MODELING THE GLOBAL ATMOSPHERIC CARBON CYCLE IN PREPARATION FOR OCO DATA

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Abstract

We propose to build on process-level understanding and global simulation capability developed in previous work to synthesize an improved modeling/data analysis procedure capable of incorporating OCO and other relevant data to more precisely characterize the atmospheric carbon budget. Recent progress in simulating atmospheric CO_2 using models driven by analyzed meteorology from the NASA GEOS-4 data assimilation demonstrates considerable skill in reproducing observed variability on time scales from hourly to interannual. The ability to meaningfully compare simulated CO_2 with real-time, local observations allows us to better exploit the information content of more extensive and intensive observations including those from the Orbiting Carbon Observatory (OCO) scheduled for launch in 2008. These observations comprise a wealth of information on the distribution and sensitivity of carbon cycle processes over a wide range of time and spatial scales. Better understanding of these processes and their representation in numerical models is key to resolving long-standing uncertainties in the CO_2 budget and confidently projecting interactions of the carbon cycle with climate change. Our goal is to utilize OCO and other data constraints to reduce uncertainty in the atmospheric carbon budget and its dependence on changing weather and climate.

Specific tasks include: 1) Continue to evaluate and quantify uncertainty in atmospheric transport and its impact on top-down inference of carbon source/sink distributions including evaluation of the transport characteristics of GEOS-5. 2) Integrate, evaluate, and refine terrestrial biogeochemical process models constrained by global satellite observations including simulation of COS as an indicator of vegetation processes. 3) Prepare for OCO by testing inverse models and pseudo-data consistent with expected OCO instrument sampling, and, when available, use OCO data to infer CO_2 sources and sinks. The results will be improved models and process understanding directly relevant to the objectives of NASA Earth Science and Carbon Cycle Research.

1. Introduction

Carbon dioxide (CO_2) is the largest known anthropogenic forcing of climate change, yet substantial uncertainty is attached to the current atmospheric CO_2 budget. Global, decadal budgets summarized for the 1980s and 1990s infer a large residual sink for atmospheric CO_2 with attached uncertainty of 50 to 100% or more [IPCC, 2001; SOCCR, 2007]. Several lines of evidence suggest that the northern hemisphere terrestrial biosphere is responsible, but the magnitude, location, and mechanisms producing the sink are not well determined [Tans et al., 1990; Fan et al., 1998; Bousquet et al., 2000; Yang et al., 2007]. Furthermore, interannual variability in the increase of atmospheric CO_2, and hence variation in the terrestrial sink (and to a lesser extent ocean), is large, but the forcing/response mechanisms and connection to decadal processes are not quantitatively resolved [Conway et al., 1994; Langenfelds et al., 2002; Nemani et al., 2003]. Attempts to locate sources and sinks using diagnostic models are hampered by data limitations and uncertainty in atmospheric transport representation [Gurney et al., 2002].

As a result, carbon-climate interaction is among the leading sources of uncertainty in prediction of future climate. The projections depend on the details of the processes that couple carbon and climate [Cox et al., 2000; Dufresne et al., 2002, Fung et al., 2005]. For example, current ecological models are very sensitive to treatments of stresses, i.e., response of vegetation and soils to changing CO_2 and nutrient fertilization, temperature, moisture, fires, and management practices, that are difficult to validate. Hence, detailed, quantitative knowledge of the processes underlying the terrestrial sink and their accurate representation in models is needed for informed policy decisions regarding carbon and climate. We propose to address several aspects of this problem through modeling and data analysis as described below.

Progress in understanding the terrestrial sink and carbon/climate coupling will require improved models and enhanced data. New global remote sensing data from satellites hold great promise to advance carbon cycle science and reduce carbon process uncertainties. New and planned satellite data products include atmospheric CO_2 column abundance, location and intensity of biomass burning, vegetation photosynthetic activity, and improved land use/land cover change. In particular, the Orbiting Carbon Observatory (OCO) [Crisp et al., 2004] is scheduled for launch in late 2008, targeting for the first time, high precision, space-based global measurement of CO_2. The new parameters, coverage, and resolution provided by these data will require new modeling approaches to reap their benefit, and similarly to exploit new in situ observations. The ability of the models to accurately simulate processes must be improved in concert. The expected result of our proposed activity is a closer link between top-down and bottom-up estimates of processes and their sensitivities such that uncertainties are significantly reduced.

The overall objective is better scientific understanding of atmospheric and terrestrial carbon process and their model simulation. The proposed approach is to construct and test a model/data analysis system to incorporate OCO and other data and run that system when OCO data become available. Figure 1 shows a schematic of the main model and analysis components that are required. Several lines of model development/testing and uncertainty reduction are needed to support this structure. Within the scope of this proposal we will concentrate in 3 areas:

1) Continue to evaluate and quantify uncertainty in atmospheric transport and its impact on top-down inference of carbon source/sink distributions. This will include extension of our previous model/data comparisons [Kawa et al., 2004; Parazoo et al., 2006] to more locations and conditions including the tropics, further analysis under the Transcom-C and Upper Air model intercomparison protocols, and evaluation of the transport characteristics of the latest version of the NASA meteorological data assimilation model: GEOS-5. The critical question of the fidelity of the model vertical transport will be specifically addressed (e.g., Bian et al. [2006]).

2) Integrate, evaluate, and refine terrestrial biogeochemical process models constrained by global satellite observations and GEOS meteorology and transport. We will continue to improve parameterizations of biophysical flux processes (e.g., GPP, NPP, Rh) and sensitivity to meteorological forcing over a range of time scales using SiB-3, CASA, and the global SiB-CASA combination [Schaefer et al., 2007]. Model diagnostics will include simulation and comparison with COS data as an indicator of vegetation photosynthetic uptake in the absence of respiration (e.g., Kettle et al. [2002]; Montzka et al. [2007]). We will attempt to isolate impacts of El Nino and biomass burning on the CO_2 growth rate for the EOS satellite era using remote sensing and other constraints [Justice et al., 2002; van der Werf et al., 2006]. These process models form building blocks for multidisciplinary coupled Earth-system models to be used for carbon data assimilation and carbon-climate projection.

3) Prepare for OCO. Prior to launch we will exercise inverse models using priors derived from above with existing real-time data, in particular testing the advantages of the global Maximum Likelihood Ensemble Filter (MLEF) methodology [Zupanski and Zupanski, 2006]. We will also test varying aggregation strategies for OCO data with pseudo-data and sampling constraints consistent with the OCO instrument model. We will use our best estimate of the time-dependent

global CO_2 distribution derived from forward runs of the above models for comparison with ground based column observations and zero-order OCO data validation as they become available. When OCO data are validated we will use them to infer sources and sinks.

Relevance to NASA

The NASA Science Plan (2007) outlines five core scientific segments (variability, forcing, response, consequences, and prediction) required to address the overall Earth Science goal of answering "How is the Earth changing and what are the consequences for life on Earth?" The research proposed here primarily addresses the top-level questions associated with variability and response, which naturally bear on questions of prediction. We address "How is the global Earth system changing?" and more specifically "How are global ecosystems and atmospheric composition changing?" through detailed simulation of atmospheric carbon distributions and the ecosystem processes driving the carbon fluxes. We address "How does the Earth system respond to natural and human-induced change?" and specifically "How do ecosystems, biogeochemical cycles, and atmospheric trace constituents respond to and affect global environmental change?" through comparison of observations and simulations with data-constrained models. Progress in understanding and simulating these processes leads directly to "How will the Earth system change in the future?" and, in particular, "How can we improve our predictions?" Finally, all this rolls up toward the coupled prediction questions [NASA, 2007]: "How will future changes in atmospheric composition affect climate?" and "How will carbon cycle dynamics and terrestrial ecosystems change in the future?"

In terms of research objectives, the proposed research contributes directly to: 1) Understand and improve predictive capability for changes in climate forcing associated with changes in atmospheric composition, and 2) Improve carbon cycle and ecosystem models [NASA, 2007]. Within the Carbon Cycle and Ecosystems theme we enable the following objectives: document and understand how the global carbon cycle and ecosystems are changing, quantify global productivity and carbon fluxes, and provide useful projections of future changes in global carbon cycling and ecosystems as inputs for improved climate change predictions. We aim at the Global Carbon Modeling and Analyses Theme of the NRA, primarily focused on OCO, while bringing new and improved models and carbon data fusion along in the process. Through our collaborations, the global research also couples to the Regional Studies Uncertainties Theme, e.g., NACP.

2) Scientific Task Plan

The proposed task plan covers 3 main areas of research detailed below: transport model evaluation, terrestrial biosphere carbon flux process modeling, and preparing for OCO (including inverse modeling). Through each of these tasks runs a basic premise that time-resolved, spatially explicit observations contain significant information on CO_2 flux distributions and processes that can inform overall understanding of processes and their sensitivity to forcings. We seek to exploit that information in addition to the time/spatially averaged behavior and climatological representations used previously for the most part. To do this, we need models with concomitant spatial and temporal resolution, and process sensitivity. Global meteorological data assimilation, advanced biogeochemistry models, and new global observations give us the opportunity.

2.1 Transport Model Evaluation

We plan to continue development of the off-line parameterized chemistry and transport model (PCTM) using analyzed meteorological fields from the Goddard Global Modeling and Assimilation Office (GMAO) through comparison to real-time data in both forward [Kawa et al., 2004] and inverse [Baker et al., 2006a, b] modes. This task forms the basic framework for subsequent tasks, and the fundamental goal is to reduce tracer transport model uncertainty. Of course, transport model evaluation is closely coupled to the surface flux process models discussed below since diagnosis by comparison with tracer observations requires proper simulation of both transport and flux.

Our previous work showed relatively good simulations of seasonal cycles, global gradients, and, to some extent, synoptic variations using climatological fluxes and GMAO winds (given the constraint of a balanced biosphere and lack of a “missing sink”) [Kawa et al., 2004]. Subsequent work has used the real-time analyzed meteorology to drive the biosphere models and thus produce consistent flux/transport simulations with, presumably, more realistic synoptic variability (e.g., Fig 2). We are currently analyzing diurnal-to-interannual transport simulations for 1998-2004 with CASA 3-hourly fluxes generated from GEOS-4 meteorology in a method similar to Olsen and Randerson [2004]. Figures 2 and 3 show that the models capture synoptic variations with remarkable fidelity as well as diurnal variations down to about 30 m at the forested LEF site. At lower elevations (not shown) the model fails to resolve the shallow nighttime boundary layer and CO_2 accumulation near the surface. Note that these comparisons also include ocean CO_2 fluxes from Takahashi et al. [2002] and seasonally varying fossil fuel fluxes from Blasing et al. [2005] and Erickson et al. [2007]. We are examining similar comparisons at a variety of sites with continuous CO_2 data with an eye to characterizing and improving the model flux response to meteorological forcing as well as the transport processes in and above the planetary boundary layer (including the tropics as discussed in Section 2.2). We plan to follow this up with a new simulation from 1998 through current including NACP and OCO time periods focused on interannual variability. The new runs will use CASA consistent with that used for generating biomass burning fluxes in GFED-2 [van der Werf et al., 2006] (discussed further below) allowing for examination of both vegetation processes and burning contribution to interannual CO_2 changes and distributions.

