Regional and Global Estimation of Terrestrial CO_2 Exchange from NIGEC Flux Data

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Summary of Proposed Work:

We will perform a scaling analysis of terrestrial carbon exchange using several of the NIGEC flux sites in different biomes (forest, C_4 grassland, C_3 agriculture), using a numerical model of the biophysics and biogeochemistry of plants and soils (SiB2), which includes calculations of the surface fluxes of CO_2, energy, and moisture. This model will be used to analyze local fluxes at each site based on observed meteorology and soil conditions, and then the site-calibrated model will be coupled to a series of atmospheric models on increasing spatial scales and with decreasing reliance on a knowledge of local conditions. These atmospheric models will include a 1-dimensional model of PBL turbulence with a grid spacing of about 10 m, a 3-D mesoscale model (RAMS) with a grid spacing of about 6 km, and a global atmospheric general circulation model (CSU GCM), with a grid spacing of about 400 km. This spectrum of atmospheric calculations will provide insight into the coupling between atmospheric transport and terrestrial ecosystem metabolism over a range of spatial scales. Our results will allow the tower flux measurements to be generalized in both space and time, providing a means for NIGEC to leverage its investment in the data collection and to obtain regional and global estimates of sources and sinks of CO_2, and will be useful in understanding the processes controlling land surface climate and CO_2 flux.

1. Introduction

It is now well established that atmospheric CO_2 is increasing rapidly due to human activity, yet only about half of the annual emissions from fossil fuel combustion remain in the atmosphere, and the fate of the remaining carbon is not completely understood. Changes in global and regional climate are likely to result from increasing CO_2, so the sinks for anthropogenic CO_2 must be better understood in order to predict the future concentration of this radiatively important trace gas. Direct measurement of the net sinks for anthropogenic CO_2 at the global scale is impossible because annual exchanges of carbon between the atmosphere, the ocean, and the terrestrial biosphere are nearly two orders of magnitude larger than the sink (IPCC, 1995). Atmospheric observations and simulation models of the carbon cycle must be used together to understand the processes that affect CO_2 concentration.

For almost 30 years, atmospheric CO_2 data have been collected at remote marine locations to avoid being biased by "local" terrestrial effects, and as a result, estimates of net terrestrial carbon fluxes are subject to large uncertainties (*e.g.*, Tans *et al.*, 1990; Denning, 1994; Enting *et al.*, 1995). The interpretation of terrestrial CO_2 measurements is complicated by large temporal and spatial variability, so collection of these crucial data is much more expensive than corresponding observations in remote marine environments. NIGEC has indicated a commitment to support the collection and analysis of such data at several sites in various ecosystems, which will significantly advance our understanding of the magnitude of terrestrial fluxes and the processes which control them. These data are invaluable, but will not be sufficient to reduce the uncertainties in the atmospheric carbon budget until they can be meaningfully extrapolated to regional and global scales.

We propose a research program to analyze the carbon flux and concentration data from several NIGEC-supported sites using a modeling system that includes representations of carbon metabolism by terrestrial ecosystems, turbulent fluxes of carbon, energy, and moisture at the land surface, and atmospheric CO_2 transport, at local, regional, and global spatial scales. The program we propose will also address the role of interactions between plant physiological processes and surface energy budgets in the response of the physical climate system to changes in CO_2 concentration. By using data collected at flux towers to validate and improve the modeling system, we will contribute to a mechanistic understanding of the processes involved and improve the reliability of model simulations and predictions. At the same time, by incorporating the experimental data in regional and global simulations, we will allow the tower data to be extended to much larger spatial scales than the immediate "footprint" of the observations and allow NIGEC to leverage its investment in the flux data.

1.1 Model Inversions of CO_2 Observations

The most compelling line of evidence for a strong terrestrial sink of anthropogenic CO_2 is the spatial structure of observed CO_2 concentration, as interpreted using simulations of atmospheric transport. Spatial and temporal changes in atmospheric CO_2 concentration contain information about sources and sinks at the surface, which can be quantitatively estimated by calculating the atmospheric transport of CO_2 using a simulation model (Keeling *et al.*, 1989; Tans *et al.*, 1989, 1990; Enting and Mansbridge, 1989, 1991; Denning, 1994; Enting *et al.*, 1995). Studies of sources and sinks performed by "inverting" atmospheric observations using various transport models have consistently found that the north-south gradient in surface CO_2 concentration would be stronger than observed unless there is a strong sink in the middle to high latitudes of the northern hemisphere. Some of the northern sink probably involves carbon storage by terrestrial ecosystems, because the required sink may be too strong to be compatible with the available oceanographic observations (Tans *et al*., 1990; Hesshaimer *et al*., 1994; Ciais *et al*., 1995).

Recently, Denning *et al*. (1995) showed that inversions of the atmospheric CO_2 record using chemical tracer models have almost certainly underestimated global terrestrial carbon uptake because of inadequate representation of the coupling between ecosystem metabolism and turbulent mixing in the planetary boundary layer (PBL). Although it has long been recognized that atmospheric dispersion of pollutants released at the ground surface depends strongly on the depth and intensity of PBL turbulence (*e.g*., Pasquill, 1961; Stull, 1988), inversion studies have represented the exchange of CO_2 between the atmosphere and the Earth's surface by assuming immediate mixing of surface fluxes into the lowest model layer, which has a fixed depth (usually about 50 mb). The models calculate CO_2 transport using winds prescribed from the output of a general circulation model (GCM) (Tans *et al*., 1989, 1990; Enting *et al*., 1989, 1991; Enting *et al*., 1995) or assimilated from observations (Keeling *et al*., 1989). They typically use a time step of 4 - 12 hours, and represent the seasonal cycles of atmospheric convection and ecosystem metabolism, but do not include variations of these processes on synoptic or diurnal time scales.

