# Dealing with noisy signals in $CO_2$ inversions using an ensemble Kalman filter

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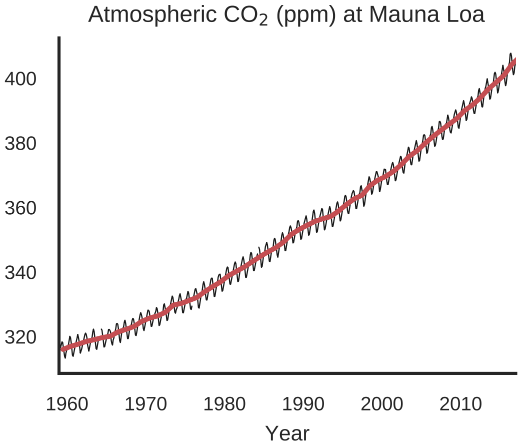
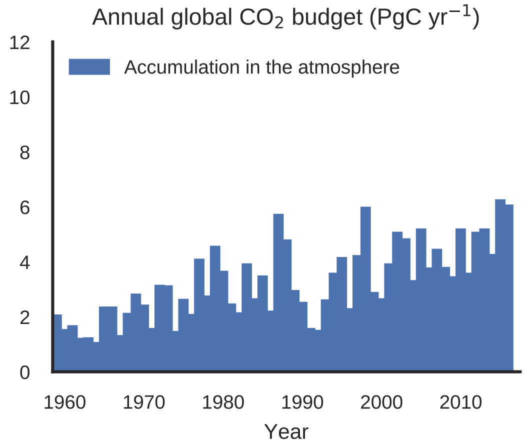
The Pennsylvania State University

# Goal: Better understand sources and sinks of $CO_2$ to improve predictions of future climate




Mauna Loa $CO_2$ records [Tans and Keeling]




The Global Carbon Budget 2017 [Le Quéré et al., 2018]

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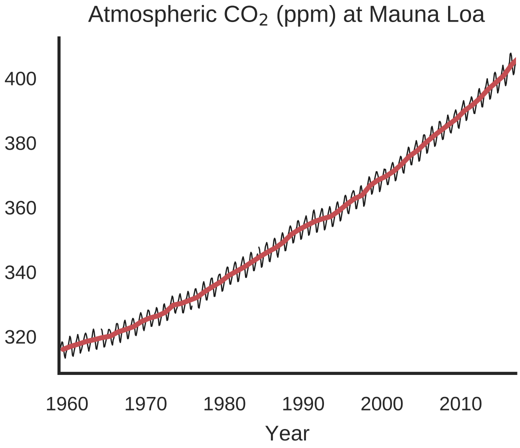


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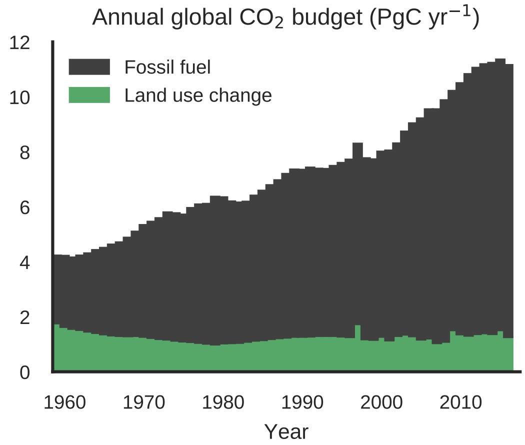


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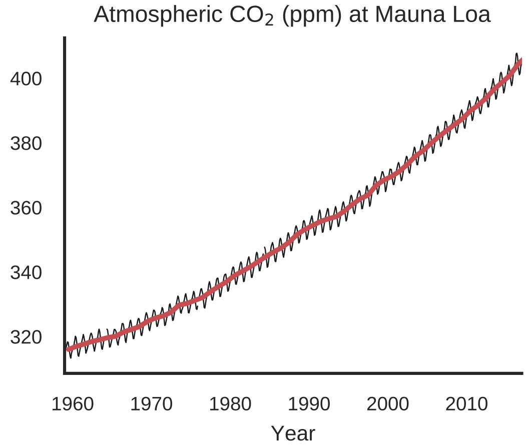


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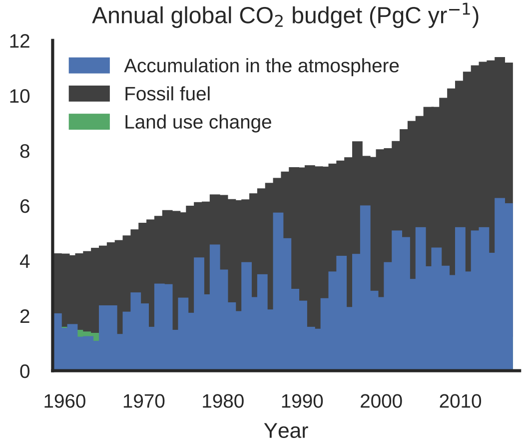


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