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

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NOAA Project Goal: Climate

• Key Words: Carbon cycle, greenhouse gases, terrestrial CO_2 sinks

• Narrative

1. LONG TERM RESEARCH OBJECTIVES AND SPECIFIC PLANS TO ACHIEVE THEM:

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.

To achieve these goals, we have used measurements of both local surface fluxes and near-surface atmospheric mixing ratio of CO_2 in a comprehensive model of photosynthesis, ecosystem respiration, and atmospheric transport over North America. We have studied the mechanisms that control the high-frequency (diurnal-synoptic) variations in atmospheric CO_2, We have developed and evaluated a global model of atmospheric CO_2 for use in specifying boundary conditions to the regional model, and performed nested grid simulations of weather and CO_2 over North America. We have used a backward-in-time Lagrangian transport model to compute the influence of upstream fluxes on the measured concentrations at the tower sites, and tested a procedure for correcting model estimates of these sources and sinks.

2. RESEARCH ACCOMPLISHMENTS / HIGHLIGHTS:

We have developed and tested a method for extrapolating these surface-layer measurements of CO_2 at flux towers to atmospheric mixed-layer values under convective (daytime) conditions, creating inexpensive “virtual tall towers (VTT).” These VTT estimates have been compared to six years of actual vertical differences measured at the WLEF tall tower. We find that hourly daytime mixed-layer mixing ratios can be estimated from surface layer values and measured fluxes to within 0.5 ppm in winter, within 0.2 ppm in summer, and within 0.05 ppm in fall and spring (Butler *et al.*, in prep). Accurate extrapolation of surface-layer data to the mixed-layer allows Ameriflux towers to contribute to regional flux estimation by inversion of large-scale transport models which cannot resolve surface-layer gradients.

We have developed several different methods for estimation of continental carbon budgets from CO_2 mixing ratio observations which combine traditional weekly flask sampling with continuous in-situ measurements. This is very challenging because of the vastly greater data volume with hourly compared to weekly observations. Older methods have estimated monthly fluxes for large regions, but this leads to unacceptable bias due to errors in the assumed spatial patterns of fluxes within regions. Finer resolution is possible using mesoscale models, but variations of CO_2 at the lateral boundary conditions is required in this case. Our strategy has been to use a global model to perform relatively coarse estimation of monthly mean fluxes, and then to use the resulting optimized 4-dimensional CO_2 field as a “first guess” for lateral boundary conditions for much higher resolution inversions using a mesoscale model.

Global inversions and transport modeling have been performed with additional support from NASA using the Parameterized Chemical Transport Model (PCTM), which is driven by analyzed meteorology produced by the NASA Goddard Modeling and Assimilation Office. We are using this model to separately estimate monthly photosynthesis and respiration for 47 regions, with 10 in North America.

At the regional scale, we have developed a method to perform flux estimation on a 100 km x 100 km grid over North America using the CSU Regional Atmospheric Modeling System (RAMS) and a backward-in-time Lagrangian Particle Dispersion Model (LPDM). RAMS transport fields are archived and used by LPDM to calculate influence functions, (partial derivative of observed CO_2 variations with respect to upstream fluxes at previous times). With a continental network of 10-20 towers making hourly measurements, it is not possible to estimate fluxes every hour for every 100 km grid cell. We aggregate fluxes for 10 days at a time using the Simple Biosphere (SiB) model coupled to RAMS, which estimates photosynthesis (GPP) and respiration every 5 minutes from physiological principles and satellite imagery. We have evaluated SiB-RAMS by comparing simulated fluxes to eddy covariance measurements. We convolved the LPDM-derived influence functions separately with simulated GPP and respiration in SiB-RAMS to produce maps of the influence of each component flux at every grid cell over 10 days on the observed mixing ratio at each tower in each hour. The inverse problem was then formulated as an estimation of multiplicative model bias in GPP and respiration in SiB-RAMS for each grid cell. Optimal estimates of these biases were applied to the simulated gridded fluxes at each time step to produce time-varying maps of GPP and respiration on the 100-km grid which are consistent with the mixing ratio variations.

We found that uncertainty in GPP and respiration was substantially reduced only in a very limited region (a few hundred km radius) around each tower unless spatial error covariance structures were introduced into the optimization. We have applied a very flexible procedure based on the Maximum Likelihood Ensemble Filter (MLEF) to perform the optimization of model bias. Unlike previous studies, we allowed for generalized error covariance and did not specify an exponential decay of spatial autocorrelation with distance. We found that with sufficiently dense observing networks (e.g., the DOE-supported Ring of Towers in 2004), the method could recover complicated spatial structures in model bias quite well. On the other hand, we found that without allowing for spatially correlated model bias the current observing network at the continental scale is insufficiently dense to constrain spatial structures over many areas.

We have used observed fluxes to study the impact of uncertain model parameters in SiB on errors in simulated fluxes (Prihodko et al, in press), and showed that model skill at synoptic to seasonal time scales was often controlled by a handful of parameters. Ricciuto et al (in press) confirmed that a model with a small number of parameters could simulate daily, synoptic and seasonal flux variability well, but Ricciuto (2006) showed that even a tuned ecosystem model had limited skill in predicting interannual variability of net ecosystem-atmosphere exchange (NEE) of CO_2 across 5 eastern U.S. temperate forest AmeriFlux sites. This suggests that changes in model structure, rather than simple parameter tuning may be required to capture interannual variability. Assimilation of multi-year records from the flux towers yielded good convergence of the parameters governing photosynthesis and forest phenology, and the parameter values were similar across these sites. Convergence of parameter values governing heterotrophic respiration, however, was weak and relatively inconsistent.