Because photosynthesis, PBL turbulence, and atmospheric convection over land are all forced by solar radiation at the surface, they are strongly correlated in nature, with strong ventilation and deeper mixing of CO_2-depleted air during the day and the growing season, and systematic retention of CO_2-enriched air under the nocturnal inversion and during the transition seasons (Fig. 1). By including these effects in a full atmospheric GCM coupled to a new version of the Simple Biosphere Model (SiB2) which predicts CO_2 fluxes at the land surface (Sellers *et al*., 1996*a,b*; Randall *et al*., 1996; Berry *et al*., 1996; Denning *et al*., 1996a; see section 3.1), we found that the covariance between terrestrial photosynthesis, PBL structure, and cumulus convection produces a "rectifier effect," which results in a vertical gradient of several parts per million (ppm) in the annual mean CO_2 concentration over land (Denning, 1994; Denning *et al*., 1995, 1996*b*). This effect is strongest over the temperate and boreal latitudes of the northern hemisphere where vegetation and PBL turbulence are most strongly correlated on seasonal time scales and where the land area is greatest, and therefore produces a north-south gradient in annual mean CO_2 concentration at the locations of the observing stations (Conway *et al*., 1994). This purely natural meridional gradient is half as strong as that produced by the combustion of fossil fuels, and amounts to an "excess" of several ppm of CO_2 at high northern latitudes that is not observed. If the rectifier effect is realistic, a net sink of more than 3 Gt C yr-1 is required in temperate and boreal ecosystems for consistency with the flask observations, which is nearly double the "consensus" estimate of the terrestrial sink (IPCC, 1995).

We propose a detailed examination of the relationships among ecosystem metabolism, PBL turbulence, and atmospheric CO_2 concentration at well-instrumented sites in the boreal forest, the tallgrass prairie, and in an agricultural area to evaluate the realism of the "rectifier" effect. The proposed research includes a spectrum of analyses of this effect, beginning at small spatial scales with the calculation driven almost entirely by the observational data and proceeding to larger and larger spatial scales with increasing reliance on remotely sensed data and numerical models for aggregation. The forest location is the site of the 450 m tall WLEF-TV transmitter tower in Northern Wisconsin. The modeling studies proposed here are part of a larger effort at this site which is the subject of NIGEC-funded study by P. Bakwin and K. Davis (proposed to continue for an additional three years), which will involve continuous measurements of CO_2 concentration, CO_2 fluxes, and PBL structure throughout the annual cycle. The prairie and agricultural sites are the subject of a related NIGEC-funded study by S. Verma and J. Berry, which involves year-round measurements of net radiation, turbulent fluxes of CO_2 and sensible and latent heat at the ARM-CART site in Oklahoma, which is already well-instrumented for documenting PBL structure. After a thorough analysis of the data and simulations at these sites, we will use the model to interpret the CO_2 flux data from the other NIGEC towers and incorporate these data into the modeling framework. Finally, we will perform a new global calculation of the distribution of sources and sinks of CO_2 at the Earth's surface that is consistent with the global CO_2 flask network, the model transport, and the tower flux data.

Preliminary analysis of the feasibility of using the coupled GCM-SiB2 model with the WLEF data is very encouraging (Fig. 2). Even with no adjustments to the global model to match site conditions, the model is able to reproduce key observations related to the rectifier effect. This suggests that most of the important physics and biology in the natural system is being captured in the simulations.

1.2 Atmosphere-Biosphere Interactions and Climate Change

In addition to the direct radiative effects of enhanced atmospheric CO_2 on the Earth's climate, changes in surface climate are likely to occur due to physiological responses of plant canopies. Plants grown in elevated CO_2 environments exhibit reduced stomatal conductance and higher water use efficiency, resulting in reduced evapotranspiration and enhanced sensible heat flux (Eamus and Jarvis, 1989; Bazzaz and Fajer, 1992). Recent studies with global models suggest that these physiological effects at the land surface may result in additional global warming in a doubled CO_2 world, over and above the direct radiative effects (Pollard and Thompson, 1995; Henderson-Sellers *et al.*, 1995; Sellers *et al.*, 1996*c*).

In a related study, S. Verma and J. Berry have been performing eddy correlation measurements of the surface fluxes of CO_2, moisture, sensible heat, and radiation over native tallgrass prairie and cultivated wheat in the ARM-CART site in Oklahoma. The native grasses in this area fix carbon through a different physiological and biochemical mechanism (the C4 pathway) than wheat (which uses C3 photosynthesis). The C4 plants have evolved a mechanism to concentrate CO_2 in their cells to achieve the kind of enhanced water use efficiency that is anticipated for C3 plants under conditions of elevated CO_2. A comparison of the sensitivity of surface fluxes at the two sites is expected to yield insights about changes in evapotranspiration, sensible heat fluxes, and surface temperature that should be expected over large regions as atmospheric CO_2 increases. Verma and Berry use the same photosynthesis-stomatal conductance model (SiB2) to analyze their data as we plan to use in the present study, so there are excellent opportunities for coordination and collaboration between the two programs.

