

Final Report for project DOE-CSU-64317

Syntheses of carbon dioxide flux and mixing ratio measurements in support of the North American Carbon Program Midcontinent Regional Intensive

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Please briefly (16000 chars or less) summarize your most recent results to date:

The following report builds upon previous reports. Please refer to those reports for prior progress and the general context of the experiment. This report represents a combination of work performed at both Penn State and Colorado State. We will summarize by laying out the original project objectives and hypotheses and indicate progress attained over the last year. This project aimed to satisfy the following objectives.

- 1. Determine the level of precision and accuracy of our project's CO₂ mixing ratio networks, including both AmeriFlux long-term measurements and the MCI temporary towers.**

Recently, Scott Richardson and co-authors submitted a paper (cf. publication list at the end of the document) describing the calibrations and the corrections applied to the mixing ratio measurements. Comparisons to the NOAA data and flask analysis were performed. Long term drift and water isotope corrections were also described to reach a high level of accuracy.

- 2. Characterize and improve approaches for conducting atmospheric inversions. In particular, what ecosystem properties we should solve for, what are the spatial and temporal coherence of these properties, and how should AmeriFlux flux data be integrated into this methodology?**

Ecosystem parameters based on Plant Functional Types were optimized in the VPRM vegetation model (PhD work of Tim Hilton at PSU) using Ameriflux sites. A new map of optimized fluxes was generated for 2005-2006 at 1km resolution over North America, with their related uncertainties. This work will be combined with the PSU inverse system in a single assimilation system. This part is still ongoing work. A validation exercise of the inverse fluxes from PSU (lauvaux)

showed increased correlations between the inverse fluxes and several eddy-flux sites in the region.

3. See whether or not these inversion results converge with independent bottom-up flux estimates.

This has been a primary focus of our research over the last year. The inventory results are shown in Figure 1 (as of Spring 2011). Highlights for crops are shown in Figure 11. There have been a few significant changes in the inventory since this image was made several months ago. The new inventory shows a deeper crop sink by approximately 20 TgC spread somewhat uniformly over the “corn belt” as well as an associated increase in uncertainty over this area. However, Figure 1 is generally indicative of the overall pattern of annual fluxes expected from the inventory for 2007. The CarbonTracker global product is shown in Figure 2 and shows a reasonable agreement to the inventory at the scale of the “entire” MCI region. However, there appears to be discrepancies at finer scales as shown in the figure. Figure 3 shows results of the 10km model and inversion run by Thomas Lauvaux (PSU) which shows better agreement with the inventory at the finer scales shown. However, the model was only run from June 1 – Dec 31, 2007 due to the “Ring 2” towers only existing from late spring onwards of 2007. Figure 5 shows a comparison of the aforementioned inversion results temporally. Both inversion models appear to deliver a deeper mid summer sink than the general suite of Transcom global models. Figure 4 shows current estimates from the CSU inversion which is running a nested inversion over the North America. Several recent fixes to the underlying coupled biosphere-meteorology model have forced a reanalysis of the results. Preliminary analysis has shown far better results than have been achieved over the last few years, where a noticeable bias in the overall continent source/sink estimate directly affected MCI results. Initial estimates over the MCI compare well with both the inventory and other inversion results (CarbonTracker and PSU/Lauvaux) in particular.

4. Determine whether or not atmospheric transport models that parameterize cloud convection (horizontal grid scales of order ten kilometers) are sufficient for accurate regional flux estimation.

This comparison has not formally been done due to time constraints. We have compared two different driving meteorology models (RAMS and WRF) at different resolutions, with RAMS operating with the Grell convection scheme at 40KM while the WRF model is running w/o any convection scheme at 10KM. While there have appeared to be differences between the two models, it is hard to decipher the causes. One thing that was noted in the RAMS simulation, which created the prior flux estimate for the CSU inversion, was a warm bias that

developed fairly consistently over the Midwest in July and August which affected, among other things, the precipitation recycling and cloud development. It is uncertain at this point, how much this increased sensible heating affected planetary boundary layer development and maximum height, which the atmospheric inversions are very sensitive to.

5. Determine the tradeoff between the density of atmospheric CO₂ mixing ratio measurements in the midcontinental region, and the accuracy of inverse estimates of regional terrestrial carbon fluxes.

Network design simulations by T. Lauvaux at PSU have shown some degree of robustness to the network employed. In other words, it is clear that certain towers could be dropped in the future without a terrible loss of fidelity to the inversion. However, it is also clear that towers are needed WITHIN the corn belt in order to properly place the mid continent sink on the resolutions of the vegetation cover in the region. Whereas the regional carbon balance seems to converge with two towers only, some specific spatial patterns diagnosed in the inverse flux estimates require the presence of tower sites in their vicinity (100km). Additional tests are being performed to evaluate the assumptions in the prior flux errors, in particular the correlation length scale in the flux error that brings an important constraint in space. Preliminary results suggest that large coherent signals affect the fluxes throughout the entire region and agree with Tim Hilton's results. Flux errors seem correlated at 100km or more, in agreement with twin tests performed by PSU. A paper will be submitted soon on these aspects.