We showed that synoptic to seasonal variations were coherent across a number of towers, but that mean annual fluxes were surprisingly heterogeneous, even over a small area. Different processes control variations at different time scales. Butler et al (in prep) show that spatially coherent responses to climate anomalies can influence timing of seasonal fluxes across a large region, producing widespread anomalies in CO_2 mixing ratio that should be interpretable via inverse modeling.

We have studied the nature of the very strong synoptic variability in CO_2 mixing ratios at continental sites using observations at six towers, the global PCTM and the coupled SiB-RAMS models. We found that variations are predominantly driven by horizontal advection rather than changes in vertical mixing, and that they can be predicted reasonably well by the models. This is encouraging for the feasibility of regional flux inversion using these models.

3. COMPARISON OF OBJECTIVES VS. ACTUAL ACCOMPLISHMENTS FOR REPORTING PERIOD- State the status of the objectives as: (can be more than one): “yet to be started,” “complete,” “in progress,” “unsuccessful,” “determined to be inappropriate,” “tech transferred**.” Include a description of the work done on each objective.

If slippage occurred between what was proposed vs. what was achieved, please explain.

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;

in progress: development is done, and evaluation is ongoing. Expect a paper in 2006.

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;

in progress. Expect to submit paper by end of 2006.

3) attribution of CO_2 sources between fossil fuel combustion and ecosystem exchange using CO and other trace gases;

determined to be inappropriate. Requires active chemistry in the model. We have adopted another strategy in collaboration with Kevin Gurney (Purdue) under NASA sponsorship.

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);

in progress. Two PhD students at Penn State have studied this, and one just defended. Two papers forthcoming.

5) evaluation of the flux and mixing ratio predictions of the forwards and inverse models;

In progress, in parallel with objective 1

6) evaluation of the strengths and weaknesses of atmospheric and ecosystem models, and the flux and mixing ratio observational networks used in these studies.

In progress, in parallel with objs 1 and 5

4. LEVERAGING / PAYOFF: (Relate research accomplishments to public interest. NOAA needs to view as tool for justifying public investment in science initiatives).

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. Coupled carbon-climate models simulate positive feedback (warming promotes additional CO_2 release to the atmosphere), but a recent comparison of 11 such models found a range of nearly 200 ppm in CO_2 and 1.5 K of warming in 2100 (Friedlingstein et al, 2006). 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. The North American Carbon Program (NACP, Wofsy and Harris, 2002; Denning et al, 2005) involves process studies, an expanded flux measurement network, remote sensing and modeling, and inversions using new atmospheric mixing ratio observations. Cross-evaluation of models and data sources and hypothesis testing at a variety of spatial and temporal scales is envisioned within a new framework of model-data fusion.

5. RESEARCH LINKAGES / PARTNERSHIPS / COLLABORATORS, COMMUNICATION AND NETWORKING: (Leveraging of NOAA funded research and spin-off to other agencies)

Strong linkages to other related projects at CSU funded by NASA and DOE

Collaboration with Randall Kawa and James Collatz at NASA GSFC

Links to Peter Thornton at NCAR

The North American Carbon Program (NACP: an integargency collaboration sponsored by 9 federal agencies):

Denning chairs NACP Science Steering Group

Davis co-chairs Midcontinent Intensive Task Force
Denning serves on MCI Task Force, Data Systems Task Force, and Synthesis Task Force

6. AWARDS/HONORS:

7. OUTREACH: (a.) Graduate/Undergraduate students (List by name, degree status and continuance after obtaining degree); (b) Seminars, symposiums, classes, educational programs; (c) Fellowship programs; (d) K-12 outreach; (e) Public awareness.

Grad Students at CSU:

Aaron Wang (received M.S. in 2005)

Nick Parazoo (will defend M.S. in 2006)

Lara Prihodko (partially supported on this, received PhD in 2004)

Joanne Skidmore (partially supported on this, received M.S. 2004)

Grad Students at Penn State:

Dan Ricciuto (PhD 2006)

Martha Butler (will defend PhD 2007)

8. PUBLICATIONS:

Prihodko, L., A.S. Denning, N.P. Hanan, I. Baker, K. Davis, Sensitivity, uncertainty and time dependence of parameters in a complex land surface model. *Agric. and Forest Meteorol.*, in press.

Wang, J.-W., A. S. Denning, L. Lu, I. T. Baker, K. D. Corbin, and K. J. Davis. Observations and

simulations of synoptic, regional, and local variations in atmospheric CO_2. Submitted to *J. Geophys. Res.*
Skidmore, J., A. S. Denning, K. J. Davis, P. J. Rayner, K. R. Gurney, J. Kleist, and TransCom 3 Modelers. Evaluation and prioritization of continuous measurements of [CO_2] from flux tower for inverse modeling. In prep for *Journal of Geophysical Research*.
Ricciuto, D.M., *Diagnosing uncertainty and improving predictions of terrestrial CO_2 fluxes at multiple scales through data assimilation*, Ph.D. dissertation, The Pennsylvania State University, 2006.
Ricciuto, D. M., M. P. Butler, K. J. Davis, B. D. Cook, P. S. Bakwin, A. Andrews, R. M. Teclaw, Determining the causes of interannual variability in ecosystem-atmosphere carbon dioxide exchange in a northern Wisconsin forest using a Bayesian synthesis inversion, *Agriculture and Forest Meteorology*, in press.
Wang, J.-W., *Observations and simulations of synoptic, regional, and local variations of atmospheric CO_2*, M. S. The Wang, J.-W., *Observations and simulations of synoptic, regional, and local variations of atmospheric CO_2*, M. S. Thesis, Colorado State University, 146 pp, 2005.