracer gradients amd frontal meteorology. This is compensated by stronger symmetric transport in the Mean Meridional Ferrel Cell. There are important implications for interpretation of satellite CO2 products because of cloud masking in frontal zones (Fig 9) where the satellite will never sample.

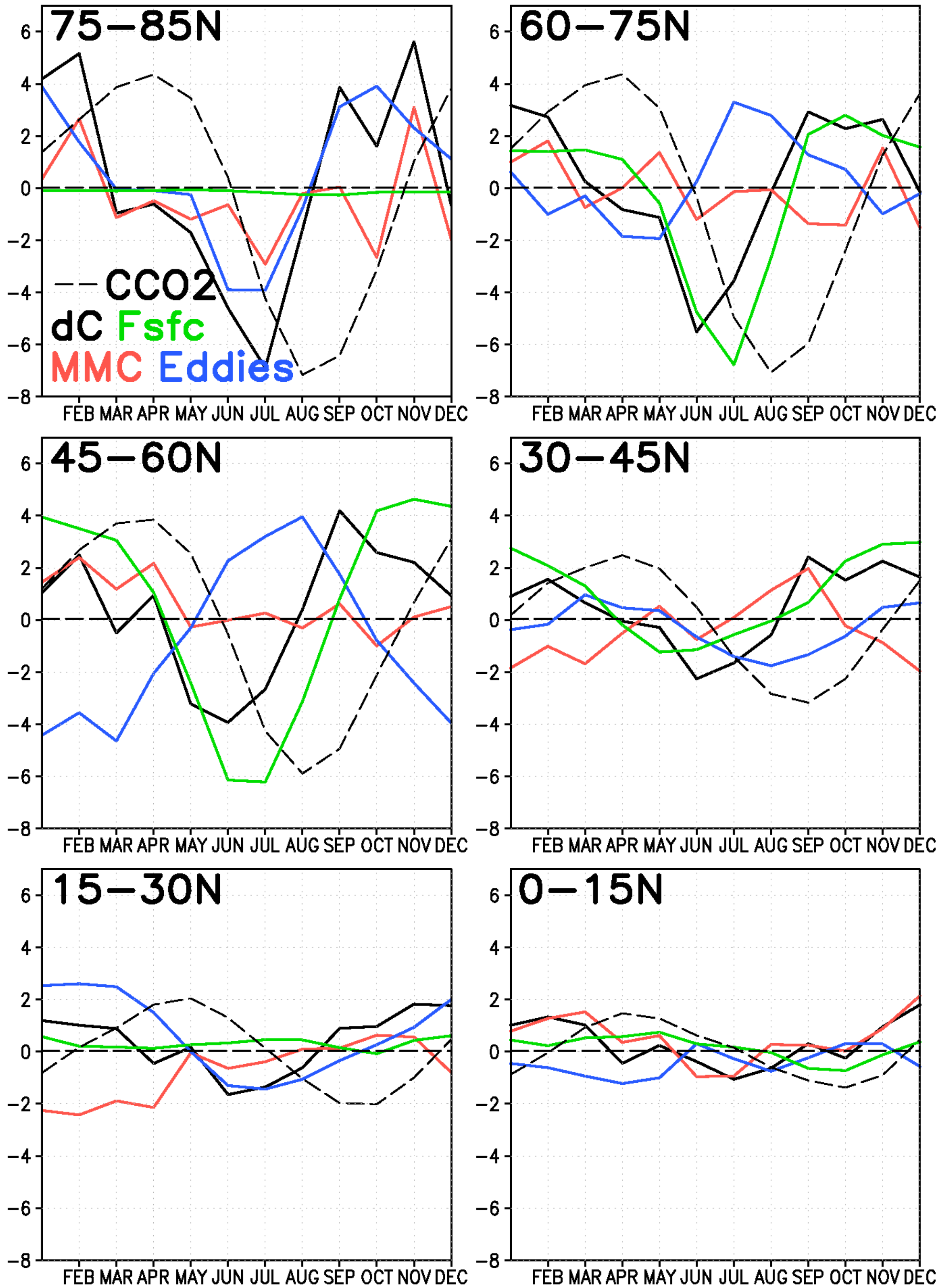


Figure 7: Vertically-integrated CO2 budgets (ppm/month) over zonal bands of the atmosphere.

