Constraining The CO_2 Missing Sink

TABLE OF CONTENTS

ABSTRACT

Constraining the CO_2 Missing Sink

Topical Area: Global Carbon Cycle Modeling and Analyses

Principal Investigator: S. R. Kawa, NASA Goddard Space Flight Center

Co Investigators: A. S. Denning, Colorado State University
G. J. Collatz, NASA Goddard Space Flight Center
D. J. Erickson, Oak Ridge National Laboratory and Duke University

We present a proposal to reduce uncertainty in the carbon cycle processes that create the so-called missing sink of atmospheric CO_2. Our overall objective is to improve characterization of CO_2 source/sink processes globally with improved formulations for atmospheric transport, terrestrial uptake and release, biomass and fossil fuel burning, and observational data analysis. The motivation for this study follows from the perspective that progress in determining CO_2 sources and sinks beyond the current state of the art will rely on utilization of more extensive and intensive CO_2 and related observations including those from satellite remote sensing.

Our proposed approach is to perform several interrelated tasks to advance models and data analysis methods that are required to realize the benefits of existing new and planned future observations: 1) Continue development of the parameterized chemistry and transport model using analyzed meteorological fields from the Goddard Global Modeling and Assimilation Office, with comparison to real time data in both forward and inverse modes. 2) Couple an advanced biosphere model, constrained by remote sensing data, with the global transport model to produce distributions of CO_2 fluxes and concentrations that are consistent with actual meteorological variability. 3) Employ improved remote sensing estimates for biomass burning emission fluxes in the transport model and data comparisons to better characterize interannual variability in the atmospheric CO_2 budget and to better constrain the land use change source. 4) Evaluate the impact of temporally resolved fossil fuel emission distributions on atmospheric CO_2 gradients and variability. 5) Test the impact of existing and planned remote sensing data sources (e.g., AIRS, MODIS, OCO) on inference of CO_2 sources and sinks, and use the model to help establish measurement requirements for future remote sensing instruments.

The anticipated results are improved, data-constrained models that resolve transport and emission distributions at global to synoptic scales, methods to use the information contained in simulations and data at these scales, and refined inferences of CO_2 sources and sinks and their dependence on environmental conditions. These results are of potentially high value to NASA carbon cycle science in designing remote sensing approaches to determine global distributions and fluxes of carbon, to prepare for the use of OCO and other satellite data, and to develop modeling tools that contribute to a multi-disciplinary carbon data assimilation system for analysis and prediction of carbon cycle changes and carbon/climate interactions.

TECHNICAL PLAN

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 [IPCC, 2001]. As a result, carbon-climate interaction is among the leading sources of uncertainty in prediction of future climate. Modeling studies have shown future climate predictions depend on the details of the processes that couple carbon and climate [Cox et al., 2000; Dufresne et al., 2002]. For example, current ecological models are very sensitive to treatment of stresses, i.e., responses of ecosystems to changing CO_2 and nutrient fertilization, temperature, moisture, fires, and management practices that are difficult to validate. Accurate representation of these processes requires rigorous testing of model response to seasonal and interannual forcing over global scales. The role of ocean circulation and marine carbon cycle is also important, but this problem is not addressed in depth here.

Global, decadal budgets summarized for the 1980s and 1990s infer a large residual terrestrial sink for atmospheric CO_2 with attached uncertainty of 50 to 100% or more [IPCC, 2001]. Several lines of evidence suggest that the northern hemisphere terrestrial biosphere is responsible, but the magnitude, location, variability, and mechanisms producing the sink are not well determined [Tans et al., 1990; Fan et al., 1998; Bousquet et al., 2000; Battle et al., 2000]. Suggested contributing processes include an enhancement in North American and/or Eurasian forest uptake and land use change/disturbance/recovery, although no single process has been shown to account for the terrestrial sink. This so-called "missing sink" for CO_2 epitomizes a major uncertainty in the current understanding of carbon cycle processes. 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; Keeling et al., 1995]. Attempts to locate sources and sinks using diagnostic models are hampered by data limitations and uncertainty in atmospheric transport representation (Figure 1) as well as ocean flux [Gurney et al., 2002]. Detailed, quantitative knowledge of the processes underlying the terrestrial sink 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 will require improved models and enhanced data. New global remote sensing data from satellites holds 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. 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 data. In addition, the ability of the models to accurately simulate processes must be improved in concert. The expected result of this activity is a closer link between top-down and bottom-up estimates of processes and their sensitivities such that uncertainties are significantly reduced. This goal is common to major NASA, US, and international carbon science efforts, e.g., CCRI, CCSP, NACP, CarboEurope, WCRP, and IGBP.

We propose to reduce the uncertainty in characterizing terrestrial CO_2 sinks through linked model development and data analysis in 5 areas of concentration. The first is to continue to exercise and improve our atmospheric transport model, which uses assimilated meteorological fields. The transport model forms the foundation for testing process formulations in comparison to the CO_2 observations. Inverse methods are included here. The second is to couple the meteorology and transport with a terrestrial ecosystem model, constrained by satellite observations, to test the sensitivity of biospheric processes and CO_2 flux to climate fluctuations. Comparison to real-time CO_2 observations across a range of time and spatial scales from hourly/synoptic to interannual/global will inform the representation of processes such as the "rectifier effect" and El Niño effects. The third is to use newly derived emissions from biomass burning along with the transport and biosphere models to better characterize the effect of burning on interannual variation of CO_2 and to constrain the tropical land use change source of CO_2. The fourth task is to incorporate new diurnally and seasonally varying emissions data for the fossil fuel source of CO_2 and quantify the impact on inferred sinks. To the extent that CO_2 gradients produced by temporal variations of this source are incorrectly represented, errors will be aliased into the terrestrial biosphere or ocean source/sink distributions. The fifth and final task is to begin to incorporate satellite CO_2 data into the model inverse calculations of sources and sinks, and to use the model to guide science measurement requirements for remote sensing CO_2 observations. We will develop methods for analyzing the satellite plus in situ data that will set the stage for use of OCO and future data and enable development of an interdisciplinary carbon-climate model data assimilation system.

The expected result of the sum of these tasks is quantitative characterization of variations in carbon transport, sources and sinks, and their uncertainties leading to better characterization of the "missing" sink. We will produce an improved data-driven transport model for interannual to synoptic data comparisons; global distributions of CO_2 and fluxes due to photosynthesis and respiration in terrestrial ecosystems and their sensitivity to climate fluctuations, disturbance, and recovery; distributions of CO_2 from biomass burning; distributions of CO_2 from temporally varying fossil fuel combustion emissions for the US and other areas; and methods for exploiting and optimizing new data sources especially satellite remote sensing. These products will be part of NASA's contribution toward fully coupled Earth system models capable of simulating future changes in carbon cycling and climate, tests of the models against observed seasonal and interannual variations in the carbon cycle, quantitative characterization of uncertainty in the model predictions and their components, and production of decision support information for evaluation of the impact of policy options on changing carbon cycle and climate.

This proposal is aimed primarily at the Global Carbon Modeling and Analyses area of the NRA, but it also relates closely to NACP and Regional Studies outside US, e.g., NEESPI and the response of Northern Eurasia carbon dynamics to changes in land cover, land use, and climate.

2. Scientific Tasks

The proposed activity is broken down into 5 main tasks. The following sections give the status, objectives, methods, and expected results of each.

2.1 CO_2 Transport Simulation

Our first proposed task is to continue development of the parameterized chemistry and transport model (PCTM) using analyzed meteorological fields from the Goddard Global Modeling and Assimilation Office (GMAO). Transport modeling enables comparison to real-time data in both forward and inverse modes and provides the basic framework for subsequent tasks. The objective of this task is to minimize and quantify transport model uncertainty, and to provide an optimum vehicle for evaluation of processes.

The performance of the PCTM for CO_2 transport using climatological sources and sinks is documented in Kawa et al. [2004, submitted manuscript]. The PCTM in this study is driven by analyzed meteorology from a prototype version of NASA's Goddard Earth Observation System, Version 4 (GEOS-4) data assimilation system (DAS) [*Cohn et al.,* 1998]. The model has been adapted from an established off-line full-chemistry/transport model (e.g., *Douglass and Kawa* [1999], *Douglass et al*. [2003], *Nielsen and Douglass* [2001]). At the core of the PCTM is the transport code of *Lin and Rood* [1996], whose accuracy for large-scale transport is well documented in the stratosphere [*Douglass et al.,* 2003] and troposphere [*Li et al.,* 2002]. For tropospheric trace gases the transport due to sub-grid-scale processes such as convection and boundary layer diffusion is included consistent with that of the parent GCM. To date the PCTM has been run for CO_2 using DAS output for 1998-2000 at 2.5° by 2° (longitude by latitude) with 25 levels up to 1 mbar, of which 14 are below 175 mbar. For this proposal we plan to run at 1°x1.25° for most cases. GEOS-4 analyses will be available for 1991 to present (2004).

Analysis of model diagnostics and comparisons to previous results indicates that this model performs as well as or better than most previous global transport models [Law et al., 1996; Denning et al., 1999]. The model interhemispheric gradients along with the timing and magnitude of the CO_2 seasonal cycle (e.g., Figure 2) provide inferences regarding the northern biosphere, tropical land, and southern ocean fluxes, and interannual variability [Kawa et al. 2004]. Use of the model for source/sink inversion in the TransCom 3 protocol [Gurney et al., 2004] gives results that are consistent with most other TransCom participants (Figure 3). On the synoptic scale, we find significant advantage in using the DAS analyzed winds for real-time comparisons to data. At near-equatorial observation sites, the model accurately simulates the observed atmospheric composition transition associated with the latitudinal movement of the ITCZ. Comparison to daily data from continuous analyzer sites shows the model captures a substantial amount of the observed synoptic variability in CO_2 due to transport changes (Figure 2). Realistic inclusion of synoptic events, e.g., fronts, persistent ridges, circulation anomalies, etc., which is not possible with a free-running GCM, is required in order to analyze and interpret continuous trace gas and satellite observations. These results show the potential to use high temporal and spatial resolution remote sensing data to constrain CO_2 surface fluxes, and they form the starting point for developing an operational CO_2 assimilation system to produce high-resolution distributions of atmospheric CO_2 and quantitative estimates of the global carbon budget.

The forward transport model is fully functional as it stands so model development really means just keeping pace with developments ongoing at GMAO as needed. This includes updating to use GEOS-5 inputs as the new system becomes operational, increasing resolution to 1°x1.25°, improving vertical resolution in the boundary layer, and updating the PBL diffusion and convective flux formulations to be consistent with new physical parameterizations in the GCM. Comparison to CO_2, SF_6, and other tracer observations forms the metric for improvement. We work in close collaboration with model developers in GMAO and results of our simulations and data comparisons feed back into the GCM and assimilation progress. Coordinated development of the GCM for meteorological analysis and for transport, plus availability of high time resolution output, is an advantage of the GMAO production. We also plan to test a parameterization of transport by cumulus convection using vertical mass fluxes from a new version of the parent FVGCM that is being coupled to a Cloud System Resolving Model (CSRM). The coupled ("superparameterized") FVGCM/CSRM is being developed by a NASA EOS IDS team (Prof. David Randall, PI).

We are working with GMAO (S. Pawson, related proposal) to bring carbon processes, data, and transport on line into the assimilation modeling system. Climatological CO_2 is currently being transported on line in the FVGCM as a result of our PCTM experience. In addition, support for this task will also allow us to continue to collaborate with and support PCTM users outside Goddard (at CSU, NCAR, Penn State, Harvard, U. Maryland, and others). Although we are not proposing a specific role on the NACP science team, we would certainly like to be involved in NACP if possible depending on NACP implementation plans. Global simulations at 1°x1.25° can provide useful information for North America (e.g., the state of Colorado is about 4°x5°) to resolve regional sources and sinks, provide a basis for comparison with mesoscale results, and for evaluating spatial scale dependence of fluxes. PCTM will be available to produce global boundary conditions for the NACP mesoscale process and transport modeling proposed under separate cover by S. Denning.

