SUMMARY SHEET

Title of proposal: Regional Estimation of Terrestrial CO_2 Exchange from NIGEC Flux Data, Satellite Imagery, and Atmospheric Composition

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Institution: Colorado State University

Total FY 2000/2001 requested $145,866___ (equipment $ 44,328_ travel $6,500__)

What hypothesis is to be tested or what question will be answered by the proposed research?

Question: What is the magnitude and distribution of the CO_2 sink over North America and how can we measure it?
Hypothesis: Regional-scale sources and sinks of CO_2 over North America can be reliably estimated by using coupled ecosystem-atmosphere models to interpret trace gas observations.

What is the importance of the question or hypothesis?

Establishing the distribution of the terrestrial carbon sink is an important part of our efforts to understand (and someday predict) it. We need to understand this in order to predict future CO_2 levels, and the interactions between the carbon cycle, climate, and human activities.

Summarize in two to four sentences (in non-technical terms) how your project will uniquely contribute to one or more of the critical questions relevant to society as well as to the Regional Center's thrusts, NIGEC, DOE and the global change community.

We will investigate the use of many types of atmospheric and satellite data to locate terrestrial carbon sinks in North America and understand how they work. We will do this by using models of biology and meteorology to link data collected at local scales into a larger “map” of CO_2 sources and sinks. We will contribute to the design of future measurement programs that address the question of the “missing” carbon sink.

Summary (200 words or less) of proposed work:

We propose an analysis of regional CO_2 budgets of North America, using coupled models of terrestrial ecophysiology and biogeochemistry and the physical climate system. The models will be driven by observed climates and by the time-varying observed state of the vegetated land surface as derived from satellite imagery. The coupled system will be used to predict atmospheric trace gas composition (CO_2, $\delta^{13}C$, and CO), which will be compared directly to measurements made at remote observing stations, tall towers, and by aircraft during the study period. Input data will include retrospective satellite vegetation imagery at 8 km for the period 1981-1999 and analyzed weather data. Methods will be tested at the WLEF tall tower site and in the ARM-CART Southern Great Plains site in Oklahoma, at both of which abundant atmospheric data are available. Model output will be used to test observing strategies and prioritize future data collection, as well as to estimate the carbon balance of subcontinental regions.

1. Introduction: Linking "Bottom-up" and "Top-down" Analyses of the Carbon Budget

The global carbon budget has been studied in terms of both local measurements and modeling of the processes involved, and in terms of the effects of these processes at hemispheric and global scale. The process-based studies are crucial to understanding and hopefully predicting changes in the Earth system that control the concentration of atmospheric CO_2, but the representativeness of any given field study is difficult or impossible to assess. The challenge to process-oriented researchers is to extrapolate their results to regional, continental, and global scales, from the "bottom up." Conversely, global inverse calculations of the carbon budget have the advantage of providing quantitative information about the integrated effects of biological, biogeochemical, and anthropogenic processes over huge spatial areas. These "top down" studies provide a spatially-integrated "snapshot" of the current state of he carbon cycle, but can provide little information about the processes responsible or how these might change in the future. Inverse methods are able to provide robust estimates of fluxes only at the largest spatial scales: global and hemispheric annual means are well constrained, but different transport models or inverse methods produce very different estimates of even continental fluxes on monthly basis (Fan *et al*, 1998; Rayner *et al*, 1999). The challenge to inverse modelers is to refine the resolution of their calculations to the point that they can provide a meaningful integral constraint for the "bottom-up" studies of processes.

Very few studies have addressed the gap in spatial scales between whole-ecosystem studies of long-term carbon flux by eddy covariance (with a "footprint" of perhaps 1 km^2) and time-dependent tracer transport inversions (which are difficult to interpret over areas much smaller than 10^8 km^2). This huge spatial gap was identified as a priority for future data collection in a recent set of recommendations for carbon cycle research (Sarmiento *et al*, 1999), but the design of mesoscale observing systems will require preliminary studies of the variability of CO_2 and other relevant tracers to be effective. The spatial gap between bottom-up process studies and top-down spatial studies involves more than missing data: filling it will require a concerted effort to develop new theory and methods as well. One advantage of research in the spatial gap is that advances in "upscaling" process-based understanding of CO_2 exchange will help to "downscale" the inverse methods, and vice versa.

Without a deliberate effort to develop methods and models to address the spatial gap in carbon cycle research, policymakers are left with absurd default methods such as multiplying the annual net ecosystem exchange (NEE) flux of each AmeriFlux site by the global area of its "biome" to estimate the terrestrial sink. A more sophisticated upscaling method has been recommended by Running *et al* (1999). They recommend the use of timeseries data collected at flux towers to develop robust models of ecosystem productivity that can be extrapolated using remotely sensed data on the state of the vegetation measured from satellites. This approach is likely to lead to significant advances, but will require a parallel effort to develop independent observational constraints at spatial scales larger than the flux footprints of the towers. A model developed and calibrated at 1 km^2 flux footprint scales is not well evaluated by either point measurements or by global CO_2 trends.

