Title: Regional ecosystem-atmosphere CO_2 exchange via atmospheric budgets

Principal Investigators: A. Scott Denning, Colorado State University, and
Kenneth J. Davis, The Pennsylvania State University
Co-Investigator: Scott Richardson, The Pennsylvania State University

Budgets:

Sep 2002 – Feb 2003: $37,648
Mar 2003 – Feb 2004: $121,868
Mar 2004 – Feb 2005: 127,166
Mar 2005 – Aug 2005: $66,395

Total (3 years): $353,077

Project Summary:

We propose to estimate regional fluxes of CO_2 by three independent and complementary methods, in order to develop and test modeling and observational methods. We will evaluate the utility of continuous, highly accurate measurements of the mixing ratio of CO_2 in the atmospheric surface layer for regional flux estimation by inversion of a mesoscale transport model. Regional flux estimates will be compared to calculations made by a gridded ecophysiological model (from the "bottom up"), and to estimates from a highly resolved global data assimilation model (from the "top down").

Instrumentation for a regional network of six to eight high-precision, high-accuracy CO_2 mixing ratio measurements will be developed and deployed on a regional network of surface layer flux towers. Two regional experiments will be conducted, one during the growing season and one during a season of net respiration. Airborne measurements will also be employed whenever possible. This regional network of CO_2 measurements will be nested so as to sample CO_2 mixing ratio changes over the course of a few hours (tower spacing of ~100km) and over the course of a day (tower spacing of ~400km). These methods will be important components of the planned North American Carbon Program.

Suggested reviewers:

David Hollinger/Bev Law/Jim Randerson/David Baker/Dave Schimel

Results from prior support most relevant to this proposal:

WLEF tall tower research: Flux and mixing ratio profile measurements from the 447 m WLEF TV tower have been collected, analyzed, and made available to the scientific community via submission to the AmeriFlux and Fluxnet programs. Data collection started in 1995. Publications have documented analyses of the mixing ratio profile data (Bakwin et al, 1998), persistent horizontal advection in the atmospheric boundary layer (Yi et al, 2000), flux measurement methodology (Berger et al, 2001), and the annual cycle of CO_2 and H_2O fluxes, detailed error analysis of the annual cumulative CO_2 flux, and comparison of eddy fluxes and boundary layer CO_2 budgets (Davis et al, 2002).

Willow Creek, Lost Creek and Sylvania flux towers: Ongoing eddy covariance flux measurements have been established at three sites near the WLEF tower, an upland forest, a wetland, and an old growth forest. An annual cycle of fluxes from Willow Creek (upland forest) has been analyzed. The annual cycle of fluxes is similar to WLEF, but differs in that the rate of summer uptake and net annual uptake are both much larger than the values at WLEF (Cook et al, submitted). Comparisons with the Lost Creek wetland and the Sylvania wilderness old growth flux towers are ongoing.

Vertical profiles and mixing of CO_2 in and above the atmospheric boundary layer:

Methodology for interpreting surface layer mixing ratio data that is central to this proposal was developed via tall tower and radar observations at WLEF (Davis et al, 1998). A close relationship was found between daytime atmospheric boundary layer (ABL) depth and the surface energy balance (Yi et al, 2001), providing a means of estimating vertical mixing in fair weather in the absence of a boundary layer radar or similar technology. Results from WLEF are being extended to Walker Branch. The diurnal and seasonal patterns of ABL CO_2, tropospheric CO_2, and marine ABL CO_2 have been explored via observations from WLEF (Yi et al, in preparation) and results are being extended to Walker Branch, NOBS and Harvard Forest. The aim is to test the ability of numerical models to simulate the diurnal and seasonal cycles of CO_2 fluxes, mixing ratios and ABL depths at continental sites. This work was the observational focus of the DoE/TCP project that we are proposing to renew.

ABL CO_2 budgets and regional flux estimates:

Davis et al (2002) analyzing WLEF data, and Bakwin et al (in prep) analyzing WLEF, NOBS and Harvard Forest data, find that transport and local NEE of CO_2 are both important contributors to the ABL budget of CO_2 except at NOBS in Manitoba where the ABL budget appears, on a monthly average basis, to be dominated by local fluxes. These results imply that regional and continental CO_2 measurement networks would be critical to determining regional NEE of CO_2 from an ABL budget approach. Helliker et al (in prep), however, when adding water vapor to an ABL budget analysis conducted at WLEF, suggest that similarity between water vapor and CO_2 may provide a means of removing the influence of advection on the ABL CO_2 budget and computing regional NEE of CO_2 entirely from a single tower. This suggests that joint analysis of CO_2 and water vapor data may improve regional inverse analyses of NEE of CO_2. Hurwitz et al (in prep) have described several rapid changes in ABL CO_2 mixing ratios, the associated frontal passages, and vertical and horizontal gradients in CO_2 over continental scales. Another manuscript focuses on powered parachute profiles of CO_2, their utility in deriving regional NEE of CO_2 on fair weather days, and the seasonal evolution of the gradient in CO_2 between the ABL and the troposphere over two mid-continental sites. The most recent powered parachute field campaign was co-located with a low-budget regional CO_2 mixing ratio network deployed during the International H_2O Project (IHOP) as a trial for the project proposed here. Finally, the high-precision and accuracy CO_2 measurements at WLEF and Willow Creek have been used as a micro-scale regional network to compute horizontal advection between these towers (Wang et al, in prep).

Chequamegon Ecosystem-Atmosphere Study (ChEAS): Collaboration with an interdisciplinary group of researchers across multiple institutions has resulted in the establishment of this program (http://cheas.psu.edu) including an ongoing series of scientific meetings, and submission of a group of papers for a special issue of Global Change Biology. Collaboration among groups is now facilitated by an NSF research collaboration network grant (Davis, PI).

Ecophysiological simulation modeling of the WLEF region: We have performed multiyear simulations of the WLEF site with SiB2, evaluated the model against tower data, and diagnosed its strengths and weaknesses (Baker et al, submitted to GCB). Model parameters have been derived for the upper Midwest from satellite imagery and soils data on a 1 km grid (Prihodko et al, in prep).

Coupled SiB2-RAMS modeling system for predicting regional fluxes and CO_2 concentration.

We have developed and tested a mesoscale model of coupled ecophysiological and meteorological processes and performed several experiments with it. Denning et al (2002) reported on eddy-resolving simulations of PBL development and CO_2 variations near WLEF. We have performed a 5-day simulation of a $(600\ km)^2$ domain using a nested grid and compared the results to local observations (Nicholls et al, submitted to JGR).

Evaluation of Boundary Layer parameterization in a General Circulation Model: Day-by-day and seasonal cycle comparison of simulated and observed PBL depth at WLEF using the CSU GCM, radar wind profiler data and vertical profiling of CO_2 (Zhang, 2002)

Modeling framework for deriving mesoscale surface fluxes: Bayesian synthesis inversion methodology applied to estimate variations of regional CO_2 fluxes from concentrations measured at towers and by aircraft, using a mesoscale atmospheric model to drive Lagrangian particle dispersion calculations (Uliasz et al, in prep.)