We propose a series of model simulations using a series of atmospheric models coupled to SiB2 as modified by Verma and Berry, to investigate the interactions between stomatal conductance, photosynthesis, evapotranspiration, sensible heat flux, and PBL turbulence over the C_3 and C4 sites. The atmospheric models represent a hierarchy of increasing spatial scales, from local to regional to global. Through these simulations, we will quantify the role of plant physiology in controlling local climate as well as the role of climate in controlling the CO_2 and moisture fluxes. It is expected that these experiments and simulations will provide information on near-surface climate dynamics and land-surface hydrology that will benefit the ARM-CART program and the GCIP program.

2. Research Objectives and Hypotheses

The broad objective of the proposed research is to estimate the regional and global carbon balance of the land surface, using the tower flux data and collocated observations collected by NIGEC, remotely sensed data on the state of the vegetation, and numerical models of the vegetation and atmosphere. In support of this general program objective, we identify the following specific objectives:

1) Evaluate the parameterization of vegetation biophysics and terrestrial carbon flux for a forested site (the WLEF tower), a C_4 grassland site, and a C3 agricultural site (both in the ARM-CART area). This will involve validation of the off-line (0-D) version of SiB2, and calibration as necessary to improve the realism of the coupled modeling system.
2) Investigate the coupling of PBL structure and plant physiology in terms of the relationships between stomatal conductance and photosynthesis, evapotranspiration, and sensible heat flux. This investigation is intended to lead to better understanding of the mechanisms for physiologically forced climate change under elevated $CO_{2.}$
3) Evaluate the realism and spatial scaling of the CO_2 "rectifier effect" in nature by using a hierarchy of simulations at increasing spatial scales to analyze simultaneous continuous measurements of surface carbon flux and the structure of the PBL over diurnal, synoptic, and seasonal time scales.
4) Extrapolate the carbon flux measurements made at the NIGEC-supported flux towers to the scale of single GCM grid cells (10^5 km2) using remotely sensed vegetation data (AVHRR NDVI) and gridded weather analyses to drive the improved biophysical model coupled to a mesoscale atmospheric model (RAMS). This will be done for other NIGEC-supported field sites (Walker Branch, Harvard Forest, and Wind River) as well as the three sites which we use for model calibration and development.
5) Use the improved biophysics model coupled to the global GCM, in conjunction with all the available observational data on atmospheric CO_2 concentration to estimate the global budget carbon budget of the atmosphere by inversion.

The fit between the objectives of the proposed research and the research priorities of NIGEC is excellent at all four levels described in the RFP. In particular, objectives 2-5 above directly address the DOE GCRP's objective "to improve the understanding of the mechanisms, rates, and magnitudes of atmospheric and climate changes at regional and larger scales." The entire program envisioned here will address DOE's Priority Research Topic 4: Terrestrial Carbon Exchange. The proposed work blends process-oriented research at the canopy scale (using the 0-D version of SiB2, objective 1 above); meteorological research at scales from several to hundreds of km^2 (using the 1-D PBL model, the mesoscale model, and the SCM version of the GCM; objectives 2 through 4 above); and research on carbon budgets at the global scale (using the CSU GCM, objective 5 above). This scaling approach addresses NIGEC's focus on using a flux network to study the carbon balance of terrestrial ecosystems and predict future levels of atmospheric CO_2 concentrations. Finally, our objectives are directly relevant to the second research thrust of NIGEC's Western Regional Center, which focuses on carbon exchange between the atmosphere and "regional, terrestrial ecosystems, both natural and managed" and seeks to "emphasize the dynamics of the processes involved in this exchange with the goal of predicting net exchange/flux rates."

3. Proposed Methodology

We propose a hierarchical series of experiments to analyze the carbon balance of three "calibration" sites which have already been collecting data as part of the NIGEC flux network: the WLEF TV transmitter tower in northern Wisconsin, and two sites in the ARM-CART area of Oklahoma (one is a native C_4 grassland, the other is a wheat field). The analyses would proceed from being driven almost entirely by site data to greater and greater reliance on remotely sensed data and gridded meteorological data, which are available everywhere. At each step of this process, we would build confidence in our ability to represent the mechanisms of carbon exchange and atmospheric transport in the modeling system.

