Progress toward estimating surface carbon dioxide fluxes at the regional scale using an augmented Ensemble Kalman Filter

Hans W. Chen[1,2], Fuqing Zhang[1,2], Thomas Lauvaux[1], and Kenneth J. Davis[1]

[1]Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, PA

[2]Center for Advanced Data Assimilation and Predictability Techniques, The Pennsylvania State University, University Park, PA

Motivation

How are sources and sinks of carbon dioxide (CO_2), such as forests, going to change in the future? That is one of the big unknowns in predicting future climate change. In order to understand how ecosystems will respond to climate change, we need better quantification of current sources and sinks of CO_2.

CO_2 fluxes are difficult to directly measure at regional to global scales, but **inversion methods** can help constrain the fluxes using observed atmospheric CO_2 concentration combined with an atmospheric transport model. However, at regional scales **uncertainties in the atmospheric transport** can significantly impact the inversion results, and it is not obvious how to account for transport errors.

Goals

- Quantify the magnitude and structure of regional transport errors in atmospheric CO_2
- Discuss how to design a data assimilation system that includes transport errors

Methods

We use the Weather Research and Forecasting (WRF) Model with coupled chemistry (WRF-Chem) to study the time evolution and structures of transport errors in the atmospheric CO_2 field.

- WRF-Chem 3.6.1
- 27 km horizontal resolution
- 60 vertical levels
- CO_2 modeled as a passive tracer
- Initial and boundary conditions from ERA-Interim
- CO_2 initial and boundary conditions and fluxes from CarbonTracker Near-Real Time (CT-NRT) v2017

Here we focus on a case over North America in July 2016 during which the first NASA Atmospheric Carbon and Transport flight campaign took place. Two experiments were performed:

- Perturbed transport with true CO_2 fluxes
- Perturbed CO_2 fluxes with true transport

The atmospheric transport was perturbed by perturbing the initial conditions, and then assimilating ideal sounding experiments using an Ensemble Kalman Filter based on the PSU Unified Data Assimilation system. The ensemble consists of 40 members.

CO_2 flux perturbations

To create an ensemble of CO_2 fluxes (F), the prior CT-NRT optimized biological and oceanic CO_2 fluxes were perturbed by a scaling factor λ for each ecosystem,

$$F_{\text{perturbed}}(x, y, t) = \lambda(\text{ecosystem}, t) \cdot F_{\text{prior}}(x, y, t),$$

where x and y are the horizontal coordinates and t is time. 40 flux realizations were created by randomly drawing λs from a normal distribution with a mean of 1 and a standard deviation of 0.8 for terrestrial ecosystems and 0.4 over the oceans.