Project Description

1. Introduction

The atmospheric burden of CO_2 is steadily increasing in response to widespread anthropogenic combustion of fossil fuels, approximately 7 PgC yr^{-1} of emissions to the atmosphere. A large portion of this carbon, about 4 PgC yr^{-1}, is absorbed by the earth's oceans and terrestrial ecosystems. This uptake varies annually from 1 to 6 PgC yr^{-1} (Conway et al, 1994). Approximately one-half of this large and variable sink is believed to be due to net uptake by terrestrial ecosystems (Ciais et al, 1995; Battle et al, 2000). Understanding the causes and documenting the spatial distribution of this terrestrial sink of carbon are primary goals of carbon cycle science. Another primary need is to understand the cause of the large interannual variability in the terrestrial carbon sink. Such understanding would enable us to better predict the future response of the carbon cycle to climate and land use change, and may suggest ways to mitigate climate change via management of the terrestrial carbon cycle. Progress is hampered by our limited ability to quantify the terrestrial carbon cycle on appropriate spatial and temporal scales. Measurements of ecosystem-atmosphere CO_2 exchange that integrate over domains of similar ecosystem and climate, and across seasons would greatly extend our understanding of the terrestrial carbon cycle.

Current atmospheric techniques for measuring the exchange of carbon dioxide between the earth's surface and the atmosphere yield results representing disparate spatial scales. Tower-based eddy covariance measurements provide estimates of net ecosystem-atmosphere exchange (NEE) at scales ranging from 0.01km^2 to 10 km^2 (e.g. Wofsy et al, 1993), whereas global CO_2 mixing ratio measurements provide the means to infer (by inversion of atmospheric tracer transport) NEE at hemispheric and perhaps continental scales (e.g. Enting et al, 1995; Fan et al, 1998; Rayner et al, 1999; Bousquet et al, 2000; Gurney et al, 2002). Estimating carbon fluxes using both methods has been critical to elucidating the processes that govern the terrestrial carbon cycle: tower-based methods provide an understanding of specific mechanisms that govern carbon fluxes in particular ecosystems (e.g. Goulden et al, 1998; Baldocchi et al, 2001), while inverse estimates of NEE integrate the effects of all the physical, biogeochemical, and anthropogenic processes operating over large scales.

Models of ecosystem physiology, evaluated at flux sites, can be used to extrapolate to larger scales using remotely sensed imagery and analyzed climate data (e.g., Denning et al, 1996; Schaefer et a, 2002). Such calculations allow the analysis of the full space and time variations of ecosystem carbon balance, but are difficult to evaluate against observations at larger scales.

Ultimately, the integral of predicted fluxes must be compared to inverse analyses, but these currently provide information only at very large (continental) scales because of the sparse network of background CO_2 measurements. This is inadequate for model testing because many of the processes believed to be responsible for long-term carbon sinks (e.g., forest regrowth, woody encroachment) are not amenable to eddy covariance measurements or represented in ecophysiological models (Casperson et al, 2000; Pacala et al, 2001; Moorcroft et al, 2001; Birdsey and Heath, 2001; Hurtt et al, 2002). Testing the impact of these "slow" ecosystem processes on terrestrial carbon budgets will require independent estimation of carbon exchange on regional scales. This may be possible eventually through the use of remotely sensed

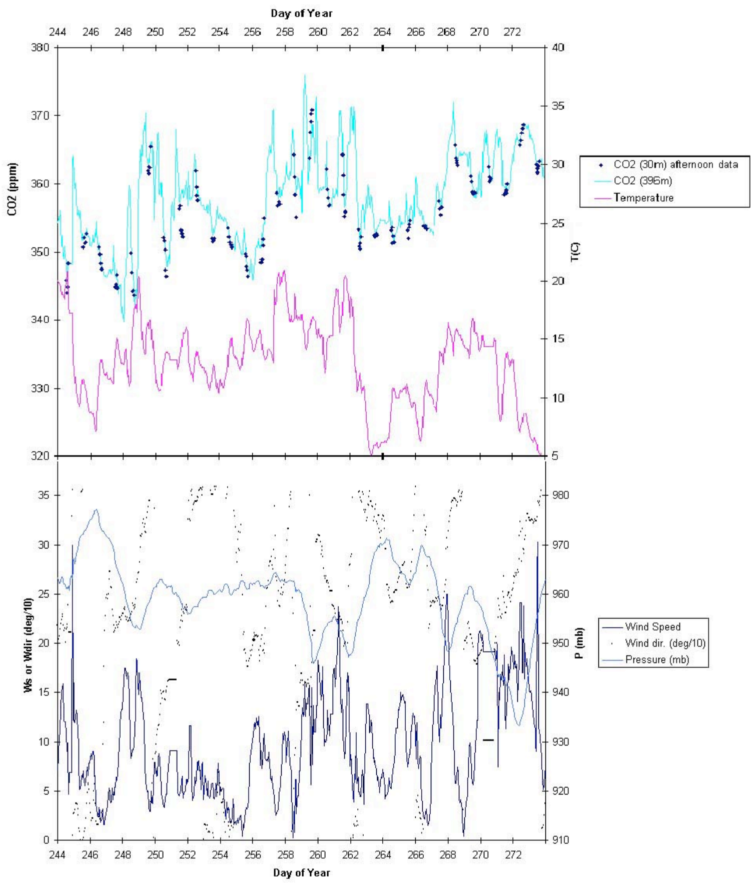


Figure 1: 1997 timeseries of CO_2 measured at two heights on the WLEF-TV tower. Meteorological variables are also plotted to show influence of wind directions and frontal passages.

atmospheric CO_2 mixing ratios (Rayner and O'Brien, 2001, Engelen et al, 2001), but is not currently feasible because of the sparse observations.

Traditional inverse modeling of surface carbon exchange is based on interpretation of very subtle spatial patterns in CO2 mixing ratios in the monthly or annual mean (Gurney et al, 2002). To obtain "representative" concentration measurements, samples are collected far from local sources and sinks, mostly in the remote marine boundary layer (Masarie et al, 1995). Differences among sites are very small, so the measurements must be made very precisely, and intercalibration among different sites and laboratories is crucial (Masarie et al, 2001). Differences in annual mean concentrations between stations in the Atlantic and the Pacific, for example, are less than 1.0 ppm, and estimates of the overall sink in North America are very sensitive to errors of the order of 0.2 ppm in this difference.

Network optimization studies have consistently shown the potential for better estimation of continental sources and sinks that is possible by sampling the continental atmosphere (Rayner et al, 1996; Gloor et al, 2000). The concentration field is much more variable over the continents than in the marine boundary layer though, which raises serious questions about the representativeness of point samples taken weekly. The traditional inversion methodology regards these variations as "noise" and seeks to interpret smoother time-averaged spatial patterns.

An emerging idea in the inverse modeling community is that there may be much more information content in the high-time frequency variations in CO2 in the continental PBL than in the time mean spatial patterns. The new idea is to invert these variations rather than smooth them by time averaging, turning the "noise" into "signal." Variations on hourly to synoptic time scales of the order of 10-20 ppm are common in data collected at the WLEF-TV tower in northern Wisconsin. These variations are more than an order of magnitude stronger than those interpreted by traditional inverse modeling from time-averaged data, and appear to be systematically related to particular trajectories, based on their association with wind directions and frontal passage (Fig 1).

Law et al (2002) have studied this idea using synthetic (model-generated) data to estimate monthly CO2 fluxes from every grid cell using daily rather than monthly data from a handful of sites near Australia. They found that the flux uncertainty was much smaller using the daily data, because high- or low-concentration "spikes" in the daily record could usually be traced backward to particular source/sink areas. Interpretation of concentration "events" like this may require mesoscale transport modeling for better tracking of airmass trajectories. Wang and Barrett (2001) successfully used such a model to estimate Australian CO_2 exchange on a very fine grid from continuous measurements taken at Cape Grim. The European Union's AEROCARB project (http://www.aerocarb.cnrs-gif.fr) is taking a similar approach to high-resolution estimation of sources and sinks in Europe, using a suite of five different mesoscale models (Ciais et al, 2002). The Europeans have emphasized continuous measurements at tall towers and extensive airborne sampling, and are much further in both observational deployment and model development than similar efforts planned in the US (Wofsy and Harriss, 2002) via the North American Carbon Plan (NACP). The NACP call explicitly for regional campaigns such as the one proposed here.