A variety of model experiments are proposed to address the science issues at hand. A baseline forward run to examine the influence of interannual transport variations with climatological sources and sinks will be done for the period of available meteorological analysis, 1991-2004. The influence on atmospheric CO_2 from biospheric changes in response to meteorological changes will be examined in a parallel set of runs as discussed below (Section 2.2). Runs with the biomass burning source derived from satellite data for 1997-2004 will also be compared for interannual variability (Section 2.3). The impact of temporally varying fossil fuel emissions (Section 2.4) will probably require only a few years of simulation, and likewise for testing of transport model parameterization upgrades.

The primary focus of our proposed activity is the terrestrial CO_2 sink, but this sink cannot be evaluated independent of the ocean CO_2 sink. Although the uptake and release of CO_2 at the ocean surface is known with a higher degree of confidence than that of the terrestrial surface, significant uncertainty (0.7 $PgCyr^{-1}$ or ±30%) still resides in the global ocean flux [IPCC, 2001]. Latitudinal, seasonal, and interannual variations in the ocean sink are even more uncertain, e.g., interhemispheric transport and the Southern Ocean sink. Errors in the ocean sink will potentially lead to errors in estimating residual terrestrial sources/sinks and their regional distributions [Gurney et al. 2002]. Thus, tests of the sensitivity of our data comparisons to ocean flux specification will be required. Extensive testing of ocean processes and flux optimization is beyond the scope of this effort. We will test one or two alternate ocean flux specifications beyond the Takahashi et al. [1997] TransCom fluxes in collaboration with Ning Zeng at the

University Maryland and Watson Gregg of NASA GSFC, who are developing them under separate support. Comparison of forward runs and inversions will show if differences are significant and quantify their influence on inferred terrestrial fluxes.

Inverse Approaches

We will pursue several approaches to inverse modeling in order to take advantage of new data sources and model improvements. In addition to TransCom-style and higher resolution synthesis inversions for fluxes, uncertainties, and comparison to previous results, we will begin to test alternate inverse approaches to better exploit real time model-data comparison. Ensemble Data Assimilation (EnsDA, below) is a Kalman filter approach being developed under a related Denning proposal. Adjoint transport approaches [Roedenbeck et al., 2003; Andrews et al., 2002] are being developed in collaboration with A. Andrews at NOAA CMDL and under a related Pawson data assimilation proposal. These alternate approaches have the advantage of being able 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.

Selected years and runs will be used in synthesis inversion calculations similar to TransCom (Figures 1, 3). This will include using new available in situ data from the surface, towers, and aircraft (Figure 4) for *a priori* constraints and concentration data comparison as well as the use of satellite CO_2 data (Section 2.5). A new set of interannual basis functions for synthesis inversion will be run with a larger number of source regions (perhaps as many as 100) to reduce aggregation error. We will use the land carbon model (below) to guide the regional delineation. The CO_2 flux scenarios described in the following sections will produce differing pre-subtraction fields and residuals. Synthesis inversions will include highly resolved a priori estimates of seasonal variations in terrestrial ecosystem photosynthesis, respiration, and decomposition constrained by MODIS imagery and GEOS-4 weather analyses; improved estimates of fossil fuel emissions and their temporal variations; and emissions due to wildfires and other biomass burning (Sections 2.2-2.4). We expect to significantly improve the uncertainty estimates of Figure 1 through a better description of carbon cycle processes led by comparison with enhanced observations.

The EnsDA framework will involve merging several streams of observational data into the coupled biogeochemical/disturbance/transport model being developed, but will 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. It will also calculate transport by advection, convective mass fluxes, and PBL turbulence. Finally, it will calculate hourly mixing ratios of CO_2 on a 1°x1.25° grid. These 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, AIRS, and eventually OCO sensors. The optimization will be performed by solving for magnitudes and uncertainties of physiological parameters in SiB3, initial biogeochemical pool sizes in the new BCM module, combustion efficiencies for biomass burning in the fire module, and PBL diffusivities in PCTM.

2.2 Coupled Biosphere/Transport Modeling

The focus of this task is to provide realistic net CO_2 fluxes from the land surface to the atmosphere on a global grid with an hourly resolution; seasonal and interannual variations will be estimated. The mechanisms responsible for these fluxes will be examined and estimates of uncertainty will be provided. The primary tool for this work will be a version of a coupled SiB-BCM (Simple Biosphere-Biogeochemical Cycle Model), with constraints imposed from a variety of observations and atmospheric analyses. The derived fluxes will be used as boundary conditions in the transport model, and the consistency of bottom-up and top-down estimates will be evaluated in terms of the underlying processes.

The net land-surface CO_2 flux is determined by the imbalance between uptake by photosynthesis and release by respiration, fires, and industrial emissions. The biological fluxes are defined as follows. Heterotrophic respiration (RH) is the consumption of net primary productivity (NPP), which is the difference between gross primary productivity (GPP) or photosynthesis and autotrophic respiration. RH is largely determined by the decomposition of above- and below-ground organic carbon. Models of primary production have been successfully implemented in climate models yielding plausible results (e.g., Sellers et al. [1997]), especially those that use satellite observations to prescribe seasonality in biophysical parameters such as leaf area index (e.g. Denning et al. [1996]).

Parameterization of RH is more problematic and has hindered progress in understanding and predicting net fluxes. RH depends on the size and quality of the organic carbon pool. Such pools are often large, with relatively long turnover times. Turnover times are strongly dependent on previous productivity, as well as soil temperature and moisture, so models that parameterize these processes require long spin-up times (centuries). In addition, RH partially controls the availability of plant nutrients by releasing nutrients that are bound in the organic carbon pools, which in turn affects net primary production. The type of vegetation and soil, the history and type of disturbance, climate variability, and human management all influence primary production and the size of organic carbon pools. Observations that would allow us to prescribe the carbon pool states are lacking.

Our initial strategy will be to develop a land-carbon model that is driven off-line by the analyzed meteorological fields from FVDAS. The land model will make best use of real (not “potential”) vegetation distributions, EOS phenological descriptors, and fire products in a self-consistent model of terrestrial ecosystems (Table 1). This can be evaluated against observations at local (tower), regional (campaign), and global (trace gas) scales. The model will resolve diurnal/synoptic time scales, track carbon pools/disturbance/fire/recovery, couple to transport on an hourly basis, and remain true to MODIS product constraints. The land model is an important component for efforts to build a carbon data assimilation system. Coupled Land-Atmosphere modeling and the assimilation of land-surface biophysics is a longer-term goal of this work.

Description of the SiB-BCM

The land-carbon model will initially be run off line, constrained by meteorological analyses and space-based observations, but will be developed in a flexible manner to allow coupling to the atmospheric model. In off-line mode, it will be forced by GEOS-4 meteorological analyses, at a

Table 1: Sources of Data for Constraining the Land Model	
Data	Sources
Vegetation Index (FPAR, LAI)	MODIS (2000-present) AVHRR (1982-present) GIMMS SeaWiFS (1997-present) GIMMS
Vegetation Classification	MODIS vegetation classification product MODIS continuous fields product (%woodiness) ISLSCP I and II vegetation products
Fire	TRMM/VIRS fire count product (1998-present) MODIS fire detection product (2000-present) MODIS burned area product (proposed by others)
Meteorological Drivers	GEOS-4 analyses and reanalysis

horizontal resolution of 1°x1.25°, to generate land-surface CO_2 fluxes with a temporal resolution of one hour. The model is illustrated schematically in Figure 5.

SiB3 is the latest version of a model with a strong heritage in studies of the biosphere [Sellers et al., 1997; Denning et al., 1995; Schaefer et al., 2002]. Recent model development has included adoption of substantial code and algorithms from the Community Land Model [Bonan et al., 2003]. The model now includes a second-order accurate numerical scheme for predicting temperature, water, and ice content in 10 soil layers, and an adaptive grid for predicting the temperature and density of up to five layers of snow. Simulation of drought stress and deep soil moisture is much improved over earlier versions of the model [Liu et al., 2003]. The surface-energy budget now includes prognostic calculation of temperature and moisture in a canopy air space [Baker et al., 2001]. The mixing ratio and stable isotope ratio of CO_2 in the canopy air reflects influences by both photosynthesis and respiration. SiB3 is quite modular; it has been coupled to a mesoscale atmospheric model for evaluation with data from regional atmospheric campaigns [Denning et al., 2003; Nicholls et al., 2003].

SiB3 calculates GPP, canopy and soil temperatures, and soil moisture at hourly time steps for use by the respiration modules. Absorption of solar radiation by the canopy is derived from satellite estimates of vegetation index. An allocation parameterization partitions GPP into autotrophic respiration at an hourly time step and into living biomass pools (leaves, roots and stems) at a daily time step. Allocation will be constrained with satellite observations of LAI and fractional woody coverage (see Table 1). Carbon enters non-living organic matter pools on a daily time step through the delivery of biomass to litter (leaf, root and coarse woody debris) pools. Fixed carbon is then respired back to the atmosphere and delivered to other soil carbon pools controlled by pool-specific rate constants, which are scaled by temperature and moisture conditions at an hourly time step. Versions of the SiB model have been used to simulate net carbon fluxes by a simple "balanced" approach [Denning et al., 1996], however, this approach masks important underlying processes through aggregation and cannot account for longer term sources and sinks.

The decomposition pools and processes are adapted from the CASA model [Potter et al., 1993]. This framework can be easily expanded to account for ^{13}C fluxes [Fung et al., 1997; Randerson et al., 2002]. The important parameters that control the GPP flux are the maximum biochemical capacity for CO_2 fixation by photosynthesis, the fraction of solar radiation absorbed by the canopy, and the degree of water stress. Parameters that characterize the temperature and soil moisture response of decomposition are important determinants of the respiration fluxes. The model net flux is evaluated in comparison to data from CO_2 flux sites (e.g., Figure 6). Autotrophic respiration and RH are also highly dependent on carbon pool sizes, which are state variables of the model. We will derive the optimal values of these parameters and state variables and the sensitivity of the fluxes to them with atmospheric observations and inverse approaches (Section 2.1).

Land Carbon Strategy

Spin up of the BCM requires use of mean meteorological conditions and GPP for 1000 years with a one-month time step, followed by an additional 100 years with a one-hour time step. When carbon pools have reached equilibrium, time series of analyzed meteorology and observed vegetation index for the analysis period will be used as boundary conditions to generate hourly carbon fluxes (Figure 7). Initialization of the analysis with equilibrium conditions excludes simulation of long-term source and sinks, such as those caused by recovery from disturbance or CO_2 fertilization, but does allow study of circulation-driven interannual variability. The spatial distribution of secular sources and sinks will be derived using the inverse methods applied to the atmospheric transport model and CO_2 observations. Optimization analysis of the states of relevant carbon pools that could plausibly account for sources and sinks (e.g. live wood pool, coarse woody debris) would identify regions and conditions that could be validated with regional information (e.g. Forest Inventory and Analysis, USFS).

Others have argued that interannual variability in terrestrial carbon fluxes is influenced by feedbacks between the carbon cycle and the cycling of soil nutrients, especially nitrogen [Braswell et al., 1997; Vukicevic et al., 2001]. While our approach currently does not address the impacts of nutrient fertilization/pollution, it does implicitly account for feedbacks between GPP and RH that arise due to variability in nutrient availability. By prescribing the amount of green vegetation from satellite observations, variability caused by changes in nutrient availability is implicitly included [Braswell et al., 1997].

High frequency CO_2 measurements such as shown in Figure 2 and the seasonal cycle of satellite observed phenology strongly constrain land carbon fluxes such that uncertain modeled processes such as autotrophic respiration and response of GPP and RH to temperature and soil moisture may be inferred from coupled top-down bottom-up inversion techniques. Interannual variability in physiological response is less well constrained but with improved NDVI and fire observations from satellites, along with improved parameterization of seasonal dynamics, it should be possible to use mutually constrained inversions to identify processes controlling interannual variability in atmospheric CO_2 growth.

