Dealing with noisy signals in CO$_2$ inversions using an ensemble Kalman filter

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Goal: Better understand sources and sinks of CO$_2$ to improve predictions of future climate

- **Atmospheric CO$_2$ (ppm) at Mauna Loa**

- **Annual global CO$_2$ budget (PgC yr$^{-1}$)**

Mauna Loa CO$_2$ records [Tans and Keeling]

The Global Carbon Budget 2017 [Le Quéré et al., 2018]
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Goal: Better understand sources and sinks of CO\textsubscript{2} to improve predictions of future climate

Atmospheric CO\textsubscript{2} (ppm) at Mauna Loa

Annual global CO\textsubscript{2} budget (PgC yr\textsuperscript{-1})

Mauna Loa CO\textsubscript{2} records [Tans and Keeling]

The Global Carbon Budget 2017 [Le Quéré et al., 2018]
Regional CO$_2$ fluxes from the terrestrial biosphere are highly uncertain

Mean CO$_2$ fluxes from different vegetation models for July 2010 [Huntzinger et al.]

Large-scale and long-term differences in the total terrestrial biosphere CO$_2$ fluxes
Atmospheric inversions constrain CO$_2$ fluxes using atmospheric CO$_2$ observations

Prior fluxes → Modeled CO$_2$ → Inversion → Posterior fluxes

Minimize mismatch

Images from CarbonTracker [https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/]
Atmospheric inversions constrain CO$_2$ fluxes using atmospheric CO$_2$ observations

Transport model → Inversion → Modeled CO$_2$ → Posterior fluxes

Prior fluxes

Minimize mismatch

Observed CO$_2$ → Observation error

Images from CarbonTracker [https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/]
How do observation representativeness errors affect CO$_2$ inversions?

How can we deal with such uncertainties?
Constraining CO₂ fluxes using a regional ensemble Kalman Filter system

Based on the **Advanced PSU EnKF system**

Atmospheric transport model: **WRF-Chem**

Atmospheric CO₂ and scaling factors for fluxes are added to the state vector:

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

\[
F_{CO_2}(x, y, t) = \lambda(x, y) \cdot F_{CO_2}^{\text{prior}}(x, y, t)
\]

where

- \(F_{CO_2}\) are CO₂ fluxes
- \(F_{CO_2}^{\text{prior}}\) comes from a vegetation model (CASA)
CO$_2$ fluxes are constrained through scaling factors

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

$\Rightarrow$ Reduces degrees of freedom from $F_{CO_2}(x, y, t)$ to $\lambda$(ecosystem) (regularization)

Further assume that $\lambda$s vary by ecosystem and are constant on subseasonal time scales.
CO₂ fluxes are constrained through scaling factors
How well can we constrain CO$_2$ fluxes using atmospheric CO$_2$ observations?

CO$_2$ observation at 100 m every 540 km

“True” scaling factors, $\lambda_k \sim \mathcal{N}(1, 0.8)$
If all assumptions are met, CO₂ fluxes can be well constrained.
If all assumptions are met, CO$_2$ fluxes can be well constrained.
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If all assumptions are met, CO$_2$ fluxes can be well constrained.

Relax scaling factor perturbations to initial perturbations to maintain spread.
How do noise from unresolved scales influence the inversion results?

CO₂ observation at 100 m every 540 km

Add 50 % noise ($L = 100$ km) to truth
How do noise from unresolved scales influence the inversion results?

CO₂ observation at 100 m every 540 km

Add 50% noise ($L = 100$ km) to truth
Noise from unresolved scales can lead to significant biases

Eco 4

Scaling factor

Eco 10

First guess

Ensemble mean

Truth
Future work: How to use an ensemble Kalman smoother to make the inversion more robust to noise

Idea: Errors average out → Use future observations to constrain past scaling factors
Conclusions

- CO$_2$ inversion is an under-constrained problem that requires assumptions about spatial and temporal scales.

- Noise from unresolved scales and lead to significant errors and biases in the inversion results.

- Need to work on making the ensemble Kalman Filter system more robust to noise (use a smoother?)
Extra
Huntzinger, D.N. and Coauthors: NACP MsTMIP: Global 0.5-deg Terrestrial Biosphere Model Outputs (version 1) in Standard Format. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1225.


Dr. Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsc02.ucsd.edu/).
How are atmospheric CO$_2$ mole fractions linked to CO$_2$ flux perturbations?

Ensemble correlation between $\lambda$ and CO$_2$ at 100 m ($F_{CO_2} = \lambda \cdot F_{CO_2}^{prior}$)
Real CO$_2$ tower observation network