We propose a three-year program of development and testing of measurements and modeling tools for estimation of regional CO_2 exchange using continuous variations of CO_2 in the atmosphere. We will build and deploy a network of continuous, high-precision CO_2 analyzers for the estimation of regional NEE. We will estimate surface fluxes and regional CO_2 variations using a performing a 1° x 1.25° data assimilation using continuous CO_2 measurements in conjunction with data from the global flask sampling network. We will compare the inferred fluxes to estimates made from the "bottom up" by calibrating an ecophysiological model against several flux towers in the region, parameterizing it with satellite imagery, performing coupled simulations in a mesoscale meteorological model. These fluxes will be evaluated by comparing simulated CO_2 concentrations to measurements made at the regional scale. Finally, we will develop and test a method for mesoscale synthesis inversion of NEE from our regional network using the mesoscale atmospheric model.

This project represents both a viable stand-alone project focused on determining regional, seasonal NEE of CO_2 via atmospheric inversions, and a component of a broader research effort to document regional, seasonal NEE of CO_2. This proposal is most closely linked to the NSF proposal of Davis and Caspersen (pending) which proposes to merge direct flux measurements over the region using the University of Wyoming King Air flux aircraft and flux towers to map spatial variability in NEE of CO_2, compare these flux maps to predictions of a land surface model that incorporates land use history data to better constrain the annual cumulative NEE of CO_2, reach conclusions regarding the validity of such a model (ED, Moorcroft et al, 2001) at a regional scale, and examine the root causes of spatial variability in NEE of CO_2 in the Chequamegon Ecosystem-Atmosphere Study (ChEAS) area. This effort to derive regional, seasonal NEE of CO_2 using inversions and SiB2 would complement the work with airborne eddy covariance flux measurements, ED, and forest inventories by bringing together and testing independent means of quantifying regional, seasonal NEE of CO_2. If an NACP project with stronger scientific opportunities emerges, the work proposed here for ChEAS could be relocated as a component of that experiment.

This work also complements the continental scale work proposed including aircraft profiles (Bakwin, NOAA GCC proposal) and semi-permanent high-precision and accuracy CO_2 mixing ratios at AmeriFlux towers (Davis and Richardson, NOAA GCC proposal). These projects would employ similar measurements strategies to focus on better describing the continental-scale annual, cumulative NEE of CO_2. The larger scale data would provide valuable boundary conditions to this regional study, and the regional study should provide insight into the small-scale details of processes that must be aggregated to estimate continental-scale, annual net fluxes.

2. Hypotheses

1) Inverse analyses of atmospheric CO_2 mixing ratio data collected via surface layer flux towers can be used to estimate NEE of CO_2 integrated across regions of at least 10^4 km^2 and averaged over temporal scales ranging from hours to a few days. Such inverse analyses can be performed during both the growing season and the senescent season, and will be used to estimate average fluxes and synoptic variability in fluxes over the period of one month. The uncertainty in the monthly averaged NEE of CO_2 derived using this method will be reduced to less than or equal to 0.3 gC m^{-2} d^{-1} or roughly 10% of the net daily flux. Variability in regional fluxes induced by synoptic weather events will be resolved. CO_2 mixing ratio data from aircraft and tall towers, when available, will improve the results of the inverse analyses.

2) High-time-frequency variations in surface layer CO_2 mixing ratios can be quantitatively interpreted in terms of regional sources and sinks upwind. Inversion of high-frequency mixing ratio measurements will produce regional flux estimates that are significantly less uncertain than inversions based on time-mean spatial patterns of mixing ratio in the free troposphere or remote boundary layer.

3) Independent methods of evaluating regional NEE of CO_2 will be comparable to the net fluxes derived using the inverse approach. The application of multiple independent methods will be taken advantage of via related projects so as to generate the greatest possible confidence in the suite of methods available. Biophysical models driven by remote sensing data of land surface parameters and calibrated to local AmeriFlux towers will be a primary source for comparison produced by this project.

4) The regional fluxes derived using atmospheric inversions will help to determine the processes governing regional fluxes in the study area by determining how regional flux tower measurements of ecosystem respiration (RE) and net primary productivity (NPP) can be upscaled to match the atmospheric inversion results.

5) Global scale inversion results are limited by the quality of their regional, synoptic transport. Regional scale data and analyses that explicitly evaluate regional transport and synoptic and diurnal variability will elucidate the strengths and weaknesses of global inversion models used to derive continental-scale, annual NEE of CO_2. The two proposed regional field experiments will be effective test-beds for the small-scale components of these global inverse models.

3. Expected results

1) A. The utility of atmospheric inversions for deriving regional NEE of CO_2 at seasonal time scales will be established. The deployable network developed and tested here will be available for regional experiments called for by the North American Carbon Plan. An NACP-endorsed regional experiment may be substituted for one or both of the Wisconsin experiments if the scientific opportunities exceed those available at the ChEAS site. The instruments assembled here will be deployable on typical flux tower and airborne platforms. The modeling tools will also be adaptable to experiments held in other geographic regions.

   B. These experiments will provide the experience needed to design semi-permanent regional networks that will be used in future years to monitor interannual changes in seasonal NEE of CO_2. The regional, seasonal nature of these results will enable researchers to determine, in collaboration with flux towers and process-level measurements within the region, the mechanisms governing interannual variability in the terrestrial carbon cycle at regional scales.

2) The design of future regional flux experiments will emphasize continuous measurements and resolution of synoptic events in order to improve the precision of the flux retrievals using atmospheric inversions.

3) A. Independent validation of the regional, seasonal fluxes estimated by extrapolation of flux tower results using a biophysical model (SiB2) will be achieved for the first time. These results will parallel, for regional and seasonal scales, the results of Pacala et al (2001) who used a combination of forest inventory analyses (FIA), the Ecosystem Demographics model (Moorcroft et al, 2001), and global inversions to arrive at independent estimates of the annual average NEE of CO_2 for the United States. An important difference would be that ED's annual NEE of CO_2 is based primarily on land use history data (FIA) while the seasonal SiB2 results would be calibrated by regional AmeriFlux towers.

   B. If a companion proposal is successful (Assessing Regional Variability of CO_2 Fluxes: Measurements, Modeling and Mechanisms, Davis and Caspersen, submitted to NSF Carbon Cycle), the regional fluxes derived via atmospheric inversion will be compared to a regional version of the ED model which incorporates land use history via FIA data for northern Wisconsin and airborne eddy-covariance flux measurements from the University of Wyoming King Air, in addition to the estimates of the SiB2 model calibrated using regional flux tower data.

4) The regional representativeness of the ChEAS flux towers will be determined by the inverse fluxes and comparisons during the summer and fall seasons. In particular it will be shown whether or not the strong summer uptake observed at the Willow Creek mature deciduous forest site or the much more modest summer uptake observed at the WLEF tall tower mixed forest site are more representative of the region. The contributions of NPP and RE will be distinguished using the summer and fall experiments.