6. Examine the robustness of the “virtual tall towers” method of interpreting surface layer CO₂ measurements derived at the WLEF tall tower by examining data from at least one additional tall tower with flux and mixing ratio measurements.

This work has been conducted by Martha Butler (PhD at PSU), tested over North America. Several flux towers were used successfully in a global inverse system as “virtual tall towers”, and brought significant constraint to the posterior fluxes. The use of higher resolution model for the MCI didn't require the use of similar techniques. Results from Martha Butler will be submitted soon.

We will endeavor to answer six main hypotheses.

1. Instrumental accuracy and network precision will be 0.2 ppm or better for the 18 months the campaign mixing ratio measurements are deployed.

This work is now submitted to AMTT (Richardson et al., 2011). Results suggest 0.2 to 0.3 ppm accuracy for both CRDS towers and calibrated flux towers at Missouri Ozarks.

- 2. The difference between modeled terrestrial net ecosystem-atmosphere exchange (NEE) of CO₂ and AmeriFlux NEE observations has a smoother distribution in space and time than the flux measurements themselves. The smoothness of this difference enables us to estimate fluxes at fine space/time scales using “fast” model biophysics, but to correct erroneous model state variables (e.g., wood, soil carbon, stand age), ecosystem parameters (V_{max}, maximum LAI), or unmodeled processes (e.g., fertilizer application) using the atmospheric inversion.**

This has been investigated on an ancillary basis using data including crop towers, but also the full suite of flux towers included in the NACP Site Synthesis project. The general picture that emerges is that ratios of the modeled NEE and AmeriFlux NEE are smooth in time, although the smoothness in space is still uncertain. However, the difference over time is not simply due to state variables such as wood, soil carbon, and/or stand age. There are systematic model errors embedded into the “long term” difference signal which means that future conceptual inversion models will have to address this. One example is shown in Figure 11, where it is obvious that there are differences over the periods of multiple years but there is also a very model error which occurs at a seasonal scale. Investigation of model errors then must partition this signal into pieces due to systematic model errors (for example, incorrect respiration modeling as a function of temp/water), and longer-term processes resulting from changes in longer lived carbon pools.

- 3. Top-down and bottom-up regionally aggregated carbon fluxes within the MCI domain converge to within 0.2 gC m⁻² d⁻¹ during the growing season, and to within 20 gC m⁻² yr⁻¹ annually.**

Final numbers needed for this comparison are still being tabulated. Initial estimates appear to show that this level of agreement might be possible on the scale of the entire MCI region but is likely not possible at smaller scales, e.g. 100km by 100km resolution. Results will likely be more consistent during the growing season due to more active mixing in the atmosphere and therefore better transport modeling. However, 0.2 gC m⁻² d⁻¹ sensitivity, which translates to about 18 gC m⁻² over the growing season on the background of about 1500 gC GPP seems a bit optimistic at this point. Actual calculations from PSU inversion indicates 35gC.m⁻² error annually at 20km resolution for the inverse fluxes only. Combined bottom-up and top-down estimates will offer higher precision but are

still ongoing work. A methodology paper by Dan Cooley is in preparation, using a Lagrange multiplier methodology to reconcile both estimates. The method was chosen for the absence of prior, using the two methods as independent. However, we will not know until the final comparison of the inversion w/ final inventory numbers.

- 4. Continental inversions based on 20 km resolution transport fields, parameterized cloud convection in RAMS, and covariance smoothing using Maximum Likelihood Ensemble Filtering provide unbiased inverse estimates of NEE of CO₂. High resolution, cloud-resolving transport models are not necessary for the inverse problem at these space and time scales.**

Again, this hypothesis appears to look promising at larger resolutions over the MCI but the inherent transport resolution and limited towers would seem to prohibit accurate estimation at higher resolutions of say 200km by 200km or less. At a minimum, high resolution models appear to show better results for estimation at these higher scales (< 200 km) although continuing work by T. Lauvaux shows that careful work is needed in the a priori construction of the finer scale tower networks.

Figure 6 shows transport comparisons between a 40km parameterized convection model and a 10km no-parameterized convection model. However, due to recent corrections in the CSU/RAMS model, these comparisons will have to be updated. However, there was a reasonable amount of agreement between the WRF/LPDM and RAMS/LPDM transport fields with the main issue being an overall surface sensitivity bias in the CSU/RAMS model which we believe is now fixed. New comparisons based on these new runs are forthcoming.

- 5. A network of similar density to the proposed NOAA network of roughly 15 tall towers, plus weekly aircraft, plus our own Ameriflux CO₂ measurements, is sufficient to yield regionally aggregated estimates of NEE of CO₂ with an accuracy of 0.2 gC m⁻² d⁻¹ for the growing season fluxes, and 20 gC m⁻² for the annual cycle using SiB-CASA-RAMS plus MLEF.**

This point will be considered when inventory and inversion results are combined in one final flux estimate.