An alternative method for evaluating estimates of ecosystem-atmosphere carbon exchange on larger spatial scales is to use airborne instruments to measure atmospheric fluxes or. Both of these techniques provide only a “snapshot” of the ecosystem fluxes at the time of measurement, but have the advantage that they provide information on much larger spatial scales than flux towers. Airborne flux measurements are extremely expensive to collect, and involve essentially the same eddy covariance method as applied on towers, with sonic anemometers and high-frequency analyzers mounted on a low-flying aircraft (Desjardins *et al*, 1995, 1997; Dobosy *et al*, 1997). Concentration measurements are less expensive to collect, but more difficult to interpret. Measurements of spatial (and sometimes temporal) variations in atmospheric concentrations, turbulence, and winds are analyzed to estimate area-averaged fluxes by constructing mass balance budgets for the lowest couple of km of the atmosphere (Wofsy *et al*, 1988; Raupach *et al*, 1992; Denmead *et al*, 1996; Chou, 1999). CBL budget estimates from airborne concentration measurements have a footprint dictated by the structure of the turbulence, and may be more than 10^2 km^2. Airborne flux measurements have a footprint as large as the flight plan (and budget) allows, with a maximum coverage of perhaps 10^3 km^2.

Another enticing alternative is to apply the classic “top-down” techniques at the regional scale. This would involve routine collection of concentration data at many continental locations, and the use of regional tracer transport models and inverse methods to optimize estimates of fluxes. Tans *et al* (1996) proposed an operational sampling program for North America, for example, using light aircraft to sample weekly vertical profiles in the lower troposphere above about 100 locations. Such a program might be able to bridge the spatial gap and provide information about the spatial and temporal variations of carbon exchange on scales of 10^4 to 10^6 km^2, depending on sampling density and frequency. Unfortunately, the interpretation of CO_2 concentrations over the continents is complicated by severe local-scale variability due to heterogeneous vegetation, soils, anthropogenic emissions, and meteorological conditions. The global flask network has focused for 40 years on remote marine locations precisely to avoid this complexity.

These problems are addressed to some degree by repeated, routine sampling to characterize the time-mean state of the atmosphere, but interpretation of the time mean is also somewhat difficult due to strong covariance between ecosystem metabolism and atmospheric transport. Photosynthesis, PBL turbulence, and deep cumulus convection over land are all forced by solar radiation at the surface, so they are strongly correlated, 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. Denning *et al* (1995, 1996*a,b,* 1999) found that the covariance between CO_2 fluxes and transport 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. 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 surface observing stations (Masarie and Tans, 1995). 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).

Potosnak *et al* (1999) used a statistical deconvolution of the timeseries of continuous concentration measurements of several chemical species to separate the effects various influences on CO_2. They estimated the contributions of anthropogenic emissions (using CO as a surrogate for fossil fuels), the diurnal rectifier effect (by averaging by time of day), and the local offset of concentration in the surface layer (from local flux measurements), to obtain a presumably representative "background" value suitable for use in inversions. An ambitious aircraft sampling program (the CO_2 Budget and Rectification Airborne project – COBRA, Stephens *et al*, 1999; S. Wofsy, pers. comm.) was initiated in 1999. This will involve a series of measurements of multiple tracers (CO_2, CO, SF_6, $\delta^{13}C$, $\delta^{18}O$, O_2/N_2, and O_3) throughout the depth of the troposphere under various meteorological conditions, to characterize spatial and seasonal variability, observe the rectifier effect in nature, and investigate methods for mesoscale budgets.

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. Finally, we hope to develop and test methods for regional-scale CO_2 inversions, and contribute to the development of the next generation of continental carbon observing systems.

2. Objectives and Hypotheses

The broad objective of the proposed research is to *develop methods for regional extrapolation of the AmeriFlux sites which can be tested directly against atmospheric data*. In support of this general program objective, we identify the following **specific objectives**:

1) Extrapolate the carbon flux measurements made at three NIGEC-supported AmeriFlux towers to the scale of single GCM grid cells (10^5 km^2) using remotely sensed vegetation data and gridded weather analyses to drive the improved biophysical model coupled to a mesoscale atmospheric model (RAMS).
2) Evaluate the realism and spatial scaling of the CO_2 "rectifier effect" over forests, grasslands, and croplands by using a hierarchy of simulations at multiple spatial scales to analyze simultaneous continuous measurements of surface carbon flux and the structure of the PBL over diurnal, synoptic, and seasonal time scales.
3) Test several methods for estimation of area-averaged carbon exchange from concentration data, using "pseudodata" generated by the modeling system.

Hypotheses to be tested are:

H$_1$: Local-scale heterogeneity of vegetation and soils is “smeared out” by atmospheric transport with increasing measurement height (and flux footprint), so that measurements aloft can be used to estimate area-averaged fluxes

H$_2$: Covariance between ecosystem metabolism and PBL turbulence redistributes CO_2 in the vertical over terrestrial ecosystems, enriching the air near the surface in the time-mean and depleting it aloft (the “rectifier effect”)

H$_3$: Ecosystem models calibrated with tower data can be coupled to remotely sensed radiance and atmospheric models to estimate mesoscale CO_2 fluxes that can be evaluated using aircraft sampling

H$_4$: Total CO_2 concentration in the atmosphere can be decomposed into contributions from anthropogenic emissions, balanced “natural” background conditions, and a residual “net sink” using information about the variations of multiple trace gases in space and time.

H$_5$: “Upscaled” area-averaged fluxes from AmeriFlux sites can provide significant constraint on inverse calculations of carbon exchange over larger regions using synthesis inversion.

3. Proposed Methodology

We will develop and test methods for recovery of regional carbon balance from atmospheric data using both “bottom up” and “top down” techniques. We will use a land-surface model (SiB2) to predict spatial and temporal variations in NEE on multiple spatial scales at the WLEF forest site, and at a C_4 grassland site and a C_3 wheat site in Oklahoma. The land-surface model is coupled to a mesoscale atmospheric model (RAMS), so our simulations will predict ecosystem fluxes, weather, and atmospheric trace gas transport in a self-consistent framework. These simulations can be compared directly to the abundant atmospheric data at the WLEF and ARM-CART sites, so that systematic errors in the modeling system can be identified and corrected. They will also provide a regional context for the measurements made by other researchers in those areas (see section 4 below). The modeling system will be driven at these scales by analyzed weather (as a lateral boundary condition and an initial field), and satellite imagery (for specification of physiological parameters in SiB2). Model predictions, validated against local and regional atmospheric data, will then constitute process-based “maps” of carbon exchange and atmospheric properties across a domain of about 10^5 km^2 (centered on the towers) that are consistent with all available observations (fluxes, concentrations, climate, and vegetation properties measured from space).