Similar simulations using the Simple Biosphere-3 model (SiB-3) [Schaefer et al., 2002; Baker et al., 2003] vegetation fluxes are being used to examine the synoptic transport characteristics of the GEOS meteorology and provide a comparison point for the sensitivity of the biogeochemical models to weather and climate. Composite time series of frontal passage events at various sites show varying typical CO_2 changes depending on prevailing winds and upstream distribution of sources and sinks (Fig 4). A focus of future work in this area will be comparison and compositing of vertical profiles in comparison to aircraft CO_2 profile measurements in order to better evaluate boundary layer and convective transport parameterizations in the model. Errors in atmospheric model vertical transport have recently been accused of exaggerating the inferred northern hemisphere terrestrial CO_2 sink [Yang et al., 2007; Stephens et al., 2007].

We have also submitted results to the Transcom-Continuous model intercomparison [Law et al., 2007], which include SF_6 and radon tracers in addition to CO_2. We will continue to participate in this activity and will also submit runs for the Transcom Upper Air (http://www.purdue.edu/transcom/transcom03_upperAir.php) and planned satellite simulation intercomparisons in the near future. These projects are closely aligned with our proposal objectives.

Transition to GEOS-5

Another major task will be to evaluate and incorporate transport and meteorological analysis developments ongoing at GMAO. GEOS-5 has now replaced GEOS-4 as the operational assimilation model and a Modern Era Retrospective-analysis for Research and Applications (MERRA) is planned for 1979-present using GEOS-5. GEOS-5 is a significant development step from GEOS-4 (http://gmao.gsfc.nasa.gov/systems/geos5/) including new physical parameterizations, different grid and output specifications, and a new assimilation methodology. We expect the improved physical parameterizations and enhanced resolution (0.5° x 0.66° x 72 layers) will lead to improved tracer transport simulation, but a careful evaluation (and perhaps adjustment) is necessary, in particular for transport in convection (e.g., Bian et al. [2006]). We have a close relationship with model developers in GMAO and formal collaboration with S. Pawson that allows our findings for tracer transport and vegetation sensitivity to influence the meteorological model development. We share a common goal of developing an interdisciplinary Earth system model for carbon cycle assimilation and projection. Through our collaboration with the Modeling and Analysis Program activity ("Atmospheric Modeling, Assimilation, and Source-Sink Estimation for the Carbon Cycle," P.I., S. Pawson), we also have access to alternate formulations for oceanic CO_2 flux including interannual variability (discussed below) [Doney et al., 2006]. We will test the sensitivity to varying ocean flux in one or two scenarios in comparisons similar to those discussed for terrestrial biosphere, but the details of the ocean flux are mostly beyond the scope of this proposed effort.

Finally, under this activity we propose to continue collaborative support for outside users of our model output, the PCTM, and selected GMAO meteorological datasets that we prepare. In addition to the co-Is and collaborators listed on this proposal, other users are found at NCAR, Penn State U, U Iowa, U Maryland, U Michigan, Cal Tech U, and elsewhere. Further, this proposed effort provides the foundation for our mutually beneficial participation in Aura validation activities and expected contribution to NACP.

2.2 Terrestrial Biogeochemical Process Modeling

A strong motivation for studying atmospheric CO_2 variability and deploying OCO is to learn about the processes that control carbon surface fluxes especially at interannual to decadal time frames. Realistic characterization of the 4-D distribution of CO_2 in the atmosphere requires realistic surface fluxes from the land and oceans. The surface flux models are used to produce our best forward simulation of atmospheric CO_2 and prior fluxes for inverse calculations. The oceans are thought to absorb over half the missing CO_2 from the atmosphere through processes that are relatively better understood than those occurring on land. The land biogeochemical fluxes also account for a larger part of interannual variability in atmospheric CO_2 than either the ocean fluxes or fossil fuel emissions. For these reasons we focus on diagnosing land biogeochemical fluxes in this proposal, a manageable scope of effort under this solicitation.

Biogeochemical Models

We employ 3 models representing a range of approaches. Each of these is driven by meteorological input from GEOS consistent with that used in transport. One pair of models that have already been extensively evaluated, are better understood, and are more easily modified to correct diagnosed deficiencies is SiB3 and CASA. A more complex and complete model is currently under development soon to be implemented globally (SiB-CASA). All three models use satellite data to characterize the seasonality and interannual variability in vegetation cover. SiB3 is the latest version of the SiB-heritage of Soil-Vegetation-Atmosphere Transfer models developed to provide momentum, mass and energy exchanges to the lowest modeled atmospheric layer [Sellers et al., 1996]. Photosynthesis (GPP) along with other fluxes operates at sub-hourly time steps and is represented by a realistic biochemical/physiological model. To capture the total respiration fluxes (RE) and thereby predict the surface net CO_2 fluxes, SiB3 assumes that GPP and RE are balanced over some period ranging between 1 to 10 years (e.g., Denning et al. [1996]) according to temperature and soil moisture constraints. CASA, on the other hand, employs a very simple light use efficiency model for net primary productivity (NPP = GPP - plant respiration) while detailing the transfer and subsequent respiration fluxes between various living and detrital carbon pools [Potter et al., 1993; Randerson et al., 1996]. CASA generally works at a monthly time step. These features of CASA allow it to predict long-term carbon sources/sinks as well as actual carbon pool sizes. It has been parameterized to ingest satellite burned area products to produce carbon fluxes from fires as well as fire disturbance effects on carbon pools [van der Werf et al., 2006]. SiB3 should better capture sub-daily variability and temperature and hydrological controls on carbon fluxes because of its more sophisticated treatments of soil temperatures and moisture. CASA, on the other hand, predicts carbon pool sizes (some of which can be compared to available observations) and can be used to study longer-term carbon sources and sinks such as those arising from disturbance and recovery of vegetation. SiB-CASA combines the capabilities of both and thus is more realistic but at costs associated with greater complexity.

SiB3 fluxes are produced by the CSU land-modeling component of this proposal while the CASA fluxes are produced at GSFC. SiB-CASA is a collaborative effort between CSU and GSFC. Thus far SiB3 and CASA have been used to provide boundary CO_2 fluxes for PCTM as well as many other models participating in the TransCom experiments.

SiB3 includes a number of updates and improvements that were motivated by the need to capture observed behavior of fluxes at flux towers as well as to capture observed patterns in atmospheric CO_2. These improvements include implementation of a prognostic canopy air space variable (CO_2, temperature, humidity), multilayered soil and snow, improved physiological stress functions, and improved representation of satellite derived phenology. SiB3 is currently being used together with PCTM for analysis of synoptic effects on atmospheric CO_2 variability (Figure 4), global inversions (Section 2.3 below), and mesoscale inversions (Denning NACP project). Future plans for SiB3 include continued refinement of process representation (e.g., freeze/thaw limitation, NDVI interpolation) to improve comparison to observations both in direct comparison at FLUXNET sites and via inverse model CO_2 flux inferences.

CASA's monthly time step is a serious limitation for diagnostic use at the faster time scales of transport. For instance, it is well known that the diurnal covariance in vertical transport and physiological fluxes has important consequences for interpreting surface observations of CO_2 [Denning et al., 1996]. To correct this deficiency CASA has been disaggregated from monthly to sub-daily time steps according to the method of Olsen and Randerson [2004] in which monthly photosynthetic uptake and respiratory release of CO_2 are scaled to the diurnal variations in solar irradiance and temperature, respectively, over the course of any month. GEOS-4 meteorology is being used to drive CASA at diurnal to interannual scales (Figures 2, 3). Comparisons thus far with Ameriflux sites indicate that the GEOS-4 meteorology is consistent with the weather observed at the flux towers (Harvard Forest, WLEF, Tapajos). The modeled fluxes are broadly consistent with the observed fluxes though not capturing the long term net carbon sinks at Harvard Forest (large) or WLEF (small). At Tapajos, Brazil, CASA net fluxes follow the precipitation seasonality in the same way as observations though with an early lead of about 1 month. The CO_2 signal reproduces closely the seasonality and interannual variability in atmospheric CO_2 observed at the tower site (Figure 5). Interannual variability in CO_2 at the site seems to be driven largely by dry season precipitation variability. Analysis of the details of CASA behavior suggests that NPP experiences soil moisture stress that is not evident in the observations (but less so than other models, e.g., Saleska et al. [2003]). In order to better represent the effects of water stress on NPP and Rh as well as capture sub-monthly variations in vegetation phenology (from satellites) we are developing a daily time step parameterization for CASA using daily temperature, precipitation and solar irradiance from GEOS-4/5. This together with new multi-layer temperature, moisture and evapotranspiration parameterizations should improve the representation of stresses on NPP and Rh. We can then scale the daily fluxes into sub-daily in an analogous way to that with monthly fluxes. By interpolation of bimonthly NDVI to daily time steps we expect improvements in the simulations of the seasonal cycle of fluxes driven by phenology. Another possible approach to the hydrology problem is to use soil moisture products from other more sophisticated models/observations to prescribe moisture stress. We will explore the quality of such data from reanalysis products (NCEP, ECMWF, GEOS-4/5) and the Global Land Data Assimilation System [Rodell et al., 2004].

SiB-CASA has been evaluated at a number of AmeriFlux eddy covariance towers and with forest inventory data [Schaefer et al., 2007]. Future plans as part of this proposal include extending model evaluation and parameterization to other vegetation types (e.g. tropical forests, subtropical savannas, agricultural systems) and to implement it globally providing surface fluxes to PCTM. We will introduce a fire parameterization similar to that of CASA and use satellite burned area maps to introduce disturbance and recovery from fires.

COS Simulation

While the simulations discussed above refer separately to GPP, NPP and Rh as the processes that control the carbon balance of ecosystems, it should be noted that the CO_2 concentration of the atmosphere only reflects the net sum of much larger opposing fluxes, CO_2 uptake and release associated, in large part, with photosynthesis and respiration of terrestrial ecosystems and, to a lesser extent, with exchanges between the ocean and the atmosphere plus human emissions. CO_2 concentration by itself provides little insight into the magnitude of respiration and photosynthesis. This gap in our ability to separately measure the two key ecosystem processes controlling carbon balance at large scales makes it difficult to test the accuracy of our carbon cycle models and leads to uncertainty in inversions and data assimilation studies of the carbon cycle. Isotopologues of CO_2 have long been used to provide additional constraints on the assignment of CO_2 sinks to the ocean and terrestrial biosphere. Recent work [Montzka et al., 2007] has shown that an analogue of CO_2, carbonyl sulfide (COS), has the potential to provide similar constraints on the contributions of photosynthesis and respiration to net CO_2 exchange. We are proposing to expand our modeling system to simulate these co-tracers of the carbon cycle together with our simulations of CO_2 concentration. The rationale is to use measurements of these species to provide additional constraints on our carbon cycle models. In addition, the ability to use additional observations in data assimilation or inversion studies should provide greater insight into the processes regulating carbon sources and sinks.