- 6. The gradient functions describing the surface-ABL difference in CO₂ during well mixed conditions are found to be consistent with those derived from the WLEF tall tower.**

Liza Diaz (PhD, PSU) performed model-data residuals of mixing ratios using CarbonTracker and PSU simulations. Vertical profiles are being analyzed and compared to tall towers and aircraft profiles from NOAA. First results suggest correct representation of the vertical gradients in WRF (PSU system) but lower levels in CarbonTracker show lower vertical mixing in the first 100m of the ABL. This work focuses on transport model errors using the same fluxes but different transport models (TM5 and WRF) at different resolutions. A paper is in preparation about the transport errors and their related correlations over June to December 2007.

Other results of interest:

An additional inverse method was evaluated and tested with pseudo data over the MCI (Wu et al., sub.) with an optimal representation of the fluxes. It will be used with real data for the years 2007 and 2008. The methodology uses a refined grid with irregular grid spacing depending on the data density in space. This promising method allows a more efficient computation of the inverse fluxes.

Presentations:

Ogle, S., West, T., Schuh, A., Lauvaux, T., Davis, K., et al MCI Regional Intensive Oral Presentation at 2010 NACP Synthesis Workshop, Boulder CO.

Schuh, A. , Lauvaux, T., Davis, K., Ogle, S. et al. Top-down bottom-up comparisons of the Mid_Continental Intensive (MCI) Region Oral Presentation at 2010 AGU Fall Meeting, San Francisco, CA.

Schuh, A. , Lauvaux, T., Davis, K., Ogle, S. et al. Contrasting atmospheric CO₂ inversion results at a regional scale over the highly-inventoried area of the Mid Continental Intensive. Oral Presentation at 2011 NACP Investigators Meeting, New Orleans, LA.

T. Lauvaux, K.J. Davis, A. Schuh, et al., Applicability of atmospheric inversions of greenhouse gases at high resolution, invited presentation, MACC meeting, Utrecht, The Netherlands, 2011

T. Lauvaux, Liza E. Diaz, Natasha L. Miles, Scott J. Richardson, Andrew

E. Schuh, Andrew R. Jacobson, Arlyn Andrews, Kenneth J. Davis, and Colm

Sweeney

: Regional carbon budget with a high density CO₂ concentration tower network: Mesoscale inversion of CO₂ fluxes at high resolution, HESSS2 conference, Tokyo, Japan, 2010

Publications (Accepted, in review, in submission, in prep....)

Tristram O. West, Stephen M. Ogle, Kevin R. Gurney, Linda S. Heath, Varaprassad Bandaru, Andrew E. Schuh, Kenneth J. Davis, CO₂ Flux in the Mid-Continent Region of the United States: A National Perspective on Regional Carbon Sources and Sinks, Ecological Applications, Accepted with minor revisions

S. Richardson, N. Miles, K. Davis, E. Crosson, C. Rella, A. Van Pelt, E. Wahl, A. E. Andrews: Field testing of unattended cavity ring-down spectroscopy analyzers measuring carbon dioxide: long-term stability, water vapor effects, and uncertainty analysis, submitted to EGU AMTT.

Natasha L. Miles, Scott J. Richardson, Kenneth J. Davis, Thomas Lauvaux, Arlyn E. Andrews, Tristram O. West, Varaprassad Bandaru, Eric R. Crosson: Atmospheric detection of regional CO₂ fluxes confirmed by inventory and satellite measures, submitted to JGR-B.

L. Wu, M. Bocquet, T. Lauvaux, F. Chevallier, P.J. Rayner, and K.J. Davis: Optimal Representation of Source-Sink Fluxes for Mesoscale Carbon Dioxide Inversion with Synthetic Data, submitted to JGR-A.

T. Lauvaux, A. E. Schuh, M. Uliasz, S. Richardson, N. Miles, C. Sweeney, A.E. Andrews, L.I. Diaz, D. Martins, P. Shepson, and K.J. Davis: Constraining the CO₂ budget of the corn belt: exploring uncertainties from the assumptions in a mesoscale inverse system, in prep.

T. Lauvaux, A. E. Schuh, S. Richardson, N. Miles, K.J. Davis: Network design for mesoscale inversions of CO₂ sources and sinks, in prep.

Andrew Schuh, Thomas Lauvaux, Scott Denning, Ken Davis, Natasha Miles, Maosheng Zhao, Tris West, and Stephen Ogle Testing multiple-scale atmospheric CO₂ Inversions over a highly-inventoried landscape, in prep

