Proposal to the National Oceanic and Atmospheric Administration

Data fusion to determine North American sources and sinks of carbon dioxide at high spatial and temporal resolution

Submitted by

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2. Abstract

Data fusion to determine North American sources and sinks of carbon dioxide at high spatial and temporal resolution

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There is strong evidence that North America terrestrial ecosystems are currently a substantial sink of carbon dioxide. The magnitude of the sink has a large range of uncertainty, we have a limited understanding of how it has varied over time, and the processes responsible for this sink are not entirely clear. Our limited understanding is linked to methodological limits. Quantifying spatial patterns and temporal variability of carbon dioxide sources and sinks at continental to regional scales remains a challenging problem.

In response to this challenge a rapid expansion of the North American carbon cycle observational network is underway. This expansion includes a network (AmeriFlux) of continuous, eddy-covariance based CO_2 flux measurements and a continental CO_2 mixing ratio observing network of comparable precision and accuracy to the marine flask network. To date, inverse studies of the North American carbon budget have not utilized these emerging data sources directly (i.e. tower fluxes and continental mixing ratio observations).

We propose a program that will turn the emerging wealth of data in North America to our advantage. This can be accomplished by merging research groups at the forefronts of terrestrial boundary layer CO_2 flux and mixing ratio observations, and high resolution, land-atmosphere carbon cycle modeling. The study will explore the potential for fusion of CO_2 flux and mixing ratio observations in a coupled land-atmosphere data assimilation framework. We will accomplish this via inverse modeling incorporating the emerging North American CO_2 mixing ratio observational network, forwards modeling built upon the North American flux network, and cross-evaluation of these two model-data fusion approaches.

Expected products include: 1) development and evaluation of a comprehensive analysis system for estimation of monthly CO_2 exchange across North America at high spatial resolution; 2) dramatic reduction in the uncertainty in the annual net North American CO_2 flux and its interannual variations, as compared to currently published results; 3) attribution of CO_2 sources between fossil fuel combustion and ecosystem exchange using CO and other trace gases; 4) application of AmeriFlux observations to evaluate the mechanisms responsible for seasonal to interannual responses of ecosystem carbon exchange to climate; 5) evaluation of the flux and mixing ratio predictions of the forwards and inverse models; 6) evaluation of the atmospheric and ecosystem models, and the flux and mixing ratio observational networks used in these studies. The methods explored here will be portable to other parts of the globe.

Total proposed cost:	\$390,394 Penn State effort
	\$443,421, Colorado State effort
Budget period:	1 January, 2004 – 31 December, 2006

3. Results from prior research

Colorado State University

Impact of interactive vegetation on predictions of North American monsoons.

Monitoring and modeling isotopic exchange between the atmosphere and the terrestrial biosphere.

Atmospheric Tracer Transport Inversion Intercomparison.

Global and regional carbon flux estimation using atmospheric CO_2 measurements from spaceborne and airborne platforms.

Spatial integration of regional carbon balance in Amazonia.

Incorporating new EOS data products into models to improve estimated of biogeochemical processes.

Mapping global aerodynamic roughness length of land surface at 1 km scale.

Biological controls of terrestrial carbon fluxes. (Ojima)

Regional estimation of terrestrial CO_2 exchange from NIGEC flux data, satellite imagery, and atmospheric composition.

Regional forest-ABL coupling: Influence on CO_2 and climate.

The effects of remotely-sensed data on modeled land surface atmospheric interactions (Lara's NASA)

Atmosphere-biosphere interactions.

The Earth System Science Workbench: A scalable infrastructure for earth science information partners.

CO_2 budget and rectification airborne study – North America.

Linking biogeochemistry and atmospheric transport in the NCAR global circulation model.

Pennsylvania State University

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), interannual variability in methane emissions (Werner et al, in press), and the annual cycle of CO_2 and H_2O fluxes, detailed error analysis of the annual cumulative CO_2 flux, comparison of eddy fluxes and boundary layer CO_2 budgets (Davis et al, in press), and upscaling of regional evapotranspiration (MacKay et al, 2002). The region surrounding the WLEF tower is roughly in carbon balance with the atmosphere. Methodology for the virtual tall tower network was developed (Davis et al, 1998). Data has been shared for analyses spanning the network of CO_2 flux towers (e.g. Baldocchi et al, 2001; Law et al, 2002; Falge et al, 2002a,b). Additional results include documentation of the influence of synoptic fronts on CO_2 mixing ratios (Hurwitz et al, accepted), and water vapor-CO_2 covariance to infer NEE of CO_2 from ABL budgets (Helliker et al, in preparation).

Boundary layer profiling and CO_2: Radar remote sensing of boundary layer structure has been conducted at two sites including the WLEF tall tower. Vertical profiling of CO_2 up to 3km altitude was also conducted over two AmeriFlux towers spanning three seasons using a powered parachute. Results include documentation of ~24 months of boundary layer depths spanning two sites and two years, derivation of a close relationship between boundary layer depth and the surface energy balance (Yi et al, 2001), a multi-year comparison of tower-derived surface fluxes and simulated fluxes (Baker et al, in press) and comparison of observed and simulated CO_2 mixing ratios across the ChEAS domain (Denning et al, in press). The CO_2 rectifier effect forcing at the WLEF tower has been quantified and compared to model estimates of this effect (Yi et al, in preparation), and ABL CO_2 budgets at multiple towers has been analyzed to derive estimates of regional NEE of CO_2 (Bakwin et al, in review).

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. Nighttime tower fluxes agree well with soil chamber flux measurements (Bolstad et al, submitted). 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, in preparation). The Sylvania old growth site is a modest annual sink of carbon (Desai et al, in preparation). A tent caterpillar outbreak had an impact on fluxes across the region in 2001 (Cook et al, in preparation). Both the Willow Creek and Lost Creek sites show substantially smaller respiratory fluxes than the WLEF tall tower landscape-scale flux measurements. The cause of this contrast among sites is being investigated.

Regional fluxes via atmospheric budgets: A regional mesonet of 7 high-precision, high-accuracy CO_2 mixing ratio measurements has been deployed in a ~150km radius ring around the WLEF tall tower in northern Wisconsin. The data will be used to derive regional CO_2 flux estimates via an inverse modeling approach at very high spatial (domains of ~100km x 100km) and temporal (hours to days) spatial resolution. Data collection began in July of 2003. This will shortly be complemented with a continental scale effort just funded by DoE/TCP. The latter project represents an important building block for this proposal.

4. Statement of work

4.1 Introduction

The fate of anthropogenic CO_2 introduced into the atmosphere by the combustion of fossil fuels is one of the leading sources of uncertainty in projections of future climate (e.g., compare coupled carbon-climate scenarios of Cox et al, 2000 and Friedlingstein et al, 2001). Research leading to improved quantification and understanding of carbon sources and sinks has therefore been identified as a major priority for the US Carbon Cycle Science Program, with special focus on North America in the near term (CCSP, 2003). We propose a three-year investigation of temporal and spatial variations of carbon sources and sinks over North America that will merge newly available observations of CO_2 mixing ratio, ecosystem CO_2 flux, and spectral reflectance in a new analytical system for model-data fusion. We will test the system using synthetic (model-generated) data, and also on new observations. The system we develop will be a prototype for future monitoring of carbon cycle variations over North America, and will also be a valuable tool for prioritizing new observing system investments.

Direct measurements of carbon exchange between the atmosphere and terrestrial ecosystems by the eddy covariance method has been undertaken at an increasing number of sites in North America and around the world (Falge et al, 2002). These measurements provide information about CO_2 fluxes and their responses to climate variations on hourly to decadal time scales, but the areas represented by the flux measurements are very small (order 1 km^2). The extrapolation of tower-based flux data to continental scales is very challenging because of the spatial heterogeneity of terrestrial ecosystems, site histories, topography, land use, and land management. At continental and hemispheric scales, carbon exchange is fairly well quantified through inversion of atmospheric CO_2 mixing ratio measurements using tracer transport models (e.g., Gurney et al, 2003; Rodenbeck et al, 2003). These calculations are complementary with the tower-based flux studies, having the advantage of being inherently representative of the largest spatial scales with the disadvantage that spatial variations and relationships to local processes are not resolved. Studies of ecosystem carbon storage and release (e.g., Barford et al, 2001) suggest that land-use history (e.g., disturbance, recovery, succession, management, harvest) plays an important role in the distribution of sources and sinks. Ecosystem process studies, eddy covariance measurements, and large-scale inverse modeling have sometimes yielded conflicting pictures of the carbon balance of North America, though there is optimism that a consistent interpretation is emerging (Pacala et al, 2001).