Chamber studies [Protoschill-Krebs et al., 1996] show that both CO_2 and COS are taken from the atmosphere during photosynthesis, but unlike CO_2 there is apparently no significant physiological source of COS from terrestrial ecosystems. Therefore, if the ratio of COS uptake to that of gross CO_2 uptake (GPP) can be established, it should be possible to estimate the GPP flux of CO_2 and, thus, separate respiration and photosynthesis. We have built a COS uptake parameterization into SiB and will begin testing it in a global model context. The ocean and anthropogenic COS budget terms will initially be derived from the fluxes of Kettle et al. [2002], chemical loss from climatological OH concentrations [Bian et al., 2007], and a biomass burning source from GFED using emission factors from Andreae and Merlet [2001].

These studies will be conducted in collaborations with other groups: Berry, Caldiera, and Campbell of the Carnegie Institution; Montzka of NOAA-GMD; and Schaefer of NSIDC. Berry is studying the biochemistry and physiology of COS by plant leaves and will develop and test models of this process using SiB3. This will provide the capacity to simulate COS and CO_2 fluxes in the same model context; a similar capacity already exists for co-simulation of CO_2 and $^{13}CO_2$ fluxes. Campbell (manuscript in preparation) has assembled a large data set of CO_2 and COS measurements from the Intex-NA campaign and used a regional-scale model to demonstrate that the COS/CO_2 flux ratio varies geographically over the mid-continent by a factor of 3. Montzka is continuing to conduct high precision flask measurements from aircraft profiles and a portion of the global air-monitoring network. Schaefer is proposing to develop a data assimilation approach based on a global model of COS cycling in the atmosphere. Caldiera and Berry will couple an ocean biogeochemistry and circulation model with CO_2 and ^{13}C exchange processes. This collaboration will provide the missing piece for global simulations of atmospheric $^{13}CO_2$. Finally, we have been in discussion with the Tropospheric Emission Spectrometer (TES) retrieval team to see if COS can be retrieved globally from TES.

Interannual Variability and Fire Fluxes

Wild fires have been shown to have a significant impact on CO_2 interannual variability (e.g., Langenfelds et al. [2002]; van der Werf et al. [2004]). One of the goals of this project is to estimate the relative contributions of fires versus physiology (NPP/GPP, Rh/RE) to the large atmospheric variability associated with El Nino/La Nina and other major climate anomalies.

GFED fire fluxes are already included in the boundary conditions for PCTM (e.g., Bian et al. [2007]) but until now have been independent of the physiological CO_2 fluxes from CASA that we use. Our next step is to make the GFED and CASA fluxes consistent by inputting GFED burned area into CASA causing carbon pools to be altered by fire and run the interannually varying fluxes through PCTM. Currently GFED burned area data spans 1997-2006 with plans to continue production (Co-I Collatz is also a Co-I on the GFED team). Currently CASA-GFED monthly fire emissions are scaled to daily fluxes using Terra and Aqua daily active fire products to distribute emissions within any month. The daily burned area estimates will be used to calculate fire emissions from SiB-CASA and the daily CASA. MODIS Land Team will release a daily burned area product in 2008 spanning the period from 2000 until instrument failure/abandonment. As soon as this product is released we will evaluate differences with GFED in terms of surface fluxes and their atmospheric CO_2 signal.

Several regional to continental scale projects are currently underway to estimate carbon fluxes produced by disturbance and recovery. These projects are necessarily aimed at fine spatial scales associated with human-mediated disturbance. The characteristics of human disturbance and subsequent recovery are very region-dependent (e.g., industrial forestry, selective logging, industrial agriculture, subsistence agriculture, etc.), which precludes global generalization of disturbance. Co-I Collatz is heading a separate study to estimate disturbance and recovery fluxes from North American Forests (see Masek and Collatz [2006]), and he is Co-I on a project aimed at quantifying deforestation rates in Amazonia and Indonesia. These regional estimates of disturbance-mediated fluxes will be input to PCTM and lead to evaluation of the contribution of disturbance to variability in atmospheric CO_2.

2.3 Preparing for OCO

OCO will produce atmospheric CO_2 data of a (largely) new type (column mixing ratio) on a whole new scale of coverage, resolution, and frequency relative to those previously used to infer carbon cycle processes. The results promise to be ground-breaking, however, significant model and data handling development will be needed to make full use of the new measurements in terms of advancing carbon cycle science and understanding carbon processes. We propose to use the flux/transport process models described above along with inverse methods, OCO-like pseudo-data, and other in situ and remote sensing data to test various data-compositing and parameter estimation approaches to best infer CO_2 source/sink distributions and their uncertainties (e.g., Chevallier et al. [2007]). When OCO level 2 data become available, we will exercise this system with real observations.

Figure 1 shows a schematic diagram with process model components and data analysis systems required/desired to use OCO to better estimate CO_2 sources and sinks. The atmospheric state from GEOS-5, transport model, and surface flux components are discussed above, some explicitly and others in cited references. Data handling, including "zero level" OCO data evaluation, and inverse modeling for surface flux optimization and error analysis are discussed here.

Inverse Modeling

Our primary approach to inverse modeling will be the Maximum Likelihood Ensemble Fliter (MLEF) method [Zupanski and Zupanski, 2006]. MLEF for CO_2 fluxes has been developed under a related Denning proposal for mesoscale analysis over North America, and here we will apply the technique to the global domain. The advantage of this method is the potential to incorporate observations into the model framework corresponding to their actual time and location, rather than in a limited set of temporal and spatial averages used in synthesis inversions. The method is suitable for assimilating large observation vectors, hence suitable for satellite inversions; no sequential assimilation is required, and it is capable of incorporating nonlinear observation operators and dynamic models.

The MLEF framework involves merging several streams of observational data into the coupled biogeochemical/transport model but does not require the development of an adjoint to the coupled model. The modeling system will calculate surface carbon exchanges due to photosynthesis, respiration, decomposition, fire, fossil fuel combustion, and a residual time-mean source or sink due to unspecified processes. An example inversion is shown in Figure 6. In this application, scalar coefficients to SiB GPP and RE are jointly optimized to estimate net flux from the transported global CO_2 field in comparison to a model pseudo-data network. The result shows substantial error reduction in terrestrial regions that are well-sampled by observations (NH mid latitudes), but little additional information over oceans or in the Southern Hemisphere. The prospect for use of OCO data, however, looks promising. Similar inversions using real observations will be the next step.

The model will also calculate transport by advection, convective mass fluxes, and PBL turbulence, as well as hourly mixing ratios of CO_2 on the model grid. The outputs will be optimally matched to observations of vegetation state and fire disturbance from MODIS products, to temporal flux variations measured by eddy covariance, and to observations of trace gases from a combination of in-situ instrumentation and eventually OCO. The optimization will be performed by solving for magnitudes and uncertainties of physiological parameters and initial biogeochemical pool sizes in SiB-CASA, combustion efficiencies for biomass burning in the fire module, and PBL diffusivities in PCTM. A calculation with OCO-like pseudo-data is in planning.

OCO Data Analysis

The OCO instrument records up to 8 soundings along a 10-km wide (nadir) cross-track swath at 3 Hz, yielding up to 24 soundings per second. Individual soundings will have a spatial coverage of 1.25 km × 2.26 km at nadir, yielding up to 350 soundings over each 1° latitude increment along the orbit track where the solar zenith angle (SZA) is less than 75 to 85° depending on observing mode [Miller et al., 2007]. OCO will collect science observations in a combination of Nadir, Glint, and Target modes. The orbit will have16-d repeat track coverage at approximately 1326 local solar time. Only a fraction of the soundings will be in sufficiently clear air for precision retrieval, and signal-to-noise will vary with SZA, surface reflectivity, view angle, and atmospheric conditions. Geophysical variability will exist at all scales. Many approaches to compositing these individual soundings in time and space are possible to achieve maximum precision and accuracy. We will begin to explore these possibilities in the context of the model CO_2 and test them including combination with in situ data. This work will include collaboration with the geostatistical variance analysis project of A. Michalak at U. Michigan (Alanood et al., in prep). We will also consider the impact and possible inclusion of data from the Greenhouse gases Observing SATellite (http://www.jaxa.jp/projects/sat/gosat/index_e.html). Finally, this aspect of the project provides a lead-in to using the models to help define measurement requirements for future remote sensing instruments, e.g., the laser sounder for atmospheric CO_2 [Abshire et al., 2006].

OCO data will require considerable calibration/validation before they are ready for input to inverse models for source/sink inference. The global CO_2 models developed here present the opportunity to do simple OCO validation in parallel to other validation efforts. When level-2 OCO data become available we will use the model output as a data transfer standard between OCO at the Fourier transform spectrometer validation sites (e.g., Washenfelder et al. [2006], Bosch et al. [2006]) and other regions. We will characterize model-data comparisons at the Total Column Carbon Observing Network (TCCON) sites (http://www.tccon.caltech.edu/) before launch and apply this to FTS/OCO/model comparisons to evaluate OCO. We have an established collaboration with Dr. Paul Wennberg (OCO Lead Scientist for Validation) who is proposing to Carbon Cycle Science for continued operation and data processing of the TCCON. Finally, when OCO data are available and reasonably validated, we will run source/sink inversions as described above.

3) Management Plan

The proposed project will be managed at GSFC by the PI, Dr. Randy Kawa. Our previous project has had good success in coordination through regular bi-weekly telecons, dedicated annual project meetings, and project meetings of opportunity at other functions as well as regular email exchange. Roles and responsibilities of the project team are discussed here; levels of effort are tabulated below in the Budget Narrative section.

In addition to overall scientific oversight, coordination, and planning, Dr. Kawa will focus on analysis of forward model runs and comparison to observations from in situ, remote sensors, and OCO. In addition, he directs the activities of a scientific programmer (Mr. Zhu) and assistant research scientist (Dr. Bian). Dr. Bian is responsible for analysis of model transport parameterizations and GEOS-5 transport characteristics. Mr. Zhu does the major share of computer code modification and maintenance, met data preparation, model runs and output manipulation, and simulation quality assurance.

Dr. Jim Collatz (GSFC) is responsible for CASA modeling and overall terrestrial biogeochemical model analyses, and will actively participate with CSU in SiB-CASA global integration. He also serves as the project link to other vegetation remote sensing products used in the modeling systems (e.g., FPAR/LAI, GFED-2 burning emissions, MODIS burned area).

Dr. Scott Denning (CSU) oversees the project activity at Colorado State University focused primarily on SiB-3 and SiB-CASA development, the MLEF inverse modeling, and analysis of COS simulations in the context of carbon flux processes in vegetation. In addition, he directs the activities of a student (Mr. Parazoo) and research science staff (Dr. Lokupitaya and Mr. Baker). Mr. Baker will be supported in the first year of the project to integrate SiB-CASA into a global framework. This project will be the focus of Mr. Parazoo's PhD research analyzing the interaction of weather with the biosphere, the transport, and comparison to observations.

