Table of Contents

Cover Letter .... **Error! Bookmark not defined.**
NASA Cover Sheet .... **Error! Bookmark not defined.**
Signatures and Letters of Commitment from the CO-Is ... **Error! Bookmark not defined.**
Letters from Collaborators .... **Error! Bookmark not defined.**
Table of Contents 1
Abstract 2
Technical Plan 3
- 1 Motivation and Goals 3
- 2 Background and Justification for an Approach Based on Data Assimilation 5
  - 2.1 A Brief Review of Some Prior Studies Using Inversion Methods 5
  - 2.2 Why Use Assimilation? 7
  - 2.3 Development and Application of the Inversion Technique 8
- 3 Overview of Proposed Research 9
  - 3.1 Stage 1: Consistency of Top-Down and Bottom-Up Source-Sink Estimates 12
  - 3.2 Stage 2: Optimization using Constraints from Above and Below 13
- 4 Present Capabilities of the Science Team 13
  - 4.1 Atmospheric Modeling and Assimilation 13
    - 4.1.1 Meteorological Modeling and Assimilation 13
    - 4.1.2 Constituent Modeling 14
    - 4.1.3 Constituent Assimilation 16
  - 4.2 Assimilation of the Physical State of the Land Surface 17
  - 4.3 The Sib-BCM for Biological Flux Estimates Over Land 18
  - 4.4 Fossil-Fuel Emissions 19
  - 4.5 The WHOI Ocean Biogeochemistry Model 20
- 5 Stage 1: Consistency of Top-Down and Bottom-Up Source-Sink Estimates 21
  - 5.1 Bottom-Up Flux Estimates Over Land and Ocean 22
  - 5.2 Implementation of AIRS CO_2 Radiance Assimilation in GEOS-5 23
  - 5.3 Characterization of Forecast Error and Model Performance 24
  - 5.4 Atmospheric Inversion: Improving the Estimated Source-Sink Distribution . 25
  - 5.5 Analysis of Flux Mismatches After Atmospheric Inversion 27
  - 5.6 Implementation of OCO Radiance Assimilation in GEOS-5 28
- 6 Stage 2: Optimization using Constraints from Above and Below 30
- 7 Summary 31

References 33
Management Plan 38
Computing Plan, Including Appendix A 42
Current and Pending Funding 47
Resumes 54
Cost Plan and Budget Pages 75

Abstract

We propose to develop an assimilation system for the global carbon cycle, which will ingest in-situ and space-based observations into models of physical processes and carbon cycling. It will be used to give estimates of the seasonal cycle of carbon fluxes, including year-to-year variations, along with measures of uncertainty in these fluxes. It will extend GMAO's "physical" data assimilation systems to the carbon cycle. It will incorporate existing models for land and oceanic carbon processes; carbon species will be added to the GEOS-5 atmospheric assimilation and an inversion methodology will be implemented. The coupled assimilation will be developed in two stages.

In the first stage, we will examine consistency between carbon sources and sinks derived from bottom-up and top-down approaches; interpretation will be in terms of uncertain model parameters and potential data inaccuracies. The goal is to better understand the global behavior of the models and to develop an improved knowledge of the carbon cycle. This first stage of research will build on component models and assimilations that are funded through existing projects. Bottom-up source/sink estimates will be determined using biophysical and fossil-fuel models over land and ocean biogeochemistry, constrained by satellite data (especially from MODIS) and atmospheric analyses. The GEOS-5 atmospheric assimilation system will be extended to ingest in-situ carbon observations and AIRS (later also OCO) level-1b radiances. A detailed study of atmospheric transport uncertainty will be performed. A methodology for inverting the assimilated data to improve on bottom-up source/sink estimates will be developed, after testing of various candidate systems, one of which is a new approach based upon parameter estimation using ensembles of model forecasts. Parameter uncertainty in the land and ocean carbon models will then be tested for consistency with the atmospheric estimates. The system will be used to compute finely resolved space-time estimates of CO_2 exchanges between the atmosphere and underlying surface, with associated uncertainties. Because of data and model uncertainties, we will produce global source/sink distributions on scales of hundreds of kilometers.

In the second stage (years four-five) a coupled atmosphere-land-ocean assimilation will be developed to simultaneously constrain surface source/sink distributions using top-down and bottom-up information. Component modules will estimate very high-resolution (quarter degree or finer) global carbon fluxes. An ensemble assimilation, running on the land-atmosphere and ocean-atmosphere interfaces, will account for parameter uncertainty in the underlying models and observations. The goal is to produce reliable flux estimates on spatial scales of around 200km and temporal resolution of two weeks, describing the seasonal cycle of carbon in the environment.

The research system proposed here will be tested extensively on selected observational periods (such as NACP intensives). Sensitivity to input data inputs (e.g., AIRS and OCO radiances; NACP in-situ data) will be studied. It will later be run for an extended period, beginning with the EOS-Aqua launch.

Technical Plan

1 Motivation and Goals

The question of how carbon cycle dynamics will change in the future is a key to reliable prediction of climate change, impacts, and effective design of remedial strategies [e.g., IPCC, 2001; ESE, 2003]. Physical and biogeochemical processes in the terrestrial biosphere and ocean currently sequester about half of the anthropogenic CO_2 emissions, yet large uncertainties exist in the location, mechanisms, and evolution of these sinks [Tans et al., 1990; Fan et al., 1998; Bousquet et al., 2000]. Contemporary predictive models of global change, including an interactive carbon cycle, differ by several hundred ppmv in atmospheric CO_2 by the year 2100, leading to a difference in simulated global mean temperature of more than 2 K [Cox et al., 2000; Friedlingstein et al., 2001]; this uncertainty is comparable to that arising from disparate representation of clouds and aerosol in climate models [IPCC, 2001]. Progress in understanding the global carbon budget is largely limited by available observations. High precision global atmospheric CO_2 data are now available [Engelen et al., 2001; 2004; Crevoisier et al., 2004] or being planned [Crisp et al., 2004] and should help resolve these issues. As new CO_2 and other related measurements become available, however, analysis methods must be developed to make use of the greater density and varying sampling characteristics of the new instrumentation. Here we propose to develop a data assimilation system that will incorporate atmospheric, oceanic, and terrestrial biospheric carbon process observations into estimates of carbon fluxes and their uncertainties that will lead to better understanding of the global carbon budget and its future.

Our proposed activity will contribute directly to an operational system for continuous, high-resolution analysis of variations in the carbon cycle. Such a system is widely regarded as a requirement to exploit available and planned remote sensing data for carbon management, productivity monitoring, ecosystem and land cover change, and climate projections. A number of national strategy documents have identified this as a major research objective [e.g., McClain et al, 2002; Wofsy and Harriss, 2002]. The proposed activity also conforms closely to requirements from the NASA Carbon Cycle and Ecosystems focus area roadmap for missions to quantify regional carbon sources and sinks globally and, subsequently, to characterize CO_2 sources and sinks on a sub-regional spatial scale. Achieving these objectives will require significant advances in measurement and analysis technology relative to current methods.

We propose to develop and test components that contribute to that goal, delivering a baseline analysis system within five years. The system will comprise high-resolution atmosphere, land, and ocean models that include physical and biogeochemical processes, along with assimilation modules capable of ingesting in-situ measurements and space-based radiances. We will address science problems in a stepwise fashion with existing observations and component models, emphasizing the coupling of model components and the fusion of models and data. In the first two-to-three years of research, we will concentrate on improving “top-down” flux estimates using atmospheric assimilation, looking at consistency with fluxes obtained from “bottom-up” approaches using data-constrained ocean and land models. Emphasis will be placed on the sensitivity of flux estimates to data and model uncertainties, as well as exploring the impact of approximations used to represent processes in the component models. The later focus will be on a coupled system, building on results of earlier research and utilizing more data types, to develop and implement an assimilation framework that couples atmosphere, ocean and land processes; this will require a new assimilation methodology to estimate fluxes optimizing both “top-down” and ”bottom-up” constraints.

The results of this research will be a better understanding of the interactions between the physical climate and the carbon cycle. The goal is to provide robust estimates of carbon fluxes between the atmosphere and the land/ocean surfaces with quantified uncertainty. We aim to produce global fluxes on spatial scales of 200-500 km and temporal scales of two weeks, a scale adequate to impact socio-political decisions. The feasibility of this aim is part of the investigation. Many studies have used inversion methods based on sparse, in-situ CO_2 data to estimate global CO_2 surface sources and sinks with large uncertainty on scales of continents or ocean basins (see Section 2). We deal explicitly with atmospheric CO_2 through radiance-based assimilation of AIRS [e.g., Engelen et al., 2001] and OCO [Crisp et al., 2004] data along with the in situ observations [e.g., Wofsy and Harriss, 2002]. We include a parallel approach to optimizing fluxes from land and ocean process modeling components, again using NASA remote sensing and other data. Integration and optimization of this system will form a basis for enhancing models and for predicting future climate including the complex role of carbon species in the environmental system.

The partnership assembled for this work includes researchers with a broad range of interdisciplinary expertise. The project will be led from the Goddard Global Modeling and Assimilation Office (GMAO), where the functional system will be constructed and maintained according to ESMF conventions. This proposal defines a path for carbon-cycle research in the GMAO, in the context of a planned earth-system modeling and assimilation framework that includes physical, chemical and biological processes, through coordinated activities in oceanic, land and atmospheric science. The proposal builds on meteorological and constituent models and assimilation now available in the GMAO. Partners are essential to the success of the project, and all groups will contribute to the development of the system and the scientific analysis of the results according to their expertise: Woods Hole Oceanographic Institute (WHOI), Colorado State University (CSU), the DOE’s Oak Ridge National Laboratory, the Atmospheric Chemistry and Dynamics (916) and Biospheric Processes (923) Branches at GSFC.

Our proposal describes the research and technical work that will be performed. It starts (Section 2) with a review of inversion methods and assimilation techniques. Section 3 outlines our approach to the global flux estimation, outlining a two-stage progression that initially treats the atmosphere, ocean and land separately (but examines consistency between top-down and bottom-up flux estimates), before developing a combined methodology. Section 4 describes our existing tools that will be combined in this study. An outline of the work to be performed in “Stage 1” of this proposal is given in section 5, where we outline the links to our ongoing research projects and give details of the tasks to be performed. Section 5 concludes with a statement on what we expect to achieve in three years in terms of advances in understanding and products. Section 6 outlines our three-to-five-year plan ("Stage 2"), which builds on earlier advances, and will require further theoretical and practical advances in data assimilation to constrain flux estimates simultaneously through bottom-up and top-down data and models.

2 Background and Justification for an Approach Based on Data Assimilation

This section gives a brief review of prior work to estimate source-sink distributions, most of which have worked with sparse, in-situ datasets. In the discussion, the concept of applying the various methods to assimilated data is raised; the analyses produced by data assimilation are assumed to be three-dimensional fields on high-resolution spatial grids. The review of previous inversion studies is followed by a discussion on the advantages of using assimilation in the problem. Possible approaches that will be considered for performing the inversion will then be outlined.

2.1 A Brief Review of Some Prior Studies Using Inversion Methods

Mass balance or differential methods are useful when significant data are available near a source (sink) to be calculated. They are often used with ground-based measurements (surface concentrations) and two-dimensional models [e.g., Conway et al., 1994]. The extension of differential techniques to three dimensions requires the extrapolation of the observations to areas where there are none [Enting, 2000] and assumptions about the performance of the models in these regions. This implies that this technique might easily be combined with a data assimilation scheme, which naturally extends observational information to the entire model grid. Inversion by differential methods is generally deterministic and does not need error statistics, so such methods would not facilitate exploitation of all of the information coming from an assimilation system.

Green's Function Methods, often referred to as integral techniques, are generally Bayesian and require an estimate of error statistics for both observations and model. A Green's function is a solution to the transport equation with a single point source (sink), so that it essentially describes the global pattern of concentration that results from the single point source. The set of all Green's functions then represents a basis that can be combined linearly to represent the observed concentration field. The resulting system of equations is ill-conditioned, so that error statistics must be introduced into the inversion.

Since the resulting system of equations would become unwieldy if a Green's function were introduced for every single grid point, a synthesis approach is used to simplify and reduce the size of the system. Localized (but not point) source shapes are introduced, with a scale factor left as unknown. The system of equations is then reduced to solving for the scale factors. Numerous studies have used such Bayesian synthesis inversion methods to deduce source-sink relationships from surface concentration data [e.g., Enting et al., 1995; Baker, 2000; Gurney et al., 2002]. Some of these studies used observations with modeled winds from different periods, working with time-averaged data, so little information on the rich temporal variability of transport is included. Further, the sparse nature of the surface concentration network has restricted flux estimates to continental scales. Kaminski et al. [2001] show that large errors can occur when using synthesis inversions, particularly when the synthesis regions are large compared with the model grid.

Synthesis inversion techniques have been used in idealized OSSE-type experiments to demonstrate the feasibility that AIRS-like data can have a beneficial impact on source-sink estimation [Rayner and O'Brien, 2001; Pak and Prather, 2001]. Space-based instruments provide several orders of magnitude more observations per day than the in-situ techniques available to earlier studies, making this an expensive computational problem. This expense would be even more pronounced when using high-resolution, three-dimensional global analyses, as would be obtained from assimilating satellite data, particularly when the source-sink distribution varies with time.

A third approach that has been used for source-sink inversion is adjoint modeling. Adjoint-based inversion techniques [e.g., Giering et al., 2000] are well suited to the study of high-frequency variations, yielding better spatial and temporal resolution of CO_2 fluxes than synthesis inversions. If a model is non-linear, then the adjoint is based upon its tangent linear model (TLM), but large-scale advection of constituents is inherently linear, so its adjoint is simply the transpose of the system matrix. Adjoints provide mechanisms to propagate information backwards in time, and therefore can be used to determine the origin of constituent anomalies. Once an adjoint of a (transport) model system exists, it can be run at approximately the cost of the forward model, making it an effective tool for high-density observations. Adjoint approaches have received some attention in atmospheric inversion [e.g., Kaminski et al., 1996] and for a biogeochemical model [Kaminski et al., 2002]. Houweling et al. [1999] used surface measurements from stations and ships as input to an adjoint-inversion for atmospheric methane.

A conceptual advantage of adjoint techniques, in combination with assimilation, is that they work using anomalies. Thus, for the source-sink inversion, the adjoint can be used to propagate backwards in time a three-dimensional "error" field, the analysis increment. Adjoint techniques have been widely applied in meteorological data assimilation, including issues related to error propagation in weather forecasts [Rabier et al., 1992] and in "targeting" observations to reduce such uncertainties [e.g., Baker and Daley, 2000]. To the best of our knowledge, no group has yet applied a combined assimilation-adjoint approach to the source-sink inversion problem.

One issue that pervades all constituent modeling, affecting forward and inverse calculations, is the transport error. Studies such as Transcom [Denning et al., 1999] have compared controlled calculations made with numerous models, revealing how different transport models represent "test" situations such as age-of-air distributions, interhemispheric gradients in CO_2, and other quantities. Impacts on inversion calculations are also documented [Gurney et al., 2002]. Other recent work has illustrated the impacts of assimilation on transport: Tan et al. [2004] show how assimilation can lead to excessive mixing in transport calculations. Uncertainty in sub-grid transport, caused by limitations in parameterization schemes used in AGCMs, is another factor that must be considered. Impacts of transport uncertainty will be given prominence in this proposed research and discussed in detail.

2.2 Why Use Assimilation?

The proposed approach is to assimilate observations of chemical species, alongside meteorological and other data, using forecasts produced by transporting carbon species in the GEOS-5 AGCM. Assimilation combines, in an optimal manner, the available observations (O) with a model forecast (F) to produce an analysis (A). The optimization of the assimilation step works to "balance" the O and F fields, according to their difference (the O-F) and the assumed "forecast error" and the "observation error." The assimilation modules work to provide an analysis increment that is a global three-dimensional field of corrections to F, which is added to the forecast to produce the analysis. Assimilation can proceed directly in physical space, where concentrations or column averages are optimized, or by optimizing radiances. In the former case, satellite radiances must be inverted prior to the assimilation step, generally using a number of approximations (and with a potentially strong dependence on the a priori). In the latter case, model (forecast) fields must be converted to radiances. The observation and forecast error models must be formulated appropriately. Typical meteorological assimilation involves a hybrid approach, using both in-situ observations (temperature and wind from sondes) and radiances that describe the thermal structure and some aspects of composition (e.g., level-1b AIRS radiances).

Sequential assimilation, such as 3D-Var, proceeds in a two-step cycle. For constituents with surface sources and sinks, this is:

Step 1: Generation of a forecast, F, for time t, using the transport components of the AGCM, which is initialized from a prior analysis, $A^{t-\Delta t}$, and using a "first guess" surface source-sink distribution (S_f) as a boundary condition.

Step 2: Optimal merging of the forecast, F, with observations, O, to yield an analysis, A. This will use statistical models of observation- and forecast-error covariances, as well as physical models to map between radiances and physical variables.