It is now recognized that credible and falsifiable mechanistic documentation of spatially and temporally resolved variations in the carbon budget of North America will require a major research effort (Wofsy and Harris, 2002). The North American Carbon Program (NACP) will include process studies, an expanded flux measurement network, remote sensing and modeling, and inversions using new atmospheric mixing ratio observations. Cross-checking for consistency and hypothesis testing is envisioned within a new framework of model-data fusion that explicitly tests models against multiple sets of observations at different scales.

Successful application of atmospheric mass-balance constraints to test upscaled models of carbon exchange across North America will require a tremendous improvement in the spatial resolution of flux estimates from inverse modeling. Current estimates are based on a global network of measurements conducted on weekly air samples collected in flasks, mostly from remote marine locations to maximize representativeness and avoid local contamination. This feature of the observing network has long been cited as a limitation to confident estimation of regional terrestrial fluxes. Measurements in the continental planetary boundary layer (PBL) are also problematic due to local sources, landscape-scale flux heterogeneity, and poorly resolved PBL physics in many global transport models. Unlike marine measurements, continental CO_2 records are characterized by high temporal variability which limits our ability to interpret their monthly mean values in global inversions (e.g., Gurney et al, 2002).

An alternative approach is to turn the high-frequency variability of CO_2 variations over land to our advantage by using temporally resolved observations and explicitly calculating the flux and transport variations (treating variability as “signal” rather than “noise”). Variations of CO_2 on daily to synoptic time scales over continental areas are much stronger than seasonal and interannual changes, and are related to changes in vertical mixing and airmass trajectories (Hurwitz et al, 2003). These variations contain information about variations in upstream sources and sinks. Law et al (2002, 2003) have investigated the use of daily or continuous CO_2 data in global inversions using synthetic data and found dramatic reductions in flux uncertainty relative to the current practice of inverting monthly mean observations. These results remain hypothetical due to the dearth of continuous measurements of CO_2 mixing ratios, but new observations planned for the coming years under NACP will facilitate tremendous improvements in flux estimation from high-frequency data. Estimation of regional carbon fluxes from high-frequency continental CO_2 data will require accurate specification of meteorological transport, including PBL and cloud venting processes and synoptic-scale features such as fronts. This is difficult to achieve using global models due to the need for very high resolution, but is possible using a nested mesoscale model such as the Regional Atmospheric Modeling System (RAMS, Denning et al, 2003; Nicholls et al, 2003). As part of the proposed research, we will develop methods for estimation of seasonal to interannual variations in net CO_2 flux at high resolution over North America by applying synthesis inversion of global data ($\Delta x \sim 100$ km) and embedding a nested mesoscale inverse calculation ($\Delta x \sim 10$ km) using newly available continuous observations of the mixing ratio of CO_2.

Further challenges for implementing the model-data fusion system envisioned under NACP include the attribution of fluxes to specific processes and mapping them at high temporal and spatial resolutions of interest to land managers and policymakers. The work proposed here focuses on separation of fossil fuel emissions from biogeochemical fluxes and on estimation of seasonal to interannual variability due to climate fluctuations. Controls of long-term fluxes (by land use and disturbance history or CO_2 fertilization, for example) are beyond the scope of the proposed research. The current practice of estimating time-mean fluxes from time-mean data is untenable for inversion of time-varying fluxes from high-frequency data (Uliasz and Denning, 2003), as atmospheric transport and ecosystem carbon exchange are dynamically linked on diurnal and synoptic time scales (Denning et al, 1996; Yi et al, 2001, 2003; Zhang, 2002). Accurate recovery of time-mean net fluxes from high-frequency data will require modeling of diurnal and synoptic time scale fluctuations in these fluxes. We will test methods to estimate spatial patterns of monthly net CO_2 fluxes at high spatial resolution ($\Delta x \sim 1$ km) using a new version of an ecophysiological model (SiB3) driven by analyzed weather and satellite imagery. Model parameterizations of phenology, carbon allocation, and physiological stress will be evaluated against observations made at eddy covariance towers. The high-resolution fluxes will be compared to tower-based data across many sites across different ecosystems, climates, and land-use gradients. They will be aggregated to larger scales and compared quantitatively to fluxes (and uncertainties) retrieved from the inversions. The regional fluxes will be scaled to provide highly resolved maps of monthly carbon exchange that are simultaneously consistent with tower fluxes, atmospheric mixing ratios, and remotely sensed imagery. These will be analyzed along with the primary data (eddy covariance and mixing ratios) to better understand the mechanisms by which spatially coherent climate anomalies modulate seasonal to interannual variations in carbon exchange.

4.2 Objectives

We expect to achieve the following objectives: 1) development and evaluation of a comprehensive analysis system for estimation of monthly CO_2 exchange across North America at high spatial resolution based on the existing and emerging N. American mixing ratio and flux networks; 2) dramatic reduction in the uncertainty in the annual net North American CO_2 flux and its interannual variations, as compared to currently published results; 3) attribution of CO_2 sources between fossil fuel combustion and ecosystem exchange using CO and other trace gases; 4) application of AmeriFlux tower CO_2 flux observations to evaluate the mechanisms responsible for seasonal to interannual responses of ecosystem carbon exchange to climate variability (temperature, radiation, precipitation); 5) evaluation of the flux and mixing ratio predictions of the forwards and inverse models; 6) evaluation of the strengths and weaknesses of atmospheric and ecosystem models, and the flux and mixing ratio observational networks used in these studies. The methods explored here will be portable to other parts of the globe.

4.3 Relevance to NOAA's Global Carbon Cycle program

This project directly addresses the program's goal of, "Quantifying spatial patterns and variability of carbon sources and sinks at global to regional scales." This work will also contribute to the goals of "documenting the fate of anthropogenic CO_2 in the atmosphere and oceans" and "improving future climate predictions by incorporating a dynamical understanding of the carbon cycle into models."

This work will help to determine the strength and variability of the fluxes of carbon within North America, and how these fluxes might change in future years or decades. This work will also clarify the methods – both models and observations – needed to further refine our understanding of continental to regional scale carbon exchange, and to extend our understanding to other parts of the globe. This represents a first attempt to comprehensively merge flux and mixing ratio observational networks into a rigorous modeling framework on a continental scale. The merger of complementary methods of studying the carbon cycle for the purposes of cross-evaluation and more comprehensive understanding is a major focus of the North American Carbon Plan and the U.S. Carbon Cycle Science Plan.

4.4 Data

4.4.1 Flux measurements

The micrometeorological approach known as eddy covariance is an effective method of direct observation of ecosystem-atmosphere exchange and has been successfully applied to long-term observation of net ecosystem-atmosphere exchange (NEE) of CO_2 at many terrestrial sites (e.g. Wofsy et al, 1993). Continuous NEE observations are currently implemented at more than 200 sites worldwide (Baldocchi et al, 2001), and have been used to examine long-term carbon budgets (Barford et al, 2001), the response of ecosystem-atmosphere carbon exchange to climate across multiple biomes (Law et al, 2002), and the response of ecosystem-atmosphere carbon exchange to climate across multiple time scales (Yi et al, submitted). These measurements have proliferated in an effort to understand why terrestrial ecosystems globally are a net sink of carbon dioxide (e.g. Battle et al, 2000) and to help understand how this sink is likely to evolve in future years (e.g. Cox et al, 2000).