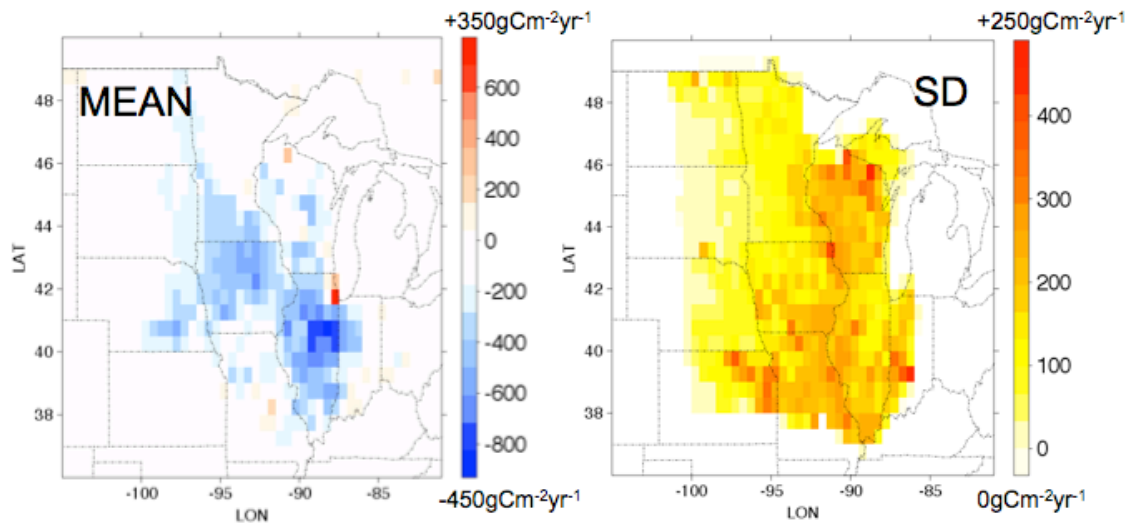


Figure 1. Current inventory-based estimate of carbon flux over the MCI region, “SD” indicates standard deviation.

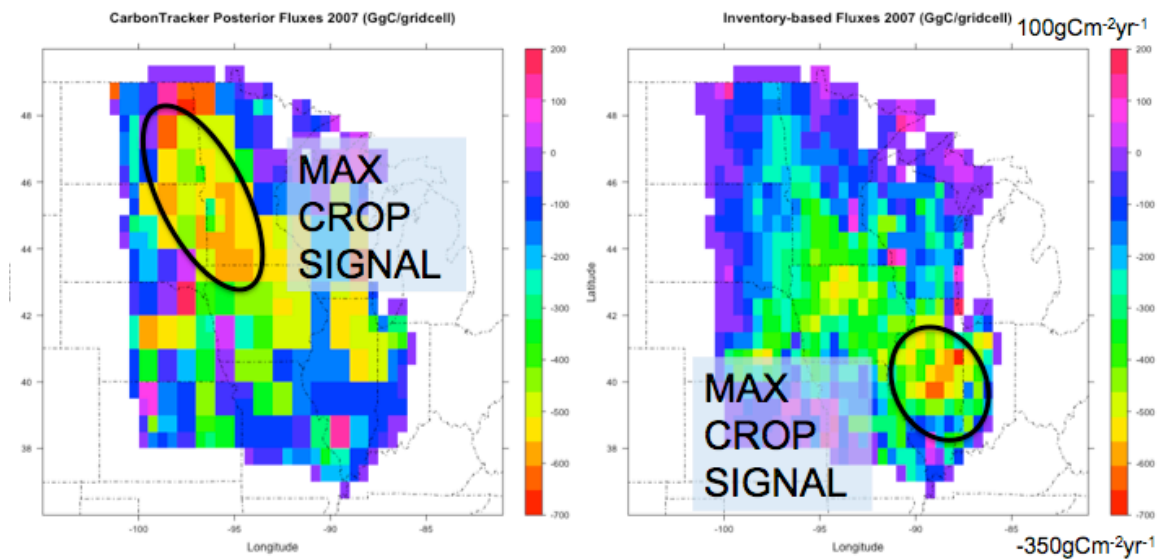


Figure 2. Comparison of CarbonTracker posterior flux estimates to inventory-based estimates.

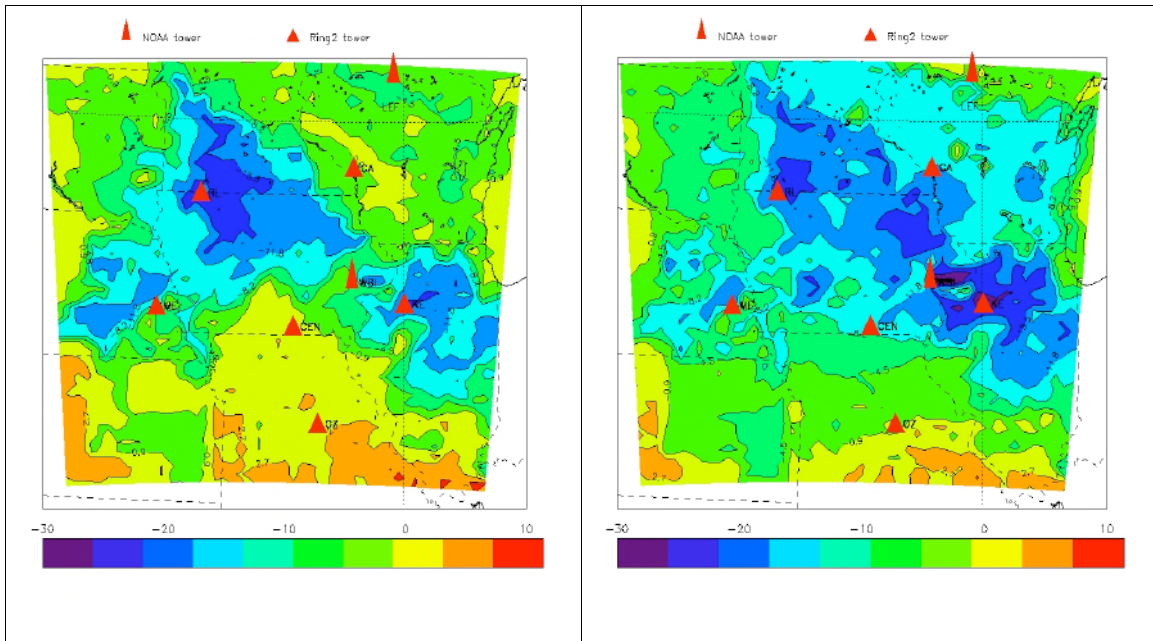


Figure 3: Prior SiBcrop fluxes (left) and posterior fluxes for the MCI region in TgC.degree-2 for June to December 2007 (PSU, Lauvaux).