At each site, we would begin with a detailed analysis of the carbon balance with SiB2, using local micrometeorological data to drive the calculation. These calculations would be validated against the eddy correlation data available at each site, and used to derive site-specific parameters for each. Berry has already begun this work at the Oklahoma sites. A field campaign would be conducted at the Wisconsin site to obtain relevant biophysical parameters (leaf-area index, canopy light extinction, etc.). The site-calibrated biophysical model would then be coupled to a new model of PBL turbulence (vertical grid spacing of order 10 m; second order closure with third moments represented by the method of Canuto *et al*, 1994), driven by the observed radiation field with large-scale divergence derived from gridded weather analyses. This will allow a quantitative analysis of the CO_2 rectifier effect at each site. The predicted vertical structure can be compared directly to the tower data for the lowest 400 m for the WLEF site; the ARM-CART site lacks deep observations of CO_2, but the structure of the PBL is well documented in the area, at least during the Intensive Observing Periods (IOPs) of the ARM program, which will provide an opportunity for validation of the physical aspects of the simulation. These simulations will be repeated using the single column version of the CSU GCM, to evaluate the realism of the simulated rectifier effect, and investigate the interactions between biophysics, the surface energy budget, and PBL structure simulated in the GCM. Next, we would acquire a series of AVHRR images of the vicinity of each site (order 200 km radius), and use these to parameterize SiB2 for the regional setting. This information would then be used to perform simulations of the regional meteorology, carbon fluxes, and atmospheric CO_2 concentration using SiB2 coupled to RAMS, using a horizontal grid spacing of 6 km, and 20 levels in the vertical. This will allow us to evaluate the effects of horizontal inhomogeneities on carbon fluxes, the surface energy balance, atmospheric transport and concentration of CO_2. The results of these simulations would allow quantitative evaluation of the rectifier effect and surface carbon balance at a spatial scale roughly corresponding to a GCM grid cell (10^5 km2).

Simulations at the ARM-CART site will also make use of studies with C_3 and C4 canopies to examine the effect of surface conductance (which should decrease as atmospheric CO_2 increases) on the meteorology (temperature, humidity and turbulence) of the PBL. Regional modeling of the ARM-CART area will be conducted in collaboration with J. Christopher Doran and colleagues at Battelle Pacific Northwest Laboratories (see attached letter of support), who have already been using SiB2 coupled to RAMS to investigate the spatial structure of latent and sensible heat fluxes in this area (Liljegren *et al*, 1996).

We will then repeat the process of calibrating the model at the sites of the other NIGEC CO_2 flux studies (Harvard Forest, Walker Branch, Duke Forest, Wind River), driving SiB2 off-line with site meteorology to evaluate the simulated fluxes across the range of ecosystems and climates. We will use remotely sensed NDVI data to extend the site-calibrated carbon flux estimates to regional scales at each site. Finally, we would use the improved model to perform a global scale, multiyear simulation of atmospheric CO_2 transport and concentration driven by global NDVI data, and use the results of this calculation to deduce the global carbon balance by inversion of the NOAA flask observations. Unlike previous calculations of this kind (e.g., Tans *et al*, 1990), this calculation would be based on credible physical coupling between ecosystem metabolism and atmospheric transport, and would be consistent with the new data generated by NIGEC.

Site Descriptions:

The ***forest site*** is the location of a 450 meter tall television transmission tower (WLEF-TV, 45° 55' N, 90° 10' W), located in the Chequamegon National Forest, 24 km west of Park Falls, WI (pop. 3200). The region is in a heavily forested zone of low relief. The Chequamegon National Forest covers an area of approximately 325,000 ha, and the dominant forest types are mixed northern hardwoods (85,000 ha), aspen (75,000 ha), and lowland and wetlands (60,000 ha). The region immediately surrounding the tower is dominated by boreal lowland and wetland forests typical of the region. Much of the area was logged, mainly for pine, during 1860-1920, and has since regrown (J. Isebrands, personal communication).

The concentration of CO_2 has been measured continuously at 6 heights (11, 30, 76, 122, 244, and 396 m above the ground) since October, 1994, and CO_2 flux has been measured at two heights at this tower (122 and 396 m) since May, 1995. Recently, a new eddy covariance package was installed to measure the fluxes at 30 m. Micrometeorology and soil temperature and moisture data are collected at the site or at the nearby USDA Forest Sciences Laboratory. During the summer of 1995, a 915 MHz radar wind profiler was operated at the site, which provided data on the height and structure of the PBL during the period. In conjunction with the vertically resolved CO_2 and flux data, the radar data provide a direct quantitative characterization of the CO_2 rectifier effect (see Fig 2). The other significant advantage of this site is that the great height of the tower provides the opportunity for observing the carbon balance over a "footprint" of several km2, approximately two orders of magnitude greater than other NIGEC flux monitoring sites.

The ***tallgrass prairie*** and ***wheat*** sites are located in the ARM-CART area in northeastern Oklahoma. These sites have been instrumented for eddy correlation flux measurements by S. Verma and J. Berry using NIGEC funds. Surface fluxes of latent and sensible heat, momentum, and CO_2 are measured continuously, and local calibration of SiB2 from these data will begin soon. The tallgrass prairie site is in C4 vegetation near Shidler, OK, and the wheat site is located approximately 60 km to the east, near Ponca City, OK. Both sites were carefully selected for characteristics of flat terrain, long fetches over horizontally homogeneous surface conditions, and lack of local disturbance. Each is situated in a 1/4 section of flat, unoccupied land. Fluxes are measured continuously by eddy correlation, and supporting micrometeorological data are specifically designed to calibrate and improve the simulation of the local carbon fluxes in SiB2. Soil moisture is recorded by time domain reflectrometry (TDR), and other regular measurements include leaf area index and biomass.

