Annual Report: NA08OAR4320893
Data fusion to determine North American sources and sinks of carbon dioxide at high spatial and temporal resolution from 2004 to 2008
Period of Performance: 6/1/2009 – 5/31/2010

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1. Introduction

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, as well as limited continental data. 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 N. American carbon cycle observational network is underway. This expansion includes a network (AmeriFlux) of continuous, eddy-covariance based CO_2 flux measurements and a network of continuous, continental CO_2 mixing ratio observations of comparable precision and accuracy to the marine flask network. Inverse studies of the N. American carbon budget have only begun to utilize these emerging data sources directly (i.e. tower fluxes and continuous continental mixing ratio observations), and how to best utilize these data together is a topic of great uncertainty and intensive research. This is the focus area of our research. We are conducting a program of research that will turn the emerging wealth of data in N. America to our advantage. This will be accomplished by a continued collaboration between research groups at the forefronts of terrestrial boundary layer CO_2 flux and mixing ratio observations, and high resolution, land-atmosphere carbon cycle modeling. This collaboration has resulted in substantial progress towards fusion of flux and mixing ratio observations in a coupled land-atmosphere data assimilation framework. This project will further develop methods for fusion of CO_2 flux and mixing ratio observations via inverse modeling incorporating the N. American CO_2 mixing ratio observational network, forwards modeling built upon the N. American flux network, and cross-evaluation of these two approaches. We have published analyses of the mechanisms controlling interannual variability of carbon fluxes over North America (Baker et al, 2010), and a separate estimate of photosynthesis and respiration derived from data fusion for North America in 2004 (Schuh et al, 2010). Further, we will apply the methods already developed via this collaborative effort to examine interannual variability of N. American carbon fluxes from 2004 to 2008.

Hypotheses:

1) Flux and mixing ratio observations can be merged into a consistent analysis at synoptic, seasonal, and interannual time scales;

2) The N. American CO_2 budget will be well constrained by our data analysis system;

3) The 2004-2008 record of N. American net annual terrestrial CO_2 fluxes will show a persistent net sink of carbon of location and magnitude consistent with previous estimates based on ecological inventory methods, and;

4) The same flux record will yield detectable, spatially-resolved, climate-driven interannual variability.

Expected products include:

1) a growing database of flux-tower based, continuous CO_2 mixing ratio observations suitable for application to continental inversions;

2) a comprehensive analysis system for estimation of monthly CO_2 exchange across N. America at high spatial resolution;

3) significant reduction in the uncertainty in the annual net N. American CO_2 flux and its interannual variations, and;

4) spatially and temporally resolved terrestrial CO_2 fluxes and uncertainty estimates for 2004 through 2008 encompassing all of N. America.

Ultimately, our results will support the development of dynamic predictions of the future carbon cycle by providing a regionally and temporally resolved multi-year record of whole continent terrestrial carbon fluxes needed to evaluate continental-scale models.

2. Research highlights.
Figures in the technical report below illustrate highlights of the ongoing research.
3. Research products.
Information concerning instrumentation and sites collecting data can be found at http://www.amerifluxco2.psu.edu and http://ring2.psu.edu.
Results of our regional inversion have been submitted to the North American Carbon Program regional interim synthesis activity for inclusion in that comparison project.

4. Peer-reviewed publications, conference proceedings and presentations.
4.a) Peer-reviewed publications:

Baker, I.T., A. S. Denning, R. Stockli, 2010. North American gross primary productivity: Regional characterization and interannual variability. *Tellus*. In press.

Schuh, A. E., A. S. Denning, M. Uliasz, K. D. Corbin, 2009. Seeing the Forest through the Trees: Recovering large scale carbon flux biases in the midst of small scale variability. *Jour. Geophys. Res.*, doi:10.1029/2008JG000842.

Schuh, A. E., A. S. Denning, K. D. Corbin, I. T. Baker, M. Uliasz, N. Parazoo, A. E. Andrews, and D. E. J. Worthy, 2010. A regional high-resolution carbon flux inversion of North America for 2004. *Biogeosciences*, **7**, 1625–1644.