In addition to the funded investigators documented above, mutually beneficial, unfunded collaboration plays an important role in our proposed project. While none of these collaborations individually is critical to the success of the project, we have found these relationships to be extremely valuable in the past. The explicit role of the collaborators is discussed.

Dr. David Erickson (ORNL) serves as our interface to the development of time-dependent fossil fuel emission scenarios for CO_2 and connection with coupled climate-chemistry simulations being run at ORNL. He will also participate in COS simulation analysis.

Dr. Steven Pawson (NASA GMAO) is our main link to the GMAO. Dr. Pawson is group leader for constituent simulation within GMAO and is responsible for use of assimilated datasets in research analyses. He also leads a project for carbon data assimilation under the NASA Modeling and Analysis Program that has several investigators and components in common with that proposed here. The primary distinction between these projects is that we mainly operate off-line from the GMAO assimilation model while the Pawson project is to develop on-line carbon-cycle capability. Each has its own advantages and objectives, while benefiting from this cooperation.

Dr. Joe Berry (Stanford Carnegie Institute) will bring his expertise on plant physiological processes and his work on COS physico-chemistry to bear on our simulations in SiB and CASA. He will help analyze COS simulations along with Dr. Elliott Campbell, soon to join their lab, and will analyze bulk tracer transport and budgets derived from the 3-D Eulerian model.

Facilities and Equipment

The only notable facilities and equipment needed for this project are adequate computers for simulation runs, output storage, and data and model analysis. A large part of the work will be done on in-house computing facilities at CSU and GSFC, both of which have outstanding available resources. A separate renewal request for computer time will be made for large production model runs and storage at the NASA Center for Computational Sciences at GSFC (https://nccs.nasa.gov/index.html).

Travel

Travel for this project includes science team visits, national and international science meetings, and agency-sponsored workshops. We try to coordinate team meetings with science meetings and other opportunities as much as possible, however, it is expected that personnel from CSU and GSFC will need to exchange visits on a regular basis to learn model operations and prepare analyses.

Schedule

The schedule for this project assumes a start at the beginning of FY2008 (Oct 2007). Each task will proceed in parallel with major accomplishments noted here.

Year 1: Obtain GEOS-5 output data and transport parameters, compare to previous formulations, and test impact on CO_2 transport with standard flux scenario, e.g., Transcom-C; integrate SiB-CASA into global framework and test with GEOS met data; run initial simulation of global COS and compare with observations; run ocean flux sensitivity test.

Year 2: Run interannual CO_2 flux/transport simulation with SiB-CASA and analyze results including GFED-2 burning emissions; exercise global MLEF inverse for land model parameter estimation, analyze process dependencies; begin to evaluate first-light OCO data, compile model comparisons with ground-based FTS; combine global COS with CO_2 analysis for vegetation flux process evaluation in forward mode.

Year 3: Run source/sink inverse calculations using OCO data and other data sources, analyze results; incorporate COS parameter constraints into inverse calculations; use CO_2 fields with proposed new instrument functions to estimate advanced satellite data impacts; publish analysis papers, contribute to IPCC Assessment, SOCCR reports.

4) Summary

We propose to synthesize an improved modeling/data analysis procedure capable of incorporating OCO and other relevant data to more precisely characterize the atmospheric carbon budget. Deliverables include an improved data driven transport model for interannual to synoptic data comparison, carbon fluxes due to photosynthesis and respiration in terrestrial ecosystems and their sensitivity to climate forcing, and methods for exploiting new data sources especially global remote sensing measurements from OCO. This will produce a closer link between top down and bottom up estimates of processes with quantitative characterization of variations in CO_2 transport, sources and sinks, and their uncertainties. These results should ultimately lead to NASA-relevant, coupled Earth system models capable of reliably simulating future changes in carbon and climate, and a decision support system for evaluation of the impact of policy options on changing carbon cycle and climate.

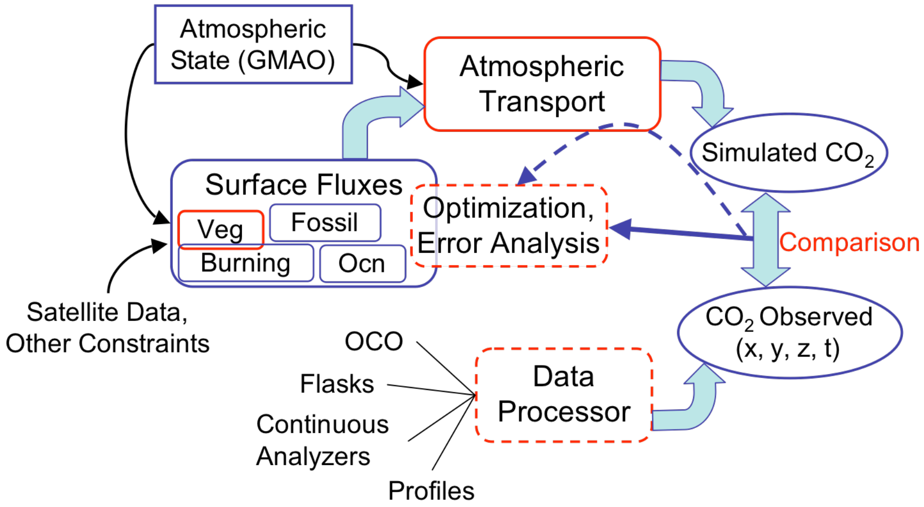
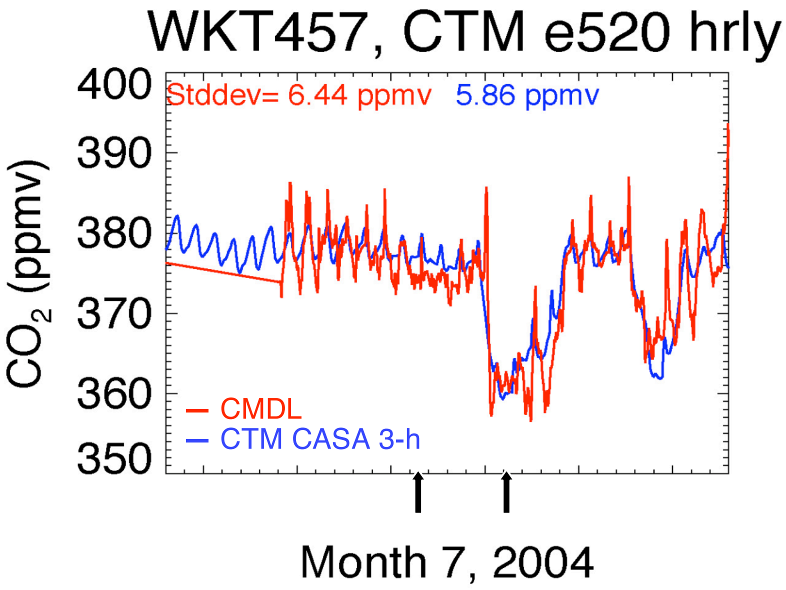


Figure 1. Schematic diagram of main components and process models required to use OCO and other data for CO_2 surface flux inference. Components outlined in red are primary focus of this proposal.



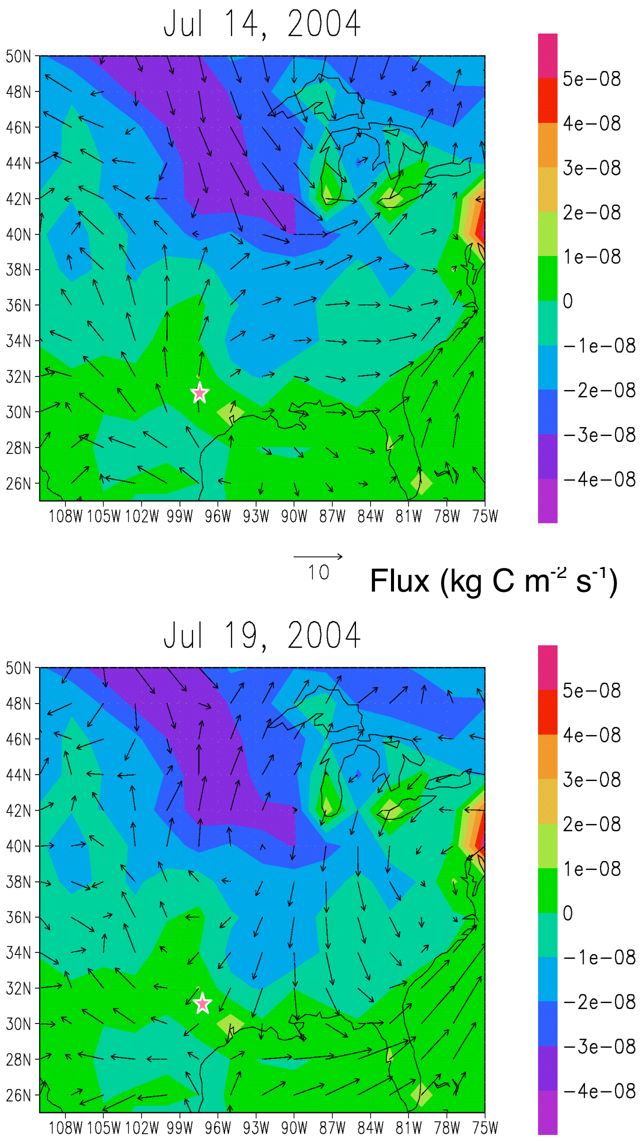


Figure 2. Time series of hourly CO_2 data and model output at Moody, TX in situ tower measurement site (above), and CASA monthly mean CO_2 vegetation flux distribution with wind vectors from GMAO meteorological analyses (right) before and after passage of "CO_2 front" seen in time series at July 17. Upstream influence of varying CO_2 surface flux is seen in large, rapid CO_2 mixing ratio change at tower site. Note that CMDL here and below refers to data provided by the NOAA Earth System Research Laboratory Global Monitoring Division Carbon Cycle Greenhouse Gases Group (http://www.esrl.noaa.gov/gmd/) whom we gratefully acknowledge.