Note that the assimilation yields not only the space-time distributions of the quantity of interest, but also distributions of the O-F (which may be given in terms of radiances) and the analysis increments, or A-F, which will be in physical units on the model grid. Key to the success of the assimilation is the error covariance modeling, which can be determined by a number of methods. Forecast errors can be determined by detailed evaluation against in-situ data and Kalman-filter approaches derived to give estimates of model uncertainty.

A number of assimilation systems have been developed for constituents. Ozone, as an important radiative gas with relatively good stratospheric observations, has received considerable attention, generally in 3D-Var systems [e.g., Eskes et al., 1999; 2003; Stajner et al., 2001; 2004]. A Kalman-filter approach was applied to long-lived stratospheric constituents [Ménard et al., 2000; Auger and Tangborn, 2004]. Retrieved CO partial profiles have been assimilated into a CTM [e.g., Lamarque et al., 1999]. Bruhwiler et al. [2000] assimilated surface CO_2 observations into an atmospheric model, solving simultaneously for concentrations and fluxes.

AIRS radiances have successfully been used to estimate atmospheric CO_2 [Engelen et al., 2004; Crevoisier et al., 2004]. They produced estimates of tropospheric CO_2

concentrations at the locations of AIRS measurements in the Tropics. In regions with persistent clouds, tropospheric CO_2 fields are poorly constrained by AIRS data causing gaps or higher uncertainty in CO_2 concentrations that were estimated. Neither of these studies used a model for atmospheric CO_2, which could propagate information globally, including these cloudy regions. We plan to use an atmospheric model constrained by surface fluxes to provide a global atmospheric CO_2 field that will be constrained through assimilation of AIRS and/or OCO radiances and other data.

Obtaining accurate distributions of constituents is important for our understanding of the atmosphere, but a number of important factors support using the assimilation step, rather than relying on "raw" observations, when performing inverse calculations:

a. It gives the best possible estimation of the true concentrations at the analysis time.
b. Error covariances can be tuned to obtain the best possible analyses [Stajner et al., 2001], by using the O-F statistics, where the forecasts are made using analyses as initial conditions. Because the forecasts make use of both model and observations, a dynamically balanced solution can be obtained. Analysis of the error statistics can also be used to obtain seasonal variations in background error covariances. This type of tuning is not available for traditional source/sink estimation methods.
c. Assimilation methods that calculate error-covariance evolution (Kalman filter and ensemble Kalman filter) could also be used, so that current error statistics are available to both state variable and source/sink estimation.
d. Analysis increments contain information on both model errors and the first guess of the source/sink distributions. Statistical analysis could be used to separate out these errors, improving the new source/sink estimates. For example, it could be expected that source/sink model errors would dominate at the lowest levels, while transport errors would be larger higher up. Differences in spatial and temporal scales for these errors could also be significant, and assimilation can help identify these differences [Dee and da Silva, 1999].
e. Information from multiple data sources can (and will) be combined, including ground-based observations. The resulting analyzed concentrations would have a single error covariance instead of the multiple error fields associated with the different observation types.

Note that the assimilation yields both analyzed constituent mixing ratios and improved estimates for model error, background error covariance and analysis error covariance.

2.3 Development and Application of the Inversion Technique

Having assimilated the observations, an inversion calculation can be used to infer surface source/sink distributions. In essence, the inversion seeks to add a correction, ΔS, to the initial (bottom-up) estimate of the surface flux, S_f.

Synthesis inversion techniques would use the analyzed constituent field as a "pseudo-observational" dataset, including a single, consistent error covariance for the entire three-dimensional concentration field. Inversion would proceed in the standard manner.

One advantage over “traditional” application of synthesis inversion methods is the global nature of the “pseudo-observations.” Note that even without assimilation, present-day satellite instruments offer much greater observation density than have previously been available, but the argument for assimilation is given above.

Despite the possibility of this approach, it may be more reasonable to use the analysis increments from the constituent assimilation as the basis for an inverse calculation. This is because, at least with a perfect transport model, these are directly related to uncertainties in the source-sink distribution. Use of the analysis increments lends itself to the use of an adjoint of the transport model. This “inversion” would result in an estimation of the difference between the model and the true system at the time the constituent is emitted from the source, and could be used to make a correction (ΔS) to the modeled source. The advantages of this assimilation-adjoint approach are:

a. Information from all types of observations is combined into a single data set that is combined with a single error covariance, rather than many different sources with different error characteristics.
b. The model also produces forecasts on a uniform grid, and on regular time intervals, using the prior analyses as initial conditions. This creates a data set that is consistent with both the observations and model and does not contain any mass balance incompatibility that might otherwise result in large errors in the source/sink estimation.

Regardless of the method used, one issue remains: how accurate is the transport calculation? Traditional inverse methods allow little flexibility in examining transport error, yet this can potentially lead to enormous errors in inferred fluxes, especially if it is systematic. For instance, it is feasible that present convection codes do not yield enough “vertical spread” in outflow, meaning that too much air may be output in the upper troposphere. It is doubtful that present data (AIRS) can adequately constrain this aspect of the problem. In this project we will need to characterize transport error for both the assimilation and the inversion steps.

3 Overview of Proposed Research

The research proposed is to estimate fluxes of carbon species between the surface and the atmosphere, assimilating NASA’s and other satellite datasets into models that represent, even if parameterized, physical and biological processes. To attain this goal, we will develop a data assimilation system for carbon-cycle studies and a robust methodology for estimating carbon exchange between the atmosphere and the underlying surface. The assimilation will be based on existing components for the physical state of the atmosphere, land and ocean that are run operationally[1] in the GMAO; this project will add the infrastructure and scientific advances needed to assimilate the carbon cycle. The techniques developed will substantially expand on

---

[1] Note that “operationally” does not necessarily mean in real-time; we propose to run the system in “late-look” and “reanalysis” modes, weeks to months after the fact, after all possible data have been collected.

previous “inversion” studies, being applicable to the large volumes of satellite data that are available, or which will come on line during the course of the research.

Through the work outlined in this proposal, we will address the following questions, which define the main goals of our research:

Question 1	How well can we constrain carbon fluxes using bottom-up and top-down methods based on large volumes of space-based and in-situ data, high resolution models, and advanced data analysis techniques?
Question 2	Can regional, in-situ observations of concentrations and fluxes be effectively combined with space-borne measurements to constrain carbon fluxes over North America?
Question 3	How does model (transport) error manifest in the assimilation-inversion process and how may we minimize its impacts on surface flux estimates?
Question 4	With what resolution (temporal and spatial) and accuracy can we constrain surface CO_2 fluxes, using present and future data sources with known sampling patterns and error characteristics?
Question 5	What are the spatial and temporal patterns of global sources and sinks of seasonal cycle of CO_2 and can persistent features in these patterns be used to identify different regional mechanisms controlling the current carbon budget?

Questions 1 addresses the technical advances we must make in this work and includes the scientific, technical and computational challenges we must meet. Question 2 addresses aspects of the carbon-species observing system. Question 3 addresses model uncertainty, including both limitations of transport processes in the models and uncertainty in the meteorological analyses used. The answer to Question 4 will incorporate results from the earlier questions, which will need to be traced through the assimilation-inversion procedure. Questions 1-4 will involve research based on case studies, linked to field missions. Question 5 will involve longer runs of the carbon-cycle assimilation system, spanning many seasons when suitable data are available; it will help identify whether the source-sink distributions can be used to distinguish among CO_2 fertilization, nitrogen deposition, boreal warming, forest regrowth, biomass burning, fire suppression, air-sea gas exchange, or other mechanisms that may explain the present carbon budget.

The intention is to provide robust estimates of carbon exchanges between the atmosphere and land/ocean. NASA’s satellite observations of the physical, chemical and biological state of the Earth System will be combined with state-of-the-art models and in-situ observations, using sophisticated data analysis techniques. The flux estimates will proceed in two stages. Stage 1 will treat the atmosphere, land and ocean separately, applying optimization techniques to estimate surface CO_2 fluxes and examining the physical consistency among the fluxes estimated by different methods. Attention will be given to parameter estimation in models, with detailed studies of the sensitivity to assumptions made in the representations of physical and biological processes in the component models. The limitations of present datasets will also be thoroughly investigated. Stage 2 will extend the work by developing a formal assimilation technique for the slowly varying component of the coupled land-ocean-atmosphere system. The end result of this research will be a data assimilation system that incorporates model components of biogeochemistry and land biophysics alongside "traditional" land, ocean and atmosphere components; the assimilation will ingest in-situ observations of the physical and chemical state of the atmosphere alongside radiance measurements from satellites. The system components will be run at high spatial resolution (half or quarter degree for the atmosphere; one third of a degree for the ocean; and 20km for the land), but the slowly varying component of the coupling will be optimized over larger spatial scales (two degrees is a goal), because of data limitations. The system will be run for the period 2002-2010, using EOS-Aqua data as its central input, and for 2008-2010 with OCO data added. Numerous shorter runs, for periods of NACP intensives and other field campaigns (when many aircraft profiles will be available, alongside the increased in-situ networks), will also be studied and detailed comparisons made with correlative field data.

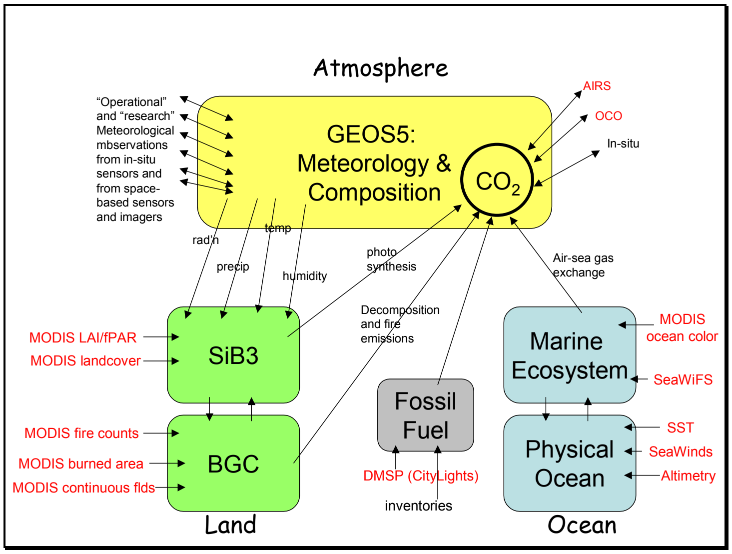


Figure 1. Schematic of the Earth System model components, illustrating the data streams that will be assimilated into these models to constrain the system.

A vast range of data is available to us. They range from "operational" meteorological data, used to constrain the physical state of the atmosphere, through information on the physical state of the land and oceans, to observations that will constrain the biological and biogeochemical components of the system. Figure 1 outlines the types of data to be included in our study and how they will be used alongside the component models.

Radiance observations from AIRS and, later, OCO will be central to the atmospheric carbon studies: a large part of this project is involved in maximizing their utility.

More details of the two stages of the proposal are now given.

3.1 Stage 1: Consistency of Top-Down and Bottom-Up Source-Sink Estimates

The first stage of the proposal will follow this sequence:

- Determine a first-guess source-sink distribution S_f from data-constrained land and ocean models, along with estimates of their uncertainty
- Run the atmospheric assimilation at high (half degree, eventually increasing to quarter degree) resolution, ingesting AIRS level-1b radiances and in -situ data
- Use high-density analysis increments in an inversion procedure, to produce coarse-grain (say 500km², possibly increasing to 200km²) "corrections" to S
- Investigate the consistency of the improved S by examining parametric uncertainties in the underlying land- and ocean-carbon models and by re-running the forward assimilation problem
- Perform a large suite of high-resolution model experiments to fully characterize error that arises from limitations in model transport and how this may propagate through the assimilation and subsequent inversion steps

Within this work, we will produce seasonal runs, with scenarios designed to investigate sensitivities in the system. In order to provide the best possible validation datasets for the assimilation-inversion study, we will initially focus attention on periods of intense field missions. The first periods will be for North American Carbon Program (NACP) intensives [Wofsy and Harriss, 2002], when Aqua (especially AIRS and MODIS) data should be available. Experimentation will allow us to optimize the different aspects of the assimilation system, as well as investigate impacts of numerous in-situ data in combination with the satellite radiance observations. We will also attempt to validate the system over other continents. The system will be run in “late-look” mode, some weeks behind real time, in order to maximize the number of data available for ingestion. Most input data for carbon species will be research-quality data, meaning there is no requirement for real-time delivery. However, the system will be developed to specifications that would allow near-real-time applications, if needed in the future.

Once integrity is achieved for the special periods, longer AIRS-based assimilation will be run; this will also include the intense in-situ network data from NACP. A similar approach will be taken with OCO radiances: limited periods will be studied in detail, before multi-seasonal runs are made. The objective will to be to run the system for a contiguous period, beginning with the OCO launch and ending with the project funding. The run will ingest OCO and AIRS (or other infrared emission) radiances. When possible, we will also exploit links to other gases, especially CO which has some correlations with CO_2 in combustion sources and a better signal-to-noise ratio in space-based data.

3.2 Stage 2: Optimization using Constraints from Above and Below

Stage 2 of the research will work towards a coupled assimilation for atmosphere-land-ocean, with multiple constraints. This will draw heavily on the results from Stage 1 of the research. The assimilation developed will be extended to encompass parameter estimation in the land, ocean, and fossil fuel emission models, with careful attention to physical processes and the utilization of many parallel data streams. This stage of research will place high demands on computing resources and data management, with important roles for both NASA and ORNL computing resources.

The proof of concept for this work will be a three-month period, following OCO launch, when validation missions and NACP activities will lead to rich validation datasets. By the end of the project, we hope to have run this system for the period since OCO launch until two months prior to the end date (to allow for latency in delivery schedules of some of the input datasets).

4 Present Capabilities of the Science Team

This section outlines our present capabilities, describing the modeling and assimilation tools that have been developed by the partners. Essential links to other ongoing research projects are also noted.

4.1 Atmospheric Modeling and Assimilation

4.1.1 Meteorological Modeling and Assimilation

A central component of the GMAO is study of the physical nature of the atmosphere and its links to land and oceans. The scope of this work ranges from “weather” through seasonal prediction and climate. The GEOS-4 AGCM and DAS are presently used to produce operational meteorological analyses and weather forecasts; development is presently focused on the successor, GEOS-5. The GEOS-5 AGCM will also include a coupled physical ocean model, presently used in combination with a different AGCM, for seasonal forecasting and climate studies.

The GEOS-4 and GEOS-5 AGCMs are based around a flux-form semi-Lagrangian formulation of the dynamical core [Lin and Rood, 1996; Lin, 2004]. GEOS-4 includes the physics package developed at the National Center for Atmospheric Research (NCAR) for the Community Climate Model, Version 3 (CCM3) [Kiehl et al., 1998]. In GEOS-5, convection is parameterized via the Relaxed Arakawa-Schubert scheme (RAS) [Moorthi and Suarez, 1992]. Large scale-clouds are treated with a hybrid statistical/prognostic fraction approach with prognostic condensate [Bacmeister 2004]. Connection of convective and large-scale clouds is accomplished using a simple updraft model with simplified microphysics embedded within RAS, similar to Sud and Walker [1999]. Solar and infrared radiation effects are calculated after Chou and Suarez [1994, 1996], including representation of cloud effects assuming the maximum/random overlap assumption with 3 cloud macro-layers [Chou and Suarez, 1996]. Turbulence is parameterized using the first-order scheme of Louis et al. [1982] in stable cloud-free situations, and the scheme of Lock et al. [2000] in unstable situations or in situations with strong cloud IR cooling. Land surface processes are modeled using a catchment-based approach [Koster et al. 2000].

GEOS-5 is coded according to ESMF standards, enabling straightforward interchange of modules: this will be crucial to some of the sensitivity studies to be performed in this project. J. Bacmeister (Co-I on this project, leads the implementation and testing of the physical parameterizations in GEOS-5.) Spatial resolution is flexible; the GEOS-5 AGCM will be run with spatial resolution of a half degree and finer. The Koster et al. [2000] LSM in GEOS-5 incorporates the necessary coupling to biological process modules needed for the carbon cycle, adapted from SiB in collaboration with J. Collatz (a Co-I on this proposal). Similarly, GEOS-5 includes the option of a coupled physical ocean model [e.g., Borovikov et al., 2001] for GMAO's seasonal forecasting studies.

Atmospheric data assimilation modules for GEOS-4 and GEOS-5 facilitate the operational production of meteorological analyses, simultaneously ingesting many types of in-situ and space-based data. The GEOS-4 DAS is based on the Physical-Space Statistical Analysis Scheme (PSAS) [Cohn et al., 1998], where model forecasts are interpolated to observation locations to determine the O-F errors. The GEOS-5 DAS is a more conventional 3D-Var system, where observations are interpolated to the model grid. In either case, the O-Fs are used alongside "observation operators" (to map between, say, the radiances observed and the physical quantities in the model) and appropriate statistical models of forecast and observation error to infer "analysis increments." These analysis increments are essentially added to the forecasts to produce the analyses. Within the GMAO, GEOS-5 is being used to study impacts of AIRS level-1b radiances on the meteorological structure, ingesting simultaneously radiances in channels that describe the thermal structure, humidity and ozone. The forward radiation model infrastructure, needed to calculate radiances from the AGCM forecasts to optimize against AIRS radiances in the assimilation, is in place in GEOS-5.