Having tested the modeling system over the forest and grassland on spatial domains of hundreds of km, we will then use the modeling system to simulate CO_2, CO, and $\delta^{13}C$ for an entire annual cycle over the North American continent. This will be done by prescribing biophysical parameters from seasonally varying AVHRR data and running the mesoscale model in “climate” mode (ClimRAMS) on a 50 km grid. Weather on the lateral boundaries will be specified from operational analyses. We will prescribe trace gas boundary conditions from a global simulation with the CSU GCM (Denning *et al*, 1996b, 1999). The global fluxes associated with these trace gas boundary conditions will be optimized through synthesis inversion to ensure that concentrations are consistent with the NOAA flask network. The ClimRAMS simulation will then produce fully populated 3-dimensional fields of the trace gases on the 50 km grid which we will archive hourly for one year. These "pseudodata" will be consistent with the field measurements of ecosystem fluxes, with observed weather, with the state of the vegetation as measured from space, and with the NOAA flask measurements at the global scale.

We will investigate the feasibility of performing mesoscale inversions on these pseudodata, by assuming various configurations of atmospheric sampling networks that might be deployed in the future using aircraft, surface measurements, tall towers, or micrometeorological extrapolation ("virtual tall towers"). We will subsample the large pseudodata volume at this hypothetical network and try to recover the regional fluxes that produced it in the model. Unlike inversions of real data, we will know the surface fluxes *a priori*, so we will be able to rigorously evaluate these inversions and quantify the error in the results depending on the configuration of the hypothetical observing network. These studies will be essential for the design of continental observing systems in the future, and we will explore the ways in which stable isotopic tracers might add value to such a network.

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 three heights (30, 122, and 396 m) since May, 1995. 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, and from March through October of 1998 and 1999, 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. 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" at least 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 C_4 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 C_3 and C_4 canopies to environmental stresses, and because of the excellent observational control on the regional meteorology. Verma and Berry are already doing extensive testing, validation, and calibration of the SiB2 parameterization for these sites, so our proposal does not include this aspect (see attached letter of collaboration). Instead, we will build on their results by analyzing the vertical mixing of the surface CO_2 and $\delta^{13}C$ 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.

Model Descriptions

The Simple Biosphere Model (SiB2)

The Simple Biosphere (SiB) Model, developed by Sellers *et al* (1986), has undergone substantial modification (Sellers *et al*, 1996*a*), 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 (Sellers *et al*, 1996*b)* rather than prescribed from the literature. 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 (Farquhar et al, 1980), 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*, 1996*a,b*). Photosynthetic carbon assimilation is linked to stomatal conductance and thence to the surface energy budget and atmospheric climate by the Ball-Berry equation (Collatz *et al*, 1991, 1992). Recent improvements include the introduction of a 6-layer soil temperature submodel based on the work of Bonan (1996, 1998), an explicit litter layer (Denning *et al*, 1996*c*), and a revised surface energy budget that includes prognostic temperature and moisture in the canopy air space reservoir. Particular strengths of SiB2 for this project include the treatment of biogeochemistry, the fact that the model has already been coupled to a suite of atmospheric models across a spectrum of spatial and temporal scales, and the ability to specify the vegetation parameters from globally-available satellite imagery. We have used SiB2 to predict the exchange of CO_2 between the atmosphere and the vegetated land surface, and coupled the model to the CSU GCM to predict atmospheric CO_2 (Denning *et al*, 1996a,b). The coupled SiB2-GCM produced excellent agreement with the observed spatial and seasonal gradients, and is the only such global model that has yet been evaluated against diurnal data.

We have performed four-year simulations of the tower site with a 10-minute time step, forced by observed weather at the WLEF site. Results of these simulations have been compared to observed soil moisture and temperature, snow depth and water content, and fluxes of heat, water, and CO_2. The results have been generally encouraging in terms of the diurnal and seasonal fluxes (Fig 1), though we have identified needed improvements for soil thermal and hydrological processes (Denning *et al*, 1998).

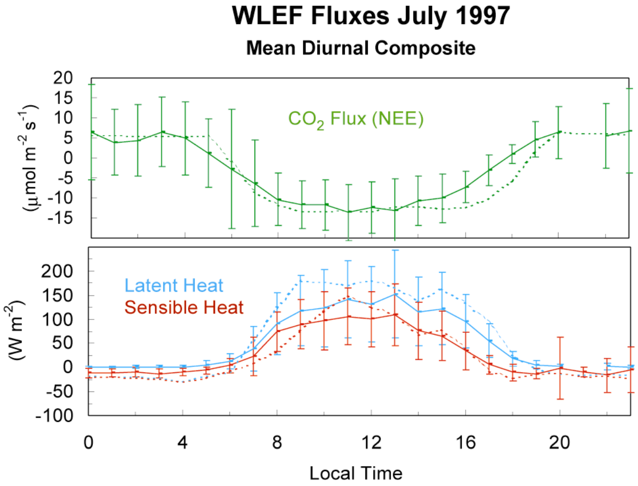

Figure 1: Diurnal cycles of fluxes of CO_2 (upper panel) and latent and sensible heat flux (lower panel). Solid lines show the observations, with 1σ "error bars" . Dotted lines indicate model simulation.