The result of this task to couple the land carbon model, data constraints, and transport will be a model and methods to consistently calculate CO_2 fluxes, their dependence on physical processes, and comparison of CO_2 distributions to observations on a wide range of scales. The model will quantify the “rectifier effect” seasonally and diurnally (Figure 8), which is required for land-based flux estimates and which must be accounted for in estimating fluxes from satellite measurements at a fixed time of day [Rayner et al., 2002]. El Niño and other climate fluctuations and their impact on CO_2 fluxes will be simulated to quantify their influence on CO_2

growth rate. The NACP domain will be simulated at 1°x1.25° within the full global context. The results will apply to the NEESPI and other efforts, which strive to understand how the land ecosystems and continental water dynamics interact with and alter the climatic system, biosphere, atmosphere, and hydrosphere of the Earth. This will lead to model improvements and validated components of models for coupled carbon-climate projection.

2.3 Biomass Burning CO_2 Emission Distributions

Interannual variability in atmospheric CO_2 growth rate is strongly driven by land processes [Battle et al., 2000; Bousquet et al., 2000] as land net flux variability is about 3 times larger than that estimated for the oceans. This variability is correlated with ENSO. For instance, the atmospheric CO_2 growth rate went from less than 1ppm/yr in 1996 to over 3ppm/yr during the strong '97/'98 El Nino. Fossil fuel burning contributed about 3ppm/yr (6 Pg C/yr) to the atmosphere during this period. The land carbon flux variability has been attributed to imbalances between photosynthesis and respiration, which are very large fluxes (~100 Pg C/yr) compared to fossil fuel emissions. Recently, however, a number of studies have argued that the response of the land surface carbon flux to ENSO is to a large extent the result of climate driven variability in global fires [Langenfelds et al., 2002; Schimel and Baker, 2002; van der Werf et al., 2004]. Clearly, in order to understand interannual variability in atmospheric CO_2 growth rate and land carbon fluxes variability in fire emissions must be taken into account.

Co-I Collatz is part of a NASA funded project aimed at estimating carbon species emissions globally from fires (JR Randerson, PI). Satellite based estimates of burned area and biogeochemical model estimates of fuel loads are used to estimate monthly CO_2, CO and CH_4 emissions from fires [van der Werf et al., 2004]. The team has released monthly fire emissions for 1997-2001 (Figure 9) and will continue to improve and make available emissions estimates through 2007 [http://www.gps.caltech.edu/~jimr/randerson.html]. Relevant aspects of the Randerson et al. project will be adopted for SIB-BCM. Emissions are prescribed from satellite-based estimates of burnt area and modeled fuel loads at daily to weekly time steps. Emissions predicted by their forward model are compared to results from atmospheric inversions and analyses concurrently for CO_2, CO and CH_4 and isotopic compositions (e.g. van der Werf et al. [2004]). In this way uncertainties in predicted CO_2 emissions from fires are evaluated and will be provided to this project.

Carbon fluxes from fires include direct emissions caused by consumption of biomass and litter pools as well as indirect effects on RH caused by transfers of carbon from killed biomass to litter pools (Figure 5). The carbon sinks caused by recovery of biomass and litter pools after fire are simulated as functions of GPP and climate. Satellite vegetation indicies, at least in part, represent the reduction of GPP followed by recovery that results from destruction of green vegetation and regrowth following fire.

The emissions estimates will be used directly as boundary conditions for the atmosphere and burned area estimates can be used to adjust the carbon pools in SiB-BCM (Section 2.2). For instance, burned area will be provided as a monthly fraction of a 1°x1° grid cell. Biomass and litter pools simulated by SiB-BCM will be adjusted to account for fire loss and mortality based on mortality and combustion efficiency algorithms developed under the Randerson project. In this way the impacts of fire on carbon pools available for heterotrophic respiration can be accounted for. The combination of burned area and growth constrained by NDVI observations (Section 2.2) gives an estimate of CO_2 flux from tropical land use change, much of which is the result of burning [Houghton, 1999]. The CO_2 biomass burning source distributions for 1997 and later will be input to the transport model for analysis of the resulting CO_2 interannual variability, latitude gradients, and altitude distributions.

Our approach for evaluating the contributions of biological processes and fire to atmospheric carbon composition differs from and expands on that of the Randerson project. That project uses a biogeochemical model that operates on a monthly time step, it does not estimate autotrophic respiration, it uses much simpler parameterizations of soil moisture and soil thermal conditions as they control biologically mediated carbon fluxes, it cannot account for non-linear responses of canopy photosynthesis and biological responses to temperature that occur at sub-diurnal time scales. Though this simplicity is advantageous in terms of computational requirements and requires fewer input drivers and parameters, it necessarily ignores important processes that need to be addressed for more detailed atmospheric analyses. For instance, SiB-BCM will account for diurnal rectifier effects and for seasonal contributions of autotrophic respiration. The diurnal behavior of SiB-BCM is capable of capturing non-linear physiological responses. SiB-BCM also simulates more realistic hydrology and thermal conditions that control biological carbon fluxes.

Land biogeochemistry models constrained by satellite observations of plant productivity (e.g. NDVI from MODIS) and fire activity (MODIS) and satellite observations of atmospheric CO_2 (AIRS, OCO), CO (AIRS), and aerosols (MODIS) provide a powerful satellite driven multi-constraint framework for understanding carbon sources and sinks that has yet to be exploited. Some issues to be addressed are emission injection heights and the influence of aerosol.

2.4 Temporally Varying Fossil Fuel Emissions

Recent fossil fuel emission estimates have revealed a significant seasonal cycle and interannual variability in the anthropogenic flux of fossil fuel CO_2 to the atmosphere for the US [Blasing et al., 2004]. This variability in CO_2 emissions is related to variability in climate and subsequent energy demands. Most previous CO_2 studies, e.g., TransCom, use fossil fuel emission distributions that are constant in time over the annual cycle. Here, we propose to implement the new high temporal resolution flux estimates in the PCTM. In addition to the monthly varying CO_2 flux estimates we will also implement 3-hour CO_2 fluxes that reflect the times of the day that CO_2 production is most concentrated.

Figures 10a,b show the seasonal cycle of anthropogenic CO_2 emissions from the US on a monthly basis from 1981-2000. Note the change from month to month is as much as 30-40%. The year-to-year trend is a reflection of the increasing combustion of fossil fuel each year. An interesting feature is that coal usage in rising faster than oil usage. This may be due to an increased demand for electricity to support increased air conditioning needs as temperatures increase over the US. Note that electricity generation is primarily from coal while heating changes are more strongly reflected in hydrocarbon (gas and oil) usage.

The monthly resolved anthropogenic CO_2 fluxes for the U.S. are available now. Monthly estimates for Canada and Mexico should be available by late 2004. These flux estimates are derived from energy usage statistics for the US [Blasing et al., 2004]. We will implement the flux globally on the grid of the PCTM by weighting them by the population. The 3-hour fluxes will be implemented by the time of day emission constraints as described by the work performed in mostly urban areas [Grimmond et al., 2002; Koerner et al., 2002].

This 30-40% month-to-month variability will influence the seasonal cycle of CO_2, especially in continental sites. We will also include the diurnal timing of the impacts [Grimmond et al., 2002; Koerner et al., 2002]. Since the stability and mixing characteristics of the boundary layer evolve over the 24-hour daily cycle, we expect significant impacts in the diurnal cycle of CO_2 in the boundary layer. The interaction of the details of the diurnal cycle of CO_2 emission and atmospheric boundary layer physics will be significantly more realistic than a yearly mean emission. There are several expected impacts in the transport simulations, seasonal cycle, diurnal rectifier, and interhemispheric gradient of CO_2. These simulations, concurrent with the SiB simulations, will quantify the time-varying sources and their role in inversions for surface sources and sinks of atmospheric CO_2.

2.5 Measurements of CO_2 from Space

We envision that information will flow in both directions between the models and instruments in this task. The remote sensing data will be used in comparison with the model to draw inferences about processes, as is done with traditional data sources. Along the way we will test different ways of compositing the satellite data to optimize their impact on inference of CO_2 sources and sinks in combination with the in situ data. Additionally, we also expect to use the model to help define measurement requirements for future remote sensing instruments in observing system simulation experiments.

Production of CO_2 data from AIRS measurements is currently being tested (C. Barnet, W. McMillan personal communication). Although AIRS was not originally designed to measure CO_2, simultaneous retrieval of temperature and CO_2 is possible from the AIRS spectra. The maximum sensitivity to CO_2 is in the mid troposphere and the vertical weighting functions are broad [Engelen et al., 2001], which reduces the sensitivity to surface source/sink influence. However, even with relatively high uncertainty and reduced sensitivity, the large number of soundings (Figure11) may make AIRS data useful for inferring fluxes especially in tropical regions where convection is active. The objective of this activity is to develop and test methods to best incorporate the AIRS data into the inverse model and combine it with traditional observations. Operational AIRS products are available from September 2002. Test CO_2 data sets will be available for the start of this project, and multiple data years will be available at the second year. The initial attempts will probably use cloud-clear, large-area (e.g., 4°x5°) time mean data (e.g., monthly as in Pak and Prather [2001]). As the data product improves and we learn more about its precision, we will take advantage of the higher time and spatial resolution in real-time comparisons. The potential biasing influence of clouds and aerosol on the data [Engelen et al., 2001] will be examined. The result will be improved estimates of CO_2 fluxes through use of additional data. The quantitative level of improvement will depend on the quality of the AIRS CO_2 data product and the ability of the analysis framework to take advantage of the satellite data. Experience using AIRS data will help prepare for the use of other satellite CO_2 data expected from TES and OCO. The combination of AIRS and/or TES CO_2 from thermal emission measurement along with the OCO data from near-IR absorption could place strong constraints on CO_2 near the surface. Modeling tools and methods developed in this task will contribute to development of a more complete CO_2 satellite data assimilation system in the future.

The modeling and analysis methods used here will also be used to help guide science measurement requirements for future sensors. This can occur at many levels from something as simple as model pseudo-data estimates of total column CO_2 gradients for estimating detection limits [Rayner and O'Brien, 2001] to full radiative transfer simulations for multi-component atmospheres (including clouds and aerosols) convolved with a proposed instrument response function [Mao and Kawa, 2004]. Our model output has been used previously by the AIRS CO_2 processing team, in development of a Fabry-Perot spectrometer for column CO_2, and for a potential CO_2 laser sounder. We will continue to support the instrument and technology development groups with model atmospheres, data impact studies, uncertainty analysis, and input for retrieval algorithms.

3. Summary

We have presented a proposal to reduce uncertainties in the terrestrial biospheric sink for atmospheric CO_2 through global modeling and data analysis. Five related tasks are proposed to address transport uncertainty, dependence of biospheric fluxes on climate variations, the biomass burning CO_2 source, temporally varying fossil fuel emissions, and use of remote sensing observations for carbon process studies. This approach is intended to bring top-down and bottom-up carbon flux estimates closer together to quantify processes globally at meaningful temporal and spatial scales.

In terms of addressing science questions, we contribute directly toward answers for several of the Enterprise research questions related to the Carbon Cycle and Ecosystems focus area as listed in the NRA: *How are global ecosystems changing? How do ecosystems, land cover, and biogeochemical cycles respond to and affect global environmental change? How will carbon cycle dynamics and terrestrial (and marine) ecosystems change in the future?* And specifically for Carbon Cycle Science, including but not restricted to North America: *What are the magnitudes and distributions of North American carbon sources and sinks on seasonal to centennial time scales, and what are the processes controlling their dynamics?*

More specifically for this proposal we will produce quantitative answers to the following questions:

- How does transport modeling uncertainty affect our inference of atmospheric CO_2 fluxes and what can be done to reduce this uncertainty?
- How does the flux of CO_2 to and from the terrestrial biosphere respond to meteorological changes and how do these changes contribute to the inferred terrestrial sink?
- What is the contribution of biomass burning to interannual variability of the atmospheric CO_2 growth rate?

- What are the uncertainties in inferred fluxes produced by neglect of temporal variation in the fossil fuel source?
- How can satellite remote sensing data best be used to constrain carbon models and elucidate carbon cycle processes?