4.1.2 Constituent Modeling

Offline constituent modeling driven by meteorological fields from the GEOS-4 (and earlier) DAS and AGCM has been the basis of chemistry-transport modeling (CTM) work in a number of groups, including the Harvard GEOS-Chem model [e.g., Li et al., 2002] and the Code 916 middle atmospheric chemistry model [e.g., Douglass et al., 2003]. These CTMs use the Lin and Rood [1996] transport mechanism.

Kawa et al. [2004] studied CO_2 transport using a CTM driven by GEOS-4 DAS data with specified source-sink distributions at the lower boundary. They demonstrated that synoptic variability can be well represented using assimilation-constrained meteorology, relating departures from observations to the lack of variability in surface sources and sinks, as well as to inadequacies in the representation of sub-grid and resolved transport. For the present study, we will use an on-line representation of transport in the AGCM, because this avoids some of the issues associated with CTMs: notably, temporal variations in (say) the PBL and convective transport are more faithfully represented at the AGCM's time resolution (30 minutes) than when aggregated over longer periods (six hours, for GEOS-4). This approach also facilitates future coupling between the advected species and the radiation transfer codes in the AGCM.

An on-line simulation of carbon species (CO_2 and CO) has been made using the GEOS-4 AGCM with a horizontal resolution of 1°, using the same surface boundary conditions as in Kawa et al. [2004]. Figure 2 shows the surface distributions of CO and CO_2 (along with surface pressure) at 12Z on 1 November of an arbitrary year, along with 500-hPa CO_2 and a section across the Atlantic at 42°N. The frontal system in the middle Atlantic has a clear signature in the constituent fields, including vertical displacements. The shallower nocturnal boundary layer over the USA is also evident.

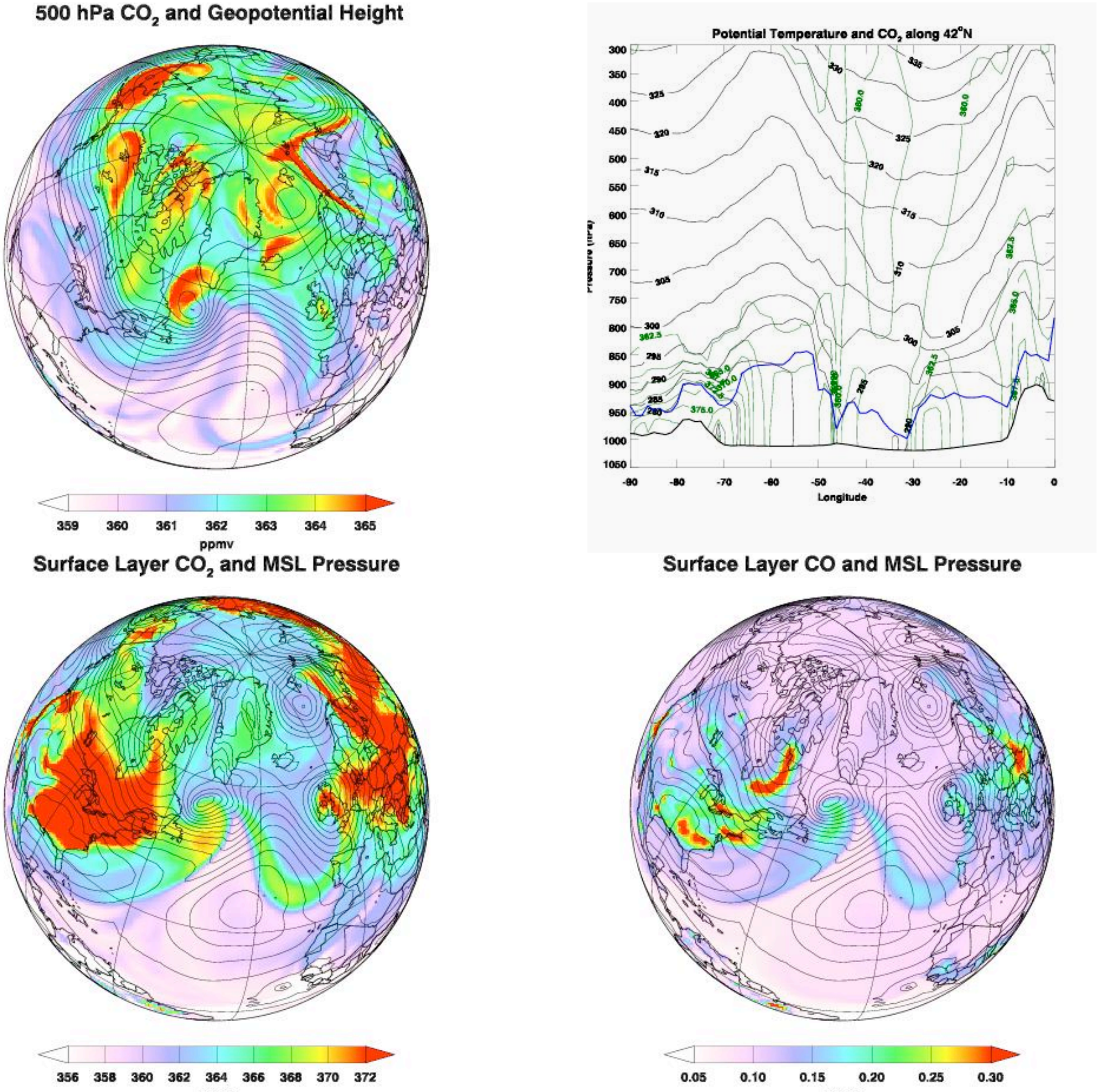
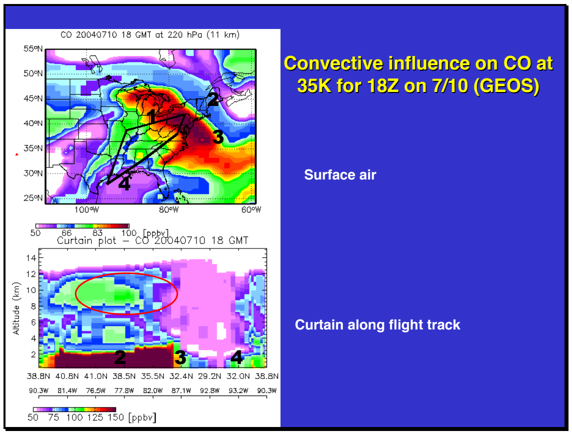


Figure 2. Horizontal distribution of CO_2 and geopotential height at 500hPa (top left) and with surface pressure (bottom left) at 12Z on Nov. 1. The CO plot (bottom right) illustrates the correlations between the two gases. The section through 42°N across the Atlantic (top right) shows the vertical and zonal CO_2 structure over USA and Europe, as well as the strong gradients in the vicinity of the cold front in the middle Atlantic.

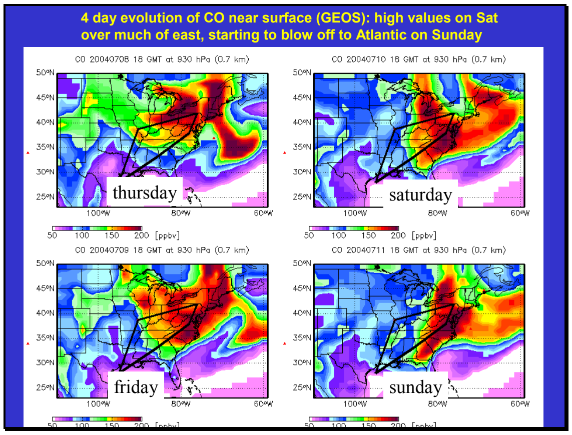
The example shown in Figure 2 is a free-running AGCM simulation that will bear no one-to-one correspondence to any real situation. Constituents may also be included in the AGCM when the meteorological fields are constrained by assimilation. (This is the on-line equivalent of the Kawa et al. [2004] CTM study.) Such a configuration was used for constituent forecasting in NASA's Intex-NA mission in July and August 2004 (where PI Pawson was a Co-I of a project led by Daniel Jacob at Harvard University; Pawson has proposed to the Aura NRA to continue such work). Figure 3 shows typical forecast fields used for the Intex-NA flight planning, illustrating the integrity of the GEOS-4 forecasts in maintaining horizontal and vertical gradients; one of the major uncertainties in the forecast constituents, revealed by comparison with the aircraft data, was the height to which they were transported by convection.

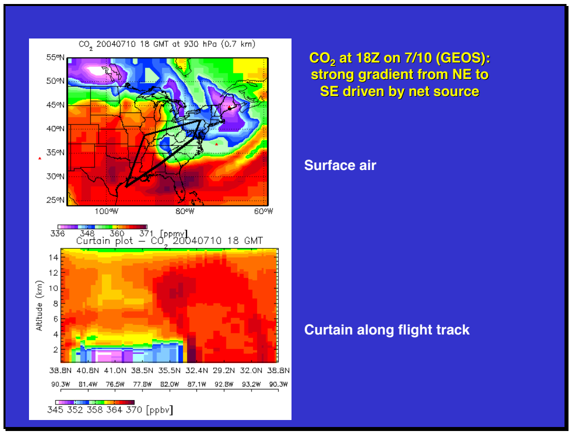
Figure 3. The GEOS-4 forecast from 00Z onThurs. 7/ 8 through Sun 7/11, used in planning for Intex-NA DC-8 flight #6 on 7/10/2004. The CO and CO_2 (right) arise from strong sources and convective lifting into the middle and upper troposphere. The time series of synoptic maps (below) shows the gradual movement of high CO concentrations from the continent to the Atlantic. Plots by D. Jacob, used in Intex-NA flight planning.


Convective influence on CO at 35K for 18Z on 7/10 (GEOS)

Surface air

Curtain along flight track


4 day evolution of CO near surface (GEOS): high values on Sat over much of east, starting to blow off to Atlantic on Sunday


CO_2 at 18Z on 7/10 (GEOS): strong gradient from NE to SE driven by net source

Surface air

Curtain along flight track

4.1.3 Constituent Assimilation

Several systems for atmospheric constituent assimilation have been developed and used at the GMAO based on PSAS or Kalman filter algorithms [Riishojgaard et al., 2000; Stajner et al., 2001; Menard et al., 2000; Lyster et al., 2004; Lary et al., 2003]. A 3D ozone assimilation system has been used to assimilate stratospheric ozone profiles and total column loadings from the Total Ozone Monitoring Spectrometer (TOMS) and Solar-Backscattered Ultraviolet (SBUV) instruments, providing near-real-time estimates of the ozone distribution. A comprehensive study of error variance models in this system was completed [Stajner et al., 2001]. It has recently been applied to monitoring of satellite data [Stajner et al., 2004]. We evaluated parameterized models for ozone chemistry in this assimilation system by measuring the agreement between model forecasts and the incoming satellite observations depending on model parameters. Other developments include extension to different data types, such as solar occultation and limb sounding instruments, increasing our experience in handling multiple data types [Stajner and Wargan, 2004]. These studies were based around an off-line CTM. The assimilation modules are now coupled to an on-line transport/chemistry module in the GEOS-4 AGCM, with positive impacts on tropospheric ozone column (which for space-based ozone data is a residual between the total column and the resolved stratospheric partial column). Other recent advances include the implementation of averaging kernels, to obtain a more faithful representation of model-data comparisons when using retrieved TOMS, SBUV or AIRS ozone columns. Further, a radiance-based approach is being examined for SBUV data. In GEOS-5, the impacts of AIRS radiances alongside SBUV data are being studied.

In the context of a NASA-funded project ("Quantifying the Sources and Global Transport of Combustion Gases …" PI Daniel Jacob, with Steven Pawson as a Co-Investigator) the ozone assimilation system is being adapted to work with CO. Data from MOPITT and possibly SCIAMACHY will be assimilated. This development work will pioneer the changes needed for on-line assimilation of multiple carbon species from multiple data streams, but will initially be based on retrieved partial columns, incorporating weightings derived from the averaging kernels. Through the present project, this work will be extended to incorporate space-based radiance data instead of retrievals.

4.2 Assimilation of the Physical State of the Land Surface

The carbon budget at the land surface is coupled to the water and energy balance through vegetation growth and decay. Consequently, reliable estimates of carbon cycling at the land surface depend on our ability to quantify land-surface water and energy stores, in particular soil moisture, and the fluxes of latent and sensible heat that are partly controlled by soil moisture. At the GMAO, soil moisture data assimilation has been developed, using an off-line Ensemble Kalman Filter (EnKF) [Reichle et al., 2002; Reichle and Koster, 2003]. The off-line system is forced with satellite observations of precipitation and surface radiation [Rodell et al., 2003], thereby avoiding the biases common in GCM-produced land surface forcings. The EnKF is well suited to the nonlinear and intermittent character of land surface processes. Its key feature is that error estimates of the model forecasts are dynamically derived from an ensemble integrations. Each member of the ensemble experiences slightly perturbed instances of the observed forcing fields (representing errors in precipitation, surface radiation, and other forcing data) and is also subject to randomly generated noise that is directly added to the land surface states (representing errors in model physics and parameters).

Off-line assimilation of soil moisture retrieved from AMSR-E on the AQUA platform (funded under a current NASA-EOS grant) will produce a high-quality land surface data set that is constrained by surface observations of soil moisture as well as precipitation and surface radiation. Reichle and Koster [2004a] showed how biases in soil moisture retrievals from satellite can be treated even for short satellite records (such as AMSR-E soil moisture). Moreover, Reichle and Koster [2004b] demonstrated that assimilation of historic soil moisture retrievals derived from SMMR into the GMAO Catchment model yields improved estimates of the average seasonal cycle and the anomalies. Land surface temperature (LST) assimilation is currently being implemented in the off-line EnKF system. The multivariate assimilation of LST and soil moisture will further improve the consistency between the land surface water and energy budgets.

4.3 The Sib-BCM for Biological Flux Estimates Over Land

The primary modeling tool for estimating net CO_2 fluxes from the land surface to the atmosphere on a global grid, with an hourly resolution, 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. In Stage 1 of this project, the derived fluxes will be used as boundary conditions in the atmospheric model, and the consistency of estimated fluxes inferred from the atmospheric distribution of CO_2 with those from SiB-BCM will be evaluated in terms of the underlying processes. In Stage 2, a combined assimilation will be performed.

The net land-surface CO_2 flux is determined by the imbalance between uptake by photosynthesis and release by respiration, fires, and fossil fuel 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 implemented in climate models yielding plausible results [e.g., Sellers et al., 1997], especially those [e.g., Denning et al., 1996] that use satellite observations to prescribe seasonality in biophysical parameters, such as LAI.

SiB-BCM development is presently being funded through NASA's Carbon NRA. Our initial strategy will be to drive the SiB-BCM off-line with the analyzed meteorological fields from the GEOS-5 DAS, with coupling on an hourly basis. Satellite observations of vegetation phenology, and fire will be prescribed as boundary conditions for the model (Table 1). The model is able to resolve diurnal/synoptic time scales, track carbon pools/disturbance/fire/recovery, and remain consistent with satellite observational 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.

Spin up of the SiB-BCM requires use of mean meteorological conditions 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. 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. Optimization analysis of the states of relevant carbon pools that could plausibly account for sources and sinks (e.g. live wood pool,

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

coarse woody debris) would identify regions and conditions that could be validated with regional information (e.g. Forest Inventory and Analysis, USFS).

A number of recent studies have argued that the response of the land surface carbon flux to El Niño-Southern Oscillation is to a large extent the result of climate driven variability in global fires [e.g., Langenfelds et al., 2002; Schimel and Baker, 2002]. 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]. A currently funded NASA project (PI: J. Randerson) has released monthly fire emissions for 1997-2001 and will continue to improve and make available emissions estimates through 2007. Relevant aspects of that project are being 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 emissions from fires are evaluated and will be provided to this project.

4.4 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. A recently funded NASA Carbon Cycle project proposes to implement the new high temporal resolution fossil flux estimates in the CTM. 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]. They are available to this project from the involvement of Co-I Collatz.

The interpretation of continental in-situ and remotely-sensed CO_2 concentration will require specification of fossil fuel combustion at higher resolution with higher-frequency variations than are available from statistical reporting. We recognize that variations in emissions are controlled by various processes: industrial, residential, transportation, and electricity generation sectors are each important and respond to different drivers. Recently funded research projects at Oak Ridge and at CSU (K. Gurney, PI) are developing models for each sector to predict energy demand as functions of the time of day, day of the week, and according to environmental temperature, for example. Detailed information on emissions from specific power plants or industrial facilities may only be available in certain countries. Emissions from other regions will be decomposed by economic sectors, and time patterns will be modeled using algorithms developed under the aforementioned research. We will predict emissions of both CO_2 and CO in each sector based on energy demand as a function of climate and time of day, week, and year. These emissions will be scaled to match inventory-based estimates at the monthly, annual, and country scales (i.e., we will apply energy modeling concepts to downscale the countrywide inventories). Spatial patterns will also be constrained by the Defense Meteorological Satellite Program (DMSP) data. Estimated CO_2 and CO emissions will be optimized against trace gas observations; parameter estimation will be used to fine-tune the energy demand models used to downscale the inventory statistics.