This area is extensively instrumented for meteorological observations (Stokes and Schwartz, 1994). The sites lie approximately halfway between the ARM wind profilers at Lamont, OK and Neodosha, KS. These sites provide an excellent opportunity to investigate spatially heterogeneous CO_2 fluxes and the rectifier effect because of the physiologically different responses of C3 and C4 canopies to environmental stresses, and because of the excellent observational control on the regional meteorology. Verma and Berry have already planned to do extensive testing, validation, and calibration of the SiB2 parameterization for these sites, so our proposal does not include this aspect. Instead, we will build on their results by analyzing the vertical mixing of the surface CO_2 signal into the atmosphere; the feedbacks between stomatal control of CO_2, the surface energy budget, and PBL structure; and on the regional aggregation of these data using remote sensing and mesoscale modeling.

3.1 Model Descriptions

The Simple Biosphere Model (SiB2)

The Simple Biosphere (SiB) Model, developed by Sellers *et al*. (1986), has recently undergone substantial modification (Sellers *et al*., 1996*a*, *b*; Randall *et al*., 1996), and is now referred to as SiB2. The number of biome-specific parameters has been reduced, and most are now derived directly from processed satellite data rather than prescribed from the literature. The vegetation canopy has been reduced to a single layer. Another major change is in the parameterization of stomatal and canopy conductance used in the calculation of the surface energy budget over land. This parameterization involves the direct calculation of the rate of carbon assimilation by photosynthesis, making possible the calculation of CO_2 exchange between the global atmosphere and the terrestrial biota on a timestep of several minutes (Denning *et al*, 1996a,b; Zhang *et al*, 1996). Photosynthetic carbon assimilation is linked to stomatal conductance and thence to the surface energy budget and atmospheric climate by the Ball-Berry equation (Ball, 1988; Collatz *et al*., 1991, 1992; Sellers *et al*., 1992*a*, *b*, 1996*a*), which is the basis for the ability of the model to calculate the climatic effects of physiological responses to elevated CO_2 (Sellers *et al*, 1996c).

Heterotrophic respiration is currently represented in the model by assuming annual carbon balance, with seasonal distribution of the flux calculated according to empirically derived functions of soil temperature and moisture (Denning *et al*, 1996a). We recognize that this method is unsuited to the direct calculation of net sources and sinks at the land surface. We have chosen to separate the effects of purely seasonal carbon fluxes with those of the net annual sources and sinks, because the net annual accumulation or release of carbon from terrestrial ecosystems is small compared to the gross one-way fluxes, and relatively small errors in the independent calculation of assimilation and respiration can lead to large net sources and sinks which are not realistic. Our approach allows us to use the observational data on atmospheric CO_2 to deduce the net annual sources and sinks (Denning, 1994), which we believe is more reliable than direct calculation from independent simulation of photosynthesis and respiration.

For the research proposed here, we will develop a new soil carbon model, including an allocation scheme which apportions the assimilation calculated in SiB2 to canopy, stems, and roots, and tracks the flow of both above- and belowground litter through a series of carbon pools. This scheme will be based on the CASA model of Potter *et al* (1993), but will be driven by conditions in the soil rather than the air, and will include vertical variation of pool status in the soil corresponding to a new multilayer soil thermodynamics and hydrology module being developed for SiB2.

The Regional Atmospheric Modeling System (RAMS)

RAMS is a general purpose atmospheric simulation modeling system consisting of equations of motion, heat, moisture, and continuity in a terrain-following coordinate system (Pielke *et al.* 1992). The model has flexible vertical and horizontal resolution and a large range of options that permit the selection of processes to be included (such as cloud physics, radiative transfer, subgrid diffusion, and convective parameterization). Two-way interactive grid nesting (Nicholls *et al.* 1995; Walko *et al.* 1995*a*) allows for a wide range of motion scales to be modeled simultaneously and interactively. For example, with nesting, RAMS can feasibly model mesoscale circulations in a large domain where low resolution is adequate, and at the same time resolve the eddy fluxes caused by juxtaposition of different land cover types, such as occur when irrigated cropland lies adjacent to drylands (Pielke *et al.* 1992).

Several major RAMS developments were completed in the last few years which greatly enhance its ability to simulate the components of the hydrological cycle. Among these is a new bulk microphysical code (Walko *et al.* 1995*b*, 1996*b*) which represents each water category (cloud, rain, large and small pristine ice, aggregates, graupel, and hail) as a generalized gamma distribution and prognoses both the mass mixing ratio and number concentration of all categories. The model includes homogeneous and heterogeneous nucleation of pristine ice, the representation of five different ice habits, conversion of ice between the large and small pristine categories resulting from vapor deposition or sublimation, and prognosis of aerosol (cloud condensation nuclei). Very efficient solvers for the stochastic collection equation based on new analytic solutions to the collection integral and for activation of cloud droplets are implemented. Accurate prediction of cloud droplet number based on aerosol concentrations and supersaturations allows the model to properly represent cloud albedo. The sedimentation routine allows differential fall speeds based on the gamma size distribution. Another development in RAMS is the ability to nest vertically to increase vertical resolution in selected areas (Walko *et al.* 1995*a*).

The CSU GCM

The CSU GCM has been derived from the UCLA GCM, which was developed at UCLA, over a period of 20 years, by Prof. A. Arakawa and collaborators. A copy of the model was brought to the Goddard Laboratory for Atmospheres in 1982, and from there to CSU in 1988. Many changes have been made since the model left UCLA, including revised parameterizations of solar and terrestrial radiation, the planetary boundary layer, cumulus convection, cloud microphysical processes, and land-surface processes. Recent model results are presented by Stephens *et al* (1993), Randall *et al* (1996), Fowler *et al* (1996), and Fowler and Randall (1996).