5) Advances in simulating regional, synoptic transport will improve the accuracy of continental-scale annual and seasonal net fluxes derived via global inversion models.

4. Methods/Experimental Plan:

4.1 Observational overview

The overall plan is to create a network of high-precision, high-accuracy, continuous measurements to characterize the regional gradients and temporal trends in the ABL CO_2 mixing ratio. Existing flux towers (either long-term or temporary) will be utilized as measurement platforms, as will an aircraft. Measurements will focus on two intensive field campaigns, one in the fall and one in the summer. The Chequamegon Ecosystem-Atmosphere Study (ChEAS) is the proposed site for this study, though the instrumentation and methodology is intended to be mobile and able to respond to initiatives stemming from the North American Carbon Plan. The network of mixing ratio measurements will be used to estimate regional NEE of CO_2 using atmospheric inverse methods.

4.2 Site: The Chequamegon Ecosystem-Atmosphere Study (ChEAS)

This site, located in north-central Wisconsin (http://cheas.psu.edu) contains continuous, large-area eddy-covariance flux measurements at the WLEF tower situated within a flat but heterogeneous forest landscape, as well as four continuous small tower measurements describing major components of the regional mosaic of fluxes. The WLEF tower flux measurements have been running with DoE/NIGEC support since May of 1995 (Bakwin et al, 1998; Berger et al, 2001; Davis et al, accepted). Three of the small towers, an upland forest (Willow Creek - Cook et al, submitted), a wetland site (Lost Creek), and an old growth maple-hemlock forest (Sylvania), have been running since August of 1999, 2000, and 2001, respectively, with NIGEC and DoE/TCP support. More details are available at http://cheas.psu.edu/fieldsites.html. In addition a recently funded NSF project (J. Chen, U. Toledo, PI) has added a jack pine flux tower in the upper peninsula of Michigan, and at least one more is planned for the Bayfield district of the Chequamegon National Forest, west-northwest of WLEF, possible sited in an aspen stand. Approximate locations of these towers are shown in Fig 3. The towers are spread out across a region spanning over 100 kilometers. RAMS/SiB2 parameterizations have been set up and run for this region (Baker et al, accepted; Denning et al, accepted; Pridhoko et al, submitted). BIOME-BGC simulations of two of the flux towers are being conducted as part of the AmeriFlux-MODIS model evaluation project. Stable isotopes are being sampled at WLEF as part of BASIN (http://gcte-focus1.org/basin.html). Population density is low so there is minimal local contamination of the CO_2 mixing ratio and flux signals from anthropogenic emissions. These towers are within a band of temperate forest in Minnesota, north-central Wisconsin and the UP of Michigan. Agricultural land borders to the south and west and the Great Lakes to the north and east.

4.3 High-accuracy, high-precision CO_2 mixing ratio measurements

Bakwin et al (1998) have developed and field-tested an automated system for measuring atmospheric CO_2 mixing ratios at high absolute accuracy and precision using commercially available instrumentation (LI-COR 6252) and high-quality CO_2 mixing ratio standard gases. (The LI-COR 7000 has been tested but appears to have minimal improvements for this application and increases the cost.) This methodology was deployed on the WITN TV tower (600m tall) in North Carolina and functioned for 7 years, and has operated on the WLEF Public Television tower (447m tall) in northern Wisconsin since 1994. This method has been proven capable of approximately 0.2 ppm precision and absolute accuracy. Continuous data is acquired except during periodic automated calibration. We will record one-minute averages. The WLEF and WITN measurements have been extensively compared to NOAA CMDL's flask CO_2 observations (Bakwin et al, 1998). The WLEF, Willow Creek, Lost Creek and Sylvania towers all maintain these continuous CO_2 measurements.

For this project six to eight additional high-precision, high-accuracy CO_2 systems will be assembled. These systems will be engineered such that they can be added to an existing flux tower and will be deployed for at least two regional, seasonal field campaigns. A trial experiment of this sort is being conducted (13 May – 25 June, 2002) as part of the International H_2O Project (IHOP, http://www.atd.ucar.edu/dir_off/projects/2002/IHOP.html). Two such systems have been successfully added to Integrated Sounding and Flux Facility (ISFF) towers deployed by the Atmospheric Technology Division (ATD) from the National Center for Atmospheric Research (NCAR). The primary costs for these systems are LI-COR 6252 sensors and high-quality calibration gases. The two existing systems will be used for this project.

4.4 Calibration

Calibration of the tower-based continuous LI-COR CO_2 sensors, as noted above, is dependent upon high-quality calibration gases (Bakwin et al, 1998). The standard gases will be provided via a calibration lab to be set up at Penn State using funds from a related project. This calibration system will use four NOAA CMDL primary standard calibration tanks to calibrate the four calibration tanks to be used at each instrumented surface layer tower. Calibration activities will be closely coordinated with NOAA CMDL to assure high data quality. If necessary, NOAA primary standards could be deployed at the flux sites. A limited amount of flask sampling could also be adopted at a subset of flux sites if it is proven to be desirable.

4.5 Carbon monoxide measurements

The proposed measurements are most valuable if they are representative of regional-scale continental CO_2 mixing ratios. This condition is violated if local sources of anthropogenic pollution occasionally contaminate the flux tower CO_2 measurements. Potosnak et al (1999) have shown the utility of carbon monoxide (CO) as a tracer of such anthropogenic pollution events. We will attempt to choose sites that are far from strong anthropogenic influences. The WLEF tower site, though remote, currently maintains continuous CO measurements. We will assemble one CO measurement system that can be deployed somewhere upwind of the study area. We will employ the methodology currently employed by the Harvard group (J.W. Munger, personal communication). This requires a CO analyzer (ThermoEnvironmental Instruments Model 48C) and a modest amount of additional gas handling equipment and maintenance.

4.6 Data interpretation

CO_2 mixing ratio measurements are easiest to use to derive regional fluxes if they are representative of a well-defined volume of air that is vigorously mixed across the region of interest. These conditions are not typically met in the continental surface layer at night, when strong stratification and intermittent mixing makes air mass mixing and transport highly variable. Measurements of mixing ratios within the continental surface layer at the base of the daytime convective boundary layer (CBL), a 1-2 km deep layer of vigorous convection, meet these conditions, particular during fair weather. The atmospheric surface layer at this time is closely coupled to the entire CBL, and the depth of the CBL is predictable (Yi et al, 2001) and routinely observed by afternoon rawinsonde launches across the globe. Given this understanding of ABL mixing, surface layer tower data can be used in a manner similar to very tall towers, which extend above the stable boundary layer most nights (Yi et al 2001) and sample the CBL during the day. Results from the WLEF tower illustrate the utility of surface layer measurements.

Figure 1 shows synoptic scale patterns of CO_2 mixing ratios from September of 1997 at WLEF. A continuous time series of 396m data is plotted, in addition to early afternoon 11m data. It is further evident from this plot that *for synoptic scale variations in CO_2 mixing ratios, surface layer mixing ratios sampled under well-mixed conditions are nearly indistinguishable from mid-CBL mixing ratios.* We will be analyzing synoptic and convective events (dominated by transport, Hurwitz et al, in preparation) in addition to the more steady day-to-day changes in mixing ratio dominated by regional NEE of CO_2. Thus we need to know if the magnitude of the draw-down (growing season) or build up (senescent season) of CO_2 in the CBL can be observed via surface layer towers in addition to the synoptic and convective events.