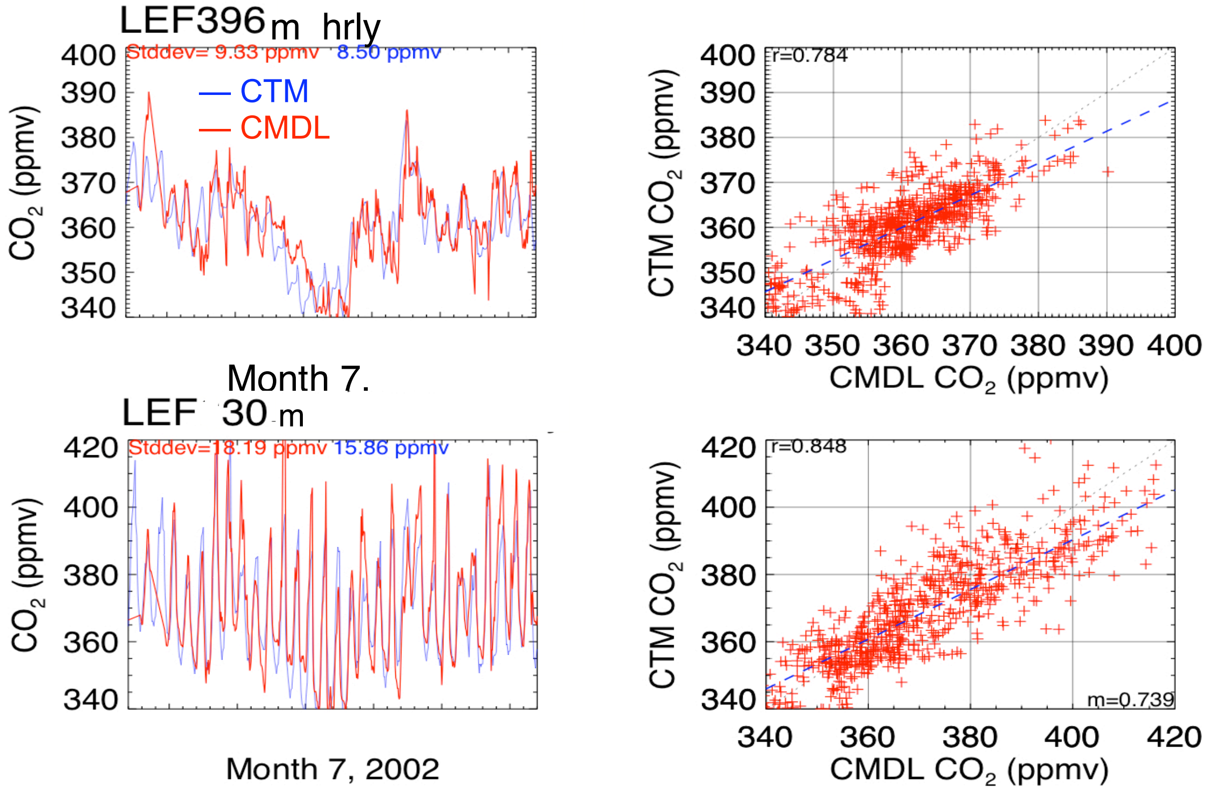


Figure 3. Time series of observations and model output at Wisconsin tower site during July 2002 showing that model captures most of the synoptic to hourly variability in CO$_2$ at altitudes down to about 30 m. Model-data correlations are also high in fall and winter when respiration and fossil fuel fluxes dominate this site.

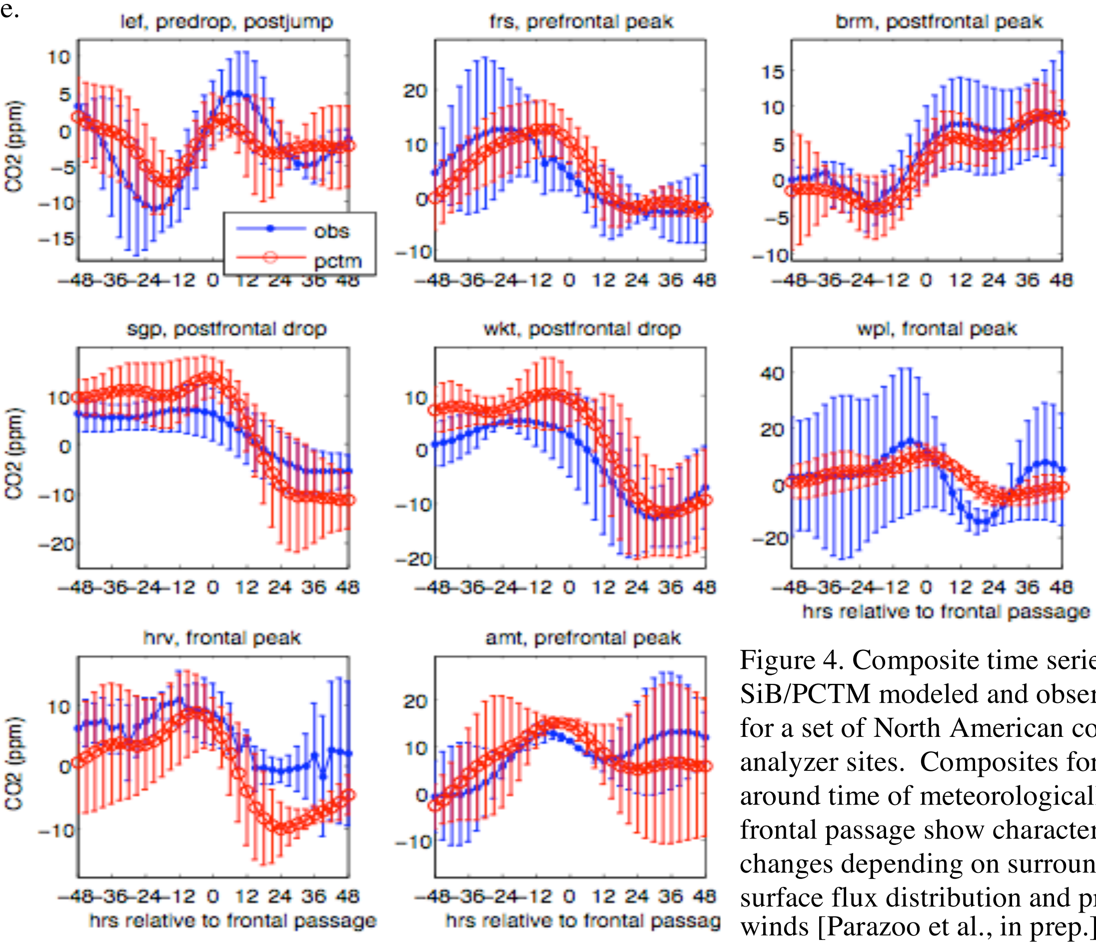


Figure 4. Composite time series of SiB/PCTM modeled and observed CO$_2$ for a set of North American continuous analyzer sites. Composites formed around time of meteorologically defined frontal passage show characteristic CO$_2$ changes depending on surrounding surface flux distribution and prevailing winds [Parazoo et al., in prep.].

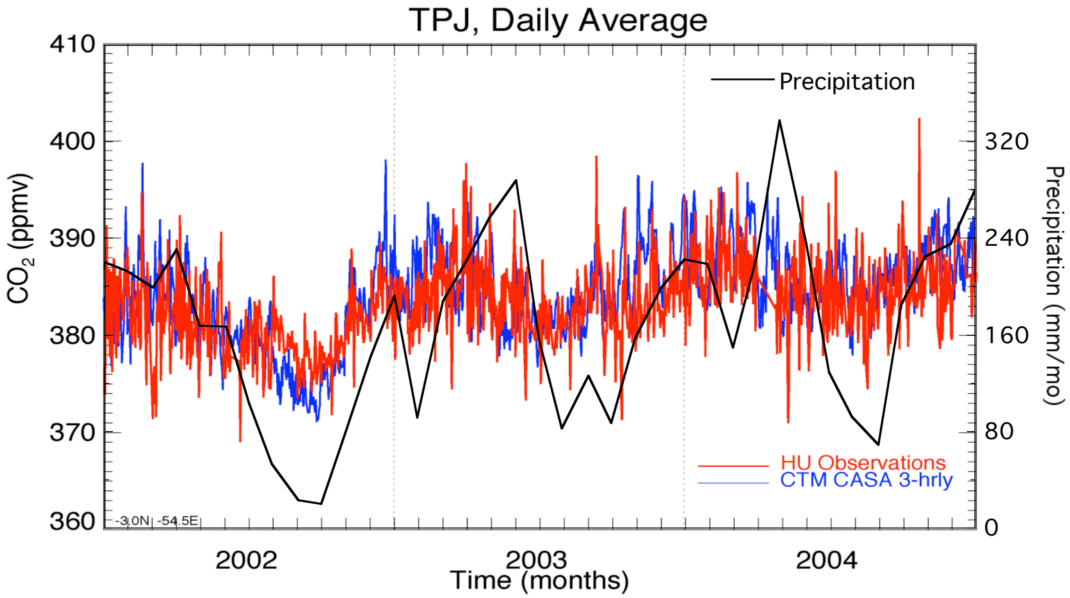


Figure 5. Time series of daily-average observations (see Saleska et al. [2003]) and model output at Tapajos, Brazil. Also shown is GEOS-4 precipitation at site. CASA captures the tropical seasonal cycle and interannual variability but with some discrepancies requiring improvement to the modeled hydrological processes.

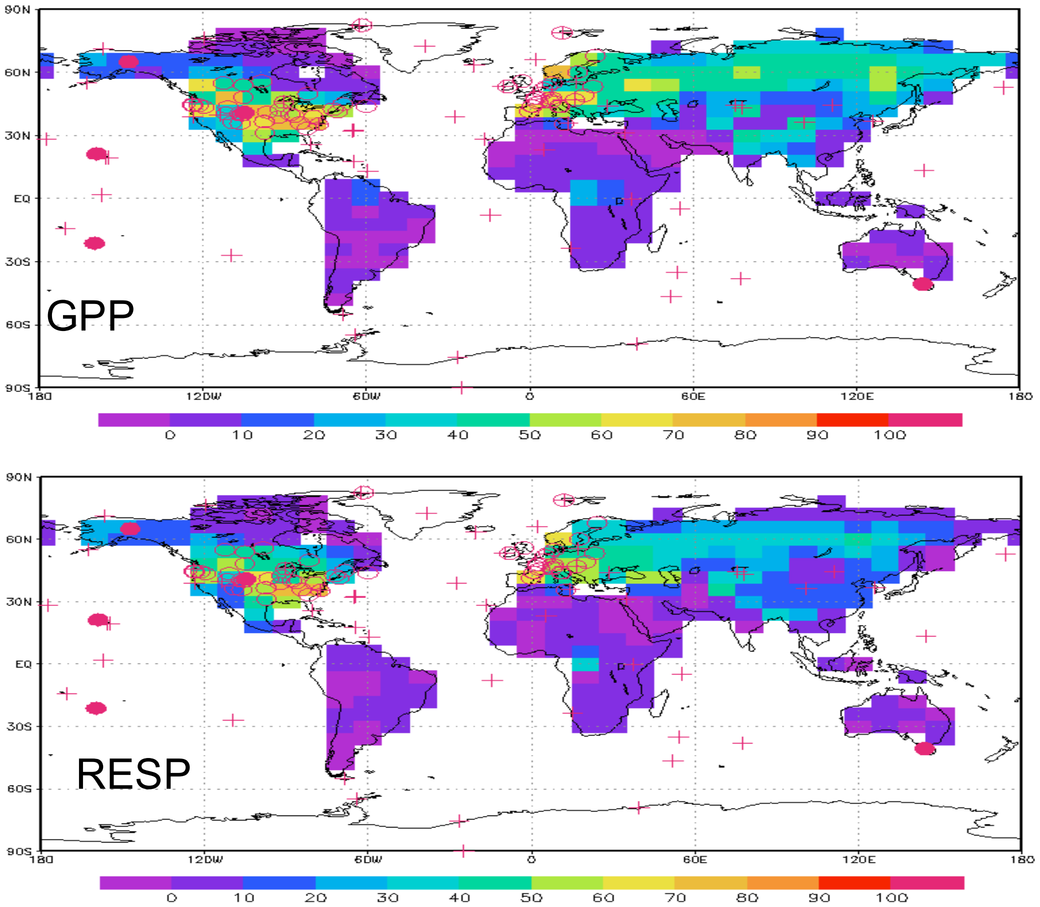


Figure 6. Example result from Maximum Likelihood Ensemble Filter flux inversion. Updates to GPP and respiration flux scalars are constrained separately to estimate net flux. Method incorporates full global grid, time-resolved pseudo-data, but significant per cent error reduction (color shading) is seen only in well-sampled regions (Lokupitiya et al., in prep.).