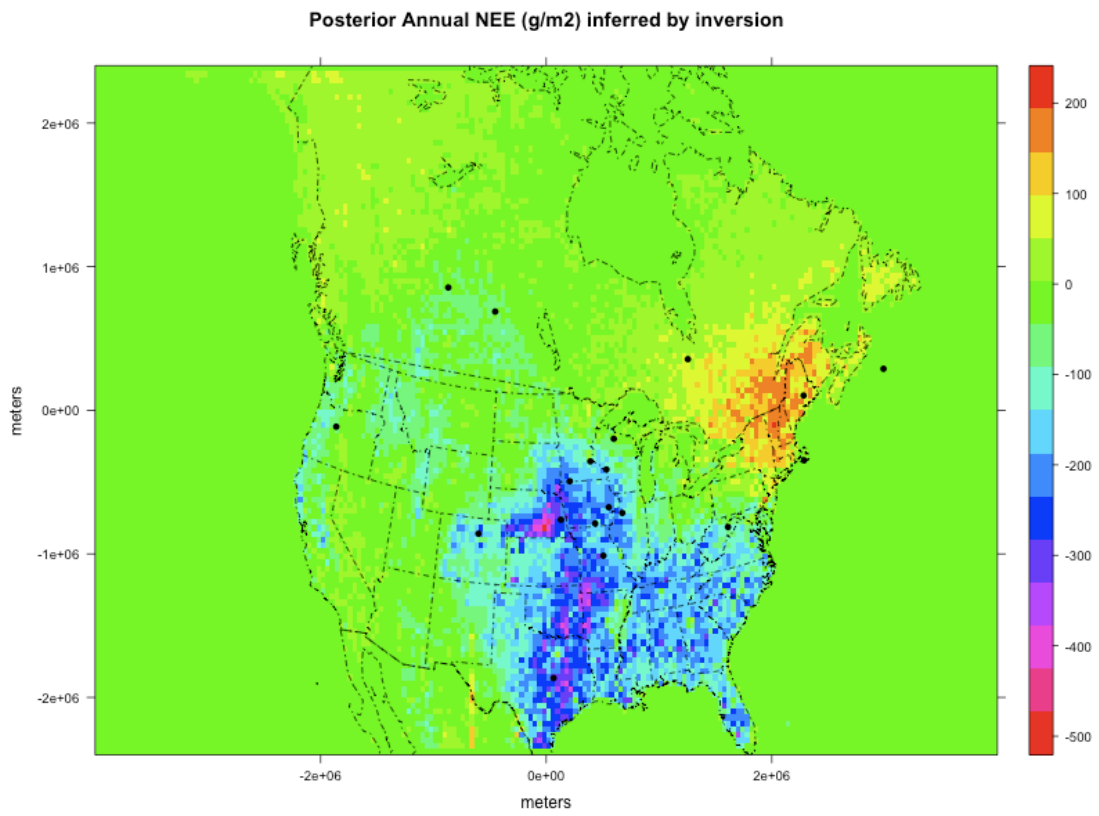


Figure 4: Prior and posterior fluxes for N.A. including MCI region (CSU, Schuh).

Time Series of Inversion Results (2007)

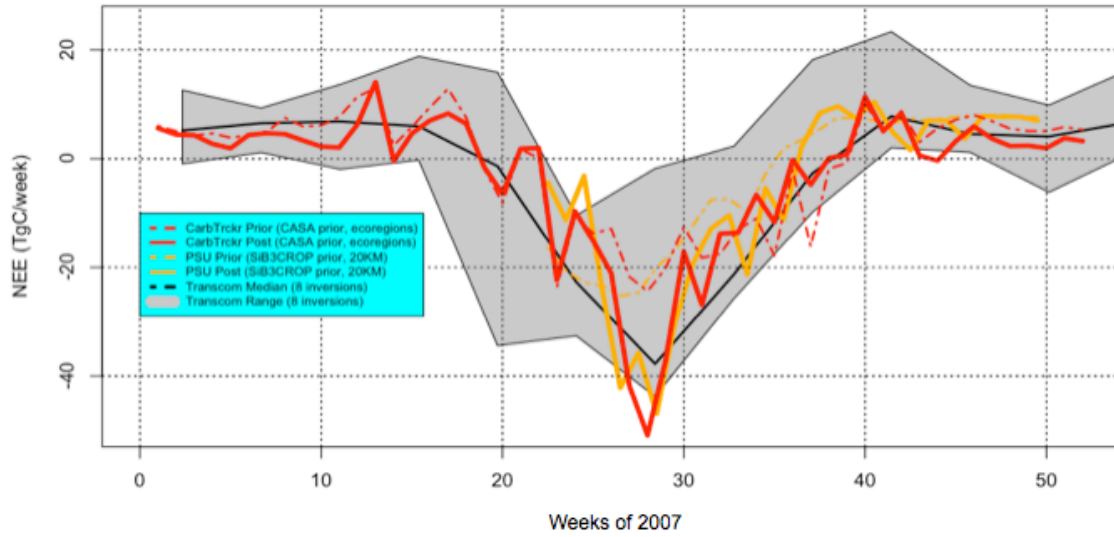


Figure 5: Comparison of inversion-based posterior fluxes for MCI region.