A parallel effort at the Carnegie Institution of Washington has produced a new parameterization of carbon and nitrogen allocation, growth and maintenance respiration, and microbial decomposition based in part on the CASA model (Potter *et al,*1993; Field *et al*, 1995). Unlike CASA, the new parameterization uses the new multilayer soil physics scheme in SiB2 to treat carbon and nitrogen cycling in a spatially (vertically) explicit manner, rather than being limited to integrated conceptual "pools." This model is already being implemented and tested in SiB2, both at the site level and globally. Under separate funding, algorithms for predicting the fractionation of stable carbon isotopes during photosynthesis and the isotopic disequilibrium of respired CO_2 have now been implemented in SiB2. Photosynthesis discriminates against the heavier ^{13}C during both diffusion into stomatal pores and biochemical fixation by carboxylation. The relative contribution of diffusion and carboxylation to this process, and hence the overall effect on the $\delta^{13}C$ of atmospheric CO_2, depend on the local environment of the plant (physiological stress, stomatal conductance, assimilation rate), which is predicted on a minute-by-minute basis in SiB2. C_4 plants have a biochemical mechanism that concentrates CO_2 near the carboxylation site, so the fractionation process is dominated by diffusion, which has a weaker ^{13}C signature. The isotopic submodel makes use of a prognostic canopy air space storage reservoir for trace gases, and can therefore be directly compared to field data for model evaluation.

Unlike many land-surface schemes used in climate and numerical weather prediction models, which treat all grid cells of the same vegetation class as identical, vegetation properties are specified from remotely sensed data allowing heterogeneous vegetation properties within a group of broadly similar grid cells (Sellers *et al*, 1996*b*). Thus we require far fewer biome classes (with their sometimes rather arbitrary parameter values), and the properties of a given grid cell can change with time.. Monte Carlo simulations with SiB2 at the WLEF site revealed that simulations run with the "default" parameters chosen from the a 1° global grid produced among the very best agreement with observed fluxes for a three-month period out of 10,000 realizations (Prihodko *et al*, 1998).

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 (Walko *et al.* 1995) allows for a wide range of motion scales to be modeled simultaneously and interactively. For example, with nesting, RAMS can feasibly model mesoscale circulations across the entire North American continent on a 50 km grid, 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).

For the research proposed here, we will develop methods for the simulation of carbon monoxide (CO) in the model, including prescribed emissions, tracer transport, and photochemical oxidation. Our interest in CO is not to develop a full-blown atmospheric chemistry code, but rather to diagnose spatial and temporal patterns of CO over a mesoscale domain. This will be used to test methods for observational decomposition of measured CO_2 concentrations in terms of anthropogenic and "background" components (Potosnak *et al*, 1999).

We have also used the coupled SiB2-RAMS model to investigate the propagation of the "signal" of forest-atmosphere CO_2 exchange into the atmosphere in the neighborhood of the tower. These simulations are crucial in terms of our Objective 2 (testing the atmospheric rectifier effect in nature and in the models). The vertical variation of CO_2 concentration has been measured at the WLEF continuously, day and night, since 1995. These data provide an excellent test of the ability of the model to realistically capture the covariance between ecosystem metabolism and atmospheric mixing.

The model was initialized with a uniform concentration of CO_2, and a nearby atmospheric sounding of meteorological variables, and then allowed to evolve for several days. These were also large-eddy resolving simulations, with a 200 m horizontal grid and a 30 m vertical grid. Lateral boundary conditions were assumed to be periodic, with outflow downwind becoming inflow upwind, and cloud-free July 1 radiation forcing was used. Turbulence generated in RAMS was fully interactive with the surface budgets of energy and momentum calculated by SiB2, and vice versa. Rates of photosynthesis and respiration calculated by SiB2 were used to calculate surface-layer CO_2 concentrations in RAMS, and the perturbed CO_2 fields were acted on by the simulated turbulence. An example of the results of one such calculation is shown in Fig 2. The concentration of CO_2 is depleted by photosynthesis during the daytime hours, and this biological influence is "felt" through about 1500 m of the vertical

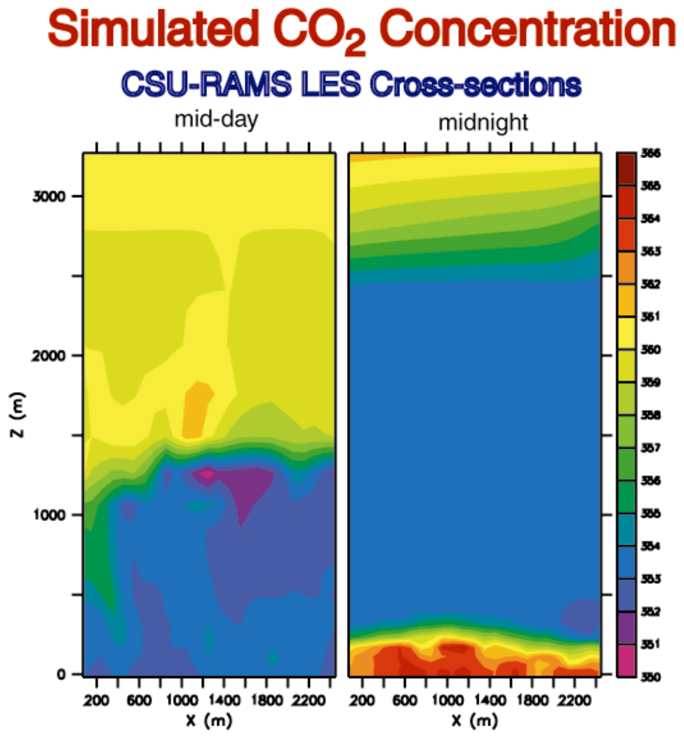

Figure 2: Vertical cross-section of simulated CO_2

domain of RAMS. At night, the simulated respiration exceeds photosynthesis, so that the flux of CO_2 is into the atmosphere, but RAMS simulates a stable inversion. This traps the respired CO_2 near the ground, leading to much higher positive concentration anomalies at night than the negative anomalies during the day, even though the magnitude of the nighttime fluxes is less than 1/3 of the daytime values.