The answers, models, and methods produced here contribute to the larger goal of credible, tested, predictive models of future carbon and climate that are needed for informed policy decisions. The models and methods we develop are expected to become part of a carbon data assimilation system for diagnosis of global CO_2 sources and sinks on a regional basis. This in turn will lead to coupled land, ocean, atmosphere models of carbon and climate processes capable of producing climate change projections with quantifiable uncertainty.

REFERENCES

Andrews, A. E., S. R. Kawa, Z. Zhu, J. F. Burris, J. B. Abshire, M. A. Krainak, D. F. Baker, An adjoint-based analysis of the sampling footprints of tall tower, aircraft and potential future lidar observations of CO2, *Eos Trans. AGU, 84*(46), Fall Meet. Suppl., Abstract A52B-0790, 2003.

Baker, I.T., A.S. Denning, N. Hanan, L. Prihodko, P.-L. Vidale, K. Davis and P. Bakwin, Simulated and observed fluxes of sensible and latent heat and CO2 at the WLEF-TV Tower using SiB2.5, Global Change Biology 9, 1262-1277, 2001.

Battle M., M. L. Bender, P. P. Tans, J. W. C. White, J. T. Ellis, T. Conway, R. J. Francey, Global carbon sinks and their variability inferred from atmospheric O_2 and d13C, *Science, 287*, 2467-2470, 2000.

Blasing, T. J., C. T. Broniak and G. Marland, The annual cycle of fossil-fuel carbon dioxide emissions in the USA, Submitted, *Tellus*, 2004.

Bonan, G.B., K.W. Oleson, M. Vertenstein, S. Levis, X. Zeng, Y. Dai, R.E. Dickinson, and Z.-L.Yang, The land surface climatology of the Community Land Model coupled to the NCAR Community Climate Model, *J. Climate, 15,* 3123-3149, 2002.

Bousquet P, Peylin P, Ciais P, Le Quere C, Friedlingstein, P, Tans PP, Regional changes in carbon dioxide fluxes of land and oceans since 1980, *Science, 290*, 1342-1346, 2000.

Braswell, BH, Schimel DS, Linder E, Moore B, The response of global terrestrial ecosystems to interannual temperature variability, *Science, 238,* 870-872, 1997.

Cohn SE, da Silva A, Guo J, et al., Assessing the effects of data selection with the DAO physical-space statistical analysis system, *Mon. Weather Rev., 126*, 2913-2926, 1998.

Conway TJ, PP Tans, LS Waterman, et al., Evidence for interannual variability of the carbon cycle from the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostics Laboratory global air sampling network, *J Geophys Res, 99,* 22831-22855, 1994.

Cox, P. M., R. A. Betts, C. D. Jones, S. A. Spall, I. J. Totterdel, Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, *Nature, 408,* 184-187, 2000.

Denning, A. S., I. Y. Fung, and D. A. Randall, "Latitudinal Gradient of Atmospheric CO_2 Due to Seasonal Exchange with Land Biota," *Nature*, *376*, 240-243, 1995.

Denning , A. S., G. J. Collatz, C Zhang, D. A. Randall, J. A. Berry, P. J. Sellers, G. D. Colello, D. A. Dazlich, Simulations of terrestrial carbon metabolism and atmospheric CO2 in a general circulation model. Part 1: Surface carbon fluxes. *Tellus B 48*, 521-542, 1996.

Denning AS, Holzer M, Gurney KR, et al., Three-dimensional transport and concentration of SF6 - A model intercomparison study (TransCom 2), *Tellus B 51*, 266-297, 1999.

Denning, A.S., M. Nicholls, L. Prihodko, I. Baker, P.-L. Vidale, K. Davis and P. Bakwin, Simulated and observed variations in atmospheric CO2 over a Wisconsin forest using a coupled ecosystem-atmosphere model, *Global Change Biology 9*, 1241-1250, 2003.

Douglass AR, and SR Kawa, Contrast between 1992 and 1997 high-latitude spring Halogen Occultation Experiment observations of lower stratospheric HCl, *J. Geophys. Res., 104*, 18739-18754, 1999.

Douglass AR, Schoeberl MR, Rood RB, et al. Evaluation of transport in the lower tropical stratosphere in a global chemistry and transport model, *J. Geophys. Res., 108* (D9): Art. No. 4259, 2003.

Dufresne, J.-L., P. Friedlingstein, M. Berthelot, L. Bopp, and P. Ciais, L. Fairhead and H. Le Treut, P. Monfray, On the magnitude of positive feedback between future climate change and the carbon cycle, *Geophys. Res. Lett., 29*, 1405, 10.1029/2001GL013777, 2002.

Engelen RJ, Denning AS, Gurney KR, Stephens GL, Global observations of the carbon budget 1. Expected satellite capabilities for emission spectroscopy in the EOS and NPOESS eras, *J. Geophys. Res. 106,* 20055-20068, 2001.

Erickson, D. J. III, P. J. Rasch, P. P. Tans, P. Friedlingstein, P. Ciais, E. Maier-Reimer, K. Kurz, C. A. Fischer and S. Walters, The seasonal cycle of atmospheric CO_2: A study based on the NCAR Community Climate Model (CCM2), *J. Geophys. Res., 101*, 15079-15097, 1996.

Fan, S., M. Gloor, J. Mahlman, S. Pacala, J. Sarmiento, T. Takahashi, and P. Tans, A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models, *Science 282*, 442-446 (1998).

Fung I, Field CB, Berry JA, Thompson MV, Randerson JT, Malmstrom CM, Vitousek PM, Collatz GJ, Sellers PJ, Randall DA, Denning AS, Badeck F, John J, Carbon 13 exchanges between the atmosphere and biosphere, *Global Biogeochemical Cycles, 11*, 503-533, 1997.

Grimmond, C. S. B., T. S. King, F. D. Cropley, D. J. Nowak and C. Souch, Local-scale fluxes of carbon dioxide in urban environments: methodological challenges and results from Chicago, *Environ. Pollution, 116,* S243-S254, 2002.

Gurney et al., Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models, *Nature*, *415*, 626-630, 2002

Gurney, K. R., et al., Transcom 3 inversion intercomparison: Model mean results for the estimation of seasonal carbon sources and sinks, *Global Biogeochem. Cycles, 18,* GB1010, doi:10.1029/2003GB002111, 2004.

Houghton, R. A. , The annual net flux of carbon to the atmosphere from changes in land use 1850–1990, *T ellus, 51B*, 298–313,1999.

Intergovernmental Panel on Climate Change (IPCC), Climate Change 2001: Synthesis Report: Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, New York, 2001.

Kawa, S. R., D. J. Erickson III, S. Pawson and Z. Zhu, Global CO_2 transport simulations using meteorological data from the NASA data assimilation system, *J. Geophys. Res.*, Submitted, 2004.

Keeling CD, TP Whorf, M Wahlen, J Vanderplicht, Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980, *Nature, 375,* 666-670, 1995.

Koerner, B. and J. Klopatek, Anthropogenic and natural CO2 emission sources in an arid urban environment, *Environ. Pollution, 116*, S45-S51, 2002.

Law, R. M., et al., Variations in modeled atmospheric transport of carbon dioxide and the consequences for CO_2 inversions, *Global Biogeochem. Cycles, 10*, 783-796, 1996.

Lin, S. J., R. B. Rood, Multidimensional flux-form semi-Lagrangian transport schemes, *Mon. Wea. Rev., 124,* 2046-2070, 1996.

Liu, J., S. Denning, N. Hanan, I. Baker, J. Kleist, D. Randall, S. Wofsy, M. Goulden, D. Fitzjarrald, P. L. Silva Dias, and M. A. Silva Dias, The Impact of Ecosystem Drought Stress on Tropical Precipitation and Carbon Exchange, Presented at the 2003 Annual Meeting of the American Meteorological Society, 2003.

Mao, J., and S. R. Kawa, Sensitivity studies for space-based measurement of atmospheric total column carbon dioxide using reflected sunlight, *Appl. Optics, 43*, 914-927, 2004.

Nicholls, M.E., A.S. Denning, L. Prihodko, P.-L. Vidale, K. Davis, P. Bakwin, A multiple-scale simulation of variations in atmospheric carbon dioxide using a coupled biosphere-atmospheric model. Submitted to Journal of Geophysical Research, 2004.

Nielsen JE, Douglass AR, Simulation of bromoform's contribution to stratospheric bromine, *J. Geophys. Res., 106*, 8089-8100, 2001.

O'Brien, D. M., and P. J. Rayner, Global observations of carbon budget 2, CO_2 concentrations from differential absorption of reflected sunlight in the 1.61 m band of CO_2, *J. Geophys. Res. 107*, 4354, doi:10.1029/2001JD000617 2002.

Pak BC, Prather MJ, CO_2 source inversions using satellite observations of the upper troposphere *Geophys. Res. Lett. 28,* 4571-4574, 2001.

Potter CS, Randerson JT, Field CB, Et Al., Terrestrial ecosystem production - a process model-based on global satellite and surface data, *Global Biogeochem Cycles 7*, 811-841, 1993.

Randerson, J.T.,Collatz GJ, Fessenden J, 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*, Art. No. 1136, 2002.

Rayner, P.J. and D.M. O'Brien, The utility of remotely sensed CO_2 concentration data in surface source inversions, *Geophys. Res. Lett., 28,* 175-178, 2001.

Rayner PJ, Law RM, O'Brien DM, et al., Global observations of the carbon budget - 3. Initial assessment of the impact of satellite orbit, scan geometry, and cloud on measuring CO2 from space, *J Geophys Res, 107* (D21): Art. No. 4557, 2002.

Roedenbeck, C., S. Houweling, M. Gloor, M. Heimann, Time-dependent atmospheric CO2 inversions based on interannually varying tracer transport, *Tellus, 55b,* 488-497, 2003.

Schaefer, K., A. S. Denning, N. Suits, J. Kaduk, I. Baker, S. Los, and L. Prihodko, Effect of climate on interannual variability of terrestrial CO2 fluxes, *Global Biogeochemical Cycles, 16,* 1102, doi:10.1029/2002GB001928, 2002.

Schimel D, Baker D, Carbon cycle: The wildfire factor, *Nature 420,* 29-30, 2002.

Sellers PJ, Dickinson RE, Randall DA, et al., Modeling the exchanges of energy, water, and carbon between continents and the atmosphere, *Science, 275*, 502-509, 1997.

Takahashi, T., R. A. Feely, R. Weiss, R. H. Wanninkhof, D. W. Chipman, S. C. Sutherland, and T. T. Takahashi, Global air-sea flux of CO_2: An estimate based on measurements of sea-air PCO_2 difference, *Proceedings of the National Academy of Science, vol. 94*, p 8929, Natl. Acad. Of Sci., Washington, D.C., 1997.

Tans, P. P., I. Y. Fung, and T. Takahashi, Observational Constraints on the Global Atmospheric CO_2 Budget, *Science*, *247*, 1431-1438, 1990.

van der Werf GR, Randerson JT, Collatz GJ, Giglio L, Kasibhatla PS, Arellano A, Olsen SC, Kasischke ES, Continental-scale partitioning of fire emissions during the 1997 to 2001 El Nino/La Nina period, *Science 303*, 73-76, 2004.

Vukicevic T, Braswell BH, Schimel D, A, diagnostic study of temperature controls on global terrestrial carbon exchange, *Tellus, 53B*, 150-170, 2001.

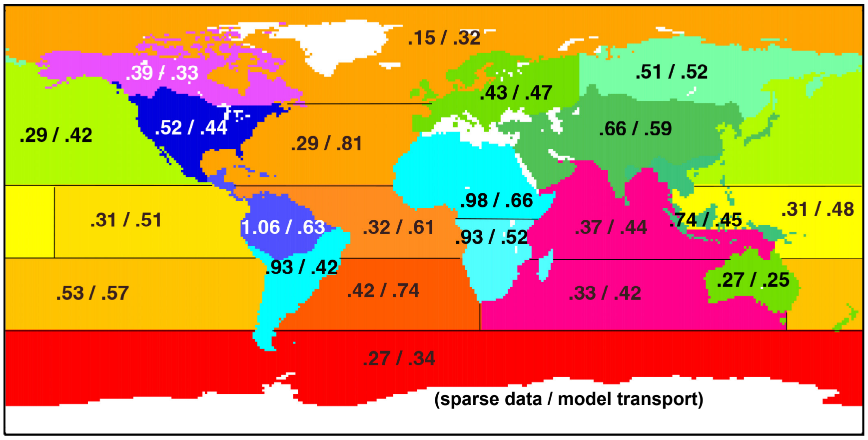

Figure 1. Distribution of uncertainties (Gt C yr^{-1}) for TransCom 3 regions averaged within/between models [Gurney et al., 2002].