Surface-layer, tower-based eddy covariance measures the net flux of CO_2 (and energy, momentum) an area of order 1 km^2 (Horst et al, 1992). The spatial footprint of flux measurements from very tall towers are roughly 100 times larger (Davis et al, in press). These measurements effectively quantify NEE of CO_2 integrated over a forest stand, and for tall tower flux measurements, many forest stands. When combined with complementary ground-based data they have proven to be excellent tools for examining the mechanisms governing NEE of CO_2 (e.g. Goulden et al, 1998).

Up-scaling the absolute value of flux measurements is challenging because of both the spatial complexity of terrestrial landscapes (e.g. soils and topography, vegetation cover, land use and land use history) and concerns about systematic errors in long-term eddy-covariance data caused by stability dependent effects such as drainage flows (e.g. Goulden et al, 1996). A tall flux tower and two nearby stand-level flux towers in northern Wisconsin, for example, show landscape scale respiratory fluxes at the stand-level sites that cannot be upscaled to explain the tall tower, large scale respiratory fluxes despite relatively small systematic error limits (Davis et al, in press; Cook et al, in prep). Thus it appears that landscape complexity in this relatively small, densely instrumented region confounds our ability to upscale the absolute value of these fluxes.

Interannual variability in fluxes, however, is coherent across sites to the degree that the causes of variability is coherent across sites. This has been found for local perturbations such as insect infestations (Cook et al, in prep) and large-scale climate perturbations (Butler et al, in prep; D. Hollinger, personal communication). Seasonal variability, driven by landscape features such as snow cover and the greening and senescence of vegetation, is similarly very coherent across space. AmeriFlux is an informal network that includes more than 50 sites spread across most of the major biomes of North America. A map of current sites can be found at http://public.ornl.gov/ameriflux/Participants/Sites/Map/index.cfm. A smaller number of sites are located in South America. Many of these sites report data periodically to a common database that is available for collaborative investigations. The density of AmeriFlux sites is sufficient to encompass the principal climatic regions of North America. Thus this network provides an effective and operational base of information concerning temporal variability in ecosystem-atmosphere carbon fluxes across the continent, and an important element of the data needed to upscale absolute values of fluxes though, as noted above, this is a more difficult problem than the temporal variability.

4.4.2 Mixing ratio measurements

The global flask network, basis for numerous previous studies of the global carbon budget, remain a critical backbone of data that will be utilized in this study. The flasks, collected weekly at sites distributed around the globe and located primarily in the marine boundary layer at coastal locations (ftp://ftp.cmdl.noaa.gov/ccg/figures/ccgmap.ps), provide an important reference to which terrestrial mixing ratio observations will be compared. These data provide global coverage, temporal continuity (in some cases lasting for decades), meticulous calibration to absolute standards, and laboratory-quality measurement precision and accuracy. They serve as a baseline for comparison to newer data sources.

CO_2 mixing ratio measurements traceable to World Meteorological Organization (WMO) primary standards were initiated on very tall communications towers in 1991 in North America by NOAA's Climate Monitoring and Diagnostics Laboratory (CMDL, Bakwin et al, 1998). From 1991 through 2002, only one to two sites were operated, including the WITN tower in North Carolina (1991 – 1999), the WLEF tower in Wisconsin (1994 – present), and the KETK tower in Texas (2001 – present). An expansion of this network is currently establishing eight additional tall tower sites. The locations of existing tall towers and the new sites to be established are shown in Figure 1. The tall tower data have the advantage that the top level where data is collected, typically 400 m to 500 m above ground, is influenced by surface fluxes for hundreds of km upwind (Gloor et al, 1999) and usually remains above the nocturnal inversion (Yi et al, 2001). Tall tower mixing ratios are analyzed continuously using carefully calibrated infrared gas analyzers (IRGAs) (Bakwin et al, 1998), thus data are available 24 hours per day at a base resolution of an observation every two minutes. These data have been carefully evaluated with respect to flask observations. The tall tower sites are also intended to include carbon monoxide (CO) and methane (CH_4) observations

The NOAA CMDL group has also initiated a limited program of periodic airborne sampling of CO_2 over North America. Measurements currently exist over Carr, Colorado and Harvard Forest, Massachusetts. Measurements will shortly be underway over the WLEF tower in Wisconsin. These airborne profiles begin in the continental boundary layer and extend up to several kilometers above ground, and currently utilize flask sampling technology (http://www.cmdl.noaa.gov/ccgg/aircraft/index.html). A variety of trace gases are sampled in addition to CO_2, including CO, CH_4, N_2O and SF_6. NOAA CMDL is in the process of expanding this network to include several additional aircraft profiling sites. Planned and existing sites are shown in Figure 1. The sampling frequency is similar to the flask sites, roughly weekly. These data extend the observations available from the tall towers into the troposphere above the continental boundary layer.

In addition to the two tall towers and two aircraft profiling sites currently in operation in North America, six additional towers in North America, one in Europe and one in South America maintain continuous CO_2 mixing ratio measurements that are traceable to WMO primary standards using methods similar to those described by Bakwin et al, (1998). All but one of these sites (5 of the 6 in North America) are eddy-covariance flux towers. In addition, instrumentation of an additional six AmeriFlux towers with high precision and accuracy CO_2 mixing ratio measurements traceable to WMO primary standards will be implemented in beginning in early 2004 (Davis and Richardson, DoE Terrestrial Carbon Processes grant). This project complements a similar network of portable CO_2 mixing ratio measurements intended for mesoscale arrays and inversions (Davis, Richardson and Denning, DoE TCP grant). The region around the WLEF tower includes two additional flux towers with high quality CO_2 mixing ratio measurements that are not included in this accounting, but are valuable for regional studies. The locations of the six existing high precision and accuracy continuous CO_2 mixing ratio measurement sites are shown in Figure 1, in addition to the locations of the six planned additional sites, and a possible deployment of four portable measurements for a mesoscale field campaign. These measurements are not based on very tall towers, but towers that extend a modest distance above the local vegetation canopy, typically 20 to 60 m above ground, thus usually within the portion of the atmospheric boundary layer (ABL) referred to as the surface layer.

Studies at the WLEF tall tower show that when subsampled for well-mixed conditions (typically midday over land, when solar heating drives vigorous convective mixing), the mixing ratio measurements collected in the surface layer are very similar to those collected in the middle of the ABL at 396 m. In addition, the difference between surface layer and mid-ABL mixing ratios can be predicted in well-mixed conditions by mixed layer similarity theory (Wyngaard and Brost, 1984; Moeng and Wyngaard, 1989). The difference between surface layer and mid-ABL mixing ratio in these conditions is proportional to the surface flux of CO_2 and also altered by the surface buoyancy flux, both of which are measured directly by flux towers. This is the basis of the virtual tall tower (VTT) method (Davis et al, 1998; Davis et al, in preparation). This approach has been borne out by the empirical success of studies using surface layer mixing ratio data including Potosnak et al (1999), and favorable comparisons of results from tall towers and surface layer towers (Bakwin et al, in review). Table 1, and Figures 2 and 3 (Davis et al, in preparation) help to quantify this discussion.

Table 1 shows that there are small monthly mean systematic biases between the surface layer CO_2 mixing ratio (data from 11 m above ground) and mid-ABL mixing ratios (396 m data) that are proportional to the daytime net ecosystem-atmosphere exchange (NEE) of CO_2 observed at WLEF (Davis et al, in press). When surface layer data are sub-sampled for afternoon (convective, unstable) conditions, *the difference between the mean monthly mixing ratio at 11m and 396m is no larger than about 2 ppm.* This difference is a maximum at times when fluxes are large (mid-summer). A secondary maximum occurs when convective mixing is weak (winter). Figure 2 shows the seasonal course of the 1998 mean mixing ratios of CO_2 for the CBL at the WLEF tower in Wisconsin, the marine boundary layer for 44.4N, and the free troposphere as represented by aircraft data at Carr, CO. It is evident from Table 1 and Figure 2 that *the difference between monthly mean surface layer mixing ratios and monthly mean boundary layer mixing ratios, when sampled during well-mixed conditions, is much smaller than both 1) the amplitude of the seasonal cycle in the continental boundary layer; and 2) the difference between monthly mean marine and continental boundary layer mixing ratios.* Thus the study of seasonal patterns could be accomplished with surface layer flux and mixing ratio data solely via sub-sampling for convective conditions. Surface buoyancy flux is a basic measurement at all AmeriFlux sites.