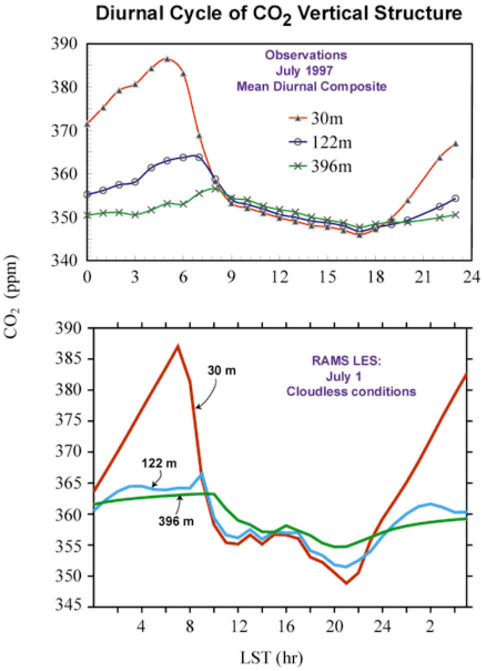

Figure 3: Timeseries of CO_2 concentration at 3 heights

We have compared the results of these simulations to data collected at the tower, and find the results to be very encouraging (Fig 3). Both the observations and the simulations show a much stronger diurnal cycle of CO_2 concentration at the bottom of the tower than the top, with about 35 ppm diurnal amplitude at 30 m above the ground. The CO_2 which accumulates near the bottom of the tower under the nocturnal inversion is mixed upwards in the morning as solar heating initiates turbulent convection, reaching the 122 m level in the first hour and the 396 m level a couple of hours later. The vertical gradient then reverses during the daytime, as CO_2 is removed from the air by photosynthesis in the forest. At sundown, longwave cooling in the forest exceeds the shortwave heating, and a stable layer forms again, with CO_2 concentration rising rapidly at 30 m although well-mixed conditions persist aloft for awhile. Eventually, the concentration rises at the 122 m level, and there is some suggestion in both the data and the model of “leakage” to the 396 m level as well, probably as a result of intermittent “bursts” of turbulence somewhere in the domain.

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, to evaluate the realism of the simulated rectifier effect, and investigate the interactions between biophysics, the surface energy budget, and PBL structure. We will evaluate the effects of horizontal inhomogeneities on carbon fluxes, the surface energy balance, atmospheric transport and concentration and stable isotopic composition of CO_2.

Simulations

We will simulate the spatial and temporal variations at both the WLEF and ARM-CART sites in SiB2-RAMS using a set of nested grids. The outer grid will be about 1700 km across, with a horizontal grid spacing of 64 km, with weather at lateral boundaries forced from NCEP operational analyses and tracer boundary conditions forced from the output of a global simulation with the CSU GCM. Two-way interactive nested grids will be run with spacing of 16, 4, 1, and 0.25 km within this outer grid. The innermost grid will resolve vegetation heterogeneity in the tall tower footprint and the vertical variations measured on the tower. Biophysical

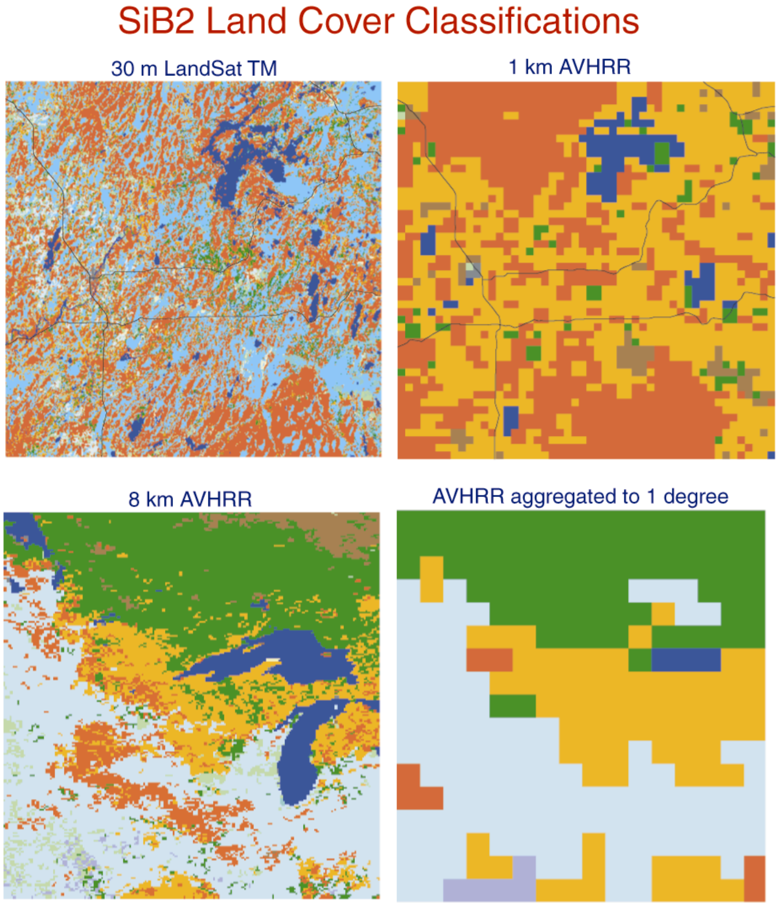

Figure 4: Vegetation classifications derived from satellite imagery centered at WLEF at 4 resolutions. Top panels are 50 km square; bottom panels are 1700 km square.