4.5 The WHOI Ocean Biogeochemistry Model

First-guess estimates of the time evolving distributions of the air-sea CO_2 fluxes over the ocean are need as boundary conditions for the analysis and source/sink calculations. The current ocean carbon observing system is too sparse by itself to supply these fluxes. Most previous studies of used a data-based, seasonal climatology such as Takahashi et al. [2002], but this neglects the substantial temporal variations from ENSO and other natural climate variability modes. Our primary tool, therefore, will be an advanced ocean ecological and biogeochemical model [Moore et al. 2002; 2004; Doney et al., 2003] coupled to a state of the art ocean physics data assimilation system (SODA) [Carton et al., 2000a; 2000b] and high resolution satellite wind speed/gas exchange maps from Quikscat. Assimilated ocean circulation fields are critical to reduce the substantial physical biases, and resulting biogeochemical errors, typical of unconstrained calculations. In-situ (time-series, VOS pCO_2 transects) and satellite data (SeaWiFS MODIS ocean color) will be utilized extensively for model-data evaluation and error analysis.

The development of the basic structure of such an analysis system is presently funded by NASA, as part of the NACP. The focus in that project is a historical reanalysis over the period 1980 through the NACP intensives. Preliminary hindcast results have been generated for the period (1979-2000) using NCEP surface forcing with an unconstrained ocean physical model. A global map of the rms variability of monthly mean air-sea CO_2 fluxes is shown (Fig. 4). The simulations show high variability (0.5-3 mol C/m2/y) over much of the temperate and high latitudes associated with variability in ocean thermal/SST balance, biological carbon uptake, and wind speed. Efforts are underway to assess the skill of the hindcast solution relative to observations and to implement the ecology/biogeochemistry simulations in a constrained ocean physics model.

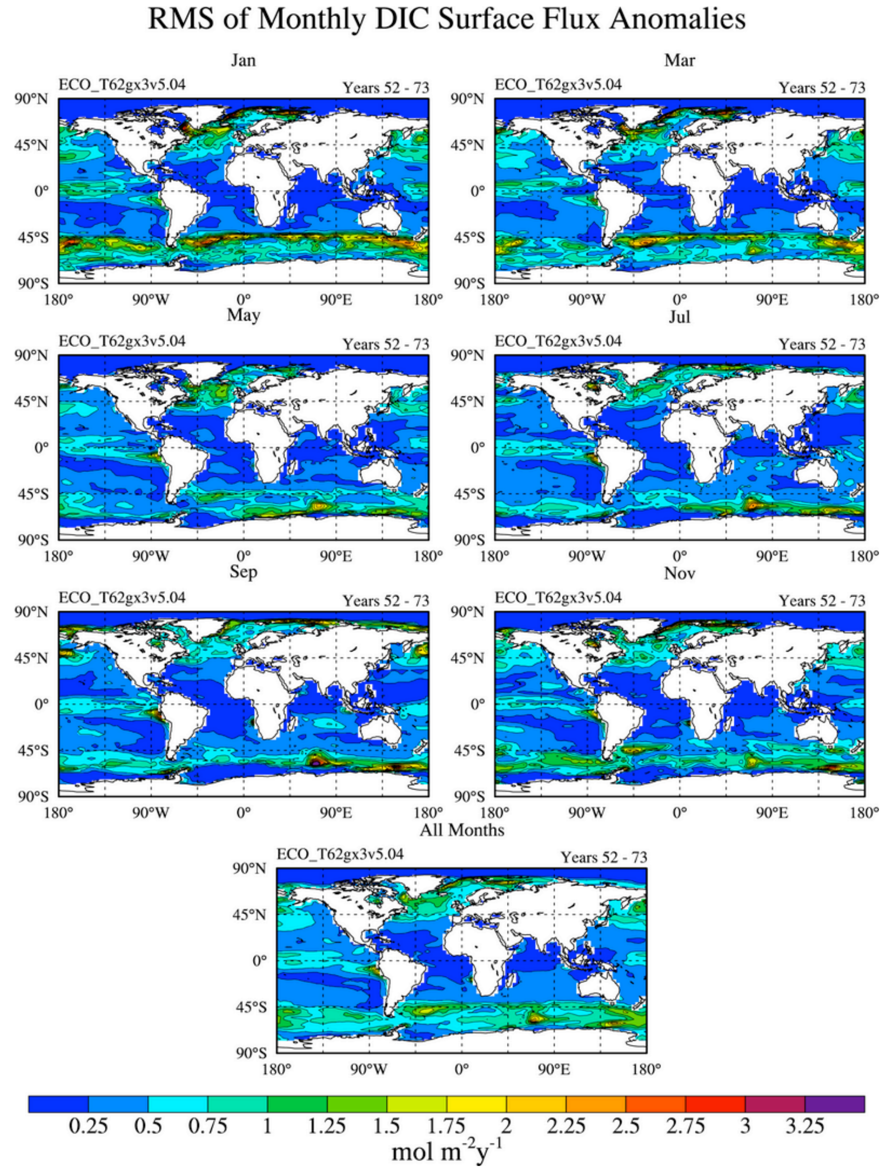


Figure 4. Root-mean-square variability of monthly air-sea CO2 flux anomalies from a climatological seasonal cycle produced by the WHOI ocean ecosyste /biogeochemistry model for the period 1979-2000.

5 Stage 1: Consistency of Top-Down and Bottom-Up Source-Sink Estimates

This section outlines the initial approach to the source-sink estimation problem, using land, ocean and atmosphere models and data to constrain fluxes. As outlined in section 3, the initial approach will involve using bottom-up flux estimates from land and ocean models as a first-guess (S_f) for the atmospheric study, imposed as a lower boundary condition on the AGCM. Improvements to these fluxes will then be determined using an assimilation-inversion approach. Substantial developments will be needed for the assimilation and inversion. These include implementation of the radiance-based AIRS CO_2 assimilation in GEOS-5, the determination of forecast errors and the manner in which transport error impacts inverse calculations, and selection of the inversion methodology.

5.1 Bottom-Up Flux Estimates Over Land and Ocean

Task 1a.1	Years 1-2	Derive first-guess land-surface fluxes from the SiB-BCM model, along with estimates of uncertainty and sensitivity to input
Task 1a.2	Years 1-2	Derive first-guess fossil-fuel emissions, along with estimates of uncertainty
Task 1a.3	Years 1-2	Derive first-guess ocean-surface fluxes from the WHOI ocean model, along with estimates of uncertainty and sensitivity to input
Task 1a.4	Years 1-3	Use surface temperature and moisture constraints from the EnKF system into the constraints in the Sib-BCM

The initial approach requires specification of realistic net CO_2 fluxes to and from the underlying surface (see Fig. 1).

Biological fluxes (Task 1a.1) over land will be determined from the SiB-BCM, constrained by MODIS and other data and atmospheric variables from the GEOS-5 assimilation. The SiB-BCM is already being run with GEOS-4 assimilated data as a boundary condition, so production of these fluxes will be a straightforward exercise; initial estimates of uncertainty in this component of S_f will also be available. Additional estimates of sensitivities to physical parameters will be obtained by using data-constrained surface moisture and temperature estimates from the land-surface assimilation (Task 1a.4).

Fossil-fuel emission estimates (Task 1a.2) will be available from the association of Co-I S. Denning with the project at CSU. These fluxes will be specified, constrained by inventory data and space-based measurements.

Oceanic fluxes (Task 1a.3) will be calculated using the WHOI biogeochemical assimilation system. To meet the requirements of the work proposed here, several additional development tasks will be essential. We will need to transition the analysis scheme from a strictly hindcast exercise into a system that runs in an operational, late-look configuration. This will require building the appropriate data pipelines for ocean physics, surface wind speed and in situ observations. One option that will be explored is to utilize ocean physical circulation fields from the GMAO near real-time ocean assimilations rather than from the SODA hindcasts. This is consistent with project goals to build around GMAO's modeling tools; indeed, this in itself will be a useful method of determining some uncertainties in the ocean flux estimates. We also will need to extend the analysis in time beyond the NACP intensives, producing continual analyses for the period since EOS-Aqua launch. A second major task will be to characterize in much more detail the time/space patterns of model-data error in the air-sea CO_2 fluxes based on comparisons with in situ data. These error fields are needed for the source/sink optimizations to be performed in this project.

An alternative potential source of S_f over oceans is available from the GMAO (W. Gregg will collaborate in providing these). Like the WHOI estimates, these are obtained by embedding a complex biogeochemical model into the GMAO OGCM. The global model has been shown to produce surface chlorophyll concentrations that are statistically positively correlated with SeaWiFS observations in all 12 of the major oceanographic basins [Gregg et al., 2003], and has also exhibited correspondence with interannual variability, including the 1997-2000 El Niño/La Niña period observed by SeaWiFS [Gregg, 2002]. Current funding is to implement carbon cycling in the model. Although strictly a model study, the pCO_2 outputs and air-sea exchanges will have the temporal variability and spatial resolution (< 1°) required by the present effort. Use of these fluxes will help quantify uncertainty in the WHOI estimates.

5.2 Implementation of AIRS CO_2 Radiance Assimilation in GEOS-5

Task 1b.1	Year 1	Add the capability to include more gases in GEOS-5 assimilation modules
Task 1b.2	Years 1-2	Optimize the CSU radiation module for the AIRS CO_2 and CO bands and implement it into GEOS-5
Task 1b.3	Years 1-2	Develop and implement observation error models for AIRS radiances
Task 1b.4	Years 2-3	Assimilate AIRS CO_2 radiances for an initial test period
Task 1b.5	Years 2-3	Validate AIRS assimilation against in-situ data

In order to assimilate carbon species, the 3D-Var assimilation code of GEOS-5 must be extended to include additional constituents (Task 1b.1). This should be relatively straightforward and it will continue in conjunction with planned work to assimilate long-lived constituents in the middle atmosphere. Initially, the additional gases will be assimilated decoupled from the main meteorological assimilation (which constrains temperature, moisture and ozone), but the importance of some gases (including CO_2) to radiation transfer will eventually necessitate a coupled system to be developed.

The work of Engelen et al. (2001) and Engelen and Stephens (2004) has led to the development, at CSU, of a fast radiation code for AIRS radiances. The first task of the radiation group at CSU will be to collaborate with GSFC to ensure that the radiance module of the GEOS-5 meteorological assimilation system is optimized for the CO_2 bands (Task 1b.2). The optimization will address not only issues of speed, but also the selection of appropriate spectral windows.

While early assimilation experiments may continue with a crude representation of observation error, stable assimilation will require development of a more complex model

(Task 1b.3). This will require detailed examination of the accuracy and stability of the suite of AIRS channels selected for the analysis. The assimilation (Task 1b.4) will initially be performed for a three-month test period, when many NACP flights are available for validation of the assimilated data (Task 1b.5).

5.3 Characterization of Forecast Error and Model Performance

Task 1c.1	Year 1	Use AGCM to examine the statistical nature of constituent transport and characterize its sensitivity to sub-grid processes
Task 1c.2	Year 2	Use test assimilations (Task 1b.4) to evaluate forecast error and construct an accurate statistical model for this
Task 1c.3	Years 2-3	Examine model parameterizations in context of new developments

Transport of constituents away from their surface sources is an important component of this research: it will receive considerable attention. A number of studies [e.g., Li et al., 2002] have demonstrated competence in the long-range transport by GEOS analyses. Equally, there is a demonstrable uncertainty in the transport by sub-grid processes. Radon, with a half-life of several days, has been demonstrated to be useful as a measure of convective transport [e.g., Jacob and Prather, 1990]. Figure 5 shows Radon profiles at a number of sites, revealing large differences in the simulations with two versions of the GEOS-4 AGCM. These model versions differ only in their convection mechanisms: Hack [1994]/ Zhang and McFarlane [1995] for shallow/deep convection from CCM3, or the GEOS-5 McRAS model [Bacmeister et al., 2004]. Column burdens and surface concentrations of Rn differ substantially over oceanic sites, a consequence of lofting of air over land and the long-range transport: more Rn is lofted by the CCM3 convection. Results such as this illustrate some of the sensitivities to sub-grid transport, which will be examined thoroughly in this work.

In Task 1c.1 we will explore the sensitivity of the convective transport of carbon species (and other gases) to the cloud parameterizations in GEOS-5. Bacmeister et al. [2004] show insensitivity of some climate measures to “tunable” parameters in the McRAS cloud scheme: specifically, changing assumptions about the re-evaporation rate in precipitating clouds has a large impact on the precipitation and cloud mass-fluxes, but little effect on the simulated climate. Given the uncertainties in these parameterizations and the insensitivity of the circulation to them, there will be some flexibility in their specification. A large suite of experiments will be performed using the GEOS-5 AGCM and DAS with specified surface fluxes of carbon species that will be transported but not assimilated. Validation against in-situ data and a comparison of radiances against AIRS observations will be performed to characterize the transport properties of the model.
A similar set of experiments will be performed with the prototype assimilation system, in order to characterize transport contributions to model forecast error for the assimilation of carbon species (Task 1c.2). However, these will also be supplemented with experiments that characterize the forecast error in terms of uncertainty in S_f. These uncertainties will be obtained from Tasks 1a.1-3. Finally in this work, Task 1c.3 will re-

evaluate the results, should more convection models become available to us in the course of this project; it may also be possible to use nested cloud-resolving models to address the problem in more detail.

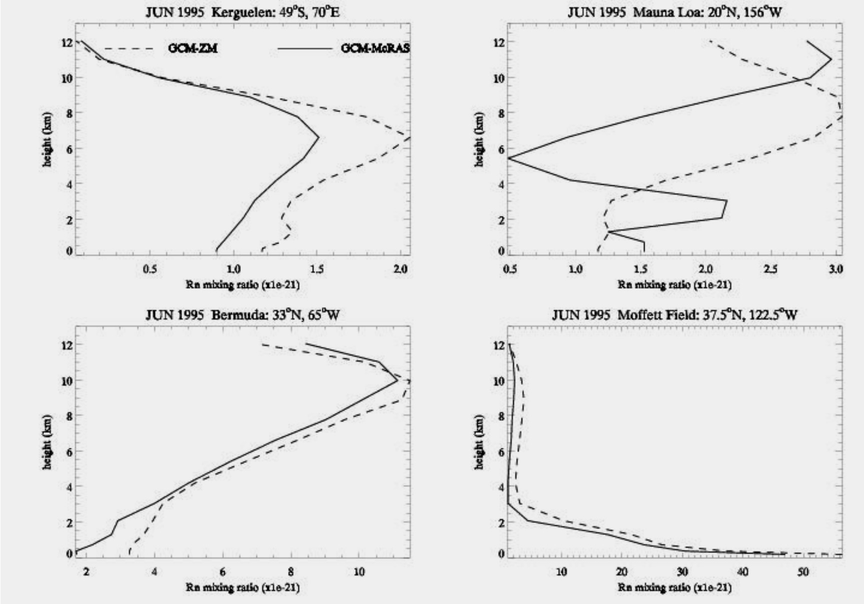


Figure 5. Profiles of Radon, at four selected locations, using the CCM3 (dashed) and McRAS (solid) convection codes. Kerguelen (top left) is a remote site in the Southern Indian Ocean, Mauna Loa (top right) represents a remote island site, affected by long-range transport from Asia and North America, Bermuda (bottom left) is in the Atlantic and Moffet Field (bottom right) is an inland site in North America.

5.4 Atmospheric Inversion: Improving the Estimated Source-Sink Distribution

Task 1d.1	Year 1	Implement and test synthesis- and adjoint-inversion models
Task 1d.2	Years 1-2	Develop a new inversion technique, based on parameter estimation methods
Task 1d.3	Years 2-3	Perform a rigorous evaluation of the inversion techniques
Task 1d.4	Years 2-4	Derive estimates of the seasonally varying fluxes from the AIRS-based runs

A key source of uncertainty in previous estimates of carbon exchanges by traditional inverse modeling from atmospheric CO_2 observations is the need to specify spatial and temporal patterns (or autocorrelation length and time scales) of these fluxes [e.g., Kaminski et al., 2001; Engelen et al., 2002]. This problem is partly addressed by efficiently populating the transport Jacobian using the adjoint of the transport operator, which allows fluxes to be estimated at the native resolution of the transport model. Current in-situ observing networks are so sparse that this can only be done by assuming stationarity of the fluxes in the monthly mean, and applying either spatial patterns or covariance length scales a posteriori [Rödenbeck et al., 2003]. The much denser space-based and in-situ networks anticipated over the next several years should permit flux estimation at much higher resolution. Furthermore, we will relax the assumption of temporal stationarity at monthly time scales, which is not justified by local observations [e.g., Baldocchi et al., 2003]. High-frequency variations in surface exchanges (due to the diurnal cycle on land and synoptic time-scale variations in wind speed and cloudiness in the ocean, for example) covary systematically with atmospheric transport [e.g., Denning et al., 1996; 1999]. These “rectifier” effects dominate model-to-model differences among flux estimates by current inverse models [Gurney et al., 2003].