Second, Figure 3a 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 30m 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 boundary layer mixing ratios.* Thus studies of regional NEE of CO_2 at synoptic time scales (days) can be conducted purely with sub-sampled, surface layer mixing ratio data.

Finally, we examine annually averaged continent-to-ocean, and interhemispheric mixing ratio differences, the subject of traditional inverse studies. Table 1 shows that the magnitude of the monthly mean difference between 11m and 396m afternoon data (0 to 2 ppm, depending on the month) is significant compared to these differences (both about 2 ppm). Table 1 also shows, however, that *the annually averaged, early afternoon WLEF surface layer mixing ratio is only 0.4 ppm lower than the early afternoon boundary layer mean*, and only 0.8 ppm lower than the 24-hour boundary layer mean. Winter and summer biases cancel in the annual average. The meteorological correction will be applied to the sub-sampled continental surface layer data to eliminate this bias. Applying and evaluating this correction is part of the focus of the funded effort of Davis and Richardson (DoE/TCP) that gets underway in the fall of 2003 and will instrument 6 additional AmeriFlux towers as VTTs. We summarize this approach below.

Extrapolation to mid-boundary layer mixing ratios will be achieved using mixed-layer similarity theory (Wyngaard and Brost, 1984). This theory states that for a well-mixed boundary where solar heating of the earth's surface drives vigorous convection, the mean vertical mixing ratio gradient is governed via the following expression:

$$\frac{\partial C}{\partial z} = -g_b\left(z/_{z_i}\right)\frac{F_0^C}{w_* z_i} - g_t\left(z/_{z_i}\right)\frac{F_{z_i}^C}{w_* z_i} \qquad (1)$$

where C is the scalar mixing ratio (e.g. CO_2), F_0^C and F_{zi}^C are the surface and entrainment fluxes of the scalar, z_i is the depth of the convective boundary layer, w_* is the convective velocity scale (a function of the surface buoyancy flux and z_i), z is altitude above ground (or, for a forest, above the displacement height) and g_b and g_t are dimensionless gradient functions that depend on normalized altitude within the convective layer.

The difference between surface layer and mid-boundary layer mixing ratios are computed by integrating the flux-gradient relationship across this vertical interval,

$$\Delta C = C\left(z_{ABL}/_{z_i}\right) - C\left(z_0/_{z_i}\right) = -\frac{F_0^C}{w_* z_i}\int_{z0}^{zABL} g_b\left(z/_{z_i}\right)\partial z - \frac{F_{z_i}^C}{w_* z_i}\int_{z0}^{zABL} g_t\left(z/_{z_i}\right)\partial z, \qquad (2)$$

where z_0 is the altitude of the surface layer measurement, and z_{ABL} is an altitude in the well-mixed atmospheric boundary layer. Note that the gradient varies linearly with the magnitude of the surface flux (so that in winter, if fluxes are very small, essentially no correction is required), and that the difference in mixing ratio is proportional to the integral of the gradient functions. Note also that for the lower half of the boundary layer, the top-down gradient function is quite small (Moeng and Wyngaard, 1989).

Moeng and Wyngaard (1989) simulated these gradient functions using large eddy simulations (LES). Davis et al (1998), using CO_2 flux and mixing ratio data from the WLEF tall tower for one month, calculated the bottom-up gradient function using data limited to convective conditions. Patton et al (2003) also computed the bottom-up gradient function from a nested forest-boundary layer LES, the first nested model of its kind.

The VTT approach is subject to random and systematic errors. We summarize the random and systematic errors in monthly and annual mean mixing ratios (Davis et al, in preparation). The random uncertainty of the *observed bottom-up gradient function*, which includes the turbulent fluctuations in fluxes and mixing ratios, all captured in the WLEF observations and propagated through equation (2), yields a monthly mean random uncertainty in monthly mean mid-CBL mixing ratio of only 0.15 ppm for midsummer fluxes. The choice of gradient function, g_b, is not entirely certain and leads to a systematic uncertainty. The maximum reasonable error that could be made is about 50% of the total change in CO_2 mixing ratio from surface layer to mid-boundary layer. Table 1 shows that on a monthly mean basis, this amounts to a maximum (mid-summer) systematic bias of 1.0 ppm between the computed and actual mid-CBL mixing ratio. Since the surface layer to boundary layer gradient changes sign seasonally, this bias will partly cancel in an annual average. Since WLEF data shows a 0.4 ppm annual bias between surface layer and mid-CBL data, we estimate a maximum annual mean systematic bias after correction of about 0.2 ppm.

Figure 3b show an example of the type of correction that will be applied to the VTT site data. The top panel (Fig 3a) shows hourly CO_2 mixing ratio data from 396m at the WLEF tower, and convectively sub-sampled data from 30m. The lower panel (Fig 3b) shows the difference between midday-mean 396m and 30m mixing ratio data (+'s) which is about 2 ppm early in the month, and decays towards 0 ppm later in the month as the deciduous forest senesces. The diamonds represent a simple mixed layer gradient correction, that is, application of equation (2) using the LES-derived gradient functions of Moeng and Wyngaard (1984) (note that gradient functions derived from WLEF data could also be used, guaranteeing close agreement). Monthly mean values are used for the mixed layer depth and all surface fluxes (Yi et al, 2001). The correction works well, and results in a monthly mean bias in the CBL mixing ratio of just under –0.2 ppm. The variability in the correction is 0.6 ppm, resulting in a monthly standard error of just over 0.1 ppm, consistent with the error propagation that predicted 0.15 ppm. Thus, both the bias and random error of *monthly* VTT mixing ratio data are small enough to detect *annually averaged* continental-to-marine mixing ratio gradients. Systematic errors will cancel (summer vs. winter the bias changes sign), resulting in even smaller bias for annually averaged VTT data.

It is important to note that only the flux and gradient footprints of the tower need to be reasonably homogeneous for this micrometeorological correction to work well. The vertical gradient footprint is similar to the flux footprint (Horst et al, 1999). The much larger region that influences the time rate of change of the ABL mean mixing ratio (e.g. Gloor et al, 1999) does *not* need to be homogeneous for the vertical gradient micrometeorological correction to be valid. Finally, we note that the global flux measurement network now includes more than 200 sites. Thus the VTT method presents an excellent and relatively inexpensive potential component of a global-scale, continental boundary layer CO_2 mixing ratio network.

4.5 Models

To analyze the data described above, we propose to use a meteorological model (the Regional atmospheric Modeling System, RAMS), and two atmospheric tracer transport models (the Parameterized Chemical Tracer Model, PCTM and a Lagrangian Particle Dispersion Model, LPDM), and an ecophysiological model (the Simple Biosphere Model, SiB3).

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 allows for a wide range of motion scales to be modeled simultaneously and interactively.

PCTM is a global offline tracer transport model driven by analyzed meteorology from the NASA Goddard Modeling and Analysis Office (GMAO, formerly the Data Assimilation Office, DAO). The model is available to the CSU team through an existing collaboration with Dr. Randall Kawa at NASA GMAO. Unlike most offline tracer models, the model does not calculate vertical transport due to unresolved subgrid-scale convective motions. Rather, the mass fluxes associated with these processes are archived from the parent operational model and applied in the offline transport code to achieve complete consistency between analyzed meteorology and tracer transport. This also has the advantage that the model is computationally efficient and self-adjoint, allowing tracer transport to be easily run either forward or backward in time (i.e., in receptor-oriented mode).