properties of the vegetation will be specified from remotely sensed data products (NDVI and subpixel mixtures of woody and herbaceous vegetation derived from 1 km AVHRR by Defries *et al*, 1999 for the outer grids, and 30 m LandSat Thematic Mapper imagery for the innermost grid, see Fig. 4). These simulations will be compared against tower data and also against flasks collected further aloft during the August 2000 intensive observing campaign over WLEF by John Birks' team using balloon and kite soundings, Ron Dobosy's team using the LongEZ aircraft, and Steve Wofsy's COBRA team up to 10 km. These campaigns will allow us to evaluate the fully coupled modeling system at multiple spatial scales (see section 4 below).

The results of the high-resolution coupled RAMS-SiB2 simulations will include realistic fully populated grids of CO_2, $\delta^{13}C$, and CO over the upper Midwest, which we will use to test methods for regional extrapolation from surface measurements over the land surface. These tests will include (1) Convective boundary-layer budgets with footprints on the order of 10 km, which attempt to solve for fluxes by mass balance of a 1-D layer of air using locally-measured concentration profiles (e.g., Chou, 1999); (2) Convective-advective mass balance using aircraft vertical profiles and upwind transects, coupled with back-trajectory analysis, emissions inventories, and mesoscale meteorological modeling (e.g., Desjardins *et al*, 1997); (3) Statistical "adjustment" of tower-based observations to correct for anthropogenic emissions, diurnal variability, and local fluxes (Potosnak *et al*, 1999); (4) Estimation of mid-CBL isotopic ratios using the "virtual tall tower" concept pioneered by Ken Davis, in which AmeriFlux data may be used to correct for local offsets to concentrations due to strong surface fluxes and turbulence to obtain regionally-representative "background" values appropriate for use in inversions; and (5) Mesoscale synthesis inversion of hypothetical concentration measurements made at NIGEC flux towers and by routine aircraft sampling. These "pseudodata" inversions are intended to provide guidance to the design of future regional sampling programs.

4. Relevance

DOE Mission, NIGEC Cross-Regional Initiative, SouthCentral Regional Thrust

The fit between the objectives of the proposed research and the research priorities of NIGEC is excellent at all three levels described in the RFP. At Level A, We address DOE's Global Change Research Priorities in program areas (2) Atmospheric Chemistry and Carbon Cycle, and (3) Ecological Processes. At Level B, we address NIGEC's Cross-Regional Initiative (2) The AmeriFlux Network of Whole Ecosystem Flux Sites. At Level C, we address the second Regional Thrust of the SouthCentral Regional Center, Net Ecosystem Exchange (See page 13 of the RFP). In particular, we "emphasize scaling of flux measurements from leaf to forest scales" and beyond. We will provide a framework for the interpretation of "precise CO_2 measurements to assist in validation of scaling studies." We make use of "existing flux measurements" and "provide direct input to researchers making these measurements." Finally we hope to "add value to existing research efforts," both at the WLEF site and at the Oklahoma AmeriFlux sites.

Coherence with Related Research

The research proposed here is part of a coherent program in local-to-regional-to-continental scaling that has emerged across multiple institutions, multiple regional centers, and even multiple funding agencies. Table 1 briefly summarizes 16 other related research projects that, taken together, constitute a major multidisciplinary program which addresses the development of scaling methods for terrestrial carbon balance in North America.

Many of the investigations of spatial scaling focus on the WLEF-TV tower AmeriFlux site in northern Wisconsin. The site has attracted multidisciplinary research from several institutions in the past, leading to the designation of the "Chequamegon Ecosystem-Atmosphere Study" (ChEAS, http://cheas.umn.edu). This reflects the value of the tall tower site with its nearly five-year continuous record of eddy covariance measurements (Peter Bakwin, PI) made at three heights (30 m, 122 m, 396 m above the ground), as well as a wealth of ancillary data on CO_2 concentration, micrometeorology, physiology, soil physical and hydrological properties, etc. The great height of the tower allows scaling methods to be directly tested against the observed fluxes, which have an enormous footprint at the top of the tower. Vince Gutschick has been conducting ecophysiological measurements in the tower footprint for several years, characterizing the variations in controls on photosynthesis at leaf, branch, canopy, and stand level across all major species and at various depths within the canopy. Paul Bolstad also makes crucial field measurements in the WLEF footprint, and measures fluxes in "end-member" ecosystems (upland maple and lowland spruce) using eddy covariance on "short" towers. These two studies have been important for our model development activities, both in terms of theoretical representation and for parameter validation. Jim Ehleringer is proposing to NOAA to lead an effort to measure ecosystem fluxes of ^{13}C and ^{18}O in CO_2 at WLEF and at several other sites. These measurements would allow us to more realistically parameterize stable isotope exchange in SiB2, and to predict multitracer distributions in the regional atmosphere (Denning is a Co-Investigator on this research). Lara Prihodko is funded by NASA to investigate the land-atmosphere fluxes near WLEF using SiB2 driven by satellite data at multiple resolutions, from 30 m TM imagery to 8 km AVHRR.