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3) NASA Atmospheric Effects of Aviation Project, Project Manager, 1996-1997, Project Scientist, 1997-1999.
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5) Participant in cooperative field research programs including DYCOMS, AASE, AASE-II, SPADE, ASHOE/MAESA, STRAT, SONEX, POLARIS, SOLVE, and AVE. Member of leadership planning team for POLARIS and SOLVE.
6) Co-author of UNEP/WMO Scientific Assessment of Ozone Depletion: 1998, 2006.
7) Involved in design and construction of instrumentation for eddy flux measurement of ozone, NO/NOy in the stratosphere, and remote sensing of column CO_2 by both passive and active methods. Orbiting Carbon Observatory science team.
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"Stratospheric Transport using Six-Hour Averaged Winds from a Data Assimilation System," S. Pawson, I. Stajner, S. R. Kawa, H. Hayashi, W.-W. Tan, J. E. Nielsen, Z. Zhu, L.-P. Chang, N. J. Livesey, J. Geophys. Res., doi:10.1029/2006JD007673, in press, 2007.

"Sensitivity of global CO simulation to uncertainties in biomass burning sources, " H. Bian, M. Chin, S. R. Kawa, B. Duncan, A. Arellano, P. Kasibhatla, J. Geophys. Res., in press, 2007.

“Estimated monthly global emissions of anthropogenic CO2 and their impact on calculated atmospheric CO2,” D. J. Erickson, III, R. T. Mills, J. Gregg, T. J. Blasing, F. M. Hoffman, R. J. Andres, M. Devries, Z. Zhu, S. R. Kawa, J. Geophys. Res., submitted, 2007.

NAME: G. James Collatz

MAJOR ACTIVITIES: Terrestrial Carbon Cycle Research using remote sensing observations and models.

EDUCATION:
1973 - B.A. Biological Sciences, UC Santa Barbara
1976 - M.A. Biological Sciences, UC Santa Barbara
1983 - Ph.D. Biological Sciences, Stanford University

PREVIOUS POSITIONS:
1990-1993 Research Associate, Carnegie Institution of Washington
1994-1995 NRC Research Fellow, NASA/GSFC
1995-Present Staff Scientist, Biospheric Sciences Branch, GSFC

SELECTED PEER REVIEWED PUBLICATIONS (51 Total)

F. G. Hall, J. G. Masek, G. J. Collatz, Evaluation of ISLSCP Initiative II FASIR and GIMMS NDVI: Products and Implications for Carbon Cycle Science. Journal of Geophysical Research 111, D22S08, doi:10.1029/2006JD007438. (Nov 2006)

van der Werf GR, Randerson JT, Giglio L, Collatz GJ, Kasibhatla PS, Arellano Jr AF, Interannual variability of global biomass burning emissions from 1997 to 2004. Atmospheric Chemistry and Physics 6, 3423-3441(August 2006)

Giglio L, van der Werf GR, Randerson JT, Collatz GJ, Kasibhatla P, Global estimation of burned area using MODIS active fire observations. Atmospheric Chemistry and Physics 6, 957-974 (March 2006)

Masek JG, Collatz GJ, "Estimating forest carbon fluxes in a disturbed southeastern landscape: Integration of remote sensing, forest inventory, and biogeochemical modeling" J. Geophys. Res., 111, G01006, doi:10.1029/2005JG000062., 2006

Arellano AF, Kasibhatla PS, Giglio L, van der Werf GR, Randerson JT, Collatz GJ, "Time-dependent inversion estimates of global biomass burning CO emissions using MOPITT measurements", *J. Geophys. Res.*, *111*, D09303, doi:10.1029/2005JD006613. (May 2006)

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Randerson JT, Collatz GJ, Fessenden JE, Munoz AD, Still CJ, Berry JA, Fung IY, Suits N, Denning AS, A possible global covariance between terrestrial gross primary production and 13C discrimination: Consequences for the atmospheric 13C budget and its response to ENSO. Global Biogeochemical Cycles 16, doi:10.1029/2001GB001845, 2002

DeFries RS, Bounoua L, Collatz GJ, Human modification of the landscape and surface climate in the next 50 years. Global Change Biology 8, 438-454, 2002

Los SO, Collatz GJ, Bounoua L, Sellers PJ, Tucker CJ, Global interannual variations in sea surface temperature and land surface vegetation, air temperature and precipitation. Journal of Climate 14, 1535-1549. 2001

Collatz GJ, Bounoua L, Los SO, Randall DA, Fung IY, Sellers PJ. A mechanism for the influence of vegetation on the response of the diurnal temperature range to changing climate. Geophysical Research Letters 27, 3381-3384. 2000

Bounoua L, Collatz GJ, Los SO, Sellers PJ, Dazlich DA, Tucker CJ, Randall DA. Sensitivity of climate to changes in NDVI Journal of Climate 13, 2277-2292. 2000

Collatz GJ, Berry JA, Clark JS, Effects of climate and atmospheric CO2 concentration on the global distribution of C4 grasses: Present, past and future. Oecologia, 114,441-454, 1998

Sellers PJ, Dickinson RE, Randall DA, Betts AK, Hall FG, Berry JA, Collatz GJ, Denning AS, Mooney HA, Nobre CA, Sato N, Field CB, Henderson-Sellers A, Modeling the exchanges of energy, water and carbon between the continents and the atmosphere. Science 275, 502-509, 1997

Denning AS, Collatz GJ, Zhang C, Randall DA, Berry JA, Sellers PJ, Colello GD, Dazlich DA. Simulations of terrestrial carbon metabolism and atmospheric CO2 in a general circulation model. Part 1: Surface Carbon Fluxes. Tellus 48B,521-542, 1996

Sellers PJ, Bounoua L, Collatz GJ, Randall DA, Dazlich DA, Los SO, Berry JA, Fung I, Tucker CJ, Field CB, Jensen TG, Comparison of radiative and physiological effects of double atmospheric CO2 on climate. Science 271,1402-1406, 1996

Collatz GJ, Ribas-Carbo M, Berry JA, Coupled photosynthesis-stomatal conductance model for leaves of C4 plants. Australian Journal of Plant Physiology 19, 519-538, 1992

Collatz GJ, Ball JT, Grivet C, Berry JA Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer. Agricultural and Forest Meteorology 54, 107-136, 1991

A. Scott Denning

Current Positions:

Monfort Professor, Department of Atmospheric Science, Colorado State University.
Associate Director, Center for Multiscale Modeling of Atmospheric Processes
Chair, Science Steering Group, North American Carbon Program

Education:

B.A., Geological Sciences, 1984. University of Maine, Orono, Maine. *Highest Honors*
M.S., Atmospheric Science, 1993. Colorado State University, Fort Collins, CO
Ph.D., Atmospheric Science, 1994. Colorado State University, Fort Collins, CO

Experience:

2003– : *Associate Professor*, Department of Atmospheric Science, Colorado State University
Atmosphere-biosphere interactions. Global biogeochemical cycles. Land-surface climate
1998–2003 : *Assistant Professor*, Department of Atmospheric Science, Colorado State University
1996–98 : *Assistant Professor*, Donald Bren School of Environmental Science and Management, University of California, Santa Barbara.

Selected Publications (from a total of 60):

Denning, A. S., I. Y. Fung, and D. A. Randall, 1995: Latitudinal gradient of atmospheric CO_2 due to seasonal exchange with land biota. *Nature*, **376**, 240-243.

Denning, A. S., J. G. Collatz, C. Zhang, D. A. Randall, J. A. Berry, P. J. Sellers, G. D. Colello, and D. A. Dazlich, 1996. Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model. Part 1: Surface carbon fluxes. *Tellus*, **48B**, 521-542.

Denning, A. S., D. A. Randall, G. J. Collatz, and P. J. Sellers, 1996. Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model. Part 2: Spatial and temporal variations of atmospheric CO_2. *Tellus*, **48B**, 543-567.

Denning, A. S., M. Holzer, K. R. Gurney, M. Heimann, R. M. Law, P. J. Rayner, I. Y. Fung, S.-M. Fan, S. Taguchi, P. Friedlingstein, Y. Balkanski, J. Taylor, M. Maiss, and I. Levin, 1999. Three-dimensional transport and concentration of SF_6: A model intercomparison study (TransCom 2). *Tellus,* **51B**, 266-297.

Denning, A. S., T. Takahashi and P. Friedlingstein, 1999. Can a strong atmospheric CO_2 rectifier effect be reconciled with a "reasonable" carbon budget? *Tellus,* **51B**, 249-253.

Gurney, K.R., R. M. Law, A. S. Denning, et al, 2002: Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models. *Nature*, **415**, 626-630.

Engelen, R.J., A.S. Denning, K.R. Gurney and G.L. Stephens. Global observations of the carbon budget: I, 2001. Expected satellite capabilities in the EOS and NPOESS eras. *Journal of Geophysical Research*, **106,** (D17), 20055-20068.

Engelen, R. J., A. S. Denning, and K. R. Gurney, 2002: On error estimation in atmospheric CO2 inversions. *Journal of Geophysical Research*, **107**, 4635, doi:10.1029/2002JD002195.

Denning, A.S., M. Nicholls, L. Prihodko, I. Baker, P.-L. Vidale, K. Davis, and P. Bakwin, 2003. Simulated and observed variations in atmospheric CO_2 over a Wisconsin forest. *Global Change Biology*, **9**, 1241-1250.

Wang, J.-W., A. S. Denning, L. Lu, I. T. Baker, K. D. Corbin, and K. J. Davis. Observations and simulations of synoptic, regional, and local variations in atmospheric CO_2. *J. Geophys. Res.,* 112, D04108, doi:10.1029/2006JD007410.

Denning, A. S., N. Zhang, X. Yi, M. Branson, P. Bakwin, K. Davis, and J. Kleist. Evaluation of Simulated Boundary Layer Depth at the WLEF-TV Tower Site. *Agric. and Forest Meteorol.*, in press.