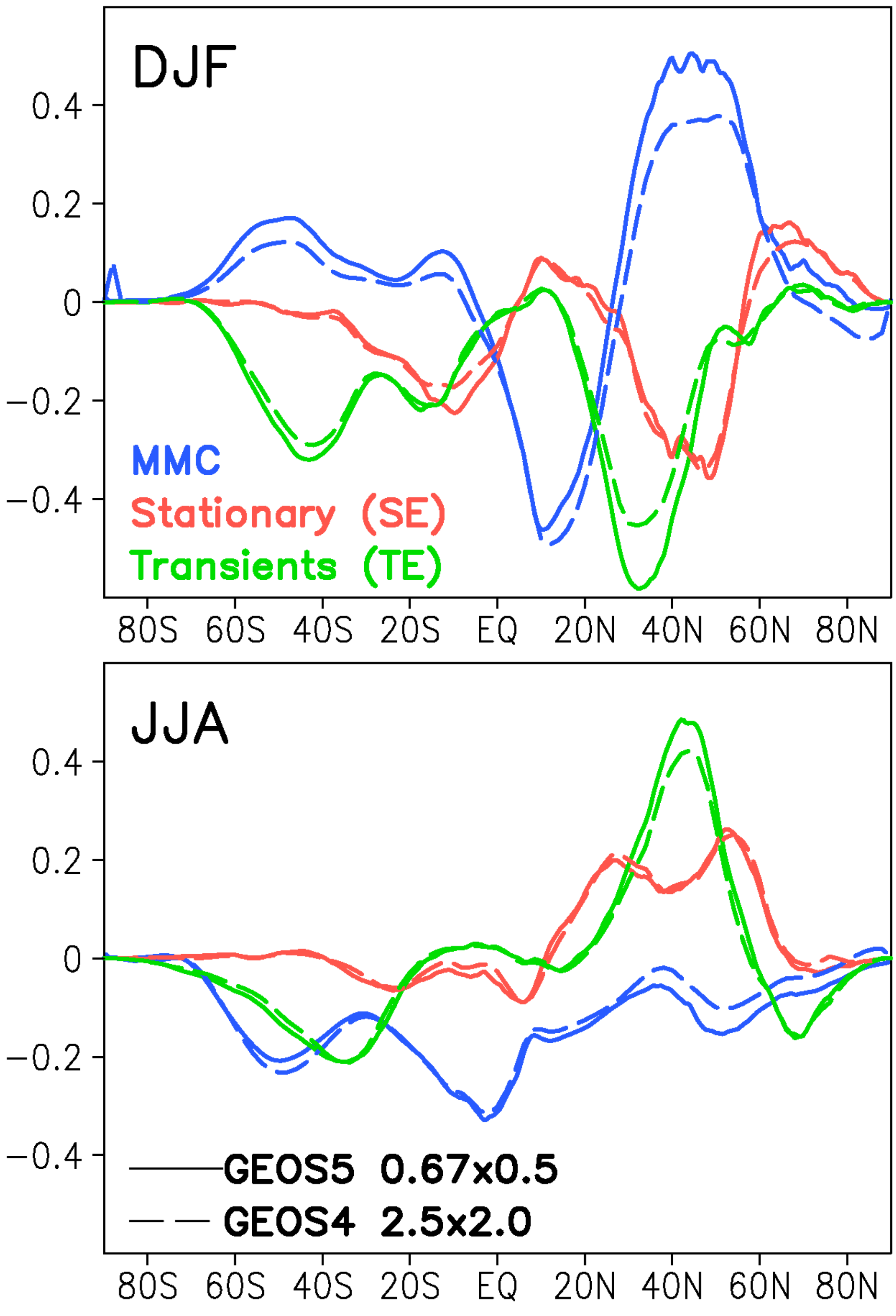


Figure 8: Meridional transport (PgC/month) by the mean meridional circulation (blue), stationary eddies (red), and transients (green) as simulated in SiB-PCTM using 2x2.5 degree (dashed) and 0.5x0.67 degree (solid) meteorology.