The LPDM is an efficient algorithm for tracing imaginary Lagrangian "particles" either forward or backward in time using specialized output from RAMS (Uliasz, 1994; Uliasz and Denning, 2003). As with PCTM, the model accounts for transport by both resolved (advective) and subgrid-scale (convective and turbulent) motions by archiving the relevant fields from the parent model. The model is extremely efficient, inherently parallel, and self-adjoint, making it ideal for the estimation of regional CO_2 flux by mesoscale inversion (Uliasz and Denning, 2003).

SiB3 is a new version of the Simple Biosphere Model (Sellers et al, 1996a,b; Denning et al, 1996a; Baker et al, 2003). The model calculates exchanges of energy, water, momentum, and CO_2 at the vegetated land surface. Photosynthesis and transpiration are linked at the leaf level through stomatal conductance (Collatz et al, 1991, 1992), and integrated to landscape scale using remotely sensed imagery. Recent improvements include the introduction of a prognostic canopy air space and a new parameterization of hydrology and thermodynamics of soil and snow following Bonan et al (2003). The model is fully coupled to RAMS, and can be run interactively with the simulated meteorology or driven from prescribed weather and remotely sensed imagery (NDVI or FPAR).

4.6 Analyses

4.6.1 Inverse analyses

We will develop, test, and implement methods for efficient estimation of monthly net carbon fluxes over North America and quantify their uncertainty at regional (~ 1000 km) scales. This effort will build on years of research in both global and regional inverse modeling at CSU, and will be augmented thorough collaboration with Dr. Peter Rayner and colleagues at CSIRO in Australia through a subcontract. We plan to perform the inverse flux estimation in two discrete steps: (1) a global inversion of available monthly mean CO_2 data (primarily flasks) will be performed using the PCTM adjoint on a 1° x 1.25° grid by methods similar to Rödenbeck et al (2003); and (2) a nested mesoscale inversion will be performed on a 10 km grid using the LPDM driven by downscaled meteorology calculated by RAMS.

We have previously shown that confidence in monthly flux estimates by global inversion are limited by sparse observations in some regions (Gurney et al, 2003). We have investigated the impact of new measurements of CO_2 mixing ratio over North America on the uncertainty of flux estimates for this region, using the TransCom framework (Fig 4). Model response functions were sampled at mid-day only (when surface layer offsets are weak and can be quantitatively corrected using the VTT methodology described above), and accumulated into monthly means. Inversions were then performed using each of 11 global transport models, allowing for σ=2 ppm uncertainty in the monthly mean mixing ratio at each actual and virtual tall tower station in North America (note that this is very pessimistic in light of the more recent evaluation of the VTT correction presented above). We found that using the five existing continuous records plus five additional VTT sites would reduce the uncertainty in the annualized carbon budget of temperate North America by a factor of two (to better than 0.25 GtC/yr, mean of 11 model results), with somewhat better results for regionally "clustered" VTTs than for coastal or transect deployments.

The TransCom inversion setup has the advantage that differences among transport models can be taken into account, but spatial patterns of monthly fluxes are fixed, which may lead to aggregation error (Kaminski et al, 2001; Engelen et al, 2002). We will relax this constraint by following the approach of Rödenbeck et al (2003), who used the adjoint of the tracer model TM3 to solve the inverse problem for monthly fluxes at each model grid cell (albeit with larger uncertainty in each flux). We will accomplish this using the PCTM adjoint running at 1° x 1.25° with 55 vertical levels. Spatial covariance among grid cell fluxes will be modeled as well. Using this approach with all the new CO_2 observations described above is expected to produce monthly maps of flux variability over North America that integrate to uncertainty of better than 0.2 GtC/yr in the annual mean.

The highly resolved fluxes obtained by inverting the new data using the PCTM adjoint will be valuable in their own right, but are only intended here as an intermediate product. We will use the time-varying grid of a posteriori CO_2 mixing ratio to specify a prior estimate of lateral boundary conditions to a mesoscale tracer simulation using RAMS. Meteorological lateral boundary conditions will be specified from the GMAO reanalysis, and the model will be integrated for one year on a 10 km grid over a domain covering most of North America and adjacent oceans. This simulation can be run in about three weeks of "wall clock" time on the 20-CPU Linux cluster available at CSU. Output from the 10-km RAMS simulation will then be used to drive a series of receptor-oriented influence function calculations using the LPDM (Ulliasz, 1994; Uliasz and Denning, 2003). These "footprints" will quantify the influence of surface flux at each model grid cell on the measured CO_2 and CO mixing ratio observed at each tall tower, aircraft sampling location, and VTT station during the year. We will use these influence functions (formally equivalent to the adjoint of the RAMS transport) to estimate monthly spatial flux variations across the domain using both a synthesis inversion (Uliasz and Denning, 2003) and a new method based on 4-dimensional variational data assimilation (4DVAR; Cohn, 1997; Menard and Daley, 1996). Quantities retrieved by this procedure will include monthly gridded surface fluxes and their uncertainties as well as corrections to the lateral boundary fluxes specified a priori from the global inversion.

Following the method of Khasibatla et al (2002), fossil fuel emissions will be specified globally from estimates available from DOE ORNL (e.g., Andres et al, 1996), CO/CO_2 emission ratios will be applied and a CO tracer will be propagated through the transport calculation using first-order photochemical decay coefficients derived by Spivakovsky et al (2000). Simulated CO anomalies will be compared to available observations and spatially-resolved "corrections" to the prior (econometric) fossil fuel emission estimates will be made as part of the inversion procedure. Using the updated gridded monthly fossil fuel emission estimates, we will decompose the overall net CO_2 flux into anthropogenic and biogenic components.

4.6.2 Forward modeling and downscaling of inverse flux estimates

Monthly fluxes estimated by 4DVAR using the mixing ratio measurements and RAMS/LPDM will be aggregated to sufficient spatial scales (hundreds of km) to achieve acceptable levels of uncertainty. Note that by performing the aggregation a posteriori, we avoid bias associated with specifying spatial patterns a priori (Kaminski et al, 2001; Engelen et al, 2002; Rodenbeck et al, 2003). These regional fluxes will then be "downscaled" using forward calculations driven by remotely sensed imagery and downscaled weather. We will drive SiB3 over the continental domain of the RAMS simulation on a 1 km grid with vegetation properties specified from MODIS imagery using the 10 km weather. Aggregated regional fluxes will then be constrained by the inverse analysis to obtain monthly fluxes that are optimally consistent with atmospheric mixing ratios, satellite imagery, and eddy covariance measurements.

Before performing the downscaling, we will perform a rigorous analysis of temporal variations of simulated fluxes at a range of Ameriflux sites in North America. In particular, we will evaluate the simulated NEE and its variations in response to light, temperature, humidity, and soil moisture. Note that our focus here is on synoptic to interannual variations in time, not the annual mean flux which may depends on site history or other factors. The time-mean fluxes will be more strongly constrained by the atmospheric inversion.

4.6.3 Model evaluation and sensitivity analysis

4.6.3.1 Sensitivity to data inputs

In addition to deriving monthly fluxes across North America for this period, we will conduct a series of sensitivity studies to determine the relative impact of various data sources on the inversion results. Because many of the data inputs have never been used before, sensitivity studies are warranted. The sensitivity of the inversion results will be tested by removing:

a) Selected CO_2 mixing ratio data sets including the VTTs, tall towers, and aircraft profiles. Weekly vs. continuous data will also be compared. The goal will be to improve our understanding of the optimal mix of observations needed to reduce uncertainty in the North American carbon budget and increase the spatial and temporal resolution with which inversions can be successfully applied.

b) Tower flux measurements. The diurnal cycles in NEE of CO_2 that were derived from the flux data will be replaced with cycles independent of the flux data. The value of AmeriFlux data in determining the priors in the inverse model will thus be tested.

c) Remote sensing of ecosystem greenness. The MODIS and AVHRR indices used to impart spatial variability in ecosystem productivity as a prior in the inverse model will be replaced with a climatological seasonal cycle. Thus the value of including year-specific remote sensing of vegetation cover will be tested.

d) Assimilated weather data. Real years of reanalyzed weather will be replaced with a multi-year mean transport field.