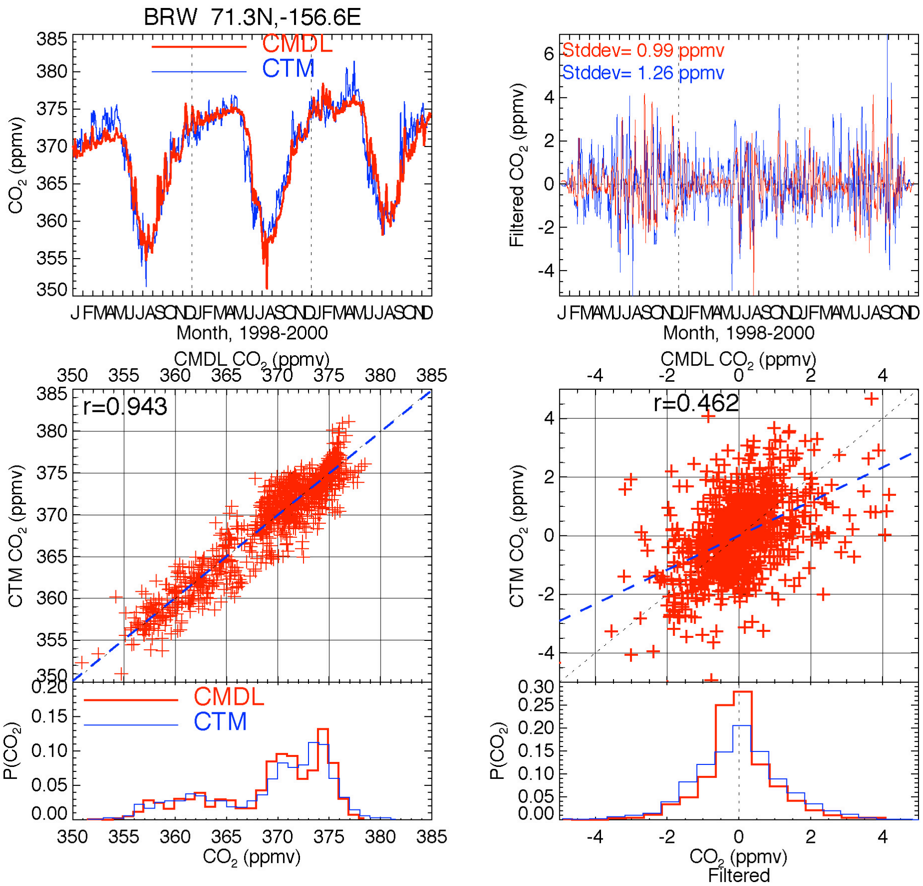

Fig. 2. Comparison of the variability of daily-mean atmospheric CO_2 in the model and continuous analyzer observations for Barrow, AK. The upper left panel shows the time series at the station for 1998-2000 with the model mean (blue) adjusted to that of the data (red). The upper right panel shows the time series of CO_2 after a high-pass filter (≤30 d) has been applied. The second row shows the observed versus modeled CO_2, unfiltered (left) and filtered (right). The 3rd row shows the normalized probability distributions of observed and modeled CO_2, unfiltered and filtered (From Kawa et al. [2004]).

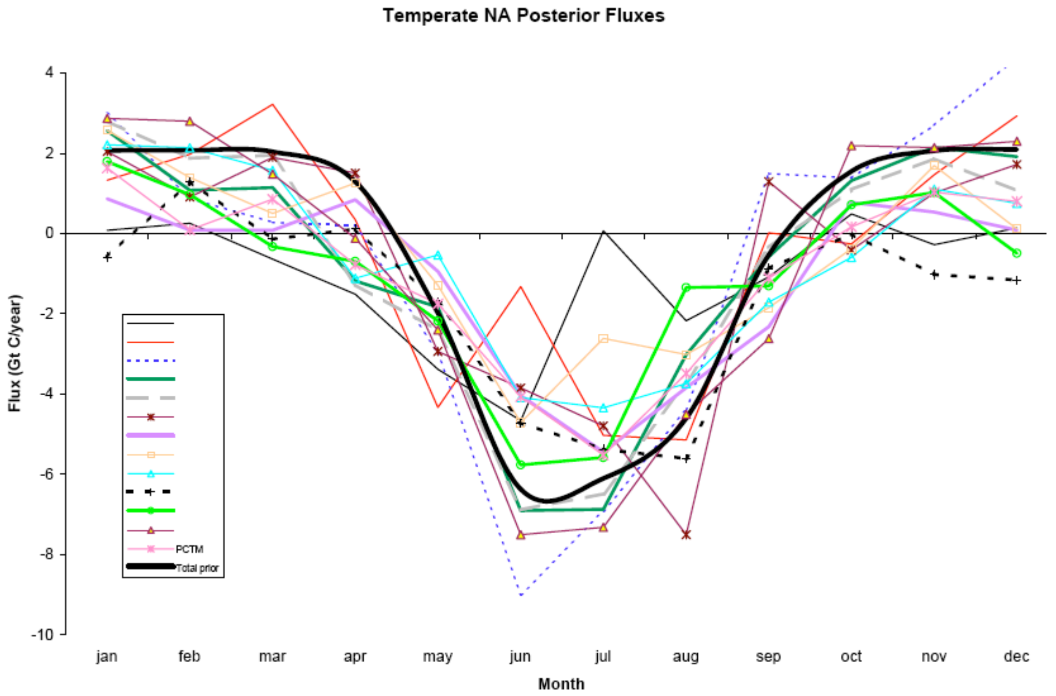

Figure 3. Inferred seasonal carbon fluxes from TransCom 3 model inversions including GSFC PCTM (pink line with asterisks) for temperate North America region (courtesy of K. Gurney, see Gurney et al. [2004]).

Current and Planned Flask (blue) and Continuous (Red) In-Situ Sampling Sites

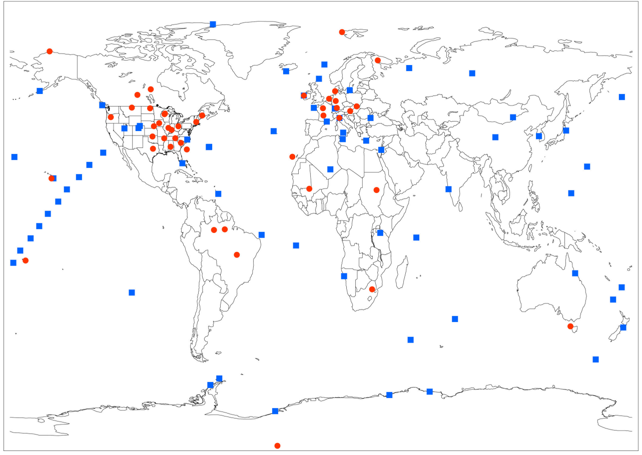

Figure 4. Estimate of available in-situ data by the end of 2005 including 114 operating GlobalView stations with at least 70% data availability since 2000, 9 new CMDL tall towers, 6 new calibrated flux towers, CarboEurope observatories, calibrated LBA towers and airborne sampling, and three new continuous sites in Africa. Canadian and Japanese sites and virtual tall tower data are also expected to be available.

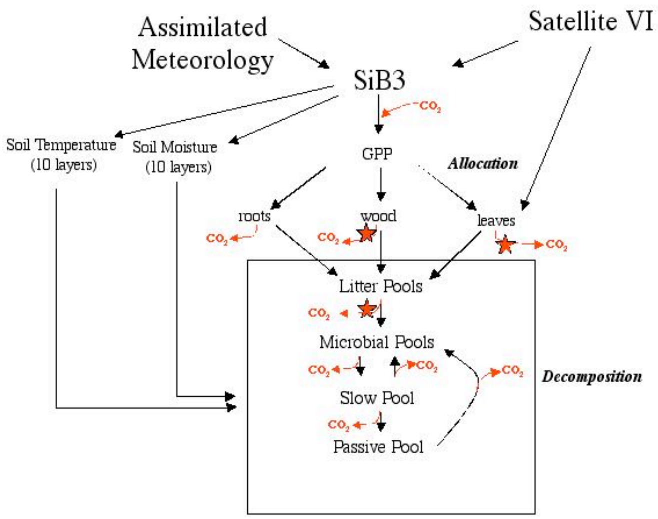

Figure 5: Schematic of the land-carbon model to be used in this work. Red stars indicate CO_2 fluxes that include fire emissions.

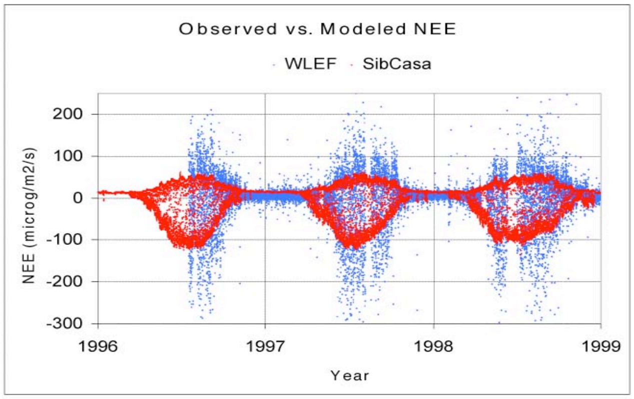

Figure 6. Comparison between observed (blue) and SiB-BCM (red) net ecosystem exchange for a three-year period at the WLEF tower in north-central Wisconsin.

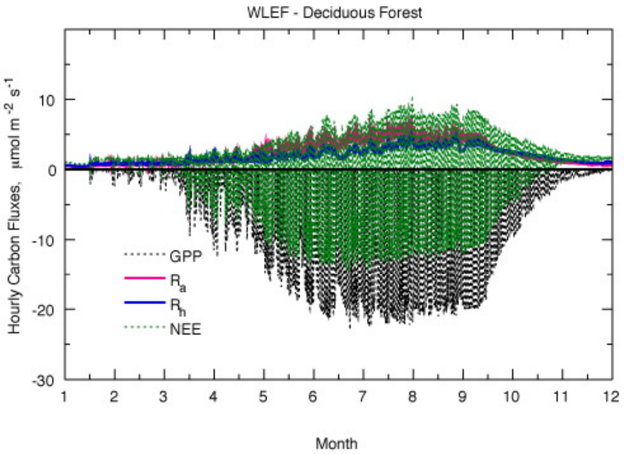

Figure 7. Net ecosystem exchange (NEE), gross primary production (GPP), autotrophic respiration (Ra) and heterotrophic respiration (Rh) simulated by SiB-BCM hourly over a year for deciduous/mixed forest at the WLEF tower in Wisconsin.