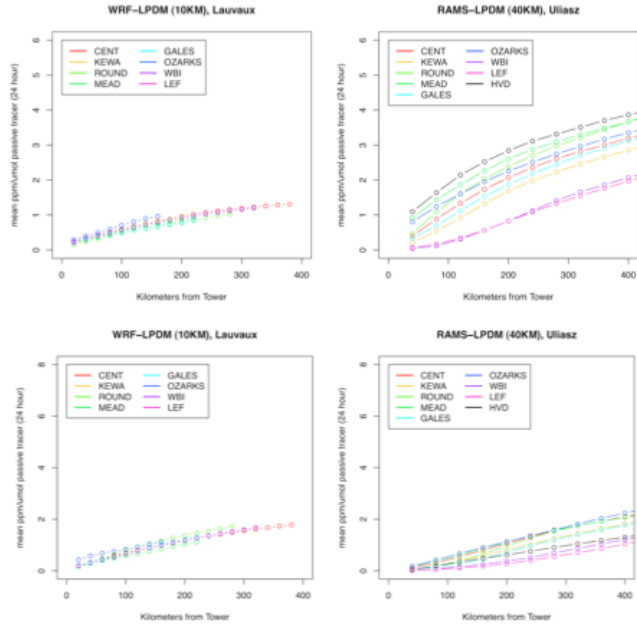


Figure 6: Transport comparison between two LPDM-based inversions with different driving meteorology.



Figure 7: Transport comparison between three LPDM-based inversions with different driving meteorology and Lagrangian models.

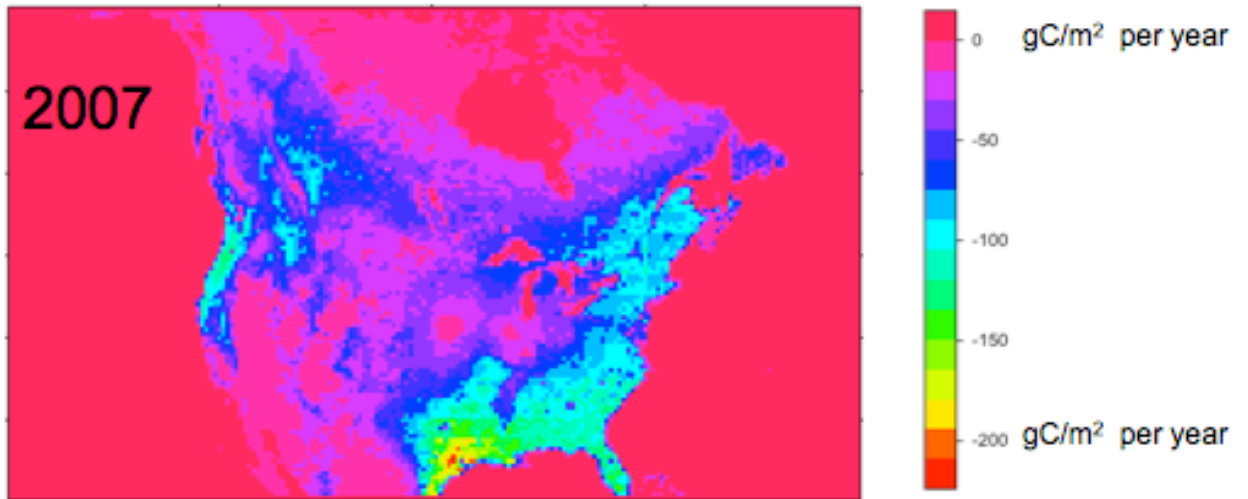


Figure 8: Sensitivity of continental nesting inversion to boundary inflow changes (between CarbonTracker and GlobalView product).