For the purposes of the research proposed here, the CSU GCM has four key features:

1) It is coupled to SiB2, the land surface parameterization of Sellers *et al* (1996*a*), which includes a physiologically realistic interaction between the surface energy budget and photosynthetic carbon assimilation;
2) It includes prognostic calculation of the mixing ratio of atmospheric CO_2 based on prescribed emission scenarios and the carbon fluxes from SiB2, and has been shown to reproduce many aspects of the observed spatial and temporal variation of CO_2 (Denning,1994; Denning *et al*, 1996*a*,*b*).
3) The model is formulated terms of a modified sigma coordinate, in which the PBL top is a coordinate surface, and the PBL itself is identified with the lowest model layer (Suarez *et al*, 1983; Randall *et al*, 1992). The mass sources and sinks for the PBL consist of large-scale convergence or divergence, turbulent entrainment, and the cumulus mass flux. Turbulent entrainment can be driven by positive buoyancy fluxes, or by shear of the mean wind in the surface layer or at the PBL top. This feature is a key to the model's ability to simulate the CO_2 "rectifier" effect (Denning *et al*, 1995).
4) The cumulus mass flux and the warming and drying of the free atmosphere due to cumulus convection are determined through the cumulus parameterization of Arakawa and Schubert (1974; see also Lord *et al*., 1982), as modified by Randall and Pan (1993). Quasiequilibrium of the cloud work function is closely approximated through the use of a prognostic cumulus kinetic energy. The ice phase is taken into account in the cumulus parameterization. Cumulus friction is included, assuming momentum conservation in the convective updrafts. The effects of convective downdrafts are included. This formulation allows a detailed accounting of the vertical transport of CO_2 due to subgrid-scale cumulus convection, which is another important component of the CO_2 "rectifier" (Denning *et al*, 1996*b*).

The model is typically integrated on a 4° × 5° (latitude × longitude) grid, with 17 levels, using a six minute time step, although both coarser and finer grids are also available for testing, or sensitivity experiments. A key advantage for the research proposed here is that by setting logical switches at run time, the model can be run in 0-D (off-line SiB2), 1-D (Single Column Model), or 3-D (GCM) modes, without any changes to the code. This allows very fast turnaround for 0-D and 1-D simulations, and facilitates testing and debugging. Parameterizations can be developed and tested off-line or in the SCM and then run in the 3-D model without modification.

3.2 Collaboration with Other NIGEC Research

The proposed research is intended to be carried out in conjunction with at least four other projects currently funded by or proposed to NIGEC:

- P. Bakwin and K. Davis (University of Colorado and University of Minnesota). Regional Atmosphere/Forest Exchange and Concentrations of Carbon Dioxide. South Central Regional Center.
- S. Verma and J. Berry (University of Nebraska-Lincoln and Carnegie Institute of Washington). Net Exchange of Carbon Dioxide in Grassland and Agricultural Ecosystems in the ARM-CART Region: Modeling and Year-Round Measurement. Great Plains Regional Center.

- V. P. Gutschick (New Mexico State University) Regularities in Plant Control of Evapotranspiration and C Gain Across Sites. South Central Regional Center.
- C. Field and J. Berry (Carnegie Institute of Washington). Linking the CASA and SiB Global Terrestrial Models: Improved Estimates of Global Carbon Stocks and Fluxes and CO_2 Responses. Western Region.

3.3 Specific Tasks to be Performed

Task 1: Biophysical and physiological characterization of the WLEF site.

This will be a necessary first step toward accurate parameterization of SiB2 for the site-specific 0-D modeling work. Leaf area will be measured with a LI-COR LAI-2000 and by destructive sampling. Leaf samples will be taken to estimate the fraction of the canopy composed of green leaves and to determine leaf nitrogen content and spectral reflectance. Light attenuation in the canopy will be measured, and the canopy integration factor used in SiB2 will be determined.

Leaf CO_2 exchange will be measured on leaves at the top of the canopy using a Campbell MPH-1000 or LI-COR 6400 gas exchange system fitted with an artificial light source. These instruments permit full control of temperature, humidity, and CO_2 concentration within the cuvette so that the parameters in the Ball-Berry equation can be determined (Ball, 1988). Some measurements will also be made on shaded leaves to assess within-canopy gradients.

If the proposal by V. Gutschick (Great Plains Regional Center) is funded, we will benefit from his estimates of spatial variability of these parameters through the canopy and the nearby forest, and temporal variability through the annual cycle. If that proposal is not funded, we will perform these calibration measurements at intervals throughout year 1 of the study to document the seasonal cycle.

Task 2: Modeling of surface carbon fluxes with off-line (0-D) SiB2.

The site-specific parameters determined under Task 1 above will be used to develop a simulation of surface carbon fluxes in which SiB2 will be driven by observed meteorological data collected near the site. This task will involve a suite of simulations in which various aspects of the physical climate system are prescribed or calculated by the model. For example, by using the maximum amount of observed data (surface temperatures, humidity, radiation, and energy budget, soil temperatures and moisture, etc.), the simulation of CO_2 flux isolates the photosynthesis-stomatal model and respiration model so that they can be evaluated independently. Alternatively, by prescribing only the atmospheric state and calculating the soil heat and moisture budget, we can validate and calibrate those modules. The intent of these simulations is twofold: (a) to improve the model and gain confidence in our ability to simulate the surface fluxes correctly for this site; and (b) to gain a better mechanistic understanding of the feedbacks involved in the coupling of surface carbon, energy, and water fluxes.