4.b) Reports to agencies:

4.c) Conference proceedings:

Denning, A. S., K. D. Corbin, I. T. Baker, E. Lokupitiya, E. McGrath-Spangler, R. Stockli, A. Schuh, K. R. Gurney, N. Parazoo, D. Zupanski, M. Uliasz, N. Miles, K. Davis, and S. Richardson. The North American Carbon Cycle as Seen In Models and Observations. Presented at the American Geophysical Union Fall 2008 Meeting, San Francisco CA, USA.

Denning, A. S., N. Parazoo, A. Schuh, and M. Uliasz. Gulf Coast Atmospheric Inflow: A Key Element of the North American CO2 Budget. Presented at the American Geophysical Union Fall 2008 Meeting, San Francisco CA, USA.

A. S Denning, N. Cavallaro, C. Ste-Marie, A. Muhlia-Melo. CarboNA: International studies of the North American carbon cycle. Invited Presentation at the American Geophysical Union Spring 2009 Meeting, Toronto, Canada.

A.E. Schuh, A. S. Denning, S.M. Ogle, K. Corbin, M. Uliasz, K.J. Davis, T. Lauvaux, N. Miles, A.E. Andrews, G. Petron, D.N. Huntzinger. 2009. Atmospheric CO2 inversions of the mid-continental intensive (MCI) region. Invited Presentation at the American Geophysical Union Fall 2009 Meeting, San Francisco CA, USA.

F.J. Breidt, D.S. Cooley, Q. Thurier, Y. Wang, A.E. Schuh, A. S. Denning, K.J. Davis, T.O. West, S.M. Ogle, 2009. Reconciliation of carbon dioxide flux estimates from atmospheric inversions and inventories in the mid-continent intensive. Presented at the American Geophysical Union Fall 2009 Meeting, San Francisco CA, USA.

I.T. Baker, A. S. Denning, and R. Stockli, 2009. B51D-0332. North American gross primary productivity: regional characterization and interannual variability. Presented at the American Geophysical Union Fall 2009 Meeting, San Francisco CA, USA.

4.d) Presentations:

Schuh, A., A.S. Denning, M. Uliasz, N.R. Miles, K.J. Davis, and S.J. Richardson, Regional-scale atmospheric measurements of CO2 sources and sinks. Plenary talk, Air and Waste Management Association First International Greenhouse Gas Measurement Symposium, 23-25 March, 2009, San Francisco, CA.

Participation in the 2nd North American Carbon Program All-Investigators Meeting. 17-20 February, 2009, San Diego, CA, including a project-related presentations:

Co-convener of session on Integrated Studies of Regional Carbon Exchange at the Fall Meeting of the American Geophysical Union, December, 2008, San Francisco, CA.

5. Student degrees supported.
Ph.D. dissertation:
Schuh, Andrew. Primary support from this project.

6. Technical Report for Year 2:

6.1 Observations

This project builds upon the NOAA Global Monitoring Division (GMD) network of flask measurements (e.g. Conway *et al.,* 1994), aircraft profiles and tall towers (e.g. Bakwin *et al.,* 1998), and enhances this network with high-quality CO_2 mixing ratio measurements on 13 AmeriFlux towers, 5 of whose CO_2 instrumentation are maintained via this project, and all of whose mixing ratio data are being combined to make a uniform data product via this project. We will also work with 3 Fluxnet Canada sites with similar data. Note that most flux towers do not maintain CO_2 measurements of sufficient absolute accuracy or long-term precision to be useful in atmospheric inversion studies. These data will be further complemented by a mountaintop network in the Rockies (Fig. 1).