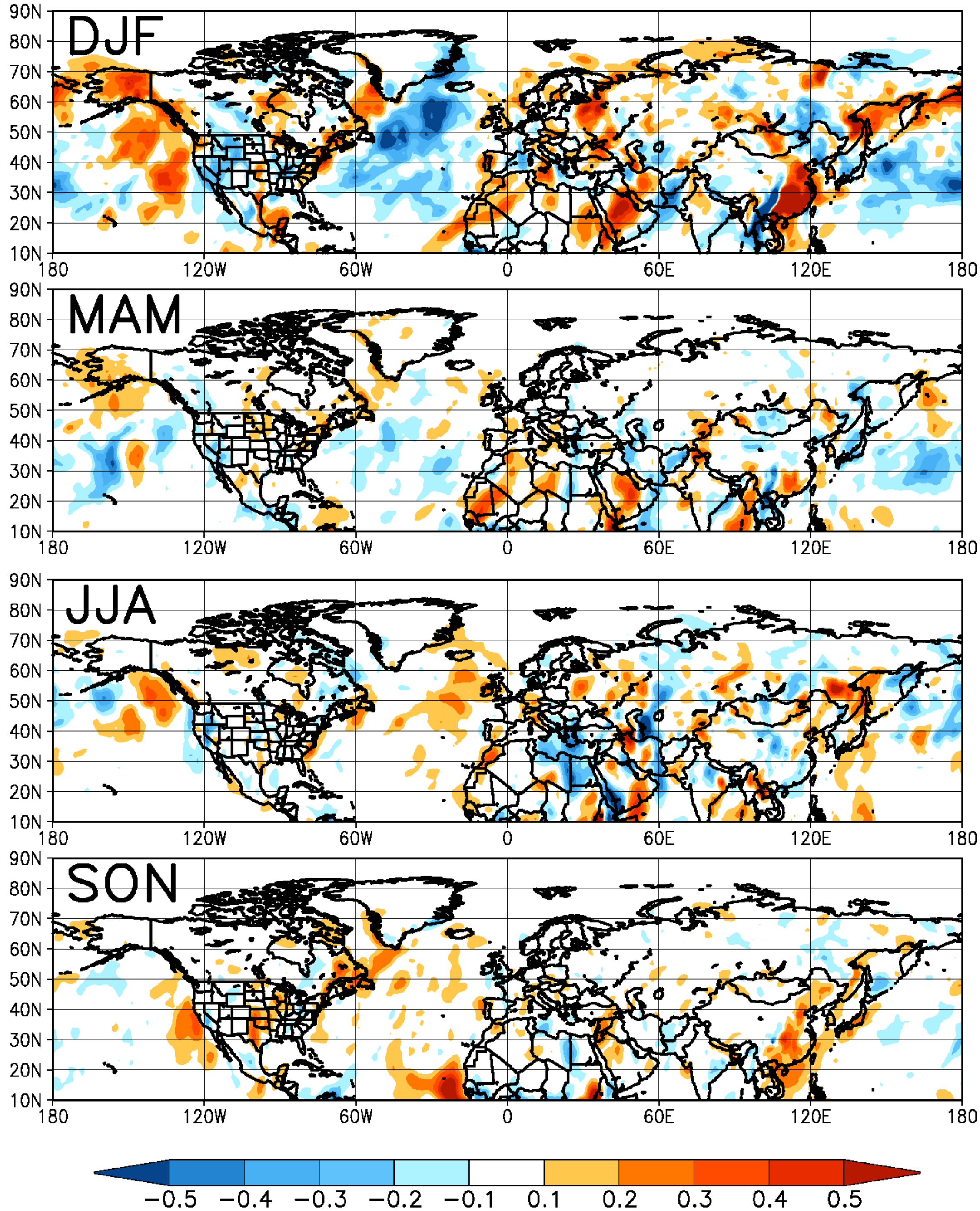


Figure 9: Difference in meridional transport (PgC/month) by stationary and transient eddies as simulated by SiB-PCTM using 2x2.5 degree vs 0.5x0.67 degree meteorology.

3. Plans for 2010

In 2010, we will repeat and extend our reanalysis using the MERRA reanalysis, and finish testing the source/sink data assimilation system, and perform a systematic comparison of our simulated global CO2 fields to the GOSAT observations. In particular, we identify the following tasks for FY 2010:

- Work with our GMAO colleagues (especially Pawson and Kawa) to obtain and process output files from the MERRA reanalysis;
- Use our ensemble data assimilation system to estimate gridded sources and sinks of CO2 over the period 2002-2009, and compare to other published results;
- Conduct a preliminary assessment of our simulated 3D global CO2 product with the GOSAT L2 products in collaboration with Denis O'Brien and the rest of our MAP-funded colleagues.

Please note that the research described herein is not supported entirely by NASA-MAP, but rather relies on substantial collaboration with other CSU projects funded by NASA, NOAA, DOE, and NSF.

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6. Figures