Table 1 shows the expected depletion of ABL CO_2 mixing ratio assuming that no mixing deeper than the maximum depth of the daytime CBL occurs (a good assumption during fair weather). The table also shows the typical offset between surface layer (11m) and mid-CBL (396m) mixing ratios during the day. It is important to note that *the spatial gradients in CBL CO_2 mixing ratio caused by regional NEE of CO_2 substantially exceed the vertical gradient induced by local NEE of CO_2.* This statement is even more valid if you consider that the vertical gradient in Table 1 is an upper limit to the potential error. If the surface layer measurements were collected over a surface with constant NEE of CO_2 at a common altitude, the vertical gradient could be completely neglected as it would be a constant offset. Thus the true error is smaller and is proportional to the difference in local NEE between two sites (for a Lagrangian analysis) or between two different times for one site (in an Eulerian analysis). This situation is analogous (though not perfectly since water vapor and temperature are not conserved scalars in the atmosphere) to the routine and effective use of surface sites in weather to determine spatial patterns and temporal trends in humidity and temperature. This claim is also illustrated intuitively with the data in Fig 1. In between windy, low pressure periods where the CO_2 mixing ratios change rapidly due to transport, steady trends in the CO_2 mixing ratios can be seen. These trends show decreasing CO_2 early in the month when the vegetation is still growing, and increasing CO_2 later in the month after most of the vegetation has stopped photosynthesizing (Davis et al, accepted). Note that this trend is evident in *both the 396m and the 11m data*. Thus the surface layer data can pick out this synoptic trend.

The estimated ABL CO_2 differences between towers (ΔCO_2) caused by regional NEE and shown in Table 1 are computed using a simple Lagrangian ABL budget, $\Delta CO_2 = L\, F / (U\, z)$, where L is the separation between sensors, U is the wind speed, z is the mixing depth, L is the separation between tower CO_2 samples, and F is the NEE of CO_2 integrated over time in the region between the towers. The mixing depth is assumed to be 1km (approximate CBL depth), and wind speeds in the ABL are assumed to be 5 m s^{-1}. Chosen fluxes are F(daytime) = 10 μmol m^{-2} s^{-1} which is approximately 10 gC m^{-2} d^{-1} and F(daily mean) = 4 gC m^{-2} d^{-1}, both typical of midsummer conditions in Wisconsin. Senescent season (October) flux magnitudes are roughly ½ those of the growing season and opposite in sign (Davis et al, accepted).

TABLE 1: Detectability of regional CO_2 gradients using surface layer measurements

Separation between sensors	100km	400km
Advection time between sensors	~1/4 day	~1 day
$\lvert\Delta CO_2\rvert$ for F(daytime)	6 ppm	not appropriate
$\lvert\Delta CO_2\rvert$ for F(daily mean)	not appropriate	10 ppm
$\lvert$ CO_2(mid-CBL) – CO_2(surface layer) $\rvert$	~ 2 ppm midday, summer fluxes	~ 2 ppm midday, summer fluxes

Further, the surface-to-mid-CBL offset is proportional to the local (order 10 km^2 footprint) NEE of CO_2 which is measured. Micrometeorological studies provide sound methods for removing this offset (e.g. Davis, 1992; Davis et al, 1998; Moeng and Wyngaard, 1989; Patton et al, 2001). Note that the ~ 10 km^2 flux footprint that determines the vertical gradient (Horst, 1999) is very different than the > 10^2 to 10^6 km^2 area flux that influences the temporal evolution of the mean CBL mixing ratio, so making this correction using eddy covariance measurements of local NEE then using the results to find regional NEE of CO_2 is not circular.

Thus we conclude that *continuous measurements of surface layer CO_2 mixing ratios at flux towers provides a sound method of tracking regional ABL CO_2 mixing ratios. These measurements, relatively simple and portable, can constitute either a stand-alone network or a complement to a more extensive experiment plan including tall towers and aircraft sampling.* The complications of the nighttime stable boundary layer make interpreting nighttime fluxes alone much more challenging. It is likely that only daytime net regional fluxes or whole-day integrals of regional net fluxes can be addressed with surface layer towers. The continuous surface layer data will, however, contain data concerning nighttime fluxes that may be interpretable as we gain experience with this approach.

4.7 Airborne observations

It should also be emphasized that the mixing depth, and exchange of CO_2 between the ABL and the free troposphere, will have a large impact on any results. Proposed airborne CO_2 profile measurements, either routine measurements proposed by Bakwin (NOAA), campaign-based flights proposed by Davis et al (NSF and DoE/NIGEC), or as an element of a future NACP-driven campaign, would be a powerful complement to the measurements proposed here. To that end, funds for an airborne high precision and accuracy CO_2 sensor are requested. This instrument will be mounted on the University of Wyoming King Air if the NSF proposal of Davis and Caspersen is funded. The King Air would measure mean CO_2 mixing ratios on ~150km horizontal transects across the ChEAS domain, flying within and just above the daytime ABL, and would also provide periodic vertical profiles up to ~3km AGL depending on ABL depth and free tropospheric layering. Approximately 6 flights would take place during each intensive field campaign. If Davis and Caspersen is not supported we will deploy the instrument on a locally rented commercial aircraft during the two intensives. In the absence of these data it appears that the marine ABL measurements, or perhaps Niwot Ridge flask data, are a fair proxy for CO_2 concentrations in the free troposphere over Wisconsin (Yi et al, in preparation; Helliker et al, in preparation).

This instrument has been developed by Atmospheric Observing Systems with an SBIR from the Department of Commerce, and with close collaboration with NOAA/CMDL. An early ship-board version of the instrument was used successfully to measure the air-sea flux of CO_2 during the GASEX98 campaign (J.R. Smith and P.P. Tans, Three techniques for the direct measurement of air-sea gas exchange of CO_2, presented at the AGU spring meeting, Boston, 1999) and was capable of resolving CO_2 differences as small as 0.005 ppm. A prototype instrument for aircraft use has already been built and will be tested at the CMDL aircraft profile site at Carr, Colorado, starting in late 2001. The instrument is designed to be low power, light weight, and to have very low sensitivity to changes in temperature and pressure, as is required for aircraft work. The analyzer does not use a chopper wheel and therefore is insensitive to aircraft motion

4.8 Instrumental deployment: Places, times, platforms

Figure 2 shows tentative locations of longer-term, flux tower based high-precision and accuracy CO_2 mixing ratio measurements (Davis and Richardson, NOAA proposal, pending review). Figure 3 shows a potential spatial layout of similar measurements for the regional experiment (complementary to the continental scale effort) proposed here. As noted, there are already several towers with high-precision and accuracy CO_2 measurements (red stars) including one tall tower (red eight-pointed star) that are part of ChEAS. All flux data processing for these sites is being managed via Penn State. CO_2 mixing ratio data is analyzed at Penn State, NOAA/CMDL and the University of Minnesota. These sites will be complemented by an array of flux towers instrumented the high-precision and accuracy CO_2 mixing ratio measurements described above. The plan, consistent with the spacing of towers analyzed in Table 1, is to have an ‘inner ring’ of CO_2 mixing ratio data to examine the ~100km scale (spatial scale corresponding to a few hours of midday advection) and a sparse ‘outer ring’ to provide both inflow boundary information for the ‘inner ring’ and data concerning mixing ratio evolution across scales of ~400km (approximate distance for advection over a full day). The continental network ideally provides inflow boundary data for this outer mesoscale domain. The precise layout may change. Phase 1 of this project (first six months of funding) will focus on both acquisition of instrumentation and network design using model pseudodata exercises.