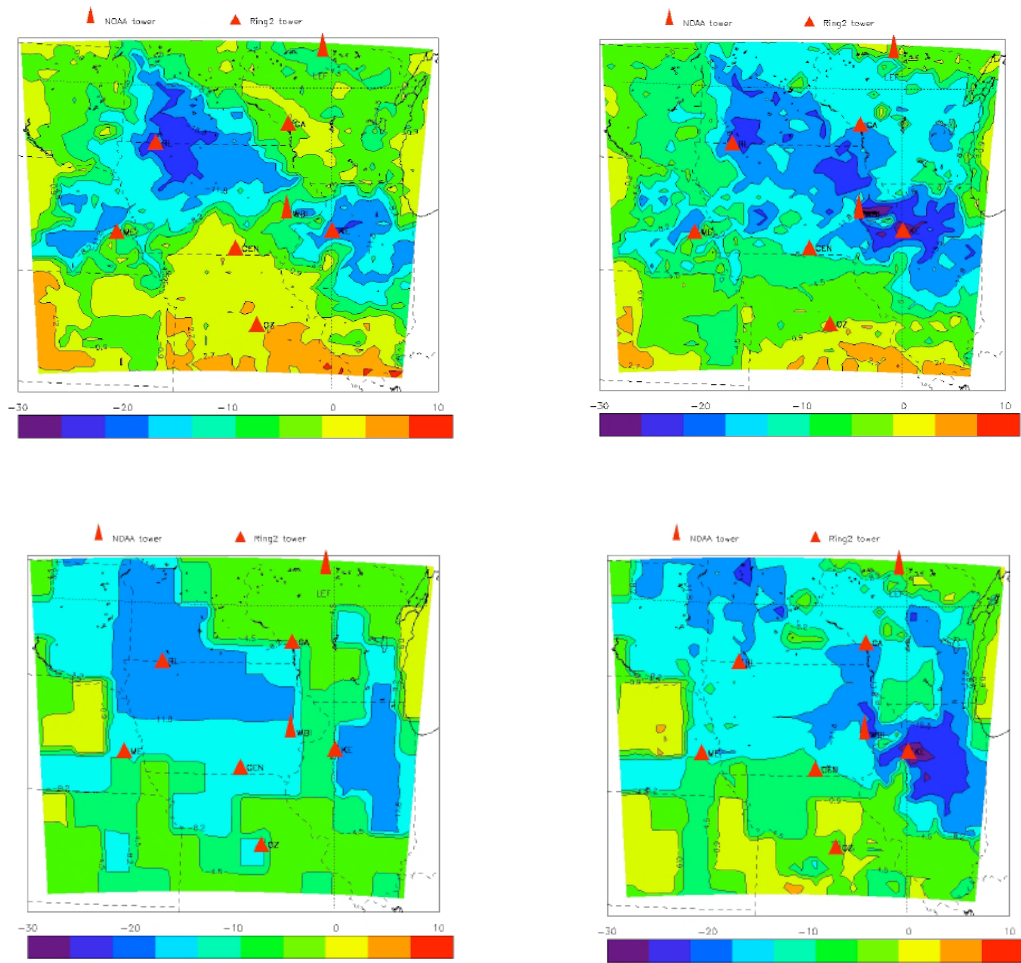


Figure 9: Inversion flux sensitivity to prior conditions for the MCI region in TgC.degree-2 for June to December 2007: SiBcrop prior fluxes (upper left), CarbonTracker prior fluxes (lower left), and their related inverse fluxes (right column)