4.6.3.2 Evaluation of inversion derived fluxes

The ability of the inversion to recover monthly fluxes will be evaluated by creating synthetic data on a 10 km grid using the coupled SiB3-RAMS model, sampling it as we would the real atmosphere, and then attempting to retrieve the (known) gridded fluxes. This exercise will allow us to evaluate the ability to separate anthropogenic and biogenic emissions, and should provide insight into the degree of a posteriori aggregation of fluxes that will be necessary with real data.

We will further employ the joint constraints of CO_2 flux and mixing ratio observations by evaluating the inverse-model derived NEE of CO_2 versus direct observations from the AmeriFlux network. This has not yet been done is a systematic fashion, partly because *no previous continental-scale inverse study has derived North American fluxes with the spatial and temporal resolution proposed here*. Studies more limited in space or time (Bakwin et al, in revision; Gerbig et al, submitted) have made first steps in this direction. NEE of CO_2 is observed continuously with half-hour time resolution at AmeriFlux towers, and these data are commonly decomposed into total ecosystem respiration and gross ecosystem productivity (e.g. Falge et al, 2002). As noted, soils, vegetation cover and land use patterns are highly heterogeneous, making it difficult to make a direct comparison between small footprint eddy-covariance NEE data and spatially coarse inverse estimates. We will focus, therefore, on the temporal variability in NEE of CO_2 which is governed primarily by climate thus coherent over large regions. Leaf-out, for example, proceeds in a coherent wave from south to north over the entire continent. Thus the inverse-derived monthly fluxes, driven by reanalyzed weather and remote sensing of vegetation for specific years, should match the onset of spring as captured by AmeriFlux towers spread across the continent. This relatively simple first test should be successful, but it has been shown, for example, that there is a substantial lag time between the seasonal cycles of NEE of CO_2 and ABL CO_2 mixing ratio, and that balancing the monthly continental CO_2 budget is very dependent upon transport and mixing (Davis et al, in press; Bakwin et al, in revision). If the reanalyzed transport fields were in error, this would lead to errors in the inverse estimates of NEE.

Evaluation of continental ABL mixing ratio data requires that the transport model handles ABL processes well. Comparisons of ABL depth measurements to past transport models (Yi et al, in preparation) have been reasonably successful, but we propose careful analysis via additional independent observations. We will utilize rawinsonde and ceilometer data maintained by the National Weather Service as a base data set. Supplementary data will come from ABL energy budget analyses of surface buoyancy flux data, which is very effective at estimating mean daytime ABL depth (Yi et al, 2001), and 915 MHz radar data or ground based Raman lidar data where available (e.g. ARM-CART region in the southern Great Plains).

4.6.3.3 Evaluation of the simulated atmospheric mixing ratios

The forwards model will provide predictions of atmospheric mixing ratios at high spatial (1^ox1.25^o, multiple tropospheric layers in the vertical) and temporal (resolved diurnal cycle) resolution. The continuous mixing ratio observations (tall towers, VTTs) have similar temporal resolution, and both the tall towers and aircraft profiles provide rich vertical structure data. The aircraft profiles should be particularly valuable since they are our only source of direct observations of mixing ratios above the continental ABL. Our evaluation of modeled mixing ratios, therefore, will span diurnal cycles within the ABL and seasonal ABL-troposphere gradients at multiple locations across the continent, and spatial gradients within the continental ABL across synoptic and seasonal time scales.

Since modeled fluxes are tuned to observe fluxes, discrepancies between observed and modeled mixing ratios could be caused by a failure to upscale the fluxes well, mixing ratio data this is not representative of the domains simulated by the model, or model transport. Given the importance of vertical transport and the fact that it is largely parameterized in global transport models, boundary layer mixing and/or convective cloud mixing are likely sources of transport error. In this project we will focus in particular on the ability of the transport model to properly represent ABL mixing via the mixing depth measures described in the data section.

4.6.3.4 Evaluation of SiB3 with respect to flux observations

Many land surface models have been compared to or calibrated with flux measurements from individual sites (e.g. Baker et al, in press). Fewer model evaluations have included multiple concurrent flux measurements (e.g. Bonan et al, 1997). A relatively small number of studies have also gone beyond the variables that dominate the short-term response of NEE to climate, that is light and temperature. In the process of fitting SiB2.5's temporal variability to the suite of AmeriFlux sites, we will evaluate SiB2.5's ability to encompass the range of sites found in AmeriFlux and the response of SiB2.5 and the observed fluxes to environmental stresses (e.g. drought/flood) that go beyond basic light and temperature response. The response of NEE to environmental factors has been found, for example, to be a function of time scale (Yi et al, submitted) . This work is a step towards creating an inverse model of ecosystem fluxes, and running an inverse model using both flux and mixing ratio observations to solve for model parameters consistent with our understanding of ecosystem biophysics..

<u>4.6.3 Data analyses</u>

Two foci of this proposal are limited primarily to data. First, we will collaborate with the work of the VTT data collection and evaluation project of Davis and Richardson to contribute to their understanding of the quality of VTT CO_2 mixing ratio data and the degree to which these data represent large regions of the continental ABL. This project has the potential, for example to guide or modify their selection of sites. Second, we will observationally evaluate our assertion that seasonal and interannual variability in NEE of CO_2 are dominated by climate, thus coherent in space and time with climate and CO_2 mixing ratio variability. The space-time coherence of flux and mixing ratio data, governed by climate, is central to our hypothesis that fusion of North American flux tower and continental mixing ratio data will prove to be a useful exercise. A preliminary study (Butler et al, in preparation) has established this coherence for a strong interannual contrast between the springs of 1998 and 1999. This proposal would support more systematic analyses of the space-time coherence among these data sets.

4.7 Time line

<u>Year 1:</u> Preparation of databases. Flux data in particular will require significant preparation to create common formats. Preparation of models and priors. Exchange of personnel among groups to integrate model and data efforts. Evaluation of SiB3 with respect to flux data base for North America, and evaluation of space-time coherence among data sets. Design and build an algorithm to use model transport fields in a 4-dimensional variational data assimilation system to retrieve surface CO2 fluxes from atmospheric concentration data
<u>Year 2:</u> Publications based on data analyses and SiB3 evaluation. Forward and global inverse model runs for a single year. Forward and inverse model evaluation as noted in analyses sections. Using simulated data (pseudodata) generated by coupled SiB3-RAMS model, test the limits of resolution and bias in the 4DVar system.
<u>Year 3:</u> Continued evaluation of models, synthesis of results. Publication of results from single year downscaled inversion of real data. Multiple year forward and inverse model runs, as possible. Collaboration with land use history and carbon pool scientists to advance inverse model evaluation, as possible.

4.8 Management plan and qualifications of investigators

- The Penn State group headed by Davis will be primarily responsible for the flux and mixing ratio data sets, as well as ABL depth measures. They will direct data analyses and participate in model-data evaluations. The groups directs eddy covariance data analyses at four AmeriFlux sites, has both directed and participated in synthesis studies across the global flux network, directs a regional upscaling and downscaling effort in northern Wisconsin (http://cheas.psu.edu), has published innovate work in the area of ABL depth detection and climatology, developed the virtual tall towers (VTT) concept and now is responsible for both mesoscale and continental scale flux tower-based CO_2 mixing ratio observational programs.

- The Colorado State group headed by Denning will be responsible for providing the forwards and inverse numerical models. They will direct the model runs and participate in model-data evaluations. They have directed the TRANSCOM project (Gurney et al, 2002), have done leading work in coupled land-atmosphere carbon cycle modeling at both regional and global scales, and have published influential work regarding the importance of boundary layer processes in terrestrial carbon cycle studies.
- The CSIRO carbon cycle modeling group led by Rayner will contribute ground-breaking expertise on using high temporal resolution mixing ratio data in inverse studies of continental and regional carbon budgets. This collaboration will enhance parallel work at CSIRO.
- The Carbon Cycle Group at NOAA's Climate Monitoring and Diagnostics Lab, led by Tans, are world leaders in both global carbon cycle data and atmospheric inverse modeling. They will supply the tall tower and aircraft profile CO_2 mixing ratio data to this study, and exchange. This collaboration will enhance parallel work underway at CSIRO.