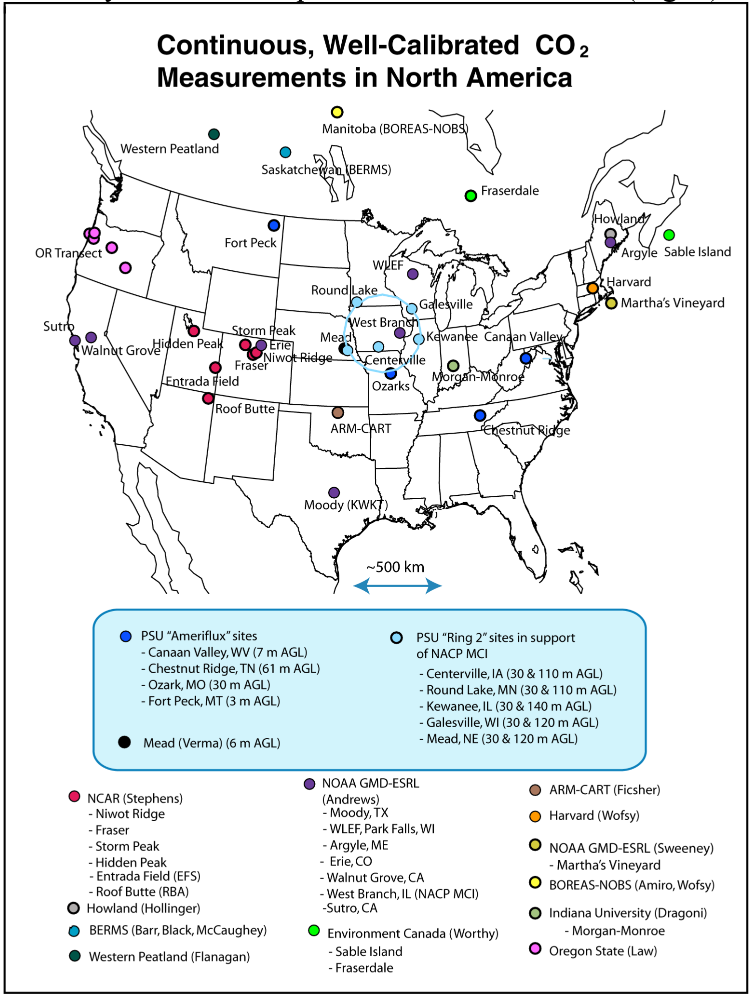

Figure 1: Locations of continuous CO2 measurement sites in North America. Sites supported under this project are indicated in dark blue.

The surface layer mixing ratios measured at these towers, when subsampled for midday conditions, are very similar to the mixing ratio of the mixed layer (e.g. Yi *et al.,* 2004). Butler *et al.,* (in preparation) shows that further, the small difference between the surface layer mixing ratio and the mid-convective boundary layer (CBL) can be estimated from micrometeorological scaling arguments that have been fitted to the CO_2 flux and mixing ratio measurements from the 447 m tall WLEF tower. The average bias for hourly data is less than 0.2 ppm in summer, less than 0.1 ppm in spring and fall, and less than 0.5 ppm in winter (when mixing is the weakest). The average annual bias for houly data is less than 0.05 ppm. Data from the surface layer, subsampled for midday conditions, contain abundant large-scale synoptic and seasonal structure (e.g. Bakwin *et al.,* 2004; Hurwitz *et al.*, 2004).

The data from the network are available at http://ring2.psu.edu and http://amerifluxco2.psu.edu, as described in the annual progress report of our co-Investigators at Penn State.

6.2 Assimilation of CO2 Mixing Ratio data into Models

A fundamental assumption in the two-step assimilation procedure we propose is that high-frequency variations in NEE are driven by radiation and weather and can be successfully modeled by the flux-tower-optimized SiB-CASA. This allows us to accumulate mixing ratio data over a longer period of time to estimate spatial variations in state variables (e.g., carbon stocks) that control the lower frequency source-sink dynamics. We use the model and environmental data to account for spatial and high-frequency time variations of photosynthesis and respiration by assuming that they are driven by well-understood and easily modeled processes (vegetation distribution, radiation, temperature, soil moisture), then solve for unknown multiplicative biases in each component flux after smoothing in space and time. This is accomplished by convolving the influence functions generated from LPDM with gridded photosynthesis (gross primary production, GPP) and ecosystem respiration (RESP) at each time step in SiB-CASA. The net ecosystem exchange (NEE) is composed of these two component fluxes:

$$NEE(x,y,t) = RESP(x,y,t) - GPP(x,y,t) \qquad \text{(eq 1)}$$

where x and y represent grid coordinates and t represents time. Sub-hourly variations in the simulated component fluxes in time are primarily controlled by the weather (especially changes in radiation due to clouds and the diurnal cycle of solar forcing), whereas seasonal changes are derived from phenological calculations parameterized from satellite imagery. Fine-scale variations in space are driven by variations in vegetation cover, soil texture, and soil moisture. To estimate regional fluxes from atmospheric mixing ratios, we assume that the model of the component fluxes is biased, and that the biases are smoother in time and space than the fluxes themselves:

$$NEE(x,y,t) = (1+\beta_{RESP}(x,y))RESP(x,y,t) - (1+\beta_{GPP}(x,y))GPP(x,y,t) \qquad \text{(eq 2)}$$