The layout also may be influenced by the locations of available tower sites. The additional mixing ratio measurements may be added to additional long-term flux towers (blue stars, J. Chen, funded NSF project), or temporary platforms, ideally NCAR-ATD Integrated Surface Flux Facility towers (red dots) that are being requested via a companion proposal (Davis and Caspersen, NSF proposal, review pending). These measurements could also temporarily be added to other ‘towers of opportunity’ in the region (e.g. flux towers that become available via expansion of the USDA flux network), and/or a smaller number of mobile towers supported via rebudgeting this proposal. Construction of additional long-term flux towers is not intended as part of this proposal. If a more centrally coordinated, NACP-driven regional experiment emerges, our CO_2 mesonet would be available for the tower network designed for the chosen

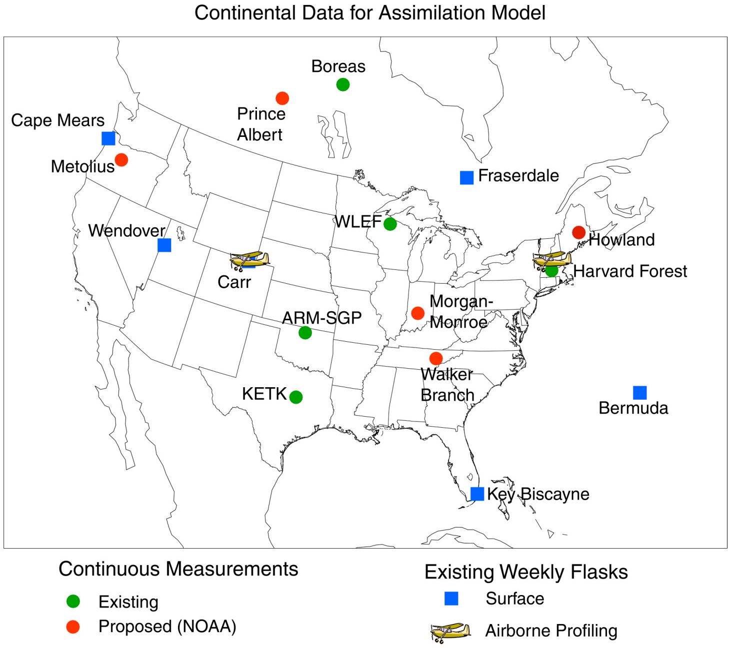


Figure 2: Locations of sampling sites to be used for global data assimilation

location. It is possible that these instruments could, in time, become part of a semi-permanent array of towers. The investigators have had recent success with such an approach, creating a coarse mesonet at a very low budget utilizing NCAR towers and existing towers for the IHOP project. With the resources requested in this proposal, at least 6 additional high-precision and accuracy CO_2 mixing ratio measurements could be deployed. In the case that our NSF request fails and no NACP project emerges, we will rebudget this project to cover additional observing platforms and conduct only one field campaign

These resources will be deployed for a minimum of 30 days for each of two field campaigns, one during the growing season and one during the fall when respiration is dominant but ideally prior to freeze. The intent is to demonstrate the ability to capture regional fluxes during each season, to examine how regional RE and NPP differ, and to examine these results in light of prior knowledge based on long-term flux towers in the region. As noted WLEF and Willow Creek NEE of CO_2 differ considerably despite the proximity of the towers. Photosynthetic rates are higher and respiration rates lower at the Willow Creek upland hardwood sites (Cook et al, AGU presentation, 2001), resulting in a much greater midsummer daily average rate of carbon storage (4 gC m^{-2} d^{-1} vs. 2 gC m^{-2} d^{-1}). The regional fluxes derived using an atmospheric inversion will help to distinguish how well each of these measurements represents the larger region.

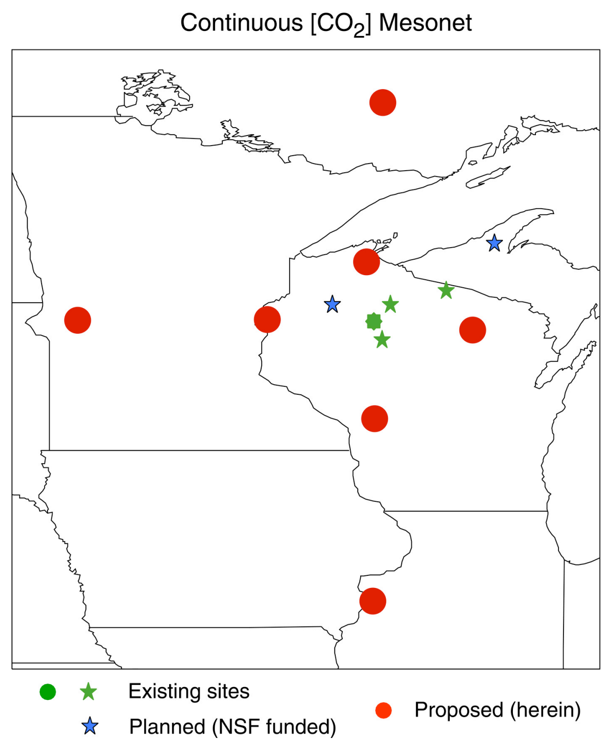


Figure 3: Possible sampling locations for regional flux estimation

4.9 Global Flux Estimation and Assimilation of Continuous [CO_2] Data

The exchange of CO_2 between the surface and the atmosphere will be estimated on a global 1° x 1.25° grid using a 4-dimensional variational data assimilation (4DVAR) method developed by D. Baker at the National Center for Atmospheric Research. The method employs a forward tracer transport model, the adjoint (backward-in-time version) of this model, and an optimization algorithm that adjusts the surface fluxes to fit simulated tracer concentrations to observations while accounting for errors in observations and the simulated transport.

The transport model is the "parameterized chemical tracer transport model" (PCTM, Lin and Rood, 1996; Riishojgaard et al, 2000) developed at NASA Goddard Space Flight Center (GSFC) and run using winds and subgrid-scale vertical mass fluxes archived by the NASA Goddard Eos Data Assimilation System (GEOS-DAS, Rood, 1997). The model uses a finite-volume transport algorithm, and has recently been improved for better performance and mass conservation accuracy (Zhengxin Zhu, NASA GSFC personal communication). A particular advantage of this system is that vertical transports by subgrid-cell processes such as moist convection are accomplished by mass fluxes that are archived by the parent GCM and are thus fully consistent with resolved winds. This system allows transport by "real" weather events (analyzed with the GCM from global observations, Lyster et al, 1997), and is very computationally efficient because all transports are pre-calculated and archived. The currently operational GEOS system runs at 1° x 1.25° with 55 levels in the vertical (8 levels below 850 mb), and the DAO plans to increase this resolution to 0.5°x 0.625°in 2003.

Another advantage of the offline transport model is that the adjoint of the model is very easy to compute. This has been coded by David Baker, and used in a full CO_2 assimilation by an NCAR Summer Study Institute on Carbon Data Assimilation, which Co-PI Denning helped to organize (http://dataportal.ucar.edu/CDAS/). The adjoint is a "backward-in-time" version of the transport model and essentially provides the partial derivative of concentration at any point in space and time with respect to the surface fluxes of CO_2 at every model grid cell at all times in the past (e.g., Kaminski et al, 1999a,b).