Unlike previous studies, our approach minimizes both temporal and spatial aggregation error by using detailed physical and biogeochemical models strongly constrained by satellite observations to simulate fine spatial patterns and high-frequency variations. We postulate that the mismatch between the data-driven forward calculation of air-sea and air-land fluxes is coherent over larger regions and for longer time periods than the fluxes themselves. These residuals will result from systematic errors in the forward models (for example due to hard-to-model processes like agricultural harvest, nitrogen deposition, and sinking particle flux), or to incorrect specification of parameters such as sensitivity to temperature or soil moisture. Such mismatches are likely to persist in time long enough to exert a measurable “signal” in atmospheric CO_2, and thus a correction ΔS (x,t) through the adopted inversion technique. We expect that using a 0.5°×0.5° assimilation system will allow production of improved source-sink distributions on a 2°×2°-grid with two-week resolution.

The first task (Task 1d.1) will be to implement and test the synthesis inversion and adjoint techniques in the GMAO. Synthesis inversion code is available through the participation of Scott Denning (Co-I), while a generalized adjoint capability for GEOS-5 is being developed under separate funding in the GMAO.

A third method will be developed here, based on parameter estimation (Task 1d.2); it should avoid many of the inherent problems associated with trajectory error.

A parameter-estimation approach will be investigated in order to begin top-down optimization of source and sink estimates while reducing the size of the problem. In contrast to the synthesis approach where sources are grouped spatially into regions, we plan to group according to the processes that are contributing to surface sources and sinks. Chosen parameters may include, for example, the soil moisture and the partitioning of production between different phytoplankton groups, both of which alter surface sources and sinks. Additionally, in order to investigate the discrepancies that may be coming from parameterizations of sub-grid scale convection we will use different convection schemes and alter their tunable parameters. The chosen surface source and sink parameters can also be used in optimization from below in order to constrain them consistently using all the available atmospheric, land, and, ocean data.

The atmospheric model will be run several times with different values of chosen parameters in order to evaluate differences in CO_2 atmospheric concentrations. Subsequently, atmospheric analysis increments will be decomposed using differences in atmospheric concentrations due to perturbations in chosen model parameters. One possible approach is to construct and use an artificial neural network to relate analysis increments to changes in model parameters. Recent applications of neural networks in geophysics go beyond their use as "black box" tools, towards understanding of errors in network weight functions and uncertainty of estimated geophysical quantities [Aires 2004]. This approach can account for nonlinearities inherent to numerical algorithms for constituent transport and parameterizations of convective processes. We plan to construct a neural network that will use differences in mid-tropospheric CO_2 as input data and provide changes to parameters in surface sinks and sources as output data. The network will be trained using the differences in the atmospheric CO_2 concentrations that were obtained by varying model parameters. In order to reduce the size of the data set presented to a neural network we may initially estimate model parameters in a limited region, or average atmospheric fields onto a coarser grid.

Tasks 1d.3 and 1d.4 will apply the inversion techniques to the longer AIRS-based assimilations. A rigorous examination of results from all three techniques will lead to a decision on which method should be used in the longer term.

5.5 Analysis of Flux Mismatches After Atmospheric Inversion

Task 1e.1	Years 1-3	Examine parameters in Sib-BCM
Task 1e.2	Years 1-3	Examine parameters in fossil-fuel model
Task 1e.3	Years 1-3	Examine parameters in WHOI ocean model

An important, unresolved research question we plan to address during Stage 1 of the project is how to systematically utilize the spatial and temporal distributions of the CO_2 flux corrections ΔS (x,t) to better understand the underlying biogeochemical mechanisms and to improve iteratively the model predictions. Tasks 1e.1-3 address these questions for the component models.

From an ocean perspective, the key factors governing air-sea CO_2 fluxes are surface temperature, net biological uptake, and upwelling, which all affect the air-sea pCO_2 difference, and wind speed, which drives the kinetics of gas exchange. The first step of the analysis will be to explore the patterns of ΔS (x,t) relative to the ocean biological forcing derived from the WHOI model constrained with satellite measurements for sea surface temperature (MODIS), ocean color (MODIS), and wind speed (QuickScat). Biological uncertainties arise because quantities observable from space such as ocean color and primary production are relatively poor indicators for net community production (NCP) that drives changes in surface carbon inventories. Model parameters that alter NCP and the related export production include the partitioning of production between different phytoplankton groups (picoplankton, diatoms), zooplankton grazing rates, remineralization, and particle sinking velocities. There is also considerable uncertainty, at present, in the form and magnitude wind speed gas exchange parameterizations. We will compare these adjustments with independent estimates of the error in the model mean seasonal and interannual variability. In an iterative process, we will use the atmospheric assimilation results to improve the air-sea CO_2 fluxes from the ocean ecosystem/biogeochemistry model and assess the underlying physical and biological mechanisms.

On land, the spatial and temporal distribution of delta can indicate the modeled mechanisms that are responsible. For example, a ΔS into the atmosphere in winter at high latitudes is a sign that the model is underestimating soil respiration either because of improper soil temperatures or improper parameterizations. Similarly, a persistent ΔS and its direction during drought dormant periods tells us if photosynthesis or respiration are being differentially affected which would cause us to re-evaluate our drought parameterizations for photosynthesis and respiration. Transpiration is coupled to photosynthesis in the model so sources of water vapor and sinks of CO_2 are often linked and provide a constraint on photosynthetic capacity and water use efficiency.

5.6 Implementation of OCO Radiance Assimilation in GEOS-5

Task 1f.1	Years 1-3	Develop and test a fast code for OCO radiances
Task 1f.2	Years 3-4	Develop and implement observation error models for OCO radiances
Task 1f.3	Years 3-5	Assimilate OCO and AIRS CO_2 radiances simultaneously
Task 1f.4	Years 3-5	Perform and analyze the inversion calculations

This part of the project will involve preparation for including OCO radiances in GEOS-5, which by then will be running with AIRS CO_2. The situation with OCO data in the near infrared (NIR) is more complex than for AIRS. Here the principal objective is to determine X_{CO2}, the column-averaged volume mixing ratio of CO_2. However, it was argued by O'Brien and Rayner [2002], and subsequently by Kuang et al. [2002], Dufour and Breon [2003] and Mao and Kawa [2004], that simple differential absorption spectroscopy will not yield X_{CO2} with sufficient accuracy unless corrections are made to compensate for scattering in the atmosphere by clouds and aerosols. O'Brien and Rayner [2002] proposed a correction procedure, in the context of an etalon spectrometer, that relied upon the correlation between the apparent optical thickness of the atmosphere in an O_2 channel with that in a CO_2 channel. Provided that the channels are selected so that their optical thicknesses are comparable, the correlation is tight; this provides a way to link the X_{CO2} to that for O_2. Kuang et al. [2002] use a technique that is similar in principle, except that two complete CO_2 bands and the O_2 A-band are employed to estimate not only X_{CO2} but also a comprehensive representation of the atmospheric state.

Because the NIR radiances are so sensitive to scattering material in the field of view, it is highly unlikely that cloud and aerosol generated by the assimilation model will be sufficiently accurate, because cloud, driven by moist processes, is diagnosed from a huge volume of satellite data, against which the minute flow from a specialized CO_2 mission will have a correspondingly minute impact. Thus, the high accuracy required for X_{CO2} suggests that cloud and aerosol should be diagnosed from the same sensor that measures CO_2, and the NWP model should assimilate an intermediate product, such as X_{CO2}, rather than the radiances themselves.

This philosophy has been adopted by OCO, whose inversion algorithm will attempt to recover not only the vertical profile of CO_2 volume mixing ratio but also the profiles of temperature, water vapor and four type of particulates (clouds or aerosols), wavelength dependent models of surface reflectance and surface pressure. With eleven layers in the profiles, there are currently eighty-four parameters to be determined from radiance spectra in three bands. Because not all of these parameters will be well determined by the data, the inversions will be conducted in a Bayesian setting, which hopefully will ensure that parameters poorly determined by the data remain close to their prior values. While the OCO team has successfully inverted the simulated radiance data, the computational cost is very high, and the algorithm in its present form is unsuitable for operational use in an assimilation system. Nevertheless, the OCO algorithm should be able to provide X_{CO2} in an off-line mode.

O'Brien (2004) suggested an alternative approach that might be suitable for the assimilation. A prototype algorithm has been developed for an etalon spectrometer with high spectral resolution and narrow spectral ranges in the 1.6 μm and 0.76 μm absorption bands of CO_2 and O_2. Its basis is a simplified model of atmospheric scattering that allows the apparent optical thickness of the atmosphere to be represented in terms of just three parameters, these being X_{CO2}, the effective height of scattering in the atmosphere, and the ratio of scattered to reflected radiance. The small number of parameters is commensurate with the independent information is the spectra; indeed, both bands are needed to fix the parameters, and conversely the data cannot be represented well with fewer. Because the model is so simple, its computational cost is very low.

Initial tests with simulated data for a limited set of`*almost* clear atmospheres suggest that X_{CO2} may be estimated with accuracy of approximately 1 ppmv. However, these results are preliminary, and the maximum optical thickness of cloud in the atmospheres tested is only 0.15, a value that is too low for the algorithm to be considered robust.

Whereas the OCO algorithm will attempt to estimate not only X_{CO2} but also many other state variables (including profiles of temperature and moisture), the simplified approach requires that these variables be derived from external sources of data. Consequently, the simplified model is well suited to operation inside an assimilation system, where the wealth of data from other meteorological instruments will provide the missing information.

Task 1e.1 will be to develop and assess the feasibility of a fast inversion algorithm for OCO and to develop an operational version of such a model if it proves to be feasible. The steps undertaken will be as follows.

a) Test the prototype algorithm more extensively with scenes with increasingly complex cloud, moisture and CO_2 profiles.
b) Adapt the algorithm from spectral regions and resolution of the etalon spectrometer to those of the OCO grating spectrographs; extend it to include polarization.
c) Test the inversions for X_{CO2} to the extent possible with ground-based measurements of absorption in the 1.6 μm CO_2 band and 0.76 μm O_2 band. In these experiments, the interferometer will be pointed downwards to collect reflected light, while the results will be verified by simultaneous upward looking measurements.
d) Develop an optimized version of the forward model to use in GEOS-5.

Tasks 1f.2 and 1f.3 will proceed in a similar manner to the equivalent tasks for AIRS data. Task 1f.3 will involve sensitivity to omitting AIRS data. Task 1f.4 will perform the inversion calculations and examine the impact of OCO data on the system.

6 Stage 2: Optimization using Constraints from Above and Below

In years four-five (2008-09), we will have a well-tested assimilation system routinely using multiple data streams to predict finely resolved surface carbon exchanges at high temporal frequency and apply slowly-varying corrections to these fields by inversion of both in-situ and space-based observations of atmospheric CO_2 and CO. Soon after the launch of OCO in late 2007, we will begin assimilating Level 1b radiance data and be able to obtain surface fluxes with much lower uncertainty. At this point, we will extend the assimilation to parameter estimation in the land, ocean, and fossil fuel emission models. We are sensitive to the need to avoid overfitting dense atmospheric CO_2 and CO observations through parameter tuning in the component models because time mean fluxes and secular trends may reflect processes that are not represented in the models (e.g., irrigation, intentional or inadvertent fertilization of land and ocean biota, insect outbreaks, or forest management). It is imperative that in optimizing model parameters to match atmospheric observations, we do not engineer “the right answer for the wrong reason.”

We will perform multiyear reanalyses of all available data in an Ensemble Data Assimilation (EnsDA) system using Kalman Smoother optimization to determine parameter values in the land, ocean, and fossil fuel emissions models that produce the best match to atmospheric CO_2 and CO, land and ocean color, sea-surface temperature and wind, and other observations. An important advantage of the EnsDA framework is that it does not require the production of the fully-coupled forward modeling system. The coupled model will be run over an ensemble of order 100 realizations using parameter values chosen to span expected variations. Predictions of MODIS, SeaWiFS, AIRS, OCO, and in-situ CO_2 and CO will then be compared to real observations over the multiyear period and used to generate an error surface as a multidimensional function of model parameters. Another advantage of the EnsDA optimization is that it allows formal estimation of model error in each component (including atmospheric transport) along with uncertainty in the optimized parameters and the final flux estimates.

Choice of parameters to optimize will be driven by; (1) a need to estimate parameters that are poorly known yet important for obtaining accurate net carbon exchange; (2) restriction to quantities that exert strong influence on observable quantities; (3) availability of observational; and (4) computational efficiency. We will evaluate the ability of the data assimilation system to estimate magnitudes and uncertainties in the following parameters, as well as quantify model error:

- Initial terrestrial carbon pool sizes (including spatial variations);
- Fractional allocation of terrestrial photosynthate into leaves, stems, and roots;
- Combustion efficiency in the fire module, and dependence on moisture status;
- Ecosystem drought stress dependence on soil moisture;
- Biome-dependent sensitivity of GPP to direct and diffuse light;
- Temperature sensitivity of autotrophic respiration and decomposition;
- Partitioning of ocean biological production between different phytoplankton groups (picoplankton, diatoms), and zooplankton grazing rates;
- ocean particle sinking velocities and rates of remineralization;
- Dependence of air-sea gas exchange coefficients on wind speed and static stability; and
- The residual monthly-mean flux of CO_2 at each model grid cell.

The result of this analysis will be a series of global maps of sources and sinks of CO_2 (and associated uncertainty) at 0.5-degree spatial scales and hourly frequency that are optimally consistent with a large suite of satellite observations and with well-tested and parameterized process models. Nevertheless, formal estimation of the residual time-mean flux and its uncertainty is essential to the science objectives of the project, since this represents the effects of all processes that are not represented in the component models. Patterns in this field will be analyzed to evaluate hypotheses about underlying controls on long-term sources and sinks. We will be especially interested in persistent residual fluxes at the highest latitudes (possibly indicating changes in permafrost), downwind of major industrial emissions (possibly indicating responses to elevated nitrogen deposition), in semiarid lands associated with changes in water-use efficiency, and in highly productive ecosystems (possibly indicating CO_2 fertilization).

7 Summary

In this research we will extend the operational data assimilation systems of the GMAO (the physical components of the GEOS-5 atmospheric-land-ocean system) to include biophysical, ecological and biogeochemical modules needed to represent the carbon cycle. We will assimilate large volumes of data into the atmosphere, land and ocean modules, then develop and apply inversion methods to understand the carbon cycle, focusing on how uncertainties in observations and model approximations impact our results. Wherever possible, we will use existing component modules (most of which are funded by NASA's ESE), but some developments and extensions will be required.

We will utilize NASA's and DOE's computing resources to run the models and assimilation systems at high global resolution, resolving as much of the temporal and spatial variability as possible. Space-based data from NASA's MODIS, AIRS, OCO, and other instruments will be combined with high-density observational data from the NACP's monitoring networks. The system will be capable, after additional development, of ingesting data from future generations of satellites (such as soil moisture measurements or active atmospheric profilers).

In the first stage of work, we will examine the component models (atmosphere, land and ocean) and attempt to understand uncertainties in each of these, making deductions about uncertainty in top-down and bottom-up flux estimates and how these may be reconciled. In the second stage, we will optimize across the land-atmosphere and ocean-atmosphere boundaries, attempting to assimilate the fluxes on spatial scales of 200-500km with a temporal resolution of two weeks. This resolution aggregates over the finer scales of the component models (tens, rather than hundreds, of kilometers) in order to improve accuracy, given the uncertainties in the components of the system.

We will produce analyses based on AIRS and in-situ data, beginning with the launch of EOS-Aqua, and incorporating OCO data after launch in 2008. In this manner, we will characterize the year-to-year variations of spatially resolved carbon fluxes over a number of cycles. Careful experimentation will elucidate uncertainties arising from model parameterizations and from changes in the observation system over this period. The results will be useful for environmental scientists and political decision makers.

References

Aires, F. (2004), Neural network uncertainty assessment using Bayesian statistics with application to remote sensing:1. Network weights, J. Geophys. Res., 109, D10303, doi:10.1029/2003JD004173.

Auger, L. and A. Tangborn, 2004, A Wavelet Based Reduced Rank Kalman Filter for the Assimilation of Stratospheric chemical Tracer Observations, *Mon. Weath. Rev*., **132**, 1220-1237.

Bacmeister, J. T., 2004: Description of GEOS-5 prognostic cloud scheme, NASA.

Bacmeister, J. T., M. J. Suarez, and F.R. Robertson, 2004: Rain Re-Evaporation, Boundary-Layer/Convection Interactions, and Pacific rainfall patterns in an AGCM, *J. Climate*, in press.

Baker, D.F., 2000: An Inversion Method for Determining Time-Dependent Surface CO_2 Fluxes. *Inverse Methods in Global Biogeochemical Cycles*, Eds. P. Kasibhatla, et al., 279-293.

Baker, N.L. and R. Daley, 2000: Observation and background adjoint sensitivity in the adaptive observation-targeting problem, *Q.J.R. Meteorol. Soc.,* **126**, 1431-1454.