Task 3: Simulation (1-D) of coupled atmosphere-biosphere dynamics (WLEF site).

The improved model developed in Task 2 above will be used in a new model of PBL turbulence which we will develop, and in the GCM in Single Column mode (1-D), to simulate the coupled evolution of the surface fluxes and the vertical structure of the atmosphere with respect to CO_2 sources and sinks, PBL turbulence, latent and sensible heat flux, and vertical stratification of tropospheric CO_2. These simulations will be directly validated by comparison to the tower observations. The site meteorological data (mean winds, radiation) will be used to drive these simulations. The results will allow us to isolate mechanisms and processes by which surface carbon fluxes are communicated to the free troposphere, which we have identified as a key determinant of spatial structure of atmospheric CO_2 at the global scale (Denning *et al*., 1995). In addition, the use of the coupled SiB2-PBL model will produce detailed information on the influences of stomatal function on the structure of PBL turbulence, the effects of environmental stress on ecosystem carbon flux, and on the feedbacks between these effects. We will repeat these calculations in the 1-D (SCM) version of the CSU GCM, to evaluate the realism of the rectifier physics as captured by the GCM at the global scale, and to improve the entrainment calculation in the GCM. For the GCM experiments, the large scale dynamics will be prescribed using mesoscale winds and temperatures derived by data assimilation at the National Meteorological Center (Rapid Update Cycle products). These data are available over North America on a 60 km grid every three hours.

Task 4: Regional Extrapolation from the WLEF site.

The site-calibrated biophysics model would then be coupled to the RAMS atmospheric model, and a series of simulations would be performed over a domain of approximately 400 x 400 km, with a horizontal grid spacing of 6 km and 20 levels in the vertical. Surface boundary conditions would be specified from AVHRR data using SiB2 (Sellers *et al*, 1996*b*). Lateral boundary conditions specified from gridded analyses obtained from the National Center for Environmental Prediction (NCEP, formerly NMC). The two models have already been successfully coupled at the ARM-CART site by J. C. Doran and colleagues (see attached letters of support). We would add the on-line calculation of CO_2 concentration to the coupled model.

Simulations would cover an entire annual cycle, to assess the seasonality of the terrestrial carbon flux as simulated by the model, and compare it to the tower data. For CO_2 concentration, lateral boundary conditions will be periodic, allowing us to focus on the effects of covariance between the regional motion field and the ecosystem metabolism on the vertical stratification of CO_2 concentration. This design will not attempt to accurately simulate the details of day-to-day variations of CO_2 at the WLEF tower, but will elucidate the spatial scaling of the CO_2 rectifier effect over the area of a single GCM grid cell. We will compare the diurnal and seasonal variations of the simulated vertical structure of CO_2 concentration with the tower data and with the earlier 1-D results. In addition, we will analyze the full 3-D distribution of the CO_2 tendencies due to vertical motion and cumulus convection, and compare these to the 1-D SCM results to evaluate the ability of the GCM to capture the CO_2 rectifier.

Task 5: Single Column Modeling over C_3 and C_4 canopies at the ARM-CART Site.

In the third year of this project, we will repeat the analysis outlined for Task 4 above, but this time for the prairie and agricultural flux towers in the ARM-CART site. For these simulations, we will use the surface parameterization developed by Verma and Berry in their proposed NIGEC research. Wind profiling radar data collected by ARM will be used to evaluate the PBL coupling, and the SCM simulations will also be driven by the NMC-RUC data products as described above. The contrast between the C_3 and C_4 ecosystems will be used to evaluate the changes in plant-PBL-CO_2 coupling under conditions of reduced stomatal conductance, which will provide insights into the kinds of changes to be expected under conditions of elevated CO_2. In addition, the site-specific model developed by Verma and Berry, when coupled to the GCM, will provide a means to evaluate the fluxes of CO_2 over the Great Plains over an annual cycle.

Task 6: Regional Simulation of the ARM-CART Site.

We will use the site-specific calibrations produced by Verma and Berry NIGEC project to extend the examination of the rectifier effect from the prairie and wheat sites to the entire ARM-CART region through coupled simulations with RAMS. As in Task 4, we will use satellite data to set time-varying surface boundary conditions and SiB2 parameters, but for this region we will use the excellent array of meteorological data produced in the ARM IOPs to set lateral boundary conditions. A nested grid will be used in RAMS to provide detailed meteorological information n the vicinity of he flux towers from the large-scale meteorology. These higher-resolution simulations will be performed in addition to the full annual cycle run driven by routine NCEP analyses. Our focus will not be on reproducing the details of the horizontal structure of CO_2, but rather in elucidating the mechanisms for vertical redistribution of CO_2 at the regional scale, and the coupling between ecosystem carbon metabolism, canopy biophysics, and boundary-layer meteorology.