The assimilation is initialized with globally gridded ("first guess") fields of atmospheric CO_2 concentrations and surface fluxes. The model is run forward for a full year, and the simulated concentrations are sampled at the locations and times of actual samples in the real atmosphere. An important advantage of this technique is that no time averaging of the observations is required: hourly data can be specified at a particular point, or once-per-week flasks can be "collected" in the model at the date and time the flask was collected in the real world. At the end of a year, simulated concentrations are compared to observations, and a "database" of model-data mismatches is calculated. The adjoint model is then run backward through the same year of weather and transport, forced by the concentration errors tabulated from the forward run. The adjoint model "predicts" (hindcasts) corrections to the surface fluxes that must be applied to minimize the forecast error, subject to constraints on surface fluxes and a formulation for errors in both the observations and the model transport. At the end of the adjoint run, a corrected initial concentration field is also produced. This is then used for a second pass with the forward transport model using the corrected surface fluxes, producing a new set of error statistics, and the process is iterated until a final result is obtained.

The output of the assimilation consists of (1) a global map of surface fluxes on the native grid of the model at each time step (15 minutes) for a year; and (2) a fully-populated 3-

dimensional grid of atmospheric CO_2 concentrations at every model time step, that are optimally consistent with the observations, the model transport, and any a priori constraints (e.g., spatial and temporal correlations or diurnal cycles of fluxes) that one wishes to apply.

This global CO_2 assimilation will be run using weekly flask samples collected by the NOAA-CMDL cooperative network and concentration timeseries measured by the continuous sampling network illustrated in Figure 2.

4.10 Forward Modeling of Regional Carbon Fluxes and [CO_2]

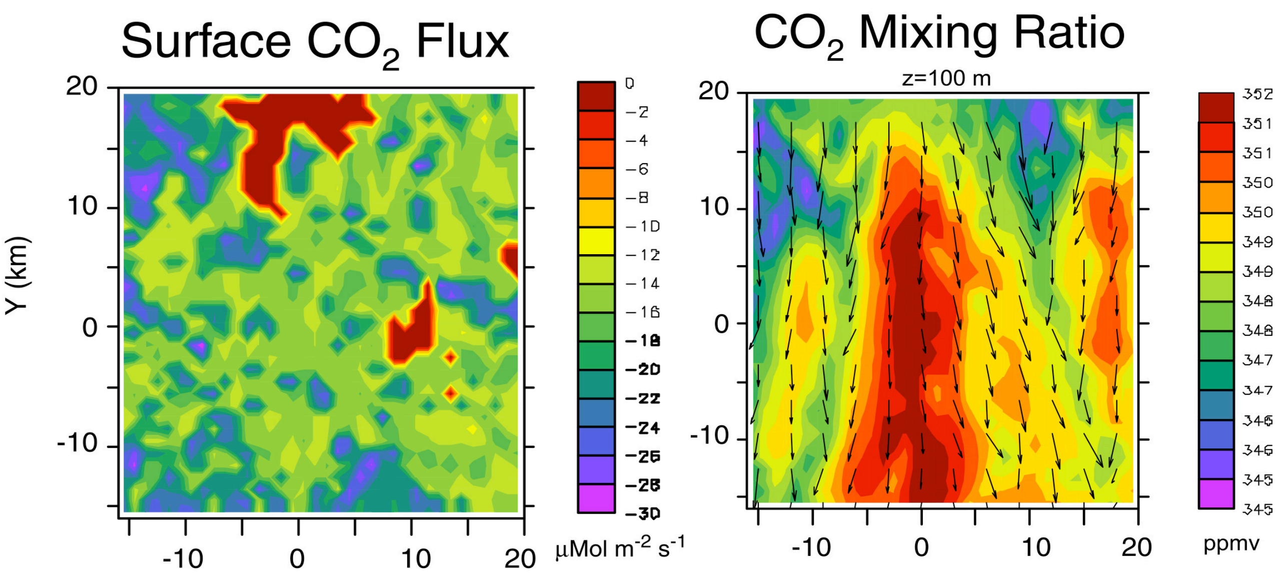
The Regional Atmospheric Modeling System (RAMS) is a mesoscale meteorological (non-hydrostatic) model and contains time-dependent equations for velocity, non-dimensional pressure perturbation, ice-liquid water potential temperature (Pielke et al, 1992), total water mixing ratio, and cloud microphysics. Vapor mixing ratio and potential temperature are diagnostic. A significant feature of the model is the incorporation of a telescoping nested-grid capability, which enables the simulation of phenomena involving a wide range of spatial scales. A second-order-in-space advection scheme is employed. The turbulence closure scheme of Deardorff (1980) is used, which employs a prognostic sub-grid turbulent kinetic energy. The two-stream radiation scheme developed by Harrington (1997) is used. At the lower boundary, the surface fluxes are computed by the coupled SiB2 model (summarized below).

The lowest level above the surface in the RAMS model is the reference level at which atmospheric boundary layer values of temperature, vapor pressure, wind velocity and carbon dioxide partial pressure are provided as upper boundary conditions to SiB2. Additionally, the direct and diffuse components of short wave and near infrared radiation incident at the surface are provided from the RAMS radiation scheme. The surface layer, which is between the surface and the reference level is incorporated as part of the SiB2 model and is based on the scheme of Holtslag and Boville (1993). The input variables provided by RAMS to SiB2 are updated every minute of simulation time. SiB2 provides back to RAMS, at the reference level, fluxes of heat, moisture, momentum and carbon dioxide, as well as the upwelling radiation.

The Simple Biosphere (SiB) Model, developed by Sellers et al. (1986), has undergone substantial modification (Sellers et al., 1996a, b), 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, Schaefer et al, 2002). 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., 1996a). Model parameters for SiB2 are computed from NDVI and soil texture data (Sellers et al, 1996b, Prihodko et al, in prep). The model is currently undergoing substantial revision, including improvements to soil hydrology and thermodynamics, snow hydrology, and stable isotope biogeochemistry.

Multiyear simulations of the fluxes of energy, water, and carbon at the WLEF site have been performed using SiB2 driven by observed meteorology, and the results have been compared to observations by Baker et al. (2002). We will perform similar model evaluation studies for each of the "satellite" flux towers in the region under this project, and make any changes in formulation or parameters necessary to account for regional landscapes.

The fully coupled SiB-RAMS model will then be integrated at coarse resolution (50 km) over a domain including all of the USA plus surrounding areas for a full year, to obtain "balanced" initial conditions for soil moisture and respirable carbon. Lateral boundary forcing for this simulation will be prescribed from the GEOS-DAS reanalysis (for meteorological forcing) and from the global CO_2 assimilation described above for trace gases. This coarse simulation will be evaluated against available meteorological and [CO_2] data. Intensive observing periods will be simulated with a two-way nested grid configuration that reduces Δx by a factor of five in progressive nests (Nicholls et al, 2002, see Fig 4). The outer grid will be a subset of the 50 km grid used for the annual cycle simulations. The second grid will use a 10 km spacing over the entire area shown in Fig 3, and a third grid at Δx = 2 km will be used over the central part of the domain containing the highest density of measurements. Simulated fluxes of latent and sensible heat and CO_2 will be evaluated against flux tower measurements in the domain, and simulated CO_2 concentration patterns in space and time will be evaluated against the array of tower measurements illustrated in Fig 3.



gure 4: Simulated surface CO_2 flux and mixing ratio at 100 m at noon on Aug 1, 1997, from an experiment with the coupled SiB-RAMS model. Δx=1 km. The read areas in the left panel are small lakes. Vectors in the right panel indicate winds. The WLEF tower is at x=0, y=0.

In year 1, the coupled model will be used to generate synthetic data for testing inversion methods and for optimizing the design and placement of the tower network.