The Davis and Denning research groups have a long history of collaborative work that will ensure close cooperation in this effort. Similarly, both groups have interacted extensively with the tall tower measurement program at NOAA CMDL. Students and research associates will be encouraged to work collaboratively across groups, thus merging the expertise of these groups and gaining a broad set of research skills.

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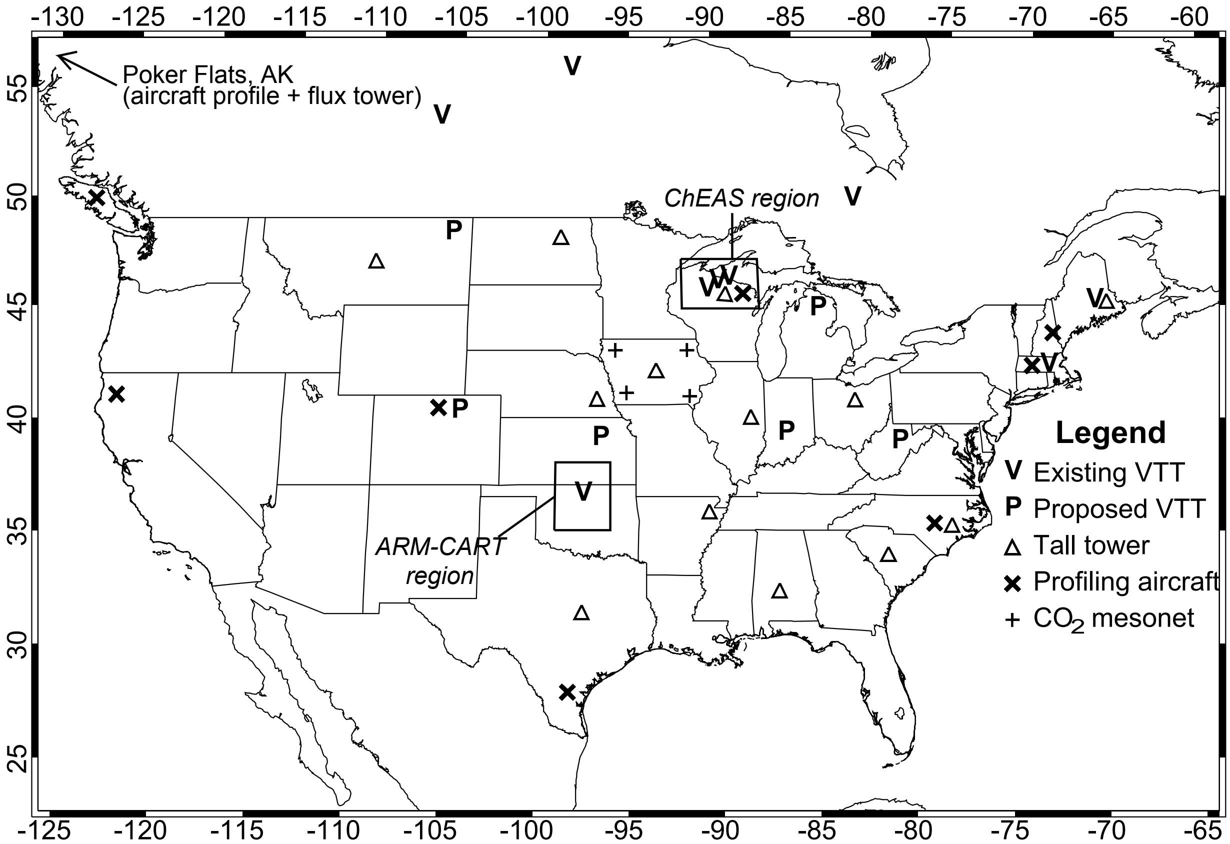
4.8 Tables and Figures

Table 1: 1997 monthly mean CO_2 mixing ratios from the WLEF tower illustrating sub-sampling and surface-mid CBL biases, and comparison to the marine-continental BL CO_2 differences.

Month	CO_2 (ppm) at 11m, early pm only	CO_2 (ppm) at 396m, early pm only	ΔCO_2 (ppm) 11m – 396m, early pm only	CO_2 (ppm) at 396m, entire day	ΔCO_2 (ppm) 396m pm – 396m entire day
1	371.4	370.3	1.1	369.7	0.6
2	371.4	371.2	0.2	371.1	0.1
3	371.4	371.0	0.4	371.0	0.0
4	370.4	370.4	0.0	370.4	0.0
5	368.1	368.2	-0.1	368.3	-0.1
6	355.5	357.3	-1.8	359.4	-2.1
7	348.0	350.2	-2.2	351.1	-0.9
8	346.1	348.1	-2.0	349.3	-1.2
9	354.9	356.2	-1.3	358.0	-1.8
10	365.8	365.6	0.2	366.0	-0.4
11	370.3	369.9	0.3	369.6	0.3
12	371.5	370.6	0.9	370.2	0.4
Annual mean	363.7	364.1	-0.4	364.5	-0.4

Annual mean at Mauna Loa, 1997, was 366.7 ppm.

Figure 1: Existing virtual tall tower sites (V), funded NOAA-CMDL tall tower (triangle) and aircraft profiling sites (X) planned for FY05 operations, planned new virtual tall tower sites (P) and proposed CO_2 mesonet deployment (+), all to be operational in FY05. See Table 2 for a list of currently existing sites.



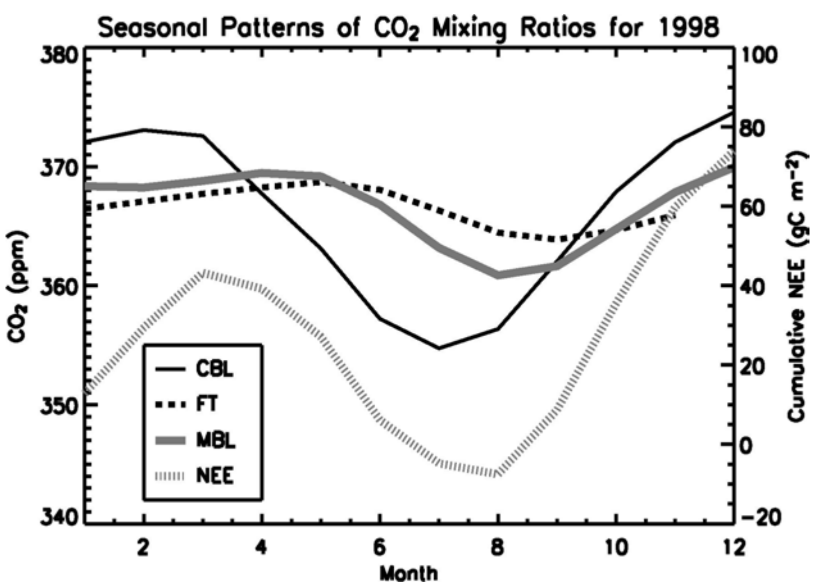


Figure 2. (left) Monthly mean mixing ratios of CO_2 for convective boundary layer (CBL, sub-sampled for convective afternoon hours at WLEF), free troposphere (FT, from aircraft flights at Carr, CO), and marine boundary layer (MBL, at 44.4N). Also shown is cumulative NEE at WLEF.

