Constraining regional-scale CO₂ fluxes using a coupled meteorological–carbon ensemble Kalman filter

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Goal: Estimate land sources and sinks of CO$_2$

Annual human CO$_2$ emissions and their partitioning between land, atmosphere and ocean [IPCC 2014]
CO$_2$ fluxes are difficult to measure at regional to global scales

Spatial and temporal scales of CO$_2$ flux measurements [Davis 2008]
Process-based models show large regional-scale differences

Monthly mean biospheric CO₂ fluxes from different vegetation models for July 2010 [http://globalcarbonatlas.org]
Atmospheric inversions use atmospheric CO$_2$ observations to constrain CO$_2$ fluxes.

Images from CarbonTracker [https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/]
Challenges for regional inversions

**Sparsness of observations**
In-situ towers and aircraft, column-average from satellites

**Ill-posed problem**
Multiple solutions that minimize the model-data mismatch

**Small signal-to-noise ratio**
Large opposing photosynthetic uptake and respiration yield a small net ecosystem exchange

**Multiple sources of uncertainties**
Errors in prior fluxes, biases in observations, atmospheric transport error
Development of a regional CO$_2$ inversion system

Based on the Advanced PSU EnKF system

Atmospheric transport model: WRF-Chem

In addition to meteorological variables, CO$_2$ mixing ratios and scaling factors for fluxes are included in the state vector, similar to Kang et al. (2012):

\[
\begin{bmatrix}
U \\
V \\
\vdots \\
\text{CO}_2 \\
\lambda
\end{bmatrix}
\]

\[
CF_{\text{true}}(t,x,y) = \lambda_{\text{true}}(x,y) \times CF_{\text{prior}}(t,x,y)
\]

$CF$: Carbon Fluxes

$CF_{\text{prior}}$ from a vegetation model (CASA)
Optimize a set of scaling factors

Assume that the true fluxes can be obtained by scaling the prior fluxes by a set of scaling factors $\lambda$

Further, assume that the scaling factors vary by ecosystem and are constant on subseasonal time scales,

$$\lambda_{t+1} = \mathcal{M}(\lambda_t) = \mathbf{1}\lambda_t$$
Assume spatial covariances in $\lambda$ depend on ecoregions

- Regularization
- Use additional information about fluxes from external source
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How is atmospheric CO$_2$ linked to CO$_2$ flux perturbations?

**Ensemble sensitivity experiment**

200 ensemble members with perturbed fluxes according to:

$$CF_{\text{member}} = \lambda_{\text{member}}(\text{ecosystem}) \times CF_{\text{prior}}(t, x, y)$$

$$\lambda_{\text{member, ecosystem}} \sim \mathcal{N}(1, 0.8)$$

All members have the same atmospheric transport
Flux signals are generally constrained to within ecoregions

Ensemble correlation between $\lambda$ and CO$_2$ at 100 m

$$CF = \lambda \times CF_{\text{prior}}$$
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Ensemble correlation between $\lambda$ and CO$_2$ at 100 m

$CF = \lambda \times CF_{prior}$
Transport errors further reduce ensemble correlations
Can we constrain CO$_2$ fluxes with the current operational observation network?

Assimilate ideal CO$_2$ tower observations every 3 hours using EnKF
With perfect knowledge about the transport, CO$_2$ fluxes can be well constrained.

... in regions with many observations ...
With perfect knowledge about the transport, CO$_2$ fluxes can be well constrained

...and in regions remote from observations
Inflate ensemble perturbations to avoid filter divergence

Ensemble perturbations relaxed back to initial perturbations to maintain spread
Inflate ensemble perturbations to avoid filter divergence

Ensemble perturbations relaxed back to initial perturbations to maintain spread
Transport errors can lead to non-converging results

Sometimes we are lucky and the errors average out
Transport errors can lead to non-converging results

But other times transport errors lead to biased inversion results
Future work: Explicitly account for transport errors in regional CO₂ inversion system
Conclusions

- Pressing need to better quantify CO$_2$ fluxes, e.g. using advanced data assimilation methods

- Transport errors can significantly degrade regional inversion results

- There is potential to improve regional inversions by explicitly accounting for transport errors in an EnKF system