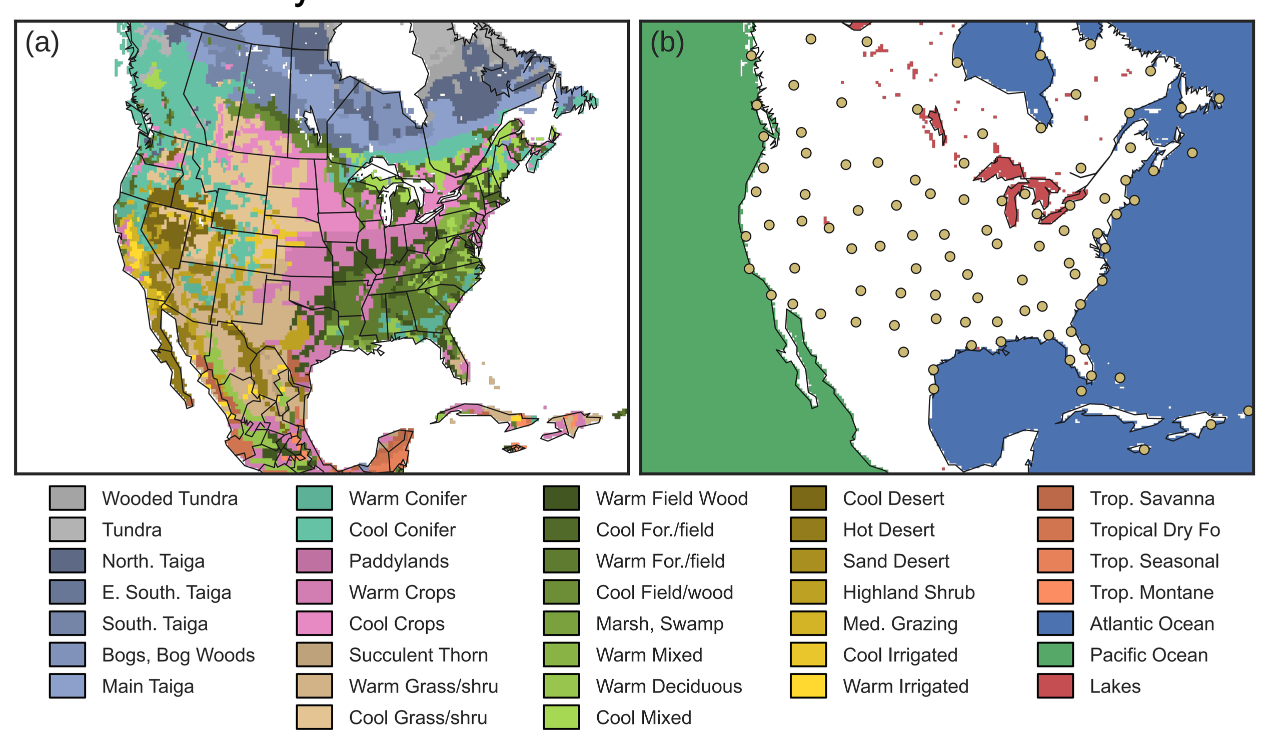

Fig. 1. Model domain and (a) ecosystems according to the Olson classification, and (b) oceans and lakes, and location of ideal sounding observations.

Flow-dependent transport errors

Atmospheric transport errors were constrained by assimilating ideal sounding observations (see Fig. 1b) every 12 hours. Domain-averaged root-mean-square errors in the U and V components of the wind are around 3 m/s.

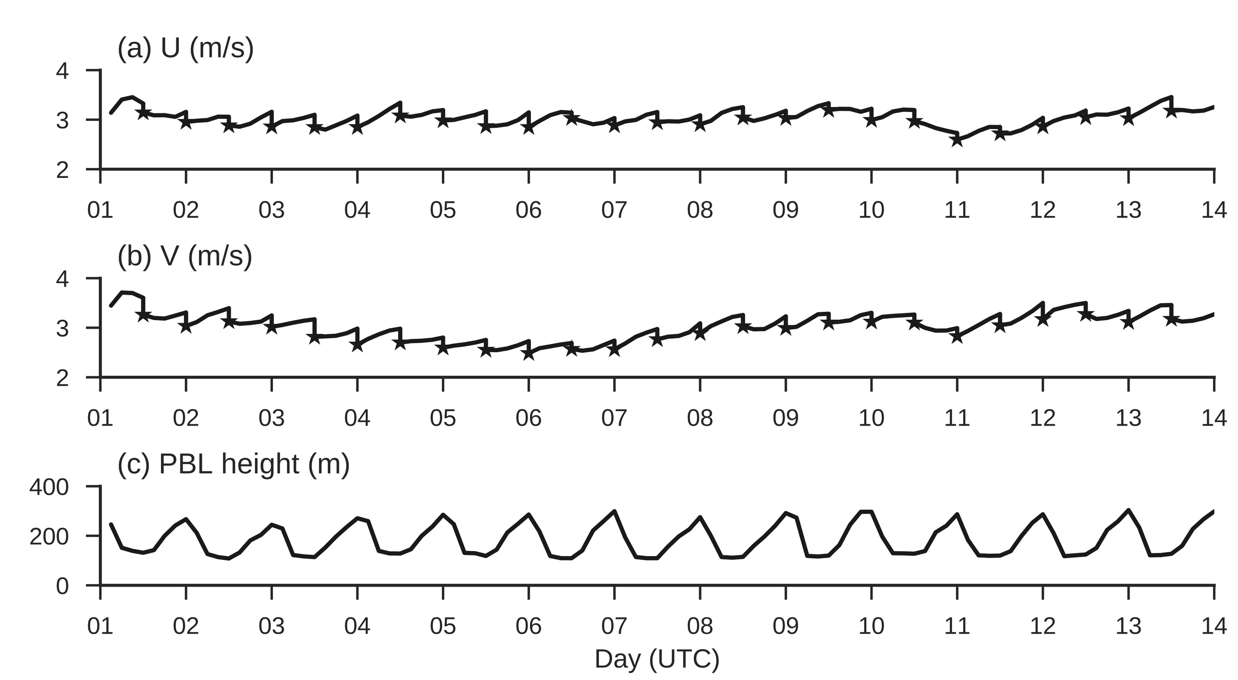

Fig. 2. Domain-averaged root-mean-square errors in the wind components and planetary boundary layer height compared with the truth simulation.

Time evolution of CO_2 sensitivities

The sensitivities of CO_2 to perturbed transport (solid lines) and perturbed fluxes (dashed lines) show that the domain-averaged magnitude of transport errors is similar to 80 % flux errors close to the surface. In the free troposphere, transport errors dominate. The errors quickly saturate after a few days.