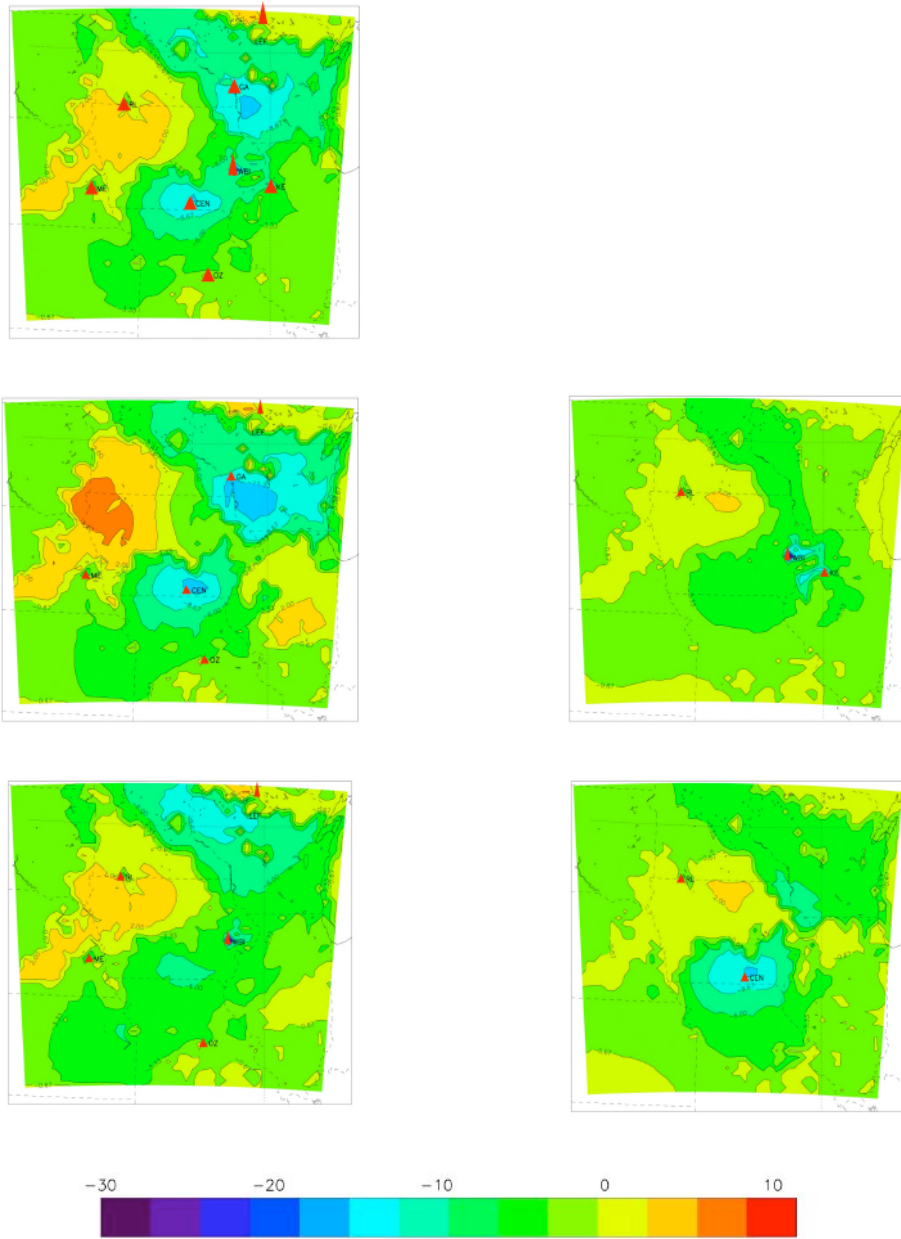


Figure 10: Network design study with the initial flux correction using the entire network (upper left), and the impact of tower removal on the corrections using different sub-sampled networks in TgC.degree-2 for June to December 2007 (PSU, Lauvaux)

Inventory: CROP NEE

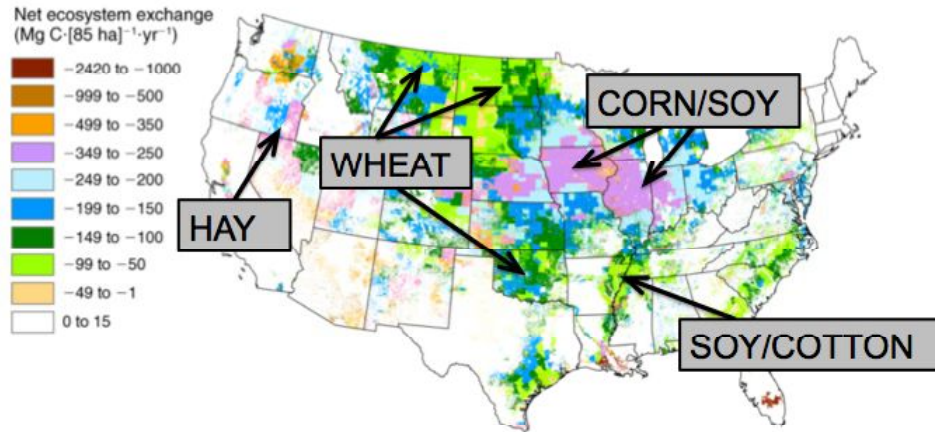


FIG. 4. Estimated annual net ecosystem exchange from U.S. croplands in 2004. Net ecosystem exchange is estimated for each 85.86-ha cropland unit. The spatial unit of 85.86 ha corresponds to NASA's moderate resolution imaging spectroradiometer (MODIS) land cover spatial unit of 926.6 × 926.6 m. Positive and negative values represent carbon fluxes to and from the atmosphere, respectively.

West et al. 2010, Ecol Apps

Figure 11: Current crop-based portion of inventor, showing major crop growing areas.

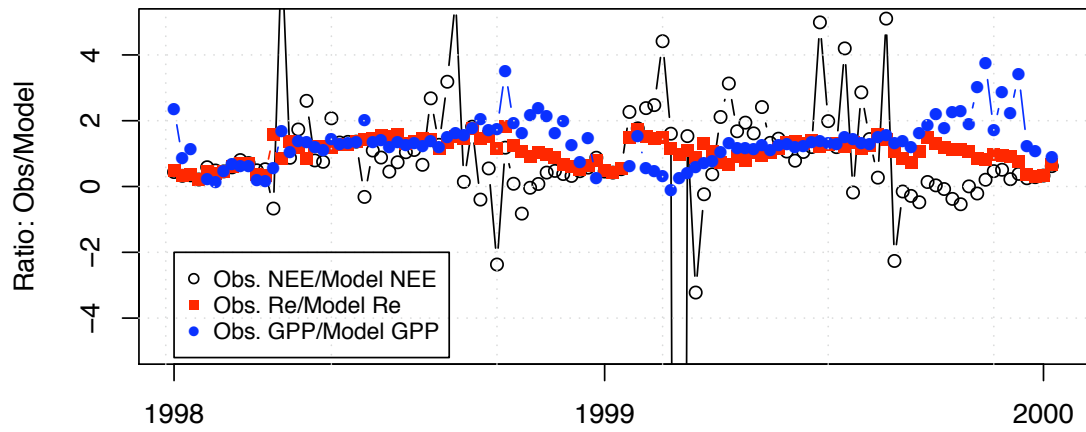


Figure 12: Two year record of data (Ameriflux) to model ratios for Howland Tower indicating the general temporal cycles of mismatch correction needed by the inversions.