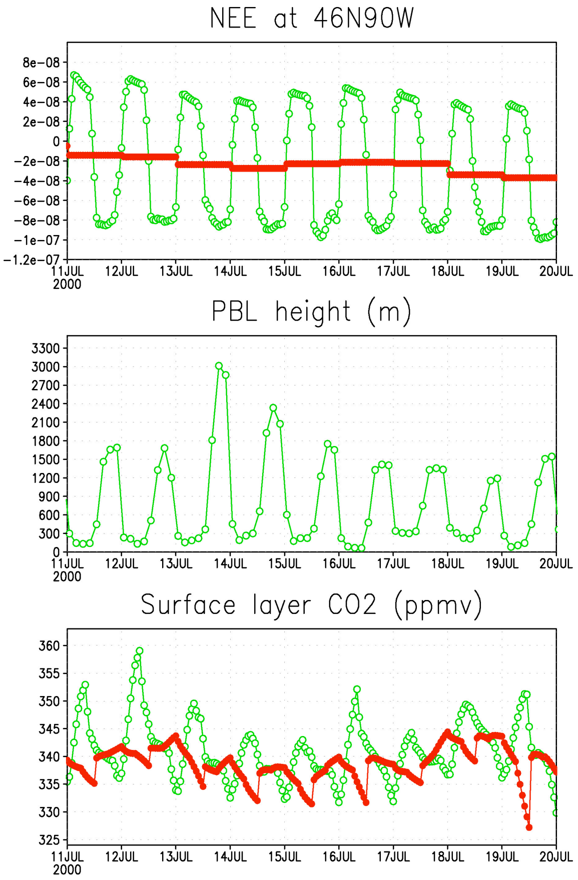

Figure 8. Example of diurnal rectifier effect over vegetated region (Wisconsin) from a global test simulation of SiB and PCTM. Upper panel shows hourly CO_2 flux from SiB net ecosystem exchange (green) and flux averaged daily (red). Middle panel shows height of planetary boundary layer from GEOS-4 meteorological analysis. Lower panel shows hourly CO_2 mixing ratio near surface calculated with transport model acting on fluxes from upper panel. Failure to resolve diurnal flux interaction with planetary boundary layer can produce large errors in calculated mean and diurnal cycle of surface CO_2 abundance.

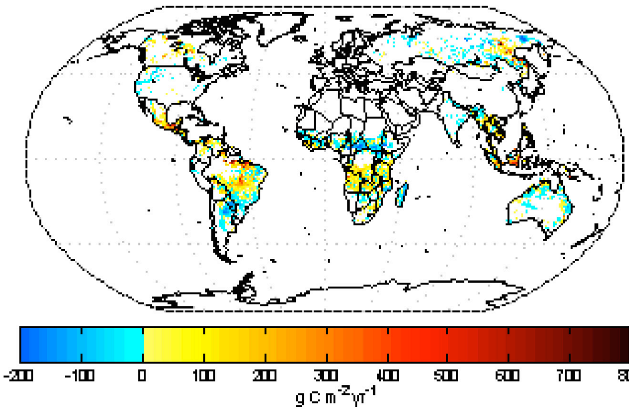

Figure 9. Mean carbon emissions from fires for the period 1997-2001 [van der Werf et al., 2004].

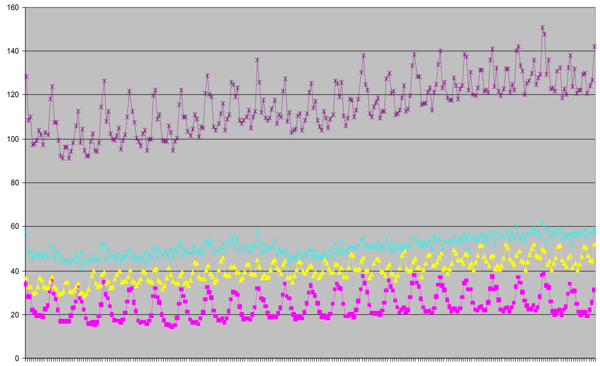

Figure 10a. Estimates of monthly CO_2 emissions (teragrams of carbon) from fossil fuel burning in the United States from 1981-2002: total (purple x), coal (yellow triangles), oil (cyan x), and gas (magenta squares).

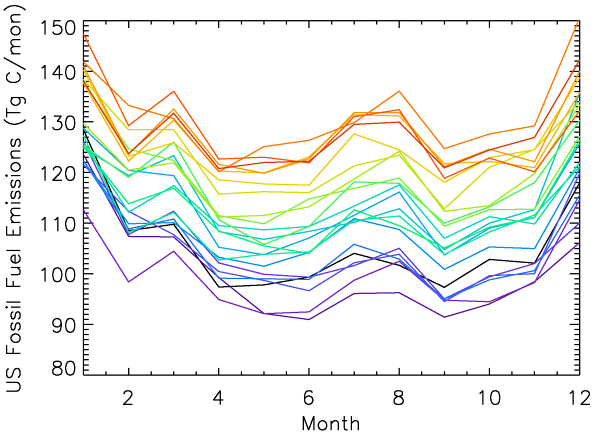

Figure 10b. Another way of looking at fossil fuel emissions to emphasize seasonal cycle for different years (different colors).

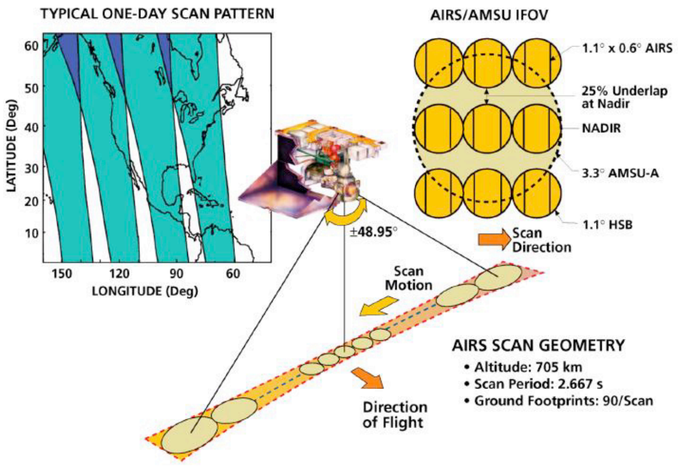

Figure 11. Illustration of AIRS/AMSU ground sampling pattern.

LIST OF ACRONYMS:

AIRS, Atmospheric Infrared Sounder (on the Aqua satellite)
ATSR, Along Track Scanning Radiometer
AVHRR, A Very High Resolution Radiometer
BCM, Biogeochemical Cycle Model
BRW, Barrow (Alaska CO2 monitoring site)
CASA, Carnegie Ames Stanford Approach
CCRI, Climate Change Research Initive
CCSP, Carbon Cycle Science Plan
CMDL, Climate Monitoring and Diagnostics Laboratory (NOAA)
CSU, Colorado State University
CTM, Chemistry-Transport Model
DAS, Data Assimilation System
ENSO, El Nino-Southern Oscillation
FPAR, Fraction of Photosynthetically Active Radiation
FV, Finite Volume
GCM, General Circulation Model
GEOS, Goddard Earth Observing System
GEST, Goddard Earth Science and Technology (University of Maryland-Baltimore County)
GMAO, Global Modeling and Assimilation Office (NASA Goddard)
GIMMS, Global Inventory Modeling and Mapping Studies (NASA Goddard)
GPP, Gross Primary Productivity
IDS, Interdisciplinary Science
IGBP, International Geosphere-Biosphere Programme
IPCC, Intergovernmental Panel on Climate Change
ISLSCP, International Satellite Land Surface Climatology Project
ITCZ, Inter-Tropical Convergence Zone
LAI, Leaf Area Index
MODIS, MOderate resolution Imaging Spectrometer
NACP, North American Carbon Program
NEE, Net Ecosystem Exchange
NEESPI, Northern Eurasia Earth Science Partnership Initiative
NDVI, Normalized Difference Vegetation Index
NPP, Net Primary Productivity
OCO, Orbiting Carbon Observatory (http://oco.jpl.nasa.gov/)
PBL, Planetary Boundary Layer
RH, Heterotrophic Respiration
SeaWIFS, Sea-viewing Wide Field-of-view Sensor
SiB, Simple Biosphere
TES, Tropospheric Emission Sounder (on the Aura satellite)
TranCom, Transport Comparison
TRMM, Tropical Rainfall Measuring Mission
UMBC, University of Maryland-Baltimore County
VIRS, Visible InfraRed Sounder
WCRP, World Climate Research Program

MANAGEMENT PLAN

Proposal Team

Dr. Randy Kawa will manage and direct this project. Dr. Kawa has extensive experience in modeling chemistry and transport of atmospheric constituents and in comparison of model results with observations. He will be responsible for planning and analysis of transport runs, organizing observations, and presentation and publication of results. He will manage a support contractor (Z. Zhu, SSAI) for scientific programming and a postdoc (H. Bian, GEST) for science analysis, as well as coordinating the work at Goddard, Colorado State, and Duke. He will interface with data providers at GMAO, NOAA CMDL, NOAA NESDIS, UMBC, and UMd College Park. He is also co-Investigator with Bill Heaps (GSFC) in the Fabry-Perot Interferometer for Column CO_2 Instrument Incubator Program and collaborator on the Goddard ground-based CO_2 laser profiler and Satellite CO_2 Laser Sounder instrument development activities.

Dr. Scott Denning and his staff at Colorado State University will take the lead on developing new inverse methods and will share responsibility for analysis of the biological transport simulations in comparison to data. They will be responsible along with Dr. Collatz for the development of the SiB-BCM model and its interface to observational constraints and the meteorological data.

Dr. Jim Collatz will work with Dr. Denning on the SiB-BCM model functions and integration with the met fields and satellite data. Dr. Collatz is also co-developer for the biomass burning CO_2 emission data, a co-investigator on a NASA funded project to improve estimation of global fire emissions, and is responsible for analysis of results from the biosphere and burning simulations.

Dr. David Erickson will contribute to the construction of the seasonal and hourly varying anthropogenic CO_2 fluxes, the overall evaluation and interpretation of the modeling results, the impact of planned remote sensing data sources and participate in the preparation of peer reviewed publications. The analysis of the model results will be similar to the analysis of the NCAR CCM2 [Erickson et al., 1996] and the NASA PCTM [Kawa et al., 2004].

In addition to funded co-investigators, this effort is supported by several very important collaborators. Dr. Steven Pawson is leader of the constituent assimilation group at GMAO, and he forms our interface to GMAO products and models. Dr. Arlyn Andrews (NOAA CMDL), formerly of our group at Goddard, will collaborate on analysis of model results in comparison to data. She will be the interface to new in situ data from CMDL and elsewhere, and will continue to pursue use of the transport model adjoint for inferring CO_2 fluxes. Drs. Chris Barnet (NOAA NESDIS) and Wallace McMillan (UMBC) are funded to produce CO_2 data from AIRS. They are eager to see the data used in transport modeling and flux estimation. They will work with us on methods to composite the AIRS data, evaluate uncertainties, and analyze impacts. Dr. Ning Zeng (U MD College Park) has volunteered to provide ocean CO_2 flux scenarios for use in the transport model and comparison to data.

Computing, Facilities, and Equipment
This project will require significant computing resources. Available workstations, desktops, and laptops will be adequate for model development, analysis of runs, compilation of observations, document preparation, and communications with relatively minor upgrades (see cost plan). Major forward transport simulations and production runs of SiB-BCM are proposed to be done on the GSFC NCCS 1392-processor Hewlett-Packard/Compaq AlphaServer SC45 (halem) with associated mass storage. The transport model is being run there currently. Run time is about 7 CPU-hrs/tracer-year @ 2°x2.5° resolution. We expect to run approximately 3000 tracer transport years including an updated set of interannual inverse basis functions. In addition most forward runs will be done @ 1°x1.25°. We estimate this will require about 7500 CPU hours/proposal-year and 1000 gigabytes of mass storage at NCCS unitree (50 GB/tracer/yr at 1°x1.25° hourly) over the 3-year duration of the project. The current cost estimate for GSFC computing is $2.25/CPU-hr including data storage, so we have included $16875/yr for computing (budget item 2.f, "Other").