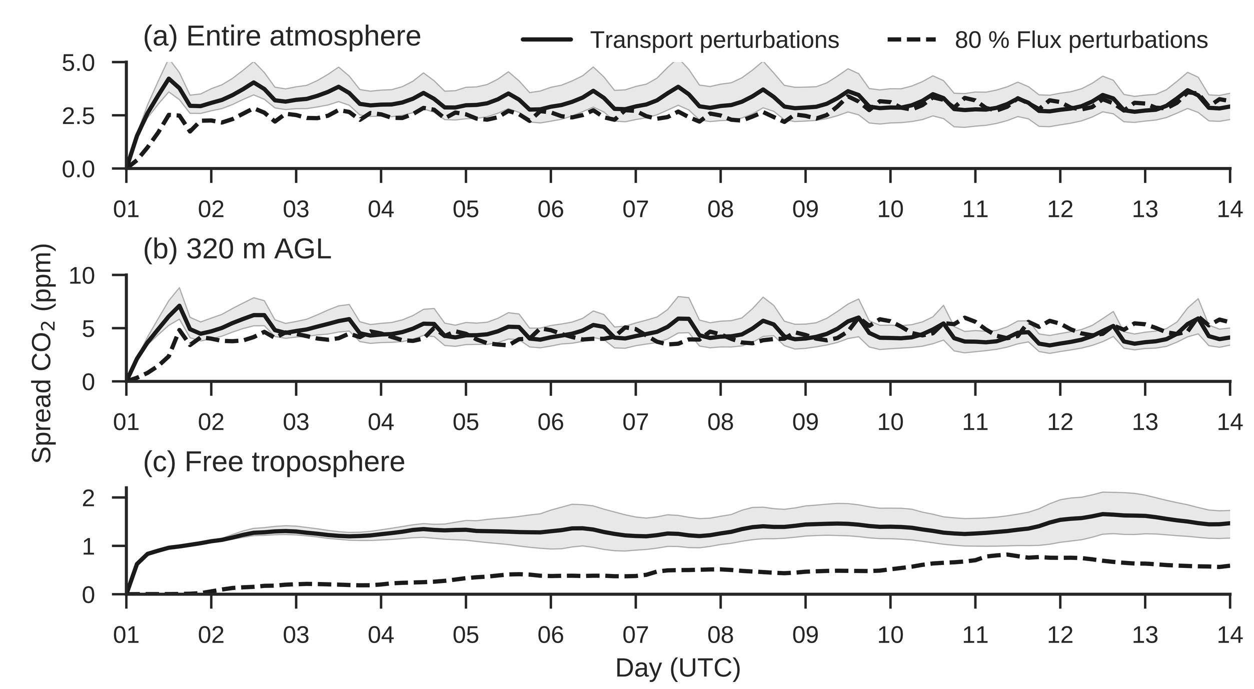

Fig. 3. Time evolution of the domain-averaged ensemble spread in CO_2 concentration at different vertical levels in the two experiments. The gray shading indicate the range of transport errors for different flux realizations.

Horizontal structure

The flux perturbations are proportional to the magnitudes of the prior fluxes due to the use of scaling factors. Transport errors in CO_2 are related to the magnitude of the prior fluxes close to the surface, but show a more flow-dependent error structure in the free troposphere, with larger errors in low-pressure systems and frontal systems where there is strong vertical mixing.