Zupanski, D., A. S. Denning, M. Uliasz, M. Zupanski, A. E. Schuh, P. J. Rayner, W. Peters, and K. D. Corbin. Carbon flux bias estimation employing the Maximum Likelihood Esemble Filter (MLEF). Submitted to *Jour. Geophys. Res.*

CURRENT AND PENDING FUNDING: S. R. Kawa (Principal-Investigator)

This proposal is not listed in the pending support since it has not, nor will be, submitted to any other Agency or sponsor.

A. Current Support
Title: Constraining the CO_2 Missing Sink
PI: S. R. Kawa
Program: NASA Carbon Cycle Science
Period: 2005-07, Budget: $1338k
Commitment (person-months): 3.6

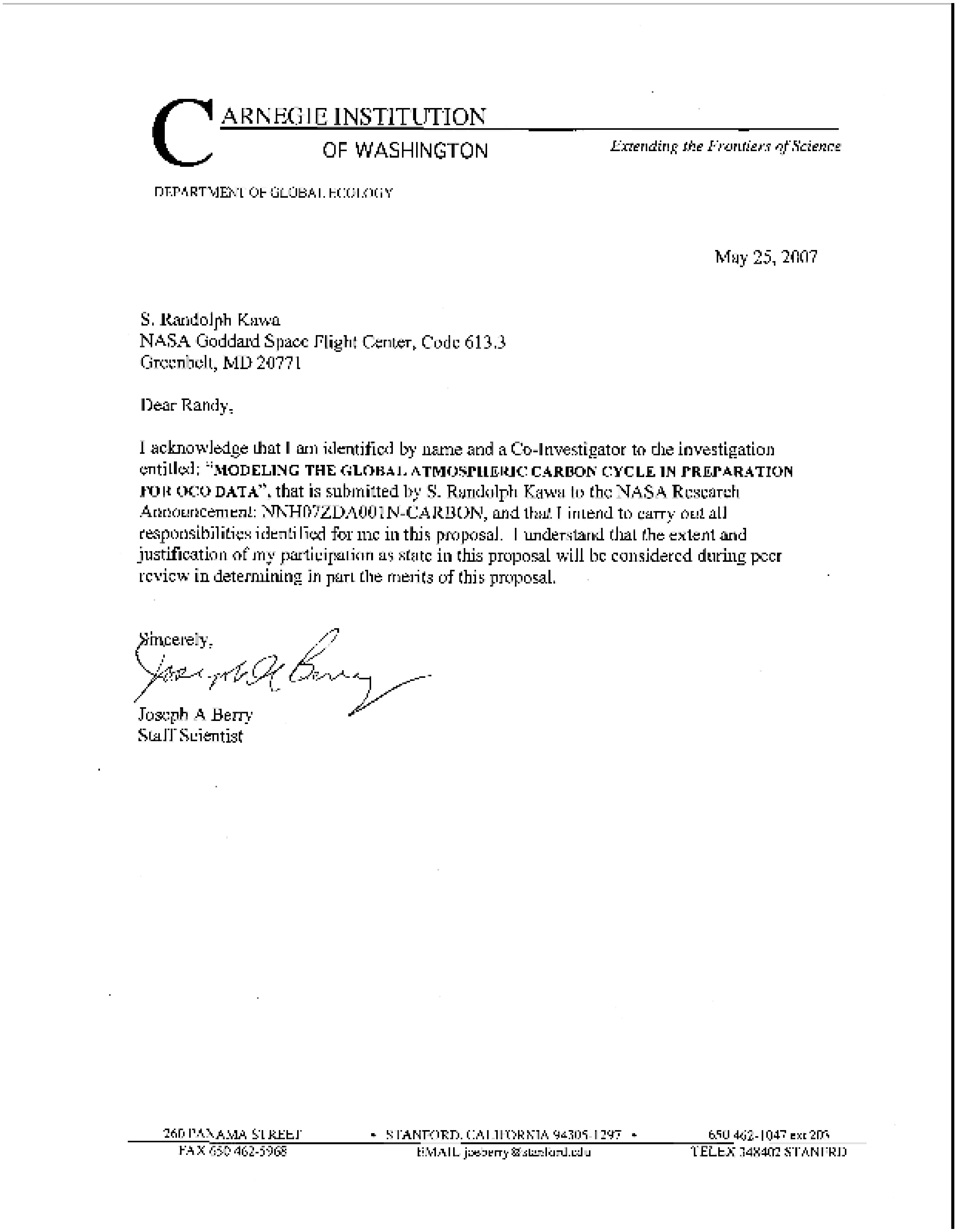
Title: Continuation of the Stratospheric General Circulation with Chemistry Project
PI: A. R. Douglass
Program: NASA Atmospheric Composition
Period: 2006-08
Commitment (person-months): 2.4-4.8

Title: Atmospheric Modeling, Assimilation and Source-Sink Estimation for the Carbon Cycle
PI: S. Pawson
Program: NASA Modeling, Analysis, and Prediction
Period: 2006-10
Commitment (person-months): 1.2

Title: Chemistry-Climate Studies Using General Circulation Models
PI: R. S. Stolarski
Program: NASA Modeling, Analysis, and Prediction,
Period: 2006-2010,
Commitment (person-months): 2.4

Title: Laser Sounder for CO_2 Measurements: Airborne Demonstration, Science Measurements and Space Technology
PI: James B. Abshire
Program: NASA Instrument Incubator Program
Period: 2006-2008
Commitment (person-months): 2.4

B. Pending Support
Title: Airborne Laser Sounder for Measuring CO2 Concentrations in the Troposphere
PI: J. B. Abshire
Program: NASA Airborne Technology Transition Program
Period: 2008-2009
Commitment (person-months): 0.6



CARNEGIE INSTITUTION
OF WASHINGTON
Extending the Frontiers of Science

DEPARTMENT OF GLOBAL ECOLOGY

May 25, 2007

S. Randolph Kawa
NASA Goddard Space Flight Center, Code 613.3
Greenbelt, MD 20771

Dear Randy,

I acknowledge that I am identified by name and a Co-Investigator to the investigation entitled: "**MODELING THE GLOBAL ATMOSPHERIC CARBON CYCLE IN PREPARATION FOR OCO DATA**", that is submitted by S. Randolph Kawa to the NASA Research Announcement: NNH07ZDA001N-CARBON, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as state in this proposal will be considered during peer review in determining in part the merits of this proposal.

Sincerely,

Joseph A Berry
Staff Scientist

260 PANAMA STREET • STANFORD, CALIFORNIA 94305-1297 • 650 462-1047 ext 203
FAX 650 462-5968 EMAIL joeberry@stanford.edu TELEX 348402 STANFRD

From: jcollatz@ltpmail.gsfc.nasa.gov
Subject: **Re: current draft**
Date: May 22, 2007 11:33:46 AM EDT
To: kawa@maia.gsfc.nasa.gov

Dear Randy

I look forward to continuing our collaborations as a Co-Investigator to the investigation, entitled "Modeling the global atmospheric carbon cycle in preparation for OCO data", that is submitted by you, Stephan R. Kawa to the NASA Research Announcement NNH07ZDA001N-CARBON, and that I intend to carry out all responsibilities identified for me in this proposal. These responsibilities include providing to PCTM, terrestrial carbon fluxes modeled by CASA and evaluating the CASA model behavior as expressed in the PCTM generated CO2 fields. I will also participate with the CSU team in developing, implementing and analyzing SiB-CASA. In addition, I will provide expertise/guidance in the use and interpretation of vegetation and fire remote sensing products. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Regards,

G. James Collatz
Hydrospheric and Biospheric Sciences Laboratory
NASA's Goddard Space Flight Center
Greenbelt, MD 20771

A. SCOTT DENNING
MONFORT PROFESSOR
DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
FORT COLLINS, CO 80523-1371

Colorado State University
Knowledge to Go Places

June 1, 2007

Dr. S. Randolph Kawa
NASA Goddard Space Flight Center
Code 613.3

Dear Randy:

I acknowledge that I am identified by name as Co-Investigator to the investigation, entitled "*Modeling the Global Atmospheric Carbon Cycle in Preparation for OCO Data*," that is submitted by you as PI to the NASA Research Announcement NNH07ZDA001N, and that I intend to carry out all responsibilities identified for me in this proposal. In particular, I intend to extend the coupled ecosystem physiology-biogeochemistry model (SiB-CASA) that we developed under our previous collaboration, to operate at a global scale, driven by GOES-5 meteorology, MODIS vegetation products, and the Global Fire Emissions Database (GFED). I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Best regards,

A. Scott Denning

A. Scott Denning

(970)491-6936 denning@atmos.colostate.edu Fax (970)491-8449

From: ericksondj@ornl.gov
Subject: **NASA NRA**
Date: May 31, 2007 8:55:29 AM EDT
To: kawa@maia.gsfc.nasa.gov
Cc: ericksondj@ornl.gov