Baldocchi, D., E. Falge, L.H. Gu, R. Olson, D. Hollinger, S. Running, P. Anthoni, C. Bernhofer, K. Davis, R. Evans, J. Fuentes, A. Goldstein, G. Katul, B. Law, X.H. Lee, Y. Malhi, T. Meyers, W. Munger, W. Oechel, K.T. Paw, K. Pilegaard, H.P. Schmid, R. Valentini, S. Verma, T. Vesela, K. Wilson, and S. Wofsy, 2001: FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem-Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities. *Bull. Am. Meteorol. Soc.*, **82**, 2415-2434.

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

Borovikov, A., M.M. Rienecker, and P.S. Schopf, 2001: Surface Heat Balance in the Equatorial Pacific Ocean: Climatology and the Warming Event of 1994-95. *J. Clim*., **14**, 2624-2641.

Bosquet, P., P. Peylin, P. Clais, C. le Quere, P. Friedlingstein, and P.P. Tans, 2000: Regional Changes in Carbon Dioxide Fluxes of Land and Oceans Since 1980. *Science*, **290,** 1342-1346.

Bruhwiler, L., P.P. Tans, and M. Ramonet, 2000: A Time-Dependent Assimilation and Source Retrieval Technique for Atmospheric Tracers. *Inverse Methods in Global Biogeochemical Cycles*, Eds. P. Kasibhatla, et al., 265-277.

Carton, J.A., G. Chepurin, X. Cao, and B.S. Giese, 2000a: A Simple Ocean Data Assimilation analysis of the global upper ocean 1950-1995, Part 1: methodology, *J. Phys. Oceanogr.*, **30**, 294-309.

Carton, J.A., G. Chepurin, and X. Cao, 2000b: A Simple Ocean Data Assimilation analysis of the global upper ocean 1950-1995 Part 2: results, *J. Phys. Oceanogr.*, **30**, 311-326.

Chou, M.-D. and M. J. Suarez, 1994: An efficient thermal infrared radiation parameterization for use in general circulation models. NASA Technical Memorandum, 104606, **10**, 84pp.

Chou, M.-D. and M. J. Suarez, 1996: A Solar Radiation Parameterization (CLIRAD-SW) for Atmospheric Studies NASA Technical Memorandum, 104606, **15**, 48pp.

Cohn, S.E., A. da Silva, J. Guo, M. Sienkiwiecz, and D. Lamich, 1998: Assessing the Effects of Data Selection with the DAO Physical-Space Statistical Analysis System. *Mon. Weath. Rev.,* **126**, 2913-2926.

Conway, T.J., P.P. Tans, L.S. Waterman, K.W. Thoning, D.R. Kitzis, K.A. Masarie and N. Zhang, 1994: 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.

Cox, P.M., R.A. Betts, C.D. Jones, S. A. Spall, and I.J. Totterdell, 2000: Acceleration of Global Warming Due to Carbon-Cycle Feedbacks in a Coupled Climate Model. *Nature*, **408**, 184-187.

Crevoisier, C., S. Heilliette, A. Chédin, S. Serrar, R. Armante, and N. A. Scott, 2004: Midtropospheric CO_2 concentration retrieval from AIRS observations in the tropics, *Geophys. Res. Lett.*, **31**, L17106, doi:10.1029/2004GL020141.

Crisp, D., R.M. Atlas, F.-M. Breon, L.R. Brown, J.P. Burrows, P. Ciais, B.J. Connor, S.C. Doney, I.Y. Fung, D.J. Jacob, C.E. Miller, D. O'Brien, S. Pawson, J.T. Randerson, P. Rayner, R.J. Salawitch, S.P. Sander, B. Sen, G.L. Stephens, P.P. Tans, G.C. Toon, P.O. Wennberg, S.C. Wofsy, Y.L. Yung, Z. Kuang, B. Chudusama, G. Sprague, B. Weiss, R. Pollock, D. Kenyon, S. Schroll, 2004: The Orbiting Carbon Observatory (OCO) Mission. *Adv. Space Res.*, **16,** 700-709, 2004.

Dee, D.P. and A. da Silva, 1999: Maximum-likelihood estimation of forecast and observation error covariance parameters. Part I: Methodology, *Mon. Wea. Rev.*, **127**, 1822-1834.

Denning , A. S., G. J. Collatz, C Zhang, D. A. Randall, J. A. Berry, P. J. Sellers, G. D. Colello, 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., et al., 1999: Three-Dimensional Transport and Concentration of SF_6: A Model Intercomparison Study. *Tellus*, **51B**, 266-297.

Doney, S.C., K. Lindsay, J.K. Moore, 2003: Global ocean carbon cycle modeling, Ocean Biogeochemistry, ed. M. Fasham, Springer, 217-238.

Douglass, A.R. M.R. Schoeberl, R.B. Rood, S. Pawson, 2003: Evaluation of transport in the lower tropical stratosphere in a global chemistry and transport model. *J. Geophys. Res.*, J. Geophys. Res., **108**, DOI 10.1029/2002jd002696.

Dufour, E., and F.-M. Breon, 2003: Spaceborne estimate of atmospheric CO_2 column by use of the differential absorption method: error analysis. *Appl. Opt.*, **42**, 3595-3609.

Engelen, R. J., and G. L. Stephens, 2004: Information content of infrared satellite sounding measurements with respect to CO_2. *J. Appl. Meteorol.*, **43**, 373-378.

Engelen, R. J., A. S. Denning, K. R. Gurney, and G. L. Stephens, 2001: Global observations of the carbon budget: I. Expected capabilities in the EOS and NPOESS eras. *J. Geophys. Res.*, **106**, 20055-20068.

Engelen, R. J., E. Andersson, F. Chevallier, A. Hollingsworth, M. Matricardi, A. P. McNally, J.-N. Thepaut, and P. D. Watts, 2004: Estimating atmospheric CO_2 from advanced infrared satellite radiances within an operational 4D-var data assimilation system: methodology and first results. *J. Geophys. Res J. Geophys. Res.*, **109**, D19309, doi:10.1029/2004JD004777.

Enting, I.G., 2000: Inverse *Problems in Atmospheric Constituent Transport*, Cambridge University Press, Cambridge, U.K.

Enting, I.G., C.M. Trudinger, and R.J. Francey, 1995: A Synthesis Inversion of the Concentration and $\delta^{13}C$ of Atmospheric CO_2. *Tellus*, **47B**, 35-52.

ESE, NASA Earth Science Enterprise Strategy, NP-2003-10-318-HQ, NASA Headquarters, Washington, DC, October, 2003.

Eskes, H. J., A. J. M. Piters, P. F. Levelt, M. A. F. Allaart, H. M. Kelder, 1999: Variational assimilation of GOME total-column ozone satellite data in a 2D latitude-longitude tracer-transport model. *J. Atmos. Sci.,* **56**, 3560-3572.

Eskes, H. J., P. F. J. van Velthoven, P. J. M. Valks, and H. M. Kelder, 2003: Assimilation of GOME total ozone satellite observations in a three-dimensional tracer transport model, *Q. J. R. Meteorol. Soc.,* **129**, 1663-1681.

Fan, S.-M., M. Gloor, J. Mahlman, S. Pacala, J.L. Sarmiento, T. Takahashi, and P. Tans, 1998: A Large Terrestrial Carbon Sink in North America Implied by Atmospheric and Oceanic CO_2 Data and Models. *Science*, **282,** 442-446.

Friedlingstein, P., L. Bopp, P. Ciais, J.-L. Dufresne, L. Fairhead, H. LeTreut, P. Monfray, and J. Orr, 2001: Positive Feedback Between Future Climate Change and the Carbon Cycle. *Geophys. Res. Lett.*, **28,** 1543-1546.

Giering, R., 2000: Tangent Linear and Adjoint Biogeochemical Models, in "Inverse Methods in Global Biogeochemical Cycles", P. Khasibhatla et al., eds., *Geophys. Monogr. Ser.*, **114**, American Geophysical Union.

Gregg, W.W., 2002: Tracking the SeaWiFS record with a coupled physical/ biogeochemical/radiative model of the global oceans. *Deep-Sea Research II*, **49**, 81-105.

Gregg, W.W., P. Ginoux, P.S. Schopf, and N.W. Casey, 2003: Phytoplankton and Iron: Validation of a Global Three-Dimensional Ocean Biogeochemical Model. *Deep-Sea Research II*, **50**, 3143-3149.

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

Hack, J.J., 1994: Parameterization of Moist Convection in the National Center for Atmospheric Research Community Climate Model (CCM2). *J. Geophys. Res*., **99**, 5551-5568.

Houweling S., T. Kaminski , F. Dentener, J. Lelieveld and M. Heimann, 1999: Inverse modeling of methane sources and sinks using the adjoint of a global transport model, *J. Geophys. Res.-Atmos.* **104**, (D21) pp. 26137-26160.

IPCC, 2001: *Climate Change 2001, The Scientific Basis*. Eds. J.T. Houghton et al., Cambridge.

Jacob, D.J. and M.J. Prather, Radon-222 as a test of convective transport in a general circulation model, *Tellus, 42B*, 118-134, 1990.

Kawa, S.R., D.J. Erickson, S. Pawson, Y. Zhu, 2004: Global CO_2 Simulations Using Meteorological Data from the NASA Data Assimilation System. *J. Geophys. Res*., **109**, D18312, doi:10.1029/2004jd004554.

Kaminski, T., R. Giering, and M. Heimann, 1996: Sensitivity of the seasonal cycle of CO_2 at remote monitoring stations with respect to seasonal surface exchange fluxes determined with the adjoint of an atmospheric transport model, *Physics and Chemistry of the Earth,* **21**, 4577-462.

Kaminski, T., P.J. Rayner, M. Heimann, and I.G. Enting, 2001: On aggregation errors in atmospheric transport inversion, *J. Geophys. Res.* **106**, 4703-4715.

Kaminski, T., W. Knorr, P. Rayner, and M. Heimann, 2002: Assimilating atmospheric data into a terrestrial biosphere model: A case study of the seasonal cycle. *Global Biogeochemical Cycles*, **16**, 1066 doi:10.1029GB001463, 2002.

Kiehl, J.T., J.J. Hack, G.B. Bonan, B.A. Boville, D.L. Williamson, and P.J. Rasch, 1998: The National Center for Atmospheric Research Community Climate Model: CCM3. *J. Climate*, **11**, 1131-1149.

Koster, R. D., M. J. Suarez, et al., 2000: A catchment-based approach to modeling land surface processes in a general circulation model 1. Model structure. *J. Geophys. Res.,* **105**, 24809-24822.

Kuang, Z., J. S. Margolis, G. C. Toon, D. Crisp, and Y. L. Yung, 2002: Spaceborne measurements of atmospheric CO_2 by high-resolution NIR spectrometry of reflected sunlight. *Geophys. Res. Lett*., **29** (15), 1716, doi:10.1029/2001GL014298.

Lamarque, J.-F., B. V. Khattatov, and J. C. Gille, 1999: Assimilation of Measurement of Air Pollution from Space (MAPS) CO in a global three-dimensional model, J*. Geophys. Res*., **104**, 26,209-26,218.

Langenfelds, R.L., R.J. Francey, B.C. Pak, L.P. Steele, J. Lloyd, C.M. Trudinger, and C.E. Allison, 2002: Interannual growth rate variations of atmospheric CO2 and d13C, H2, CH4, and CO between 1992 and 1999 linked to biomass burning, *Global Biogeochemical Cycles*, *16* (3), 1048, doi:10.1029/2001GB001466.

Lary, D. J., B. Khattatov, and H. Y. Mussa, 2003: Chemical data assimilation: A case study of solar occultation data from the ATLAS 1 mission of the Atmospheric Trace Molecule Spectroscopy Experiment (ATMOS), *J. Geophys. Res.*, **108**, 4456, doi:10.1029/2003JD003500.

Li, Q., D.J. Jacob, T.D. Fairlie, H. Liu, R.M. Yantosca, and R.V. Martin, 2002: Stratospheric versus pollution influences on ozone at Bermuda: Reconciling past analyses, *J. Geophys. Res.*, **107**, 10.1029/2002JD00213, 2002.

Lin, S.-J., 2004: A vertically Lagrangian Finite-Volume Dynamical Core for Global Models. *Mon. Weath. Rev.*, in press.

Lin, S.-J., and R.B. Rood, 1996: Multidimensional Flux-Form Semi-Lagrangian Transport Schemes. *Mon. Weath. Rev.*, **124**, 2046-2070.

Lock, AP, A.R. Brown, M.R. Bush, et al., 2000: A new boundary layer mixing scheme. Part I: Scheme description and single-column model tests. *Mon. Weather Rev.*, **128**, 3187-3199.

Louis, J., M. Tiedtke, J. Geleyn, A short history of the PBL parameterization at ECMWF, in *Proceedings, ECMWF Workshop on Planetary Boundary Layer Parameterization, Reading, U. K.*, p59-80, 1982.

Lyster, P. M., S. E. Cohn, B. Zang, L.-P. Chang R. Menard, K. Olson, and R. Renka, 2004: A Lagrangian trajectory filter for constituent data assimilation, *Q. J. R. Meteorol. Soc*, **130**, 2315-2334.

McClain, C.R., F.G. Hall, G.J. Collatz, S.R. Kawa, W.W. Gregg, J.C. Gervin, J.B. Abshire, A. Andrews, C.J. Barnet, M.J. Behrenfeld, P.S. Caruso, A.M. Chekalyuk, L.D. Demaio, A.S. Denning, J.E. Hansen, F.E. Hoge, R.G. Knox, J.G. Masek, K.D. Mitchell, J.R. Moisan, T.A. Moisan, S. Pawson, M.M. Rienecker, S.R. Signorini, and C.J. Tucker, 2002: *Science and Observation Recommendations for Future NASA Carbon Cycle Research*. NASA/TM-2002-210009.

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

Ménard, R., S. E. Cohn, L.-P. Chang, and P. M. Lyster, 2000: Assimilation of stratospheric chemical tracer observations using a Kalman filter. Part I: Formulation, *Mon. Wea. Rev.*, **128**, 2654−2671.

Moore, J.K., S.C. Doney, J.A. Kleypas, D.M. Glover, and I.Y. Fung, 2002: An intermediate complexity marine ecosystem model for the global domain. *Deep-Sea Res., II*, **49,** 403-462.

Moore, J.K., S.C. Doney and K. Lindsay, 2004: Upper ocean ecosystem dynamics and iron cycling in a global 3-D model, *Global Biogeochem. Cycles*, in press.

Moorthi, S. and M. J. Suarez, 1992: Relaxed Arakawa-Schubert - a Parameterization of Moist Convection for General-Circulation Models. *Mon. Weath. Rev.,* **120**(6): 978-1002.

O'Brien, D. M., 2004: *End-to-end simulation of an airborne spectrometer to measure CO_2 column density from radiances in the 1.6 mm absorption band of CO_2.* Technical Report prepared for NPOESS-IPO, NOAA contract NA17RJ1228, pp. 37.

O'Brien, D. M., and P. J. Rayner, 2002: Global observations of the carbon budget 2. CO_2 column from differential absorption of reflected sunlight in the 1.61 mm band of CO_2 *J. Geophys. Res.*, **107** (D18), 4354, doi:10.1029/2001JD000617.

Pak B.C., and M.J. Prather MJ, 2001: CO_2 source inversions using satellite observations of the upper troposphere, *Geophys. Res. Lett.*, **28**, 4571-4574.

Rabier, F., P. Courtier, and O. Talagrand, 1992: An application of adjoint models to sensitivity analysis, *Beitr. Phys. Atmos,* **65,** 177-192.

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

Reichle, R. H. and R. D. Koster, 2003: Assessing the impact of horizontal error correlations in background fields on soil moisture estimation, *J. Hydromet.*, **4**, 1229-1242.

Reichle, R. H. and R. D. Koster, 2004a: Bias reduction in short records of satellite soil moisture, *Geophys. Res. Lett.*, **31**, L19501, doi:10.1029/2004GL020938.

Reichle, R. H. and R. D. Koster, 2004b: Global assimilation of satellite surface soil moisture retrievals into the NASA Catchment land surface model, *Geophys. Res. Lett.*, submitted.

Reichle, R. H., J. P. Walker, R. D. Koster, and P. R. Houser, 2002: Extended vs. Ensemble Kalman Filtering for Land Data Assimilation, *J. Hydromet.*, **3**, 728-740.

Reichle, R. H., R. D. Koster, J. Dong, and A. A. Berg, 2004: Global Soil Moisture from Satellite Observations, Land Surface Models, and Ground Data: Implications for Data Assimilation, *J. Hydromet.*, **5**, 430-442.

Rodell, M., et al., 2003: The Global Land Data Assimilation System, *Bull. Am. Meteorol. Soc.*, **85**, 381-394, DOI 10.1175/BAMS-85-3-381.

Rodenbeck, C., et al., 2003: Time-Dependent Atmospheric CO2 Inversions Based on Interannually Varying Tracer Transport. *Tellus*, **B55**, 488-497.

Riishøjgaard, L. P., I. Stajner, and G.-P. Lou, 2000: The GEOS Ozone Data Assimilation System, *Adv. Space Res.,* 25, 1063-1072.