Travel
Travel for this project includes science team visits, national and international science meetings, and agency planning workshops. We will try to coordinate team meetings with science meetings and other opportunities as much as possible, however, it is expected that personnel from CSU, Duke, 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 FY2005 (Oct 2004). Each task will proceed in parallel with major accomplishments noted here.
Year 1: Run baseline forward model simulations, evaluate SiB-BCM CO_2 fluxes constrained by GMAO met fields and satellite data, run SiB-BCM fluxes in forward model for 1-2 years for evaluation, begin compiling in situ and AIRS data, assemble fossil fuel emission data, participate in NACP Mid-Continent Intensive Campaign if feasible.
Year 2:Run and analyze biomass burning and temporally varying fossil fuel CO_2 fluxes in transport model, run annual and seasonal inversions with AIRS CO_2 data, analyze biosphere CO_2 flux variability and transport with CO_2 observations, use CO_2 fields with proposed instrument functions to estimate satellite data impacts, contribute to State of the Carbon Cycle in North America report.
Year 3: Complete linkage of biosphere and transport models and perform decadal run to produce interannually varying CO_2 flux and concentration fields, exercise new inverse methods for land model parameter estimation, run ocean flux sensitivity, analyze process dependencies, test GEOS-5 formulations and met data, publish analysis papers, contribute to IPCC Fourth Assessment report.

COST PLAN

Support is requested for activities at GSFC, Colorado State University, and Duke University. Separate institutional budgets are attached as well as a summary. Budgets for GSFC reflect NASA full cost accounting procedures.

Goddard Civil Service (Work Year Equivalents):
  Kawa: 0.3
  Collatz: 0.1
Goddard Contract Personal (Work Year Equivalents):
  SSAI Scientific Programmer: 0.8
  GEST Research Associate: 0.4
Travel:
  Science and/or team meetings, [$500 airfare + 5 days x ($110 perdiem + $50 rental car)] = $1300/trip.
  GSFC Civil Service: 3 trips/yr = $3900
  GSFC Contractors: 2 trips/yr = $2600
GSFC Equipment, Supplies, and Miscellaneous:
  Local data storage disks, year 1: $2000
  Laptop replacement, year 2: $3000
  Software updates, licenses: $1000/year
  Miscellaneous supplies: $500/year
  Publication Costs: $1-2k/year
  Other (computing, detail above): $16875/year
Costs for Colorado State University:
  Total (see detail): $83-87 k/yr
Costs for Duke University:
  Total (see detail): $28-31 k/yr

CURRENT AND PENDING FUNDING

S. R. Kawa:
S. R. Kawa (0.2 WYE) and D. J. Erickson, Modeling the effect of meteorological variability on atmospheric carbon species distributions using the Goddard data assimilation system, NASA Carbon Cycle Science 2000, FY01/Q4-FY04/Q3, $170k/yr.

Heaps, W. S., and S. R. Kawa (0.2 WYE), Fabry-Perot interferometer for column CO2, NASA Instrument Incubator Program 2000, FY02-FY04, $1.4M/3 yrs.

Douglass, A. R., S. R. Kawa (0.3 WYE), et al., Proposal for continued funding of the stratospheric general circulation with chemistry project, NASA Atmospheric Chemistry Modeling and Analysis Program 2002; FY03-FY05, $300k/yr.

Heaps, W. S., and S. R. Kawa (0.2 WYE), Airborne remote sensing of CO_2 for the North American Carbon Program, NASA Carbon Cycle Science 2004, FY05-FY07, $500k/yr, proposed.

D. J. Erickson:
Climate simulation and biogeochemistry in the CCSM2, DOE-SCIDAC; FY04: 120K, FY05, 120K, FY06: $120K.

Oceanic Carbon sequestration, DOE-OBER, FY04: $30K, FY05: $40K, FY06: $40K.

Feedbacks in the climate system, ORNL/DOE-LDRD(Laboratory Directed Research and Development), FY04: $300K.

Regional modeling of Central America, USAID/NASA-MSFC,FY04: $110K, FY05: $115K, FY06: $115K.

This proposal: Constraining the CO_2 missing sink, contract to Duke University, NASA, FY05: $28K, FY06: $29K, FY07: $30K.

A. Scott Denning: Colorado State University, 2003

CURRENT

Title	Sponsor	Amount	Dates	PI Support	Grant #
Spatial integration of regional carbon balance in Amazonia	NASA	\$602,672	01/01/03 – 12/31/05	1 month	NCC5-707
Regional Forest – Regional ecosystem-atmosphere CO_2 exchange via atmospheric budgets	DOE	\$159,516	09/15/02 – 02/28/04	.5 month	DE-FG03-ER63474
Biological controls of terrestrial carbon fluxes	NSF	\$217,698	09/01/99 – 08/31/03	1 month	DEB-9977066
Forward and inverse modeling of CO_2 in the NCAR CCSM.	NSF	\$380,666	09/01/02 – 08/31/05	1 month	0223464
Atmospheric CO_2 inversion intercomparison (TransCom3).	NOAA	\$91,951	09/01/02 – 08/31/05	.25 month	Coop. Agreement NA17RJ1228
Global and regional carbon flux estimation using atmospheric CO_2 measurements…	NASA	\$1,137,914	01/01/02 – 12/31/04	1 month	NCC5-621
Impact of interactive vegetation on predictions of North American monsoons.	NOAA	\$196,864	07/01/01 – 06/30/04	.25 month	Cooperative Agreement NA17RJ1228
Monitoring and modeling isotopic exchange between the atmosphere and the terrestrial biosphere.	NOAA	\$185,000	07/01/00 – 06/30/03	.25 month	Cooperative Agreement NA17RJ1228
Mapping global aerodynamic roughness length of land surface.	CALTECH/ JPL	\$40,000	07/01/02 – 06/30/03	.20 month	1241026
PENDING					
Understanding the impacts of large-scale variability on the global carbon cycle. (Co-I)	NASA	\$306,851 (Denning portion)	09/01/03 – 08/31/06	.5 month	Funded and currently being processed.
Data fusion to determine North American sources and sinks of CO_2 at high spatial and temporal…	NOAA	\$443,421	01/01/04 – 12/31/06	1 month	Funded and currently being processed.
Development of methods for data assimilation with advanced models and advanced data sources. (Co-I)	NASA	\$105,000 (Denning portion)	05/01/03 – 04/30/06	.5 month	Funded and currently being processed.
Terrestrial carbon exchange and atmospheric CO_2 in Africa. (Co-I) (Funding coming through NREL)	NASA & NOAA	\$98,502 (Denning portion)	10/01/03 – 9/30/06	.4 month	Funded and currently being processed.
Mesoscale carbon data assimilation for NACP.	NASA	\$1,080,929	01/01/05 – 12/31/07	1 month	--
Center for multiscale modeling of atmospheric processes.	NSF	--	06/15/05 – 06/14/10	2 months	--
Constraining the CO_2 missing sink.	NASA Subcontract	\$253,566	10/1/2004 – 9/30/2007	.5 month	--
Usable science: Connecting the NACP to useful application in multiple-scales of carbon governance.	NCAR Subcontract	\$132,634	01/01/05 – 12/31/07	.2 month	--
High resolution fossil fuel emissions estimates in support of OCO-based assimilation and NACP. (Co-I.)	NASA	\$800,000	01/01/05 – 12/31/07	.5 month	--

G. J. Collatz:

Title	FTE	Funding Agency	Duration	Funding Level
Using satellite and inverse techniques to constrain regional and global fire emissions from 1997 to 2005: An approach based on the carbon isotope ratio of fire emissions (P.I. JR Randerson)	0.2	NASA	4/2004-9/2007	$287K
Synthesizing, evaluating, and distributing science community-driven carbon, water, and energy cycling data products for research	0.0	NASA	9/2003-9/2005	$200K
Pending: Effects of disturbance type, age since disturbance and climate interannual variability on carbon fluxes from North American Forests: Merging satellite time series data with a dynamic vegetation recovery model.	0.2	NASA	10/2004-9/2007	$818.6K
Pending: Reducing uncertainties of carbon emissions from land use-related fires with MODIS data: Scaling from local to global (P.I. R DeFries)	0.1	NASA	10/2004-9/2007	$70K
Pending: Effects of interannual-to-interdecadal climate variability on the global carbon cycle (P.I. N. Zeng)	0.1	NASA	10/2004-9/2007	$61K
Pending: North American natural and anthropogenic carbon perturbations 1982-2005 (P.I. CJ. Tucker)	0.1	NASA	10/2004-9/2007	$61K
Pending: Mesoscale carbon data assimilation for the North American Carbon Program (P.I. AS Denning)	0.1	NASA	10/2004-9/2007	$74K

Dr. Stephan Randolph Kawa

Physical Scientist
Atmospheric Chemistry and Dynamics Branch
NASA Goddard Space Flight Center

RESEARCH AREA EXPERIENCE: Chemistry, transport, and microphysics of atmospheric trace species; development of numerical models for analysis of data and comparison of theory and observations.

EDUCATION:
1988 - Ph.D. - Colorado State University, Department of Atmospheric Science
1985 - M.S. - Colorado State University, Department of Atmospheric Science
1972 - B.A. - University of Chicago, Biology

PREVIOUS POSITIONS:

1979 - 1981	Senior Field Technician, Air Quality Monitoring, Aerovironment Inc., Monrovia, CA
1981 - 1988	Graduate Research Assistant, Department of Atmospheric Science, Colorado State University, Fort Collins
1988 - 1992	Research Associate, Aeronomy Laboratory, National Oceanic and Atmospheric Administration, and Cooperative Institute for Research in Environmental Science, University of Colorado, Boulder
1992 - 1995	Associate Research Scientist, Universities Space Research Association, Atmospheric Chemistry and Dynamics Branch, NASA Goddard Space Flight Center, Greenbelt, MD
1995 -	AST, Atmospheric Chemistry and Dynamics Branch, NASA Goddard Space Flight Center, Greenbelt, MD

PROFESSIONAL SOCIETY MEMBERSHIPS:
American Geophysical Union, 1983 to present
American Meteorological Society, 1981 to present; Colorado State University Chapter President, 1984-1985

AWARDS:
Goddard Laboratory for Atmospheres, Scientific Achievement (Peer) Award, 1998
National Catholic Educational Association, Distinguished Graduate Award, 1998
NOAA ERL Outstanding Scientific Paper Award, 1995
NASA group achievement awards, 1991, 1994, 1995, 1998 (2), 2001
AGU Editor's Citation for Excellence in Refereeing, 1994
Colorado Fellowship, 1983

SPECIAL EXPERIENCE:	1) Goddard Laboratory for Atmospheres representative to NASA Carbon Science Task Force, 1999-present. 2) NASA Atmospheric Effects of Aviation Project, Project Manager, 1996-1997, Project Scientist, 1997-1999. 3) Principal Investigator: 7 NASA funded proposals, 1991-present, co-investigator on 7 others. 4) Participant in numerous cooperative field research programs including DYCOMS, AASE, AASE-II, SPADE, ASHOE/MAESA, STRAT, SONEX, POLARIS, and SOLVE. Member of leadership planning team for SOLVE. 5) Coauthor of UNEP/WMO *Scientific Assessment of Ozone Depletion: 1998*. 6) Convener, AGU Special Sessions: Atmospheric Effects of Aviation, 1998; Stratospheric Chemistry and Dynamics, 1994.

SELECTED PUBLICATIONS:

An Observational Study of Stratocumulus Entrainment and Thermodynamics, S. R. Kawa and R. Pearson, Jr., *J. Atmos. Sci.*, **46**, 2649-2661, 1989.

Photochemical partitioning of the reactive nitrogen and chlorine reservoirs in the high latitude stratosphere, S. R. Kawa, D. W. Fahey, L. E. Heidt, W. H. Pollock, S. Solomon, D. E. Anderson, M. Loewenstein, M. H. Proffitt, J. J. Margitan, and K. R. Chan, *J. Geophys. Res.*, **97**, 7905-7923, 1992.

In situ measurements constraining the role of sulphate aerosols in mid-latitude ozone depletion, D. W. Fahey, S. R. Kawa, et al., *Nature*, **363**, 509-514, 1993.

Interpretation of NOx/NOy observations from AASE-II using a model of chemistry along trajectories, S. R. Kawa, et al., *Geophys. Res. Lett.*, **20**, 2507-2510, 1993.

Missing Chemistry of Reactive Nitrogen in the Upper Stratospheric Polar Winter, S. R. Kawa, J. B. Kumer, A. R. Douglass, A. E. Roche, S. E. Smith, F. W. Taylor, and D. J. Allen, *Geophys. Res. Lett.,* **22**, 2629-2632, 1995.