Table 1: Related Scaling and Integration Studies Using Data from AmeriFlux Sites

Theme	*PI (Institution)*	*Funding*	*Site(s)*	*Activity*
Ecosystem-scale Measurements and Modeling	Vince Gutschick (NMSU)	NIGEC South-Central	WLEF	Leaf-canopy-landscape measurements and modeling
	Paul Bolstad (UMn)	NIGEC Midwest	WLEF, nearby upland and wetland flux towers	Component and whole-ecosystem carbon flux measurement, modeling, and scaling
	Ned Patton (UMn)	NIGEC South-Central	WLEF, others	Large eddy simulation of flux footprints and surface-layer flux-gradient relationships
	Jim Ehleringer (Utah)	NOAA OGP GCC	WLEF, ARM-CART, others	Stable isotopic exchange associated with fluxes
	Jiquan Chen (Mich.Tech)	NIGEC Midwest	N. Wisconsin	Mobile flux towers in 10 landscapes over 3 years
	Shashi Verma and Joe Berry	NIGEC Great Plains	Ponca City, OK and Shidler, OK	Flux measurements & modeling of NEE of C_3 and C_4 ecosystems
Larger-Scale Atmospheric Measurements for Scaling	Peter Bakwin (NOAA/UColo)	NIGEC Midwest	WLEF	Multi-level continuous measurement of scalars and fluxes in surface and mixed layers
	Ken Davis (UMn)	DoE (TECO), NSF	WLEF, Walker Branch	PBL Soundings with Radar and Lidar
	John Birks (UColo)	NIGEC Great Plains	WLEF, Ponca City	Soundings in and above CBL with kite and balloon borne sensors
	Steve Wofsy (Harvard)	COBRA: DOE , NSF, NOAA	WLEF, Harvard Forest, Oak Ridge, regional	Aircraft campaigns with continuous multitracer vertical profiles and horizontal transects
	Ron Dobosy (NOAA)	NOAA OGP GCC	WLEF	Spatial variation of ecosystem fluxes and high-precision CO_2 (LongEZ flux aircraft)
	Ken Davis (UMn)	NSF Career Development, NOAA OGP GCC, NIGEC South Central	Several	“Virtual tall towers” using high-precision CO_2 and CBL scaling
Remote Sensing Studies for Scaling	Stith T. Gower (Wisc)	NASA EOS Cal-Val	WLEF and others	Local to regional scaling of land-cover with multi-scale imagery
	Lara Prihodko (CSU)	NASA ESS Fellowship	WLEF	Local to regional scaling of land-cover with multi-scale imagery
Modeling Studies of Regional Fluxes	Scott Denning (CSU)	NIGEC South Central	WLEF, ARM-CART, North America	Coupled SVAT-tracer models, remote sensing, inverse modeling
	Scott Mackay (Wisc)	NASA LSHP	N. Wisconsin	Remote sensing/GIS, historical data analysis, and SVAT modeling

The work at ChEAS is now progressing upward and outward to include larger scale measurements and modeling. Jiquan Chen is proposing to use mobile flux towers to measure fluxes across a range of landscapes in the WLEF region, which would be extremely valuable as an assessment of variability, as well as for evaluating upscaled model results. Ned Patton is proposing a modeling study of the canopy-to-surface layer turbulent fluxes with an extremely high-resolution (2 m) atmospheric model that resolves canopy elements and associated coherent turbulent motions. These exchanges are unresolved in our modeling studies. We would benefit from better characterization of these canopy-scale fluxes, and we could contribute to Patton's work both in terms of ecophysiological process modeling and larger-scale extrapolation of his results. Ken Davis has now been measuring the depth of the PBL using a radar and lidar sounding system for two growing seasons at WLEF (Denning is a Co-Investigator on this research). These measurements, taken together with the eddy flux and vertically resolved concentration measurements at the tower, constitute the first ever observational study of the CO_2 rectifier, on both diurnal and seasonal time scales. Ron Dobosy is proposing to characterize the spatial variability of ecosystem carbon flux and CBL CO_2 concentration in the WLEF area. These measurements are exactly what we are predicting in the coupled models, so they would be extremely useful for model evaluation. John Birks is funded to measure vertical profiles in and above the PBL over multiple diurnal cycles. This will allow evaluation of theoretical methods to estimate mid-CBL conditions from surface layer concentrations and fluxes by accounting for turbulent flux divergence and entrainment at the CBL top. Such calculations, directly testable against the WLEF timeseries together with Birks measurements, are the basis of Ken Davis's proposal to create a network of "virtual tall towers" by instituting accurate and precise CO_2 measurements at several AmeriFlux sites. If this work is successful, it could eventually double the number of observing sites where routine CO_2 measurements are made (relative to the NOAA flask network), and add much greater spatial detail to regional inverse modeling (Denning is a Co-Investigator on this research). Steve Wofsy leads a multiyear effort to measure concentration variations of seven trace gases from the PBL up to 10 km over WLEF, across regional transects, and over other AmeriFlux sites. These data will be used to estimate surface exchanges over large areas. Our work will directly address the validity of these estimates, and we will benefit tremendously by having high-quality data aloft in the study area, since our models will predict what the airborne campaigns measure.