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

Sellers, P.J., et al., 1997: Modeling the exchanges of energy, water, and carbon between continents and the atmosphere, *Science, 275*, 502-509.

Stajner, I., and K. Wargan, 2004: Antarctic Stratospheric Ozone from the Assimilation of Occultation Data. *Geophys. Res. Lett.*, **31**, L18108, doi:10.1029/2004GL020846

Stajner, I., L.P. Riishøgjaard, and R.B. Rood, 2001: The GEOS Ozone Data Assimilation System: Specification of Error Statistics. *Q. J. R. Meteorol. Soc.*, **127**, 1069-1094.

Stajner, I., N. Winslow, R.B. Rood, S. Pawson, 2004: Monitoring of Observation Errors in Ozone Assimilation*. J. Geophys. Res*., **109**, D06309 doi:10.1029/2003jd004118.

Sud, Y., and G. K. Walker, 1999: Microphysics of Clouds with the Relaxed Arakawa Schubert Scheme (McRAS). Part I: Design and Evaluation with GATE Phase III Data, *J. Atmos. Sci.,* **56**: 3196-3220.

Takahashi et al., 2002: Global Air-Sea Flux Based on Climatological Surface Ocean pCO2, and Seasonal Biological and Temperature Effects. *Deep Sea Res., II*, **49**, 1601-1622.

Tan, W., M.A. Geller, S. Pawson, A.M. da Silva, 2004: A Case Study of Excessive Subtropical Transport in the Stratosphere of a Data Assimilation System. *J. Geophys. Res*., **109**, D11102 doi:10.1029/2003jd004057.

Tans, P. P., I. Y. Fung, and T. Takahashi, 1990: Observational constraints on the global atmospheric CO_2 budget, *Science*, **247**, 1431-1438.

Van der Werf, G.R., J.T. Randerson, G.J. Collatz, L. Giglio, P.S. Kasibhatla, A.F. Arellano, S.C. Olsen, and E.S. Kasischke, 2004: Continental-scale partitioning of fire emissions during the 1997 to 2001 El Nino/La Nina period, *Science*, **303** (5654), 73-76.

Wofsy, S.C., and R.C. Harriss, 2002: *The North American Carbon Program (NACP)*. A Report of the NACP Committee of the U.S. Carbon Cycle Science Steering Group.

Zhang, G.J., and N.A. McFarlane, 1995: Sensitivity of Climate Simulations to the Parameterization of Cumulus Convection in the Canadian Climate Center General Circulation Model. *Atmos.-Ocean*, **33**, 407-446.

Management Plan

This project will be coordinated from the GMAO and results will feed into the development of a carbon-cycle modeling, assimilation and inversion system, each component of which will be a resource for the agency. Liaison with the GMAO will ensure that the needs of this project are considered in future developments of the models and assimilation systems.

GMAO's expertise lies mainly in physical aspects of the earth system, including the use and development of models and data assimilation systems. A considerable component of the PI's efforts in this project will be to maintain a dialogue between the "physical" scientists of the GMAO and the members of this team. This will ensure that aspects of the GMAO's regular activities (such as meteorological and oceanographic assimilation) are maintained in line with the requirements of this project. For instance, one task involves extension of the meteorological assimilation to include carbon species; this will require substantial communication between Co-I Denis O'Brien and colleagues at CSU with members of the GMAO. The maintenance of such communication (and its support by GMAO management) will be central to this plan. (Note that PI Steven Pawson is on the Strategic Management Team of the GMAO.)

The science team assembled for this project includes a number of experts in carbon-cycle science, especially the biogeochemical and biophysical aspects. An important aspect of the management plan will be communication between team members; this will be facilitated by regular teleconferences and meetings about every four months. Regular communication will facilitate the flow of expertise and information between the various team members and increase the likelihood of success.

The proposed project is challenging, both scientifically and computationally. There will be a need to disperse data from GMAO's meteorological, land and oceanographical assimilation systems to all Co-Is for this project to be successful. As the project evolves, increasing numbers of members will need to be conversant with the models and assimilation systems in the GMAO. While all members will maintain their own codes in home institutions, it will be an investment for NASA to have the codes running "in house" at the GMAO. Likewise, the promise of computing resources at ORNL (see computing plan) will necessitate transfer of all systems, along with input data streams, from NASA's computing environment; this will involve cooperation between NASA- and ORNL-based staff and site visits.

Each of the Tasks identified in the proposal will have a lead scientist from among the Science Team. The tabulations here identify the responsibilities. The level-0 tasks are enabling tasks for the project; level-1 tasks are defined in the science plan. Tasks for Stage 2 will be defined in more detail as the project progresses and will involve contributions from all team members.

Task	Time	Leader	Description
0a.1	Years 1-5	Pawson	Project coordination, including reporting and liaison with GMAO
0a.2	Years 1-5	Pawson	Porting component models and assimilations, with necessary data, to GMAO
0b.1	Years 1-5	Erickson	Porting GMAO models, assimilation components and datasets to ORNL
1a.1	Years 1-2	Collatz	Derive first-guess land-surface fluxes from the SiB-BCM model, along with estimates of uncertainty and sensitivity to input
1a.2	Years 1-2	Denning	Derive first-guess fossil-fuel emissions, along with estimates of uncertainty
1a.3	Years 1-2	Doney	Derive first-guess ocean-surface fluxes from the WHOI ocean model, along with estimates of uncertainty and sensitivity to input
1a.4	Years 1-3	Reichle	Use surface temperature and moisture constraints from the EnKF system into the constraints in the Sib-BCM
1b.1	Year 1	Tangborn	Add the capability to include more gases in GEOS-5 assimilation modules
1b.2	Years 1-2	O'Brien	Optimize the CSU radiation module for the AIRS CO_2 and CO bands and implement it into GEOS-5
1b.3	Years 1-2	O'Brien	Develop and implement observation error models for AIRS radiances
1b.4	Years 2-3	Tangborn	Assimilate AIRS CO_2 radiances for an initial test period
1b.5	Years 2-3	Kawa	Validate AIRS assimilation against in-situ data
1c.1	Year 1	Bacmeister	Use AGCM to examine the statistical nature of constituent transport and characterize its sensitivity to sub-grid processes
1c.2	Year 2	Pawson	Use test assimilations (Task 1b.4) to evaluate forecast error and construct an accurate statistical model for it

1c.3	Years 2-3	Bacmeister	Examine model parameterizations in context of new developments
1d.1	Year 1	Tangborn	Implement and test synthesis- and adjoint-inversion models
1d.2	Years 1-2	Stajner	Develop a new inversion technique, based on parameter estimation methods
1d.3	Years 2-3	Denning	Perform a rigorous evaluation of the inversion techniques
1d.4	Years 2-4	Tangborn	Derive estimates of the seasonally varying fluxes from the AIRS-based runs
1e.1	Years 1-3	Collatz	Examine parameters in Sib-BCM
1e.2	Years 1-3	Denning	Examine parameters in fossil-fuel model
1e.3	Years 1-3	Doney	Examine parameters in WHOI ocean model
1f.1	Years 1-3	O’Brien	Develop and test a fast code for OCO radiances
1f.2	Years 3-4	O’Brien	Develop and implement observation error models for OCO radiances
1f.3	Years 3-5	Tangborn	Assimilate OCO and AIRS CO_2 radiances simultaneously
1f.4	Years 3-5	Stajner	Perform and analyze the inversion calculations
2	Years 4-5	Pawson	Stage-2 Tasks will be defined in detail nearer the time

The GSFC work will require one full-time postdoctoral scientist (employed through a research institute) to work on aspects of the assimilation and inversion. Additionally, one full-time programmer/scientist is required to coordinate computational activities in the GMAO: this will involve building the model and assimilation systems and running these for the required periods. This will also involve porting the system to different computational facilities, such as NASA’s Columbia machines and the ORNL computing center. Finally, a 0.3FTE assistant is required for data handling (maintaining streams of input and output data and communicating these to the science team). Work statements from the co-investigators are included.

At WHOI, Scott Doney requests support for 1.5 months per year of his own time and partial support for a scientific programmer (I. Lima). The tasks to be led WHOI are outlined in the above tables, and these manpower resources are essential for performing these tasks in collaboration with the project science team. A detailed work statement is included in the financial plan. Collaborator Watson Gregg (GMAO) will interact with Scott Doney to help evaluate uncertainties in ocean fluxes.

At CSU, Scott Denning will contribute in several ways, through his participation in atmospheric inversion computations and estimation of bottom-up fluxes over land. He will work with GMAO to port the synthesis inversion code and participate strongly in the inversion evaluation and intercomparison. His connections to the NACP will serve to enhance the communication with that team. Scott Denning will be instrumental in introducing the fossil-fuel emissions into this project. He is already collaborating with Jim Collatz (GSFC, Code 913) on the Sib-BCM. A postdoctoral assistant is needed for this work.

At ORNL, David Erickson will contribute his expertise in model and data analysis to this project, as well as leading the implementation of the models and assimilation systems onto the computing systems in his laboratory; a more detailed explanation of this contribution is given in the computing plan. A full-time assistant is required for this work.

At CSU, Denis O'Brien will develop the radiation transfer components of this proposed work. Algorithms developed will be installed in the GEOS-5 DAS and thoroughly tested. Initial work will involve AIRS radiances and the task will gradually transition to OCO. A postdoctoral scientist is required at CSU in order to complete these tasks. Collaborator Charles Miller (JPL) will interact strongly with Denis O'Brien as the algorithms are being developed.

Computing Plan, Including Appendix A

The proposed research will require substantial computational resources. We expect that this will be partially provided by NASA and partly through our partnership with the DOE's Oak Ridge National Laboratory (ORNL).

ORNL will provide computing resources to perform multi-year assimilations, ingesting all meteorological, land and ocean data to constrain the physical components of the system, and will perform the additional modeling and assimilation needed to infer sources and sinks at the atmosphere-land and atmosphere-ocean surfaces. The resources of the Climate and Carbon Research Institute (CCRI) will be made available to this NASA project. These runs will cover the period after EOS-Aqua launch, using AIRS and MODIS data, until March 2010 (the end of this project). For the latter two years, a separate assimilation including OCO data will be accommodated. Adequate resources for testing and development of these systems will also be provided. We will work with GMAO staff and other team members to port the assimilation modules, model components, and necessary datasets to the ORNL computing systems, and to test the implementation at ORNL

The requested Appendix A for computing resources has been completed and follows on the next two pages.

Following this, a description of the CCRI is included.

Computing appendix 1

Computing appendix 2

The Climate and Carbon Research Institute (CCRI), a research focus in the Center for Computational Sciences (CCS) at ORNL, provides an intellectual home and computational infrastructure for community building related to climate modeling. The institute shares several common goals: extended simulations in areas of climate science important to DOE; repositories of community codes optimized for high-end computing; a testbed for evaluations of new computer hardware and application of innovative software engineering techniques; interactions with CCS's future technologies group to push hardware beyond original vendor design specifications to achieve science missions; workshops to enhance researcher skills and train the next generation of climate modelers; increased interactions between climate research scientists and computer scientists and mathematicians; and collaborations to interpret and improve climate simulation results and to strengthen links between predictive modeling and experimental research.

Because ORNL has the people, the computational resources, and the infrastructure, DOE selected CCS to lead a partnership with a goal of creating the world's most powerful supercomputer by 2007. Energy Secretary Spencer Abraham announced on May 12, 2004, that the U.S. Department of Energy (DOE) will grant ORNL and its development partners, Cray Inc., IBM Corp., and Silicon Graphics, Inc., $25 million in funding to begin to build a 50 teraflop (50 trillion calculations per second) science research supercomputer. CCS will host the National Leadership class Computational Facility (NLCF), and ORNL will execute a plan that will pool the partnership's computational resources to achieve a sustained capacity of 100 trillion calculations per second (teraflops or TF). The NLCF partnership’s plan is to surpass the world's current fastest supercomputer, Japan's 40-TF Earth Simulator, by 2005.

The NLCF engages a world-class team from national laboratories, research institutions, computing centers, universities, and vendors to take a dramatic step forward to field a new capability for high-end science. Offering the Office of Science an aggressive deployment plan, using technology designed to maximize the performance of climate and geophysical scientific applications, and a means of engaging the scientific and engineering communities, the NLCF will provide the nation's most powerful open resource for scientific computational computing at an unprecedented scale.

Most important, CCS institute researchers will interact with the community of climate scientists in their respective fields to identify the unclassified "grand challenge" problems that can be solved only by CCS supercomputers. The institutes are a key to ensuring that CCS has the synergy of skillful climate simulation research partnerships and world-class computational technology to meet the challenges of solving national climate and environmental scientific problems.

ORNL will immediately double the capability of the existing Cray X1 at the ORNL Center for Computational Sciences and further upgrade it to a 20TF Cray X1e in 2005. The 512 processor Cray X1 (known as Phoenix) will evaluate the processors, memory system, scalability of the architecture, software environment and to predict the expected sustained performance of key DOE application codes. The Cray X1 has passed a milestone acceptance test and is undergoing evaluation on a suite of scientific computer programs including global climate modeling, high-temperature superconductivity, astrophysics, and fusion energy.

We will maintain national leadership in open scientific computing by installing a 100TF Cray X2 in 2006. We will simultaneously conduct an in-depth exploration of alternative technologies for next-generation leadership-class computers by deploying a 20TF Cray Red

Storm at ORNL and a 50TF IBM BlueGene/L at Argonne National Laboratory in partnership with the laboratories of the National Nuclear Security Administration. Cheetah (the IBM Power4) has been upgraded to new Federation switch architecture from IBM. Allowing the nodes to communicate at a data rate of 4Gb/s, double the speed of the old switch.

We will also advance the SGI Altix in partnership with the National Aeronautics and Space Administration (NASA). CCS has procured the SGI Altix for memory intensive research applications, such as computational chemistry and materials science. The Altix (dubbed "RAM") offers 2 TB of system memory and runs a single system image operating system (Linux). RAM's 256 processors are each a 1.5 GHz Intel Itanium2 and are the only high performance computer running the Intel IA64 chip which is one of Intel's fastest chips. These efforts will set the stage for deployment of a machine capable of 100TF sustained (250 TF peak) performance by 2007. We will work with industry, laboratories, and academia to deploy a computational environment that will enable the scientific community to exploit this extraordinary capability, achieving substantially higher effective performance than is possible today.

The CCS also serves as an evaluation center. ORNL and collaborating scientists evaluate different supercomputer architectures to determine which science codes work best on the new architectures. The flagship supercomputer (Cray X1) as well as the IBM and SGI Altix supercomputers have all been part of an evaluation project. These experts advise vendors on how to design next-generation supercomputers to improve scientific productivity. Researchers develop software tools that enable CCS supercomputers to run science codes more efficiently.
ORNL's computational facilities are bolstered by state-of-the-art connectivity, with a strong research capability for building even better and faster networks to connect CCS supercomputers with national networks and with links to Atlanta, Memphis, Chicago, the Research Triangle, and other sites. These networks will enable industrial firms to collaborate more efficiently with ORNL researchers on projects of interest to industry. Also at CCS, first-class visualization expertise and equipment help researchers obtain insights from their calculation results and communicate their significance.

The NLCF will bring together world-class climate simulation researchers; a proven, aggressive, and sustainable hardware path; an experienced operational team; a strategy for delivering true capability computing; and modern computing facilities connected to the national infrastructure through state-of-the-art networking to deliver breakthrough climate science. Combining these resources and building on expertise and resources of the partnership, the NLCF will enable climate focused scientific computation at an unprecedented scale.

Current and Pending Funding

Steven Pawson, PI

Pending. PI: “Meteorological and Constituent Forecasting in Support of Field Missions and Validation Experiments” (NRA NN-H-04-Z-YS-004-N), 2005-2008: total funding $970,200. (Time commitment: 25%.)

Pending. PI: “Data Assimilation to Estimate Surface Fluxes of Carbon Species Using Space-Based and In-Situ Data” (), 2005-2010. (Time commitment: 30%). Role: Atmospheric Modeling and Data Analysis.

Pending. Co-Investigator: “Chemistry-Climate Studies Using General Circulation Models” (NRA ESE-NN-H-04-Z-YS-008-N: PI: R.S. Stolarski, GSFC), 2005-2010. (Time commitment: 30%). Role: Atmospheric Modeling and Data Analysis.

Pending. Co-Investigator: “Improving Gravity Wave Parameterizations for Next-Generation Troposphere-Middle Atmosphere General Circulation Models.” (NRA ESE-NN-H-04-Z-YS-008-N: PI: J. Bacmeister, GSFC), 2005-2008. (Time commitment: 10%). Role: Study of atmospheric response to GWD parameterization.

Pending. Co-Investigator: “Validation of Aura Ozone Data Through Assimilation” (NN-H-04-Z-YS-004-N – this NRA; PI: Ivanka Stajner), Jan 1, 2005 – Dec 31, 2008: total funding $996,000 - pending. (Time commitment: 10%). Role: interpretation of assimilated ozone from Aura and impacts on climate.

Current. Co-Investigator: “Development of an Ocean Biogeochemical EOS Assimilation Model (OBEAM)" (NRA-03-OES-02: PI: Watson Gregg), 2004-2007: total funding $525,000. (Time commitment: 10%). Role: assimilation of ocean color data, related to the carbon cycle.