Task 7: Global simulations with the improved model, and incorporation of other tower flux data

Having developed improved parameterizations of land-surface processes and CO_2 fluxes in the boreal forest, C_4 grasslands, and C_3 agricultural regions, we will return our attention to the carbon budget of the terrestrial biosphere at the global scale. This will entail combining the terrestrial ecosystem fluxes modeled as described above with global “basis functions” for carbon exchange with all other reservoirs (air-sea fluxes, tropical deforestation, fossil fuel emissions, etc.), and solving for the linear combination of these concentration fields that minimizes the error as compared to the NOAA flask observations (Enting *et al*., 1995). We will produce new global maps of estimated CO_2 sources and sinks, which will be compared to the flux data collected by other NIGEC-funded flux towers, placing them in a regional and global context and also providing a check on the simulations.

3.4 Deliverables and Due Dates

7/1/98 Annual Progress Report for Year 1.

9/1/98	Manuscript submitted on the results of analysis and 0-D simulation of the surface CO_2 fluxes at the WLEF site with SiB2 (Tasks 1 and 2).
12/98	Conference paper delivered at Fall Meeting of the American Geophysical Union, on 1-D coupled simulations at the WLEF site (Task 3).
6/99	Manuscript submitted on the results of investigations of coupled atmosphere-biosphere dynamics at the WLEF site using the Single Column Model (Task 3).
7/1/99	Annual Progress Report for Year 2.
12/99	Conference paper delivered at Fall Meeting of the American Geophysical Union, on mesoscale integration of fluxes at WLEF (Task 4).
3/1/2000	Manuscript submitted on the results of investigations of coupled atmosphere-biosphere dynamics over C_3 and C_4 canopies in the ARM-CART site using the Single Column Model (Task 5).
6/2000	Conference paper delivered at Spring Meeting of the American Geophysical Union, on mesoscale integration at the ARM-CART site (Task 6).
9/1/2000	Manuscript submitted on the results of global simulations of atmospheric CO_2 using the improved model, including estimates of the geographic distribution of terrestrial sources and sinks obtained by inversion of the observational data (Task 7).
9/1/2000	Final Technical Report.

4. Summary

We have proposed a research program that will produce mechanistic simulations of interactions between the terrestrial biosphere and the atmosphere which control atmospheric CO_2 at local, regional, and global scales. Our results will allow the tower flux measurements to be generalized in both space and time, providing a means for NIGEC to leverage its investment in the data collection and to obtain regional and global estimates of sources and sinks of CO_2.The simulations will be validated and calibrated using data on the coupled system collected at flux towers located in at least three key ecosystems (boreal forest, native C_4 grassland, and C_3 agriculture), and will be useful in understanding the processes controlling the exchanges of CO_2 between the atmosphere and the land-surface. In addition, the experiments proposed here will provide insight into the role of interactions between physiology, atmospheric CO_2, and PBL meteorology in controlling surface climate, and should increase our ability to predict climate changes due to anthropogenic emissions of CO_2. The proposed work is to be seen as part of a collaborative effort involving at least four other teams currently funded by or proposing to NIGEC. This program will span several regions, and will help NIGEC move toward integrating results from many of its component programs.

5. Management Plan

5.1 Personnel

The research team has ample expertise and experience in performing the kinds of simulations proposed here. S. Denning implemented the calculation of the concentration and transport of atmospheric CO_2 in the CSU GCM, and has performed many experiments with the model (Denning, 1994; Denning *et al*., 1995). He has analyzed the effects of the covariance between PBL meteorology and carbon metabolism (Denning *et al*., 1996a,b), and used the model to calculate the global carbon budget of the atmosphere by inversion of the flask observations. J. Berry has been instrumental in developing models of photosynthesis (Farquhar *et al*., 1980), stomatal conductance (Ball, 1988), and the relationships between them (Collatz *et al*., 1991, 1992), which form the basis for the treatment of these processes in SiB2 (Sellers *et al*., 1992c, 1996a). He has already demonstrated the use of SiB2 in interpreting site data from the First ISLSCP Field Experiment (FIFE; Sellers *et al*., 1992a; Colello *et al*., 1996), and from the Boreal Ecosystem Atmosphere Study (BOREAS; Sellers *et al*., 1995). The investigators have been collaborating on research in the area of atmosphere-biosphere interactions since 1990.

5.2 Budget

A proposed budget for each of the three years is attached (Budget Summary Sheets), and justified (Budget Justification Sheets). The total project cost over three years is approximately $338,735. In the first year, $31,100 will support the purchase of permanent equipment (a workstation for the modeling work and data analysis and a Pentium PC for manuscript preparation, email, and other computing), and approximately $9,000 will support travel and supplies for the field measurement campaign described under Task 1 in section 3.3 above. Salary support for senior personnel will be minimal, with most of the budgeted salary used to support a scientific programmer and a Ph.D. student.

5.3 Computing

Model simulations will be performed on a high-speed, large memory workstation, which will be purchased with NIGEC funds in the first year of the project (see attached budget and justification sheets). We plan to purchase a Sun Ultra, model 2/200 workstation and associated hardware and software for about $25,000.

Global simulations on the Sun Ultra workstation will require approximately 1 week of real time per simulated year using a $4° \times 5°$ lat-lon grid with 17 levels and a time step of 6 minutes. These simulations require at least 128 MB of physical RAM, and will produce about hundreds of MB of output data per simulated year, so large memory and disk storage is essential. The regional simulations with RAMS will require about the same CPU and memory requirement on a 6 km grid.

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