The multi-institutional program in scaling has grown beyond the WLEF tower, with cross-regional measurement and modeling activities. Shashi Verma and Joe Berry are conducting multiyear measurements of net radiation, turbulent fluxes of CO_2 and sensible and latent heat at two AmeriFlux sites in the ARM-CART site in Oklahoma. Their measurements address the differences in ecophysiological processes controlling the fluxes over C_3 vs. C_4 ecosystems in the Great Plains, and therefore have relevance to both the isotopic studies (C_4 photosynthesis exerts much weaker fractionation of ^{13}C than for C_3 systems) and to ecological responses (C_4 systems represent a present-day analog for grasslands under enhanced CO_2). The location of these sites in the DOE ARM CART region provides unique opportunities to test models of regional scaling of fluxes and atmospheric states, because the meteorology and vertical structure is so well characterized by ARM. We will target this areas as a major focus for evaluation of our upscaling calculations, so that we can exercise the modeling system in two very different but both well-observed land-atmospheric regimes (moist forest, semiarid grassland, and cropland).

5. Specific Tasks to be Performed

Task 1: Regional calibration/extrapolation at WLEF and ARM-CART sites; comparison to data collected during intensive observing periods

We will perform high-resolution simulations of coupled ecosystem-atmospheric processes over the regions surrounding both the WLEF and ARM-CART sites. These will be done on a nested grid that is forced using analyzed weather at lateral boundaries but also resolves observable vertical structure at the towers. Vegetation properties will be prescribed using 30 m TM data on the innermost grid, and coarser AVHRR data on the outer grids. At WLEF, we will compare with tower, balloon, kite, and aircraft data collected by related projects (see Table 1). For the ARM-CART sites we will use the excellent array of meteorological data produced in the ARM IOPs to set lateral boundary conditions and evaluate simulated mesoscale atmospheric structure. These simulations will provide a detailed local-to-regional characterization of the CO_2 rectifier effect and the realism of its representation in the models.

Task 2: Pseudo-data tests of CBL budgets using "virtual aircraft" with 1-D convective and 3-D advective-convective analyses

We will use the results we obtain from Task 1 to evaluate different methods of estimating area-averaged ecosystem fluxes from airborne sampling platforms. These will include measuring the time rate of change of vertically integrated tracer mass (Chou, 1999) and mass balance budgets of the CBL using combinations of vertical profiling and upwind transects to quantify both convection and advection. These analyses will be performed on 3D grids obtained over the study regions in Task 1, in which we know the area-averaged flux and can evaluate concentration fields against abundant data. These analyses are expected to contribute to the design of "upscaling" methods to estimate area-averaged fluxes at scales of 10^2 to 10^3 km^2 from measurements of the real atmosphere.

Task 3: Continental-scale simulation of CO_2, CO, and $\delta^{13}C$ using SiB2 and ClimRAMS

Using gridded operational analyses to specify lateral boundaries and satellite data to specify time-varying vegetation parameters, we will perform continental-scale simulations of three carbon trace gases in SiB2-ClimRAMS over a full annual cycle. Lateral boundary conditions for trace gases will be made consistent with NOAA flask data through global synthesis in version with the CSU GCM. The results will be archived hourly on a 50 km grid at 20 levels in the vertical. They will include full diurnal cycles, and synoptic and seasonal variations of surface fluxes and concentrations, turbulence, and transport. They will allow us to investigate the "signal to noise" problem in estimating annual mean fluxes from atmospheric concentrations.

Task 4: Mesoscale inverse modeling using available concentration data and simulated pseudo-data.

Using the fully populated 3D grids of continental trace gas concentrations from Task 3, we will test methods for mesoscale inverse calculations of regional carbon budgets from atmospheric observations. We will subsample our pseudodata grid according to statistical methods at AmeriFlux sites (Potosnak *et al*, 1999) and using the "virtual tall tower" extrapolation method suggested by Ken Davis. We will test the feasibility of using routine airborne sampling to recover time- and area-averaged fluxes from subcontinental regions. We will evaluate various observing strategies to provide guidance to the design of future sampling programs: for a desired accuracy, we will be able to prioritize where, how often, and how high samples are collected, and which gases will need to be measured.

6. Deliverables and Due Dates

7/15/2001	Annual Progress Report for Year 1.
9/1/2001	Manuscripts submitted on mesoscale simulations and observations at WLEF and ARM-CART, and comparing simulated CBL budgets to data collected by COBRA program
12/2001	Conference paper delivered at Fall Meeting of the American Geophysical Union, on regional scaling of carbon fluxes at WLEF and ARM-CART sites
7/15/2002	Annual Progress Report for Year 2.
12/2002	Conference paper delivered at Fall Meeting of the American Geophysical Union, on mesoscale inversion of pseudodata collected by a hypothetical continental observing system across North America.
6/1/2003	Manuscript submitted on the results of regional inverse modeling of atmospheric CO_2 using both mesoscale pseudodata and global flask and aircraft data, with recommendations for observing system design
9/1/2003	Final Technical Report.

7. Management Plan

Prof. Scott Denning worked for about 10 years on analysis of the concentration and transport of atmospheric CO_2 using coupled land-atmosphere models, and is a leader in this area. He was one of the first investigators to recognize the importance of the rectifier effect for interpretation of global data. He leads an international intercomparison project of CO_2 inverse models (TransCom), and coordinates a large research group pursuing related work with SiB, RAMS, and the CSU GCM. Dr. Marek Uliasz has worked on trace gas transport at multiple spatial scales for over 20 years. He has specialized in the development of Lagrangian particle trajectory analysis relating emissions to observed concentrations, and has published many articles on his work. Lara Prihodko has more than eight years experience with the analysis of satellite vegetation data at multiple spatial scales, and has generated maps of SiB2 parameters for Wisconsin and Brazil. She has performed tens of thousands (!) of seasonal simulations with SiB2, and has analyzed parameter sensitivity at the WLEF site.

The proposed research will require very substantial computing resources, both for integrating the models and for storage of the output. We request $44,328 in the first year of the project to upgrade our existing SGI Origin 2000 compute server to enable these simulations.

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