4.11 Mesoscale Synthesis Inversion:

The monthly carbon budgets of continental scale regions have been studied for years using Bayesian synthesis inversion (e.g., Enting et al, 1995; Gurney et al, 2002). The method involves discretizing the flux into aggregated regions in space and time, and using a tracer transport model to calculate atmospheric "response functions" that would be produced by emitting a unit amount of CO_2 from each region in each month. Linear combinations of these responses are then constructed that optimally match the observations subject to a priori constraints (Tarantola, 1987; Enting, 2002). In addition to providing estimates of area-averaged monthly fluxes, the method is attractive because it produces a formal estimate of the uncertainty in the fluxes.

The mesoscale problem can be approached using the same mathematical description, but involves estimation of lateral boundary fluxes and an initial concentration field in addition to the surface fluxes. We have explored this application of the synthesis inversion technique using model-generated synthetic data (Uliasz et al, 2000) and attempted to estimate the spatial distribution of upwind surface fluxes from a timeseries at a single tall tower meant to represent the WLEF-TV tower (Uliasz et al, in prep). Instead of discretizing the domain into predetermined "regions" as has been done for global inversions, we used a Lagrangian particle dispersion model (LPDM) to calculate "influence functions" from backward-in-time trajectories associated with each concentration measurement. Each of these regions of influence in space and time were then treated as a "basis function" in the inversion, and assigned a unit amount of tracer emission. Linear combinations of the basis functions were then constructed to minimize error across the suite of observations. Because of the very strong diurnal cycle of CO_2 in the mesoscale atmosphere, we found it convenient to estimate respiration and photosynthesis (assimilation) fluxes separately, assuming a particular "shape" of the diurnal cycle of each flux.

Figure 5 shows the results of a "Monte Carlo" set of 100 inversions for variations of upwind fluxes. Random perturbations of different spatial scales (*D*) were added to known fluxes due to photosynthesis and respiration. A 24-hour timeseries of concentration measured at six heights on a tall tower was then inverted to estimate the fluxes due to respiration (*R*) and photosynthetic assimilation (*A*) in each area of size *D*. The figure shows the percent error in each perturbed upwind area, as the mean of 100 realizations. The inversion was generally better able to estimate the respiration flux (which was constant in time and felt very strongly at night), but was generally able to estimate photosynthesis to

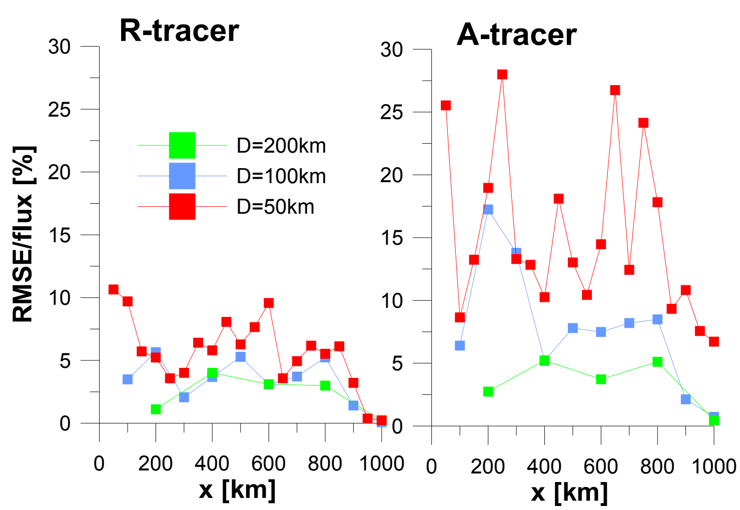


Figure 5: Percent error in estimates of upwind fluxes due to respiration (R) and photosynthetic assimilation (A) from an ensemble of 100 synthesis inversions

better than 25% as well. These calculations were made without trying to estimate the inflow flux as a separate unknown. With no knowledge of the inflow flux, the results were much less favorable, especially for photosynthesis with its strong diurnal cycle.

For the mesoscale inversions proposed here, we will use the results of the global data assimilation calculation discussed above to prescribe lateral boundary fluxes and their uncertainty as a prior constraint. In addition, we will have many more measurements along the airmass trajectories to provide information about inflow fluxes. We anticipate that uncertainties will be larger near the upwind boundary of the modeling domain, especially beyond the furthest upwind sampling site.

The advantages of this method over the global data assimilation method are the much higher spatial resolution of both the transport model and the inferred fluxes, and the much more detailed simulation of local meteorology, boundary-layer structure, and transport in the vicinity of the measurement locations. We plan to use a 10 km grid for most of the mesoscale domain, and a 2 km grid in the inner "ring" of towers planned in phase 2 of this project. The disadvantages of this approach include its much greater computational expense relative to the global model (which limits its application to specific campaigns), and the need to estimate inflow fluxes at the lateral boundaries of the domain.

5. Deliverables

1) An array of portable sensors that can be used to instrument a minimum of 5 surface layer towers for high-precision and accuracy CO_2 mixing ratio measurements, 1 tower for complementary CO measurements, and 1 airborne platform for CO_2 mixing ratio measurements will be assembled, tested and made available for regional intensives.

2) Two methods (CO_2 assimilation and mesoscale synthesis inversion) for estimating regional NEE from atmospheric CO_2 will be developed and evaluated. These models will be made available for future regional experiments.

3) Regional ABL CO_2 mixing ratio measurements spanning two intensive campaigns will be made available along with all supporting data to the carbon cycle science community as a test data set for regional atmospheric inversion and data assimilation experiments.

4) Regional net CO_2 fluxes will be computed for one month of the growing season and one month shortly after senescence in the fall. The uncertainty in these fluxes will be quantified and the net fluxes compared to alternate methods of estimating regional NEE.

5) The value of high-frequency (e.g. synoptic) variability in ABL CO_2 mixing ratios for deriving regional, seasonal NEE of CO_2 will be evaluated.

6) The ability to monitor continuously regional, seasonal NEE of CO_2 will be established so that future investigations can determine the mechanisms governing regional interannual variability.

6. Work plan

Phase 1 (9/02 – 2/03): Pre-field phase.

Field equipment is purchased and assembled. Model pseudodata studies to optimize mesoscale network design are conducted. Field sites are selected.

Phase 2 (3/03 – 8/05): Field and analysis phase.

3/03 – 2/04: First seasonal field campaign is conducted. Data is collected, quality-checked and archived. Analysis of regional fluxes begins. Preliminary results are used to guide planning of the second field campaign. Global data assimilation study at 1°x 1.25°.

3/04 – 2/05: Second field campaign is conducted. Data is collected, quality-checked and archived. Preliminary analyses begin. Final analyses of regional NEE of CO_2 from the first field campaign are completed and compared to independent flux estimates. Publications are drafted documenting the regional mixing ratio observations, presenting the flux estimates and comparisons, and evaluating the value of continuous measurements in deriving regional, seasonal NEE of CO_2. Data from the first campaign are made available to the scientific community. Global data assimilation study at 0.5°x 0.625°.

3/05 – 8/05: Final analyses of regional NEE of CO_2 from the second field campaign are completed. Comparisons between growing season and dormant season results are conducted and compared in particular to local flux towers. Publications are drafted documenting the mixing ratios and fluxes for the second campaign, the contrast between seasons, and the ability to establish observations of interannual variability in regional, seasonal NEE of CO_2. Data from the second campaign are made available to the scientific community. Models and instrumentation developed via this project are made available for future regional observations and analyses.

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