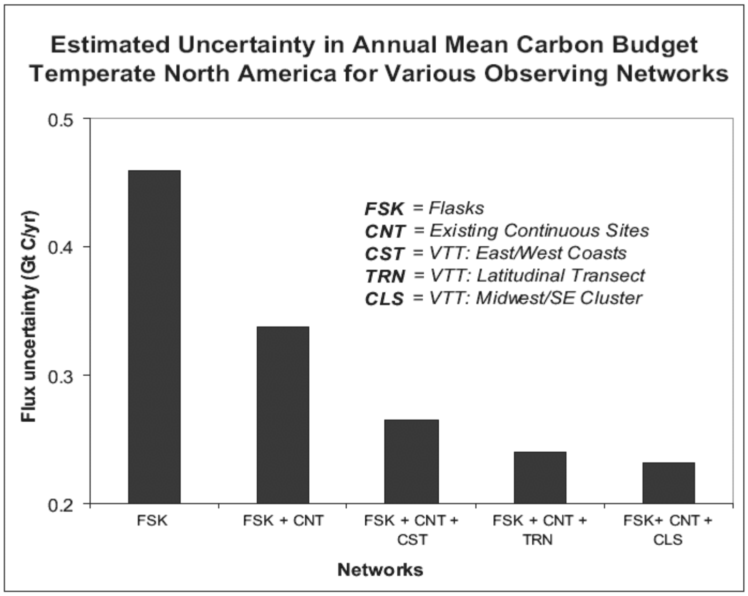


Figure 4. Estimated uncertainty of annual carbon budget from global inversion simulation using different scenarios of North American observation networks. See Table 2 for existing continuous sites, and Figures 1 and Table 2 for various proposed VTT arrays, including an array similar to the one used in this simulation. Note that the assumed monthly random error for VTT sites in this simulation was 2 ppm, at least five times greater than the expected

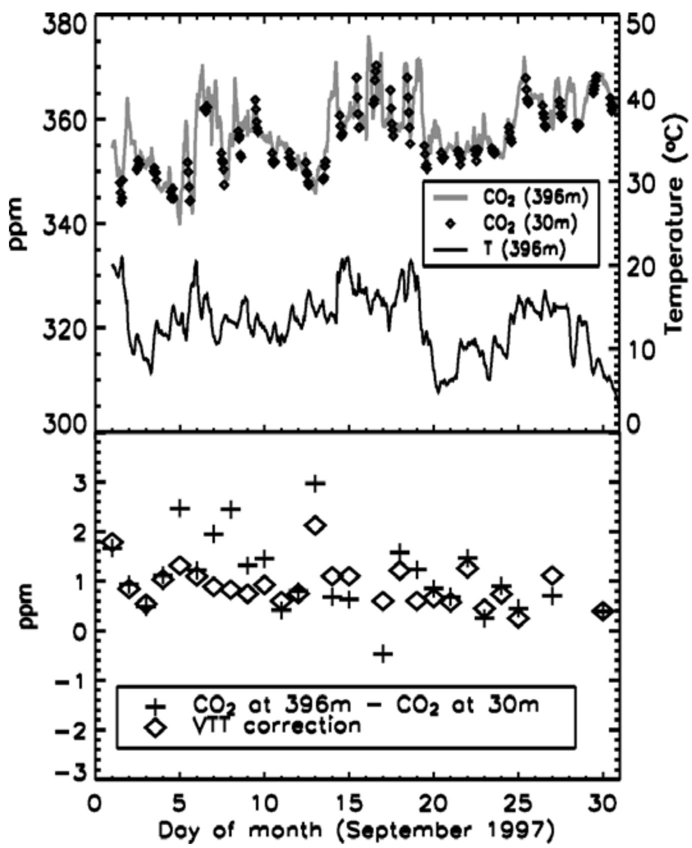


Figure 3. (a) Observed synoptic cycle of CO_2 mixing ratios and temperature (for reference) at the WLEF tower. Hourly, continuous data for 396m, data subsampled for daytime, well-mixed conditions at 30m. (b) Difference between daytime-averaged 30m and 396m CO_2 mixing ratio data (+), and a virtual tall tower correction (see section 4.3 in text) using simple assumptions and gradient functions. Bias is just under 0.2 ppm (monthly mean). Standard error (monthly mean) is less than 0.2 ppm.

Table 2: Existing Highly Calibrated CO_2 North American Measurement Network

Site	Contact	Location	Canopy Height (m)	Tower Height (m)	Years data has been collected
Surface Flux Towers (6 more to be added, see Figure 1)					
Harvard Forest	S. Wofsy Harvard Univ.	Massachusetts 42.5N, 72.2W	24	30	1991-present
Howland Forest	D. Hollinger USDA	Maine 45.2N, 68.8W	20	26	1996-present
Northern Old Black Spruce	S. Wofsy Harvard Univ.	Manitoba 55.9N, 98.5W	10	31	1994-present
ARM-CART	M. Fischer US-DOE	Oklahoma 36.6N, 97.5W	<3	60	2001-present
BERMS, Old Black Spruce	T.A. Black Univ. BC	Saskatchewan 54.0N, 105.1W	20	25	2002-present
Fraserdale (CO_2 only)	D. Worthy Met. Service Canada	Ontario 49.9N, 81.6W	NA	~30	1995-present
Tall Towers (9 more to be added, see Figure 1)					
WLEF (flux and CO_2, ChEAS network*)	P. Bakwin NOAA	Wisconsin 45.9N, 90.3W	~20	470	1994-present
Moody (CO_2 only)	P. Bakwin NOAA	Texas 31.6N 97.2W	<1	505	2001-present
Airborne Profiling Sites (7 more to be added, see Figure 1)					
Carr, CO	P. Tans NOAA		NA	NA	1993-present
Harvard Forest, MA	P. Tans NOAA	Massachusetts 42.5N, 72.2W	NA	NA	1999-present

5. Budget Justification

Salaries and Wages - The principal investigator is budgeted at the percentage of time shown using his/her actual salary in the calculation. The principal investigator's time includes both technical and project management functions. Any other individuals/positions shown are technical or administrative support staff to the principal investigator with the percentage of time shown and actual salaries used. For project time occurring after June 30 of any given year the salaries have been adjusted for a three-half percent (3.5%) per year increase.

The PI will supervise the Penn State research effort, including the graduate assistant and research associate, and will direct collaboration with colleagues from Colorado State and CSIRO, Australia. The PI will synthesize and present project results via the preparation of publications and presentations at scientific conferences. The facilities assistant will support project-related hardware and software. The graduate research associate and research associate/postdoctoral fellow will work closely with the PI to carry out the scientific analyses described in the statement of work.

Recovery of Fringe Benefits - Rates are negotiated and approved annually by the Office of Naval Research, the cognizant federal agency for this institution. Rates for the period between July 1, 2003 and June 30, 2004 are 27% applicable to Category I Salaries, 7.5% applicable to Category II Graduate Assistant Stipends, 8.1% applicable to Category III Salaries and Wages. The rates quoted above have also been used for any project period occurring after July 1, 2004 and forward in lieu of negotiated rates for the forward period.

Travel - Includes PSU travel to workshops with collaborators from Colorado State, CSIRO, and NOAA CMDL as well as travel to scientific conferences to present project results.

Materials and Supplies - Supply and expense items categorized as project specific are for expenses that specifically benefit this project, are reasonable and necessary for the performance of this work, and can be readily allocable to this project. Included in this request are funds for a laptop personal computer and desktop personal computer for project personnel

Permanent Equipment – Funds for a Linux-based workstation to support project computational needs is requested. The workstation will be accessed by all project personnel.

Communication Services - Costs that are contained in this proposal will be incurred for the sole direct benefit of the project. These costs are for long distance, fax and postage charges. In Penn States normal course of business, such charges are directly chargeable to a specific contract/project rather than to an overhead account.

Other Direct Costs - Other direct costs shown are those items not included above necessary to carry out the project. This category includes computation services and tuition.

Graduate Assistant Tuition - Computed using the approved tuition charges for a one-half (1/2) time graduate assistant at $4,175 a semester beginning Fall 2003. The charges quoted above are increased by ten (10%) percent for any project period occurring after Summer Session 2004, and each Summer Session thereafter

Recovery of F&A - Rates are negotiated and approved annually by the Office of Naval Research, the cognizant federal agency for this institution. Rates for the period between July 1, 2003 and June 30, 2004 are 44% of Total Modified Direct Costs (MTDC). The rates quoted above have also been used for any project period occurring after July 1, 2004 and forward in lieu of negotiated rates for the forward period.

*All rates listed are provisional pending approval from ONR.