Activation of Chlorine in Sulfate Aerosol as Inferred from Aircraft Observations, S. R. Kawa, et al., *J. Geophys. Res.*, **102**, 3921-3933, 1997.

Assessment of the Effects of High-Speed Aircraft in the Stratosphere: 1998, S. R. Kawa, J. G. Anderson, S. L. Baughcum, C. A. Brock, W. H. Brune, R. C. Cohen, D. E. Kinnison, P. A. Newman, J. M. Rodriguez, R. S., Stolarski, D. Waugh, S. C. Wofsy, NASA Technical Publication, NASA/TP-1999-209237, 1999.

The interaction between dynamics and chemistry of ozone in the set-up phase of the northern hemisphere polar vortex, S. R. Kawa, R. Bevilacqua, J. J. Margitan, A. R. Douglass, M. R. Schoeberl, K. Hoppel, B. Sen, *J. Geophys. Res.*, **107**, 8310, doi: 10.1029/2001JD001527, 2002.

Sensitivity studies for space-based measurement of atmospheric total column carbon dioxide using reflected sunlight, Mao, J., and S. R. Kawa, *Appl. Optics,* **43**, 914-927, 2004.

A. Scott Denning

Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523-1371
(970)491-6936 `denning@atmos.colostate.edu` FAX 491-8449

Education:

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

Professional Experience:

2003– : *Associate Professor*, Department of Atmospheric Science, Colorado State University
Atmosphere-biosphere interactions. Global carbon cycle. Land-surface climate.

1998–03 : *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.

1994–96: *Postdoctoral Research Associate*, Department of Atmospheric Science, Colorado State University, Fort Collins, CO. David A. Randall, supervisor. (NASA supported).
Global-scale atmosphere-biosphere interactions using a general circulation model.

1990–1994: *Graduate Research Assistant*, Department of Atmospheric Science, Colorado State University, Fort Collins, CO. David A. Randall, supervisor. (NASA supported).
Synthesis inversion of the global carbon budget using a general circulation model.

1986–90: *Research Associate*, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO. Jill S. Baron, supervisor. (NPS supported).
Biogeochemical and hydrologic dynamics of an alpine-subalpine watershed.

1985–86: *Wellsite Geochemist*, GEO Inc., Denver, CO.
Gas chromatographic and lithologic analyses in support of oil exploration objectives.

1980–85: *Research Assistant*, Department of Geological Sciences, University of Maine.
Paleolimnologic Investigation and Reconstruction of Lake Acidification.

Selected Publications:

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.

Law, R. M., P. J. Rayner, A. S. Denning, D. Erickson, M. Heimann, S. C. Piper, M. Ramonet, S. Taguchi, J. A. Taylor, C. M. Trudinger, and I. G. Watterson, 1996. Variations in modelled atmospheric transport of carbon dioxide and the consequences for CO_2 inversions *Global Biogeochemical Cycles*, **10**, 783-796.

Sellers, P. J., R. E. Dickinson, D. A. Randall, A. K. Betts, F. G. Hall, J. A. Berry, C. J. Collatz, A. S. Denning, H. A. Mooney, C. A. Nobre, and N. Sato, 1997. Modeling the exchanges of energy, water, and carbon between the continents and the atmosphere. *Science,* **275**, 502-509.

Ciais, P., A. S. Denning, P. P. Tans, J. A. Berry, D. A. Randall, G. J. Collatz, P. J. Sellers, J. W. C. White, M. Trolier, H. J. Meijer, R. J. Francey, P. Monfray, and M. Heimann, 1997: A three-dimensional synthesis study of $\delta^{18}O$ in atmospheric CO_2. Part 1: Surface fluxes. *Journal of Geophysical Research,* **102**, 5857-5872.

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.

Potosnak, M.J., S.C. Wofsy, A.S. Denning, T.J. Conway and D.H. Barnes, 1999. Influence of biotic exchange and combustion sources on atmospheric CO_2 concentrations in New England from observations at a forest flux tower. *Journal of Geophysical Research*, **104**, 9561-9569.

Gurney, K.R., R. M. Law, A. S. Denning, P. J. Rayner, D. Baker, P. Bousquet, L. Bruhwiler, Y.-H. Chen, P. Ciais, S. Fan, I.Y. Fung, M. Gloor, M. Heimann, K. Higuchi, J. John, T. Maki, S. Maksyutov, K. Masarie, P. Peylin, M. Prather, B.C. Pak, J. Randerson, J. Sarmiento, S. Taguchi, T. Takahashi and C.-W. Yuen, 2001: Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models. *Nature*, **415**, 626-630, Feb. 2002.

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.

Schaefer, K., A.S. Denning, N. Suits, Jorg Kaduc, I. Baker, S. Los, and L. Prihodko, 2002: The effect of climate on inter-annual variability of terrestrial CO2 fluxes. *Global Biogeochemical Cycles,* **16**, 1102, doi:10.1029/2002GB001928.

Baker, I.T., A.S. Denning, N. Hanan, L. Prihodko, P.-L. Vidale, K. Davis and P. Bakwin, 2003: Simulated and observed fluxes of sensible and latent heat and CO_2 at the WLEF-TV Tower using SiB2.5. *Global Change Biology,* **9**, 1262-1277.

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.

Nicholls, M.E., A.S. Denning, L. Prihodko, 2003: A multiple-scale simulation of variations in atmospheric carbon dioxide using a coupled biosphere -atmospheric model, *Journal of Geophysical Research*, in press.

NAME: **G. James Collatz**

MAJOR ACTIVITIES: EOS-Interdisciplinary Science Research: Study of Biosphere-Atmosphere Interactions and Terrestrial Carbon Cycle using remote sensing observations and models.
GSFC Carbon Cycle Team Land Discipline Leader.

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

RECENT AND SELECTED PEER REVIEWED PUBLICATIONS (39 Total)

van der Werf GR, Randerson JT, Collatz GJ, Giglio L, Kasibhatla PS, Arellano AF, Olsen SC, Kasischke ES, Continental-scale partitioning of fire emissions during the 1997 to 2001 El Nino/La Nina period. Science 303, 73-76, 2004

Hicke JA, Asnert GP, Kasischke ES, French NHF, Randerson JT, Collatz GJ, Stocks BJ, Tucker CJ, Los SO, Field CB, Postfire response of North American Boreal Forest net primary productivity analyzed with satellite observations. Global Change Biology 9, 1145-1157, 2003

van der Werf GR, Randerson JT, Collatz GJ, Giglio L, Carbon emissions from fires in tropical and subtropical ecosystems. Global Change Biology 9, 547-562, 2003

Still CJ, Berry JA, Collatz GJ, DeFries RS, The global distribution of C3 and C4 vegetation: carbon cycle implications. Global Biogeochemical Cycles 17 doi:10.1029/2001GB001807, 2003

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

Bounoua L, DeFries RS, Collatz GJ, Sellers PS, Khan H, Effects of land cover conversion on climate. Climate Change 52, 29-64, 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

DeFries RS, Field CB, Fung I, Collatz GJ, Bounoua L, Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity. Global Biogeochemical Cycles 13, 803-815. 1999

Bounoua L, Collatz GJ, Seller PJ, Randall DA, Dazlich DA, Los SO, Berry JA, Fung I, Tucker CJ, Field CB, Jensen TG. Interactions between vegetation and Climate: Radiative and physiological effects of double atmospheric CO2. Journal of Climate 12, 309-324, 1998

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

Sellers PJ, Randall DA, Collatz GJ, Berry JA, Field CB, Dazlich DA, Zhang C, Colello GD, Bounoua B, A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model Formulation, Journal of Climate 9, 676-705 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

Sellers PJ, Berry JA, Collatz GJ, Field CB, Hall FG, Canopy reflectance, photosynthesis and transpiration. Part III: A reanalysis using enzyme kinetics-electron transport models of leaf physiology, Remote Sensing of Environment 42, 187-216, 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

Close Collaborators: JA Berry, AS Denning, SR Kawa, JR Randerson, GR van der Werf, H Margolis, CJ Tucker, JG Masek, S Los

David Julius Erickson III

Education:

1987	Ph.D. (Chemical Oceanography/Atmospheric Chemistry) Graduate School of Oceanography University of Rhode Island Narragansett, Rhode Island
1982	B. S. (Chemistry) The College of William and Mary Williamsburg, Virginia

Professional Experience:

2000-present	Senior Research Staff Member Director, Climate and Carbon Research Institute Computer Science and Mathematics Division Oak Ridge National Laboratory Oak Ridge, Tennessee
2003 - present	Adjunct Professor Division of Earth and Ocean Sciences Nicholas School of the Environment and Earth Sciences Duke University Durham, North Carolina
1999 – 2000	Scientist Universities Space Research Association Laboratory for Atmospheres NASA/Goddard Space Flight Center Greenbelt, Maryland
1990 - 1999	Scientist National Center for Atmospheric Research Boulder, Colorado
1987 - 1990	Post-doctoral Research Fellow Scripps Institution of Oceanography University of California, San Diego La Jolla, California

Appointments, Panel Memberships, Steering Committees:

1994 - present	Panel Member, United Nations Environment Program (UNEP), Environmental Effects of Ozone Depletion
1994 - 1998	Steering Committee Member, International Global Atmospheric Chemistry Program (IGAC), Reactive Chlorine Inventory
1995 - present	Member, Advisory Board, Tropical Atmospheric Science Center (TASC), University of Puerto Rico
1996 - 2002	Member, Executive Committee, Chairman, Air-sea Interaction Group, Atmospheric Sciences Section, American Geophysical Union (AGU)

1997 - 1999	Panel Member, National Research Council (NRC)/National Academy of Sciences (NAS), Panel on Atmospheric Effects of Aviation
2001 - present	Member, Scientific Planning Team, Surface Ocean-Lower Atmosphere Study (SOLAS)
2001 - present	Editorial Board, Chemosphere: Global Change Science

Scientific Collaborators (past 4 years):

Drs. R. Kawa, F. Hoffman, S. Pawson, R. Oglesby, W. Keene, W. Gregg, R. Zepp, P. Matrai, E. Atlas, J. Drake, S. Marshall, L. Klinger, C. Seuzaret, A. Khalil, J. Hernandez, S. Pryor, J. Taylor, J. Corredor

Scientific Interests:

Global climate modeling, numerical models of atmospheric chemistry, S, N, C and Fe simulations in global climate models, air-sea gas exchange, NASA satellite data merging with GCMs to simulate global biogeochemical cycles, geochemical cycle models on all time scales

6 Relevant Publications:

Erickson, D. J. III, 'Variations in the global air-sea transfer velocity field of CO_2', Global Biogeochem. Cycles, 3, 37-41, 1989.

Erickson, D. J. III, S. Ghan and J. Penner, 'Global ocean to atmosphere dimethyl sulfide flux', J. Geophys. Res., 95, 7543-7552, 1990.

Erickson, D. J. III, J. J. Walton, S. J. Ghan and J. E Penner, 'Three-dimensional modeling of the global atmospheric sulfur cycle: A first step', Atmos. Environ., 25A, 2513-2520, 1991.

Erickson, D. J. III, 'A stability dependent theory for air-sea gas exchange', J. Geophys. Res., 98, 8471-8488, 1993.

Erickson, D. J. III, P. J. Rasch, P. P. Tans, P. Friedlingstein, P. Ciais, E. Maier-Reimer, K. Kurz, C. A. Fischer and S. Walters, ‘The seasonal cycle of atmospheric CO_2: A study based on the NCAR Community Climate Model (CCM2)’, J. Geophys. Res., 101, 15079-15097, 1996.

Erickson, D. J. III, R. Zepp and E. Atlas, ‘Ozone depletion and the air-sea exchange of greenhouse and climate reactive gases’, Chemosphere - Global Change Science, 137-149, 2000.

Oglesby, R. J., S. Marshall, D. J. Erickson III, J. O. Roads and F. R. Robertson, ‘Thresholds in atmosphere-soil moisture interactions: Results from climate model studies, J. Geophys. Res., 107, D14, 10.10294/20015D001045, 2002.