A persistent bias in photosynthesis might result from underestimation of leaf area, available nitrogen, or soil moisture, whereas a persistent bias in respiration might result from overestimation of soil carbon or coarse woody debris. In any case, it is reasonable that such biases vary much more slowly than the fluxes. We generate surface flux influence functions by integrating the backward-in-time particle trajectories from LPDM. Using these, we can represent the mixing ratio observed at a given station k at time m as

$$C_{k,m} = \sum_{i,j,n} \Big(\big((1+\beta_{R,i,j})RESP_{i,j,n} - (1+\beta_{A,i,j})GPP_{i,j,n} \big) C^{*}_{k,m,i,j,n} \Big) \Delta t_f \Delta x \Delta y + C_{BKGD,k,m} \text{(eq 3)}$$

where i and j are grid indices in the zonal and meridional directions, n is the time at which GPP and Respiration occurred (not usually the time at which the resulting change in mixing ratio was measured!). Fossil fuel combustion is specified according to an hourly analysis on a 32-km grid being developed in collaboration with K. Gurney and tested at CSU. The influence function $C^*_{k,m,i,j,n}$ is then the discrete form of the partial derivative of the observed mixing ratio with respect to the NEE at grid cell (*i,j*) at time step *n*. The length scales Δx and Δy are the sizes of the grid cells in the zonal and meridional direction, and Δt_f is the time step over which the fluxes are applied. The term $C_{BKGD,k,m}$ represents the contribution of "background" CO_2 flowing into the model domain from the larger scales (estimated from the global PCTM analyses). With a little algebra and a healthy dose of computer time, we obtain a simpler representation more practical suitable for optimization:

$$C_{obs} = \sum_{cell=1}^{nCell} (1+\beta_{RESP,cell}) C^*_{RESP,obs,cell} + \sum_{cell=1}^{nCell} (1+\beta_{GPP,cell}) C^*_{GPP,obs,cell} + C_{BKGD,obs} \qquad \text{(eq 4)}$$

where *obs* is an observation number (combines indices *k* and *m*), and *cell* is a grid cell number (combines indices *i* and *j*). The influence functions have been convolved with the GPP and RESP terms from the forward model and integrated over the time period over which the bias terms are assumed to apply:

$$\begin{aligned} C^*_{RESP,obs,cell} &= \Delta t_f \Delta x \Delta y \sum_n RESP_{cell,n} C^*_{obs,cell,n} \\ C^*_{GPP,obs,cell} &= -\Delta t_f \Delta x \Delta y \sum_n GPP_{cell,n} C^*_{obs,cell,n} \end{aligned} \qquad \text{(eq 5)}$$

Equation 4 is a linear system which can be written simply as

$$\vec{y} = h\vec{x} \qquad \text{(eq 6)}$$

where $\vec{y}$ is the vector of observations C_{obs} and $\vec{x}$ is the vector of unknown bias terms $\beta_{\text{GPP,cell}}$ and $\beta_{\text{Resp,cell}}$. The Jacobian matrix *h* contains the influence functions $C^*_{GPP,obs,cell}$ and $C^*_{RESP,obs,cell}$. The rows of *h* correspond to each observation, and each column corresponds to an unknown bias term β_{RESP} or β_{GPP} at a given grid cell over the 10-day integration period. In practice, we treat the background mixing ratio by prescribing lateral inflow from the global PCTM. We treat errors in this boundary condition additively by augmenting the vector of unknowns $\vec{x}$ with lateral boundary concentrations and "transporting" them to the receptor by augmenting matrix *h* with additional influence functions for these fluxes.

We minimize a cost function that penalizes model-data mismatch and is regularized by imposing a weak prior constraint:

$$J = (\vec{y} - h\vec{x})^T r^{-1} (\vec{y} - h\vec{x}) + (\vec{x} - \vec{x}_p)^T p^{-1} (\vec{x} - \vec{x}_p)$$

where *r* is the observation error covariance, and *p* is the prior error covariance of the unknown β's.

Please see the attached article (Schuh et al, 2010) which presents the results of our analysis of the 2004 carbon budget of North America, and the attached article (Baker et al 2010) which presents our results on the mechanisms for interannual variability of the carbon cycle.