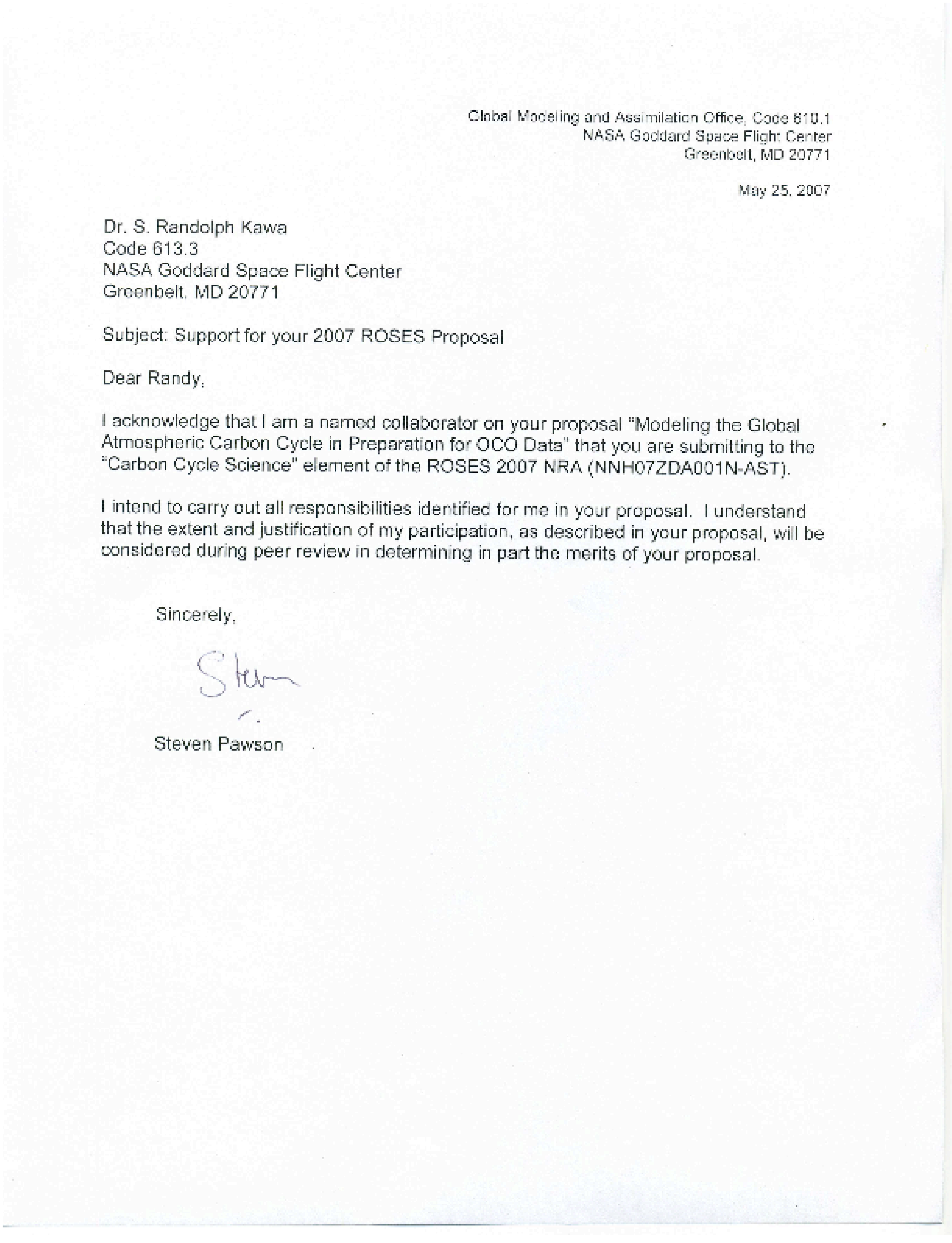
Dear Randy

I look forward to continuing our collaborations as a collaborator to the investigation, entitled "Modeling the global atmospheric carbon cycle in preparation for OCO data", that is submitted by you, Stephan R. Kawa to the NASA Research Announcement NNH07ZDA001N-CARBON, and that I intend to carry out all responsibilities identified for me in this proposal.

These responsibilities include providing to PCTM global grids of OCS fluxes and assisting in evaluating PCTM generated CO2 and OCS fields. I will also participate in creating high resolution anthropogenic CO2 fluxes. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Regards,

David J. Erickson
Oak Ridge National Laboratory



Global Modeling and Assimilation Office, Code 610.1
NASA Goddard Space Flight Center
Greenbelt, MD 20771

May 25, 2007

Dr. S. Randolph Kawa
Code 613.3
NASA Goddard Space Flight Center
Greenbelt, MD 20771

Subject: Support for your 2007 ROSES Proposal

Dear Randy,

I acknowledge that I am a named collaborator on your proposal "Modeling the Global Atmospheric Carbon Cycle in Preparation for OCO Data" that you are submitting to the "Carbon Cycle Science" element of the ROSES 2007 NRA (NNH07ZDA001N-AST).

I intend to carry out all responsibilities identified for me in your proposal. I understand that the extent and justification of my participation, as described in your proposal, will be considered during peer review in determining in part the merits of your proposal.

Sincerely,

Steve

Steven Pawson

BUDGET JUSTIFICATION: NARRATIVE AND DETAILS

The following is provided in addition to the NSPIRES budget items, Budget Summary (shown on NSPIRES Cover Page/s from budget data entry), and Total Budget (the required pdf attachment to NSPIRES).

Budget Justification: Narrative

The following table includes all GSFC personnel necessary to perform the proposed investigation.

(a) Table of Proposed Work Effort (*Person Months*)

Name and/or Title	Role	Institution	**Yr-1**	**Yr-2**	**Yr-3**	Total
Dr. S. Randolph Kawa	PI	NASA/GSFC	3.6	3.6	3.6	10.8
Dr. G. James Collatz	Co-I	NASA/GSFC	1.2	1.2	1.2	3.6
Dr. H. Bian	Asst Research Scientist	GEST/GSFC	3.6	3.6	3.6	10.8
Mr. Z. Zhu	Scientific Programmer	SSAI/GSFC	9.6	9.6	9.6	28.8
TBD	Resource Analyst	NASA/GSFC	0.5	0.5	0.5	1.5

(b) Description of Facilities and Equipment

The facilities needed to carry out the proposed research are available at the PI's institution, NASA/Goddard Space Flight Center. These include computers and programs in the Laboratory for Atmospheres Code 613, in the Science & Exploration Directorate, Code 600.

(c) Rationale and Basis of Estimate

(1) Direct Labor (salaries, wages, and fringe benefits) - GSFC:

The cost of direct labor of the GSFC PI and Co-Is (shown in the above table) is based on GSFC's established rate for a Senior Scientist skill level. The cost of the proposed Resource Analyst support, which will manage the funding resources and procurement activities associated with this research, is based on GSFC's established rate for a Professional Administrative skill level. GSFC fringe dollars are calculated as a percent of direct salary dollars, using GSFC established rates per year.

Support is requested for 3.6 months per year of a GEST assistant research scientist (H. Bian) to analyze the forward transport parameterizations and characteristics of GEOS-5. To perform the programming needed for the project, a Scientific Programmer is needed for 9.6 months each year. The cost estimates are based on currently established loaded rates for the GEST and SSAI contracts that already exist at GSFC.

The basis of estimate for participating Co-I institutions is described under "Sub-awards" below. The Total Estimated Cost, the cost of Direct Labor, and Administrative Cost (e.g., overhead) are provided in the NSPIRES "Total Budget" attachment.

(2) Other Direct Costs

(a) Subcontracts / Subawards – Funding is requested for Colorado State University (CSU) to perform the SiB-3, SiB-CASA, COS, and MLEF work. The itemized budget is included in the NSPIRES "Total Budget" attachment. Total budgeted amount each year is shown in the Budget Detail section below. The following is the budget rationale and basis of estimate:

CSU, Rationale and Basis of Estimate:

Year 1

Personnel -

A. S. Denning, Professor	0.4 month
I. Baker, Research Associate	6 months
W. Turkal, Research Associate	1 month
TBD, Research Coordinator	1 months
Ph.D. Level Graduate Student	0 months

Supplies - Books/Research literature required to perform proposed research, $250; color printer expendables to produce presentation and publication materials, $400; data storage media, $300.

Other Direct Costs:

Publication Charges- 1 paper in an American Meteorological Society Journal (or equivalent), costs include page charges and color figure charges, total $2000.

Computer access - $267. In order to perform the proposed research it is necessary to use the Atmospheric Science ethernet to connect with the internet and from there to NASA supercomputers. The Department charges a fee for such connections. The amount is $32 per number of personnel months supported.

Misc. Other Direct Costs - Long distance and fax services, $211; Printing services, $250.

Tuition - $0.

Travel - One 2-person trip to Greenbelt, MD, 5 days/4 nights.

Airfare	$630 x 2 =	$1260
Hotel ($150/night)	$600 x 2 =	$1200
Per Diem ($64/day)	$320 x 2 =	$ 640
Rental Car	$250	$ 250
Mileage & Parking	$150	$ 150
Total		$3500

The first year graduate student expenses will be fully covered under an award from the Center for Earth-Atmosphere Studies (CEAS, http://pita.gsfc.nasa.gov/metadot/index.pl?iid=1894) at no cost to this proposal.

Year 2

Same as first year, except 12 months of Ph.D. GRA, $29,066; two semesters of in-state tuition for GRA, $4,460; no salary for I. Baker; Conference Travel for GRA, $1560; Registration fee for conference, $312; fringe benefits are 24.6% for Faculty and Academic Professionals, and 4.2% for GRAs; all other costs inflated by 4% from the first year.

Year 3

Same as second year except fringe benefits are 25.10% for Faculty and Academic Professionals, and 4.7% for GRAS; all costs inflated by 4% from the second year.

(b) Consultants: none required.

(c) Facilities and Equipment: none requested.

(d) Supplies

GSFC's budget includes materials and supplies to cover local computer hard drive additions, software licenses, and incidentals. Cost estimates are based on recent similar procurements initiated by GSFC.

(e) Travel

The following standard cost assumptions apply:

- Estimated airfare and auto rental costs were obtained from either GSFC's customary source, CI Travel, or from other airfare estimating search engines (i.e., Travelocity, etc.); also, per diem costs were obtained from http://www.gsa.gov/
- miscellaneous costs include local mileage using current prevailing rate of $0.485 for privately owned vehicle (POV), obtain from http://www.gsa.gov/; estimated incidental costs include airport parking, tolls, etc.
- inflation of 3% per year is applied for annual occurrences

Expected Travel

		Est Airfare (R/T)	Per Diem	Auto Rental	Misc	Yr-1	Yr-2	Yr-3	Total
Unit Price $		500	110	50					
People		2	2	1					
Days			5	5					
Departure									
Destination	AGU, Project Team Mtg, Science Wkshp (3 trips)								
	Total	3000	3300	750		7050	7050	8550	21150

Additional assumptions:

- each trip occurs during each November

- One additional international trip shown for the third year.
- Approximately 75% of this travel is reflected in the Civil Service Travel budget and 25% in the Contractor costs.

(f) Other Costs

(i) Computer Support – supercomputer time will be requested directly to the NASA Center for Computational Sciences at GSFC. Supercomputer resources are generally available to approved Earth Science projects on a no exchange of funds basis.

(ii) Publications – Costs included for journal publications, page charges, reprints, and abstract fees are estimated at $1000/article with 2 in the first year and 3 each in the second and third year.

*(iii)*Other Direct Costs, SED - These costs, as discussed in NASA financial regulations, are for services to support the research effort that go beyond the standard costs considered under Center Management and Operations (Center Overhead), and are not incurred elsewhere within GSFC. Within the Sciences and Exploration Directorate these costs cover system administration for the complex information technology services required to support the proposed research activities, administrative and resource analysis support, and supplies to support the research effort.

(3) Facilities and Administrative (F&A) Costs, GSFC - Beginning in FY07, the indirect costs for Facilities, Information Technology (IT), and General and Administrative (G&A) will be administered directly from NASA/HQ under CM&O (Center Management and Operations) and are therefore excluded from this proposal. Beginning in FY08, RDMS (Research and Development Multiple Support) is also included in CM&O.

(4) Other Applicable Costs – None

(5) Proposed Cost Sharing - None.

Budget Justification: Detail

As required by ROSES-2007 NRA, section IV(iii), the Budget Detail given here is restricted to Other Direct Costs and Other Applicable Costs, and does not specify Total Estimated Cost, Direct Labor costs, or Administrative costs.

Description			Costs			
2. Other Direct Costs			**Yr-1**	**Yr-2**	**Y-3**	Total
	Subcontracts / Sub-awards		$90k	$94k	$98k	$282k
	Consultants					
	Facilities and Equipment					
	Supplies		$0.5k	$0.5k	$0.5k	$1.5k

	Travel		$5.4k	$5.4k	$6.9k	$17.7k
	Other Direct Costs	Computer Support				
		Fabrication				
		Publications	$2k	$3k	$3k	$8k
		Other Dir Costs, SED	$19.1k	$19.9k	$20.8k	$59.8k
3. Facilities and Administrative Costs						
4. Other Applicable Costs						
Total			$117k	$122.8k	$129.2k	$369k