Current. Co-Investigator: “Quantifying the Sources and Global Transport of Combustion Gases and Aerosols Using MOPITT, MODIS, MISR and Related Satellite Observations” (NRA-03-OES-02: PI, Daniel Jacob, Harvard University), 2004-2007: Pawson’s funding $159,457 from a total budget of $700K. (Time commitment: 5%). Role: leading efforts to develop CO assimilation from MOPITT data.

Julio T. Bacmeister, Co-I

Project Title: *Moist physics development for GEOS-5 using single column models with parameterized dynamics*
PI: Bacmeister
Time Commitment: 0.33 person/yr
Duration of award: 3/1/05-2/28/08
Funding Agency: NASA
Status: pending

Project Title: *Improving gravity wave parameterization for next generation troposphere/middle atmospheric general circulation models*
PI: Bacmeister
Time Commitment: 0.33 person/yr
Duration of award: 3/1/05-2/28/08
Funding Agency: NASA
Status: pending

Project Title: *Improving the representation of cloud processes in GEOS-5: Advanced cloud parameterizations and data assimilation of EOS satellite observations*
PI: Norris
Time Commitment: 0.20 person/yr
Duration of award: 3/1/05-2/28/08
Funding Agency: NASA
Status: pending

Project Title: *Improved Estimates of Aerosol Direct and Indirect Effect on Climate Through Inclusion of Aerosol Microphysics and Aerosol Indirect Effect Paramerizations in GMAO's GEOS-5 Atmospheric GCM Aerosol*
PI: Colarco
Time Commitment: 0.20 person/yr
Duration of award: 3/1/05-2/28/08
Funding Agency: NASA
Status: pending

Project Title: *Chemistry-Climate Studies Using General Circulation Models*
PI: Stolarski
Time Commitment: 0.10 person/yr
Duration of award: 3/1/05-2/28/10
Funding Agency: NASA
Status: pending

Project Title: *Applications, Evaluation and Improvement of a Coupled, Global and Cloud-Resolving Modeling System*
PI: W. K. Tao
Time Commitment: 0.10 person/yr
Duration of award: 3/1/05-2/28/08
Funding Agency: NASA
Status: pending

Project Title: *Using satellite measurements to improve the modeling of low and middle clouds and their climate feedbacks*
PI: M. Zhang
Time Commitment: 0.10 person/yr
Duration of award: 3/1/05-2/28/08
Funding Agency: NASA
Status: pending

Project Title: *Single column modeling studies of water isotopes and other trace constituents in the tropical tropopause layer (TTL)*
PI: Bacmeister
Time Commitment: 0.15 person/yr
Duration of award: 10/1/04-9/30/07
Funding Agency: NASA
Status: pending

Project Title: *Atmospheric Modeling, Assimilation and Source-Sink Estimation for the Carbon Cycle*
PI: Pawson
Time Commitment: 0.10 person/yr
Duration of award: 3/1/05-2/28/08
Funding Agency: NASA
Status: pending

Project Title: *Atmospheric Data Assimilation Development*

PI: Gelaro
Time Commitment: 0.10 person/yr
Duration of award: 3/1/05-2/28/08
Funding Agency: NASA
Status: pending

G. James Collatz, Co-I

PI: GJ Collatz
NASA CAN-02-OES-01: Synthesizing, evaluating and distributing science community-driven carbon, water and energy cycling data products for research. ISLSCP Initiative III.
Project Duration: 10/2004-9/2005
Total Award: $200k
Effort: 0.1 FTE

PI: J Randerson
NASA NRA-03-OES-02: The use of satellite fire products and models to investigate the effects of fire on the global carbon cycle .
Project Duration: 7/2004-6/2007
Total Award (Collatz): $280k
Effort: 0.2 FTE

PI: SR Kawa
NASA NRA-04-OES-01: Constraining the missing carbon sink.
Project Duration: 01/2005-12/2007
Total Award (Collatz): $90k
Effort: 0.1 FTE

PI: AS Denning
Title: Mesoscale carbon data assimilation for NACP.
Project Duration: 1/2005-12/2007
Total Award (Collatz): $90k
Effort: 0.1 FTE

PI: R. DeFries
Title: Reducing uncertainties of carbon emissions from land use-related fires with MODIS data: From local to global scale.
Project Duration: 1/2005-12/2007
Total Award (Collatz): $90k
Effort: 0.1 FTE

PI: CJ Tucker
Title: Identifying and understanding carbon cycle implications of North American natural and anthropogenic disturbances: 1982-2005.
Project Duration: 1/2005-12/2007
Total Award (Collatz): $90k
Effort: 0.1 FTE

Scott Doney, Co-I

Scott C. Doney - Current & Pending Support

Principal Investigator(s) and Project Title	Supporting Agency	Yr1	Yr2	Yr3	Yr4	Yr5	Yr6	Yr7	Period Covered	Award Amount	Location of research	WHOI Prop. No.
		Person mo./yr. committed										
Current Support												
WHOI Education Program	WHOI Education	2.0							1/1/04 to 12/31/04		Woods Hole Oceanographic Institution	WHOI Internal
Coordination and Management of the U.S. JGOFS Synthesis and Modeling Project: The Second and Final Phase	NSF; OCE-0335589	2.0							5/12/03 to 4/30/05	$ 153,226	Woods Hole Oceanographic Institution	CH10990
The Role of Ecosystem Dynamics on the Global Ocean Carbon Cycle: A JGOFS Model-Data Synthesis	NSF; OCE-0222033	2.0	2.0	2.0					7/1/02 to 6/30/05	$ 430,008	Woods Hole Oceanographic Institution	CH10780
The Influence of Iron Availability and Physical Forcings on Southern Ocean Primary Productivity and New Production	NASA NAG5-12520	2.0	1.0	1.0					9/1/02 to 8/31/05	$ 302,310	Woods Hole Oceanographic Institution	CH10857
Generalized Carbon Cycle Data Assimilation System for the Carbon Cycle	NOAA; NA16GP2008	2.8	2.8	2.8					9/1/02 to 8/31/05	$ 176,430	Woods Hole Oceanographic Institution	CH10807.02
Biocomplexity: Collaborative Research: Oceanic N2 Fixation and Global Climate	NSF; OCE-0323332	0.0	0.0	0.0					4/1/03 to 3/31/06	$ 232,339	Woods Hole Oceanographic Institution	CH10925
ITR: Collaborative Research: Diversity of Biogeochemical Processes: Modeling Multiple Biomes on Multiple Flow Scales in the Eastern Pacific Ocean	NSF; OCE-0312710	1.0	1.0	1.0					9/1/03 to 8/31/06	$ 200,000	Woods Hole Oceanographic Institution	CH10902
PARADIGM: Partnership for Advancing Interdisciplinary Global Modeling	NOPP; Subcontract w/ URI 061902/535495	1.0	1.0	1.0	1.0	1.0			2/1/02 to 1/31/07	$ 400,000	Woods Hole Oceanographic Institution	CH10825
Collaborative Research: Global Ocean Repeat Hydrography, Carbon and Tracer Measurements (Co-PI's, W.Jenkins, T.Joyce)	NSF; Subcon. w/Columbia U. OCE-0223951	0.0	0.0	0.0	0.0	0.0	0.0		1/1/03 - 12/31/08	$ 1,558,500	Woods Hole Oceanographic Institution	CH10805.01
Principal Investigator(s) and Project Title	Supporting Agency	Yr1	Yr2	Yr3	Yr4	Yr5	Yr6	Yr7	Period Covered	Award Amount	Location of research	WHOI Prop. No
		Person mo./yr. committed										
Pending Support												
Improved Quantification of Regional Carbon Budgets using High-Density CO2 and CO Data from Satellites and Aircraft	NASA Subaward w/Harvard	1.0	1.0	1.0					4/1/05 to 3/31/08	$ 218,904	Woods Hole Oceanographic Institution	CH11218
Atmospheric Modeling, Assimilation and Source-Sink Estimation for the Carbon-Cycle	NASA	1.5	1.5	1.5	1.5	1.5			4/1/05 to 3/31/10	$ 635,786	Woods Hole Oceanographic Institution	CH11217
Marine Biological Responses to Meso- and Submesoscale Physical Forcing: A Multi-sensor Approach (D. Glover, Co-PI)	NASA	2.0	2.0	2.0					2/1/05 to 1/31/08	$ 697,367	Woods Hole Oceanographic Institution	CH11104
The Climate Responses and Potential Feedbacks of Changing Oceanic Dimethylsulfide (DMS) Concentrations (D. Toole, Co-PI)	NASA	1.0	1.0	1.0					1/1/05 to 12/31/07	$ 606,920	Woods Hole Oceanographic Institution	CH11115
Hindcasting Seasonal to Interannual Variability in Air-sea CO2 Flux for the North American Carbon Project (D. Glover, Co-PI)	NASA	3.0	3.0	3.0					10/1/04 to 9/30/07	$ 1,085,322	Woods Hole Oceanographic Institution	CH11103

A. Scott Denning, Co-I

CURRENT					
Title	**Sponsor**	**Amount**	**Dates**	**PI Support**	**Grant #**
Data fusion to determine North American sources and sinks of CO_2 at high spatial and temporal…	NOAA	$443,421	07/15/04 – 07/14/07	1 month	Cooperative Agreement NA17RJ1228
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 – 02/28/05	.5 month	DE-FG03-ER63474
Terrestrial carbon exchange and atmospheric CO_2 in Africa (Co-I)	NOAA	$105,000	07/15/04 – 07/14/07	0.4 month	Cooperative Agreement NA17RJ1228
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	$61,994	09/01/02 – 08/31/05	.25 month	Cooperative 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	$133,965	07/01/01 – 06/30/04	.25 month	Cooperative Agreement NA17RJ1228
Understanding the impacts of large-scale variability on the global carbon cycle. (Co-I)	NASA	$105,000 (Denning portion)	04/15/04 – 04/14/07	.5 month	NNG04GH53G
Development of methods for data assimilation with advanced models and advanced data sources (Co-I)	NASA	$35,000 (Denning portion)	04/15/04 – 04/14/07	.25 month	NNG04GI25G
Using satellite observations of CO to improve estimations of CO_2 sources and sinks.	NASA Student Fellowship	$72,000	08/15/04 – 08/14/07	0 mo.	NNG04GQ15H
PENDING					
Mesoscale carbon data assimilation for NACP.	NASA	$1,089,929	01/01/05 – 12/31/07	1 month	--
Constraining the CO_2 missing sink.	NASA Subcontract	$253,566	01/01/05 – 12/31/07	0.5 month	--
Center for multiscale modeling of atmospheric processes.	NSF STC	$325,000	06/15/05 – 06/14/10	2 months	--
High resolution fossil fuel emissions estimates in support of OCO-based assimilation... (Co-I)	NASA	$551,260 (CSU portion)	01/01/05 – 12/31/07	0.5 month	--

David J. Erickson, Co-I

Erickson, D. J. III, Climate simulation and biogeochemistry in the CCSM series of models, DOE-SCIDAC, 750K, FY01-06.

Erickson D, J, III, Regional modeling of Central America, USAID/NASA-MSFC, 345K, FY04-06.

Erickson D. J. III, Oceanic Carbon sequestration, DOE-OBER, 150K, FY04-06.

Erickson, D. J. III, Promoting ORNL – Core university climate modeling interactions, DOE/ORNL/LDRD, 95K, FY03-FY06.

Erickson, D. J. III (with R. Kawa), Constraining the CO_2 missing sink, Contract to Duke University, NASA, 95K, FY05-07.

S. Randolph Kawa, Co-I

Current. PI: “Constraining the CO_2 Missing Sink” (NRA-04-OES-01), FY2005-FY2007. (Time commitment: 30%.) Studies of the carbon cycle using atmospheric data and models, with emphasis on determining the sink.

Current. Co-Investigator: “Proposal for continued funding of the stratospheric general circulation with chemistry project” (NRA-02-OES-03; PI: A. R. Douglass) FY2003-FY2007. (Time commitment: 30%.) Role: development and interpretation of chemistry models.

Pending. Co-Investigator: “Meteorological and Modeling support for the Aura validation Campaigns” (NN-H-04-Z-YS-004-N – this NRA; PI: Paul A. Newman), Proposed for FY2005-FY2007. (Time commitment: 20%.) Role: Chemistry forecasts for Aura mission support.

Denis O’Brien, Co-I

None

Rolf Reichle, Co-I
Current
Project Title: Assimilation of AMSR-E data and application to the initialization of soil moisture reservoirs in a seasonal forecasting system
PI: Rolf Reichle
Co-Is: R. Koster, X. Zhan, U. Jambor, J. Bacmeister, P. Houser
Source of Support: NASA NRA-03-OES-02 (“EOS”)
Performance Period: 10/01/04 – 09/30/07
Total Budget: $680,000
Commitment: 8 months/year

Current
Project Title: Global estimates of evaporation from variational assimilation of multi-platform land surface temperature into a dynamic model of the surface energy balance
PI: Dara Entekhabi, MIT
Co-Is: S. Margulis, R. Reichle
Source of Support: NASA NRA-03-OES-02 (“EOS”)
Performance Period: 10/01/04 – 09/30/07
Total Budget: $614,000
Commitment: 1 month/year

Pending
Project Title: Enabling improved prediction of the global water and energy cycle through assimilation of land surface hydrological observations from NASA satellites into the NASA GMAO seasonal forecasting and weather prediction system
PI: Rolf Reichle
Co-Is: M. Bosilovich, R. Kelly, R. Koster, C. Sun, R. Todling
Source of Support: NASA NN-H-04-Z-YS-005-N (“NEWS”)
Performance Period: 04/01/05 – 04/01/10
Total Budget: $1,459,000 (pending)
Commitment: 3 months/year (pending)

Ivanka Stajner, Co-I

Current, PI: Proposal for “Ozone assimilation for studies of polar regions” is NASA-funded for years 2003-2005 (22% time commitment).

Current, PI: Proposal for "Validation of Ozone Monitoring Instrument (OMI) ozone products through data assimilation” is NASA-funded for years 2000-2005 (25% time commitment).

Pending, PI: Proposal for “Validation of Aura ozone data through assimilation” was submitted to NASA for years 2005-2008 (25% time commitment).

Andrew Tangborn, Co-I

PI: “Geomagnetic Assimilation and Dynamo Modeling” (NSF Collaborative Research Award), September 1, 2003 – August 31, 2007: total funding $520,880. (Dr. Tangborn has a 20% time commitment to this funded research.)

Resumes

Pawson – p1

Pawson – p2

Bacmeister – p1

Bacmeister – p2

Collatz – p1

Collatz – p2

Denning – one page

Doney – p1

Doney – p2

Erickson – p1

Erickson – p2

Kawa – p1

Kawa – p2

O-Brien – p1

O’Brien – p2

Reichle – p1

Reichle – p2

Stajner – p1

Stajner - p2

Tangborn – p1

Tangborn p2

Cost Plan and Budget Pages

The annual budgets and their total for this proposal are summarized for reference: details follow on each individual budget sheet and the breakdown is on the NASA cover pages.

Year 1	Year 2	Year 3	Year 4	Year 5	Total
$1,465K	$1,507K	$1,556K	$1,654K	$1,713K	$7,895K

The GSFC Budget is summarized here; it is not separated into the different groups and all new staff (1.0 Postdoc and 1.3FTE Contractors) will be based in the GMAO.

Manpower:

Name	Institution	FTE	Role	Work
Steven Pawson	CS-GMAO	0.3	PI	Atmospheric modeling and assimilation
G. James Collatz	CS-923	0.1	Co-I	Land-surface carbon
S. Randolph Kawa	CS-916	0.1	Co-I	Atmospheric transport
Julio Bacmeister	GEST	0.1	Co-I	Cloud/PBL transport
Rolf Reichle	GEST	0.1	Co-I	Land-surface assimilation
Ivanka Stajner	SAIC	0.2	Co-I	Atmospheric assimilation
Andrew Tangborn	JCET	0.8-1.0	Co-I	Atmospheric assimilation and inversion
Postdoc	GEST	1.0		Atmospheric inversion
Scientific assistants	Contractor	1.3		Data porting and preparation, technical and computing assistance, data analysis

Travel (CS and contractor): Attendance of working-group meetings (three per year, one in the GSFC vicinity, two remote), including travel for C. Miller, Co-I; attendance of scientific meetings (AGU, IUGG, Carbon workshops, etc.)

Equipment: Computing equipment, including workstations, laptop computers and data storage devices, which are essential for the work in this project. We expect to need one new workstation and one new laptop in each of the first two project years, with additional (less substantial) needs later in the project.

Supplies: Contributions to material resources (paper, printer ink, etc.) needed for this project

Other: Publication fees for refereed scientific journals

The following contains:

- (i) The NASA GSFC budget pages (pp90-100)
- (ii) The WHOI/Doney budget and justification (pp101-112)
- (iii) The CSU/Denning budget (p 113), justified in the letter on p9
- (iv) The ORNL/Erickson budget (pp 114-115)
- (v) The CSU/O'Brien budget (pp116-117)