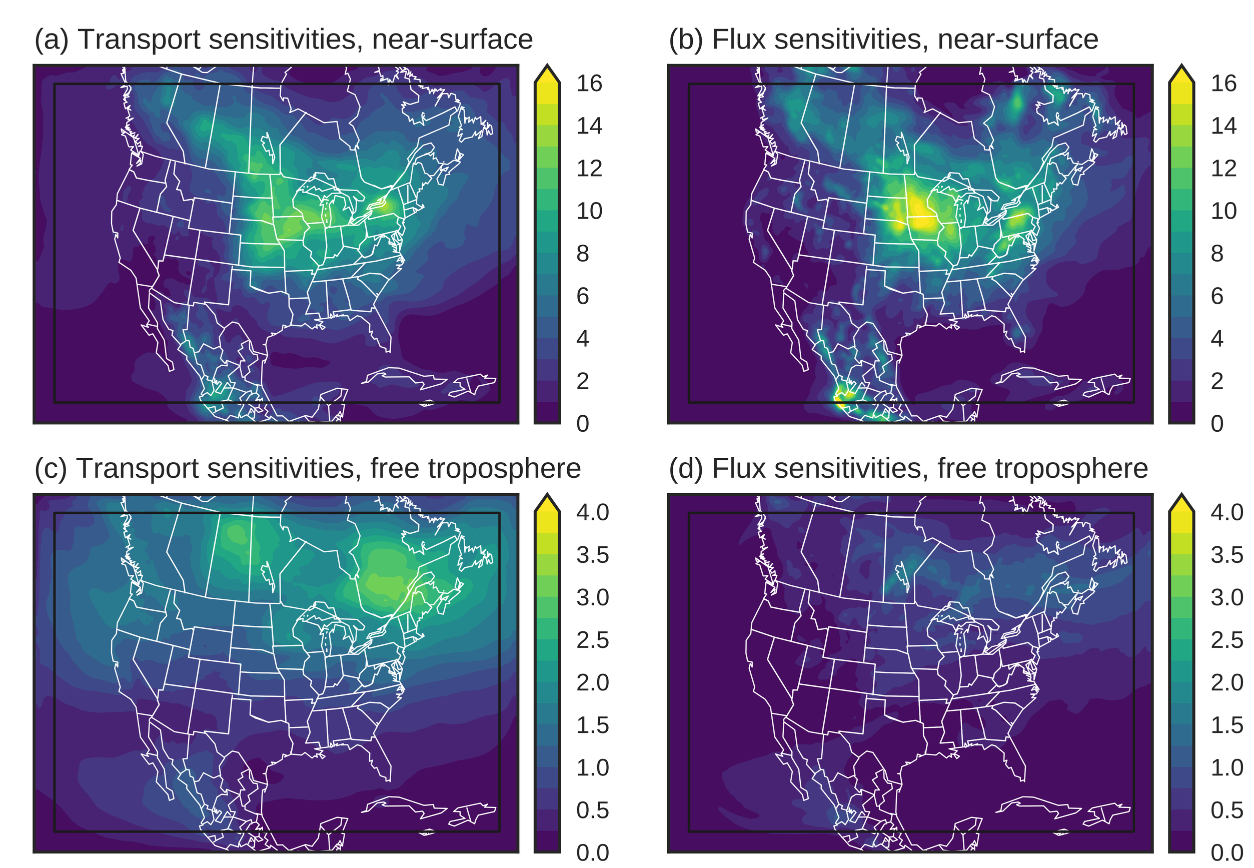

Fig. 4. Time-averaged horizontal distribution of ensemble spreads in CO_2 due to perturbed transport (left) and perturbed fluxes (right).

Ensemble Kalman Filter

We are developing a regional Ensemble Kalman Filter data assimilation system that simultaneously optimizes the meteorological state and the CO_2 fluxes and concentration states. To include CO_2 in the system, the state vector is augmented by including the CO_2 concentration and CO_2 fluxes:

$$\mathbf{x} = [\mathbf{T}, \mathbf{U}, \mathbf{V}, \ldots, \mathbf{CO_2}, \mathbf{F}_{CO_2}]^T$$

Scaling factors of CO_2 fluxes are optimized by assimilating CO_2 concentration:

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{P}_b\mathbf{H}^T(\mathbf{H}\mathbf{P}_b\mathbf{H}^T + \mathbf{R})^{-1}(\mathbf{y} - \mathbf{H}\mathbf{x}_b),$$

where $\mathbf{x}_a$ and $\mathbf{x}_b$ are the analysis and background state vectors, respectively, $\mathbf{H}$ is the observation operator to relate the model state to observations, $\mathbf{R}$ is the observation error covariance matrix, and $\mathbf{y}$ contains the observations. $\mathbf{P}_b$ is the background error covariance matrix estimated from the ensemble members:

$$\mathbf{P}_b = \frac{1}{N-1}\mathbf{X}'\mathbf{X}'^T,$$

where each column in $\mathbf{X}'$ is a state vector of an ensemble member minus the ensemble mean (i.e., the ensemble anomalies), and N is the number of ensemble members.

The ensemble members are created by perturbing both the transport and the CO_2 fluxes; thus, the covariances in $\mathbf{P}_b$ include both transport errors and flux errors.

In the future we will optimize the data assimilation system for CO_2 inversion and explore necessary techniques to obtain reliable results, e.g. covariance inflation, localization, etc.

Conclusions

- Transport errors have a significant impact on the regional CO_2 concentrations and are similar in magnitude to 80 % summertime flux errors near the surface, and almost double the flux errors in the free troposphere.
- In the presence of transport errors, afternoon observations of boundary layer CO_2 concentration are most useful to learn about regional CO_2 fluxes.
- Transport errors can be accounted for using advanced data assimilation techniques. In particular, a coupled meteorological–carbon data assimilation system can optimize both the meteorological and CO_2 flux states simultaneously, while including the uncertainty in atmospheric transport in the CO_2 inversion.

Contact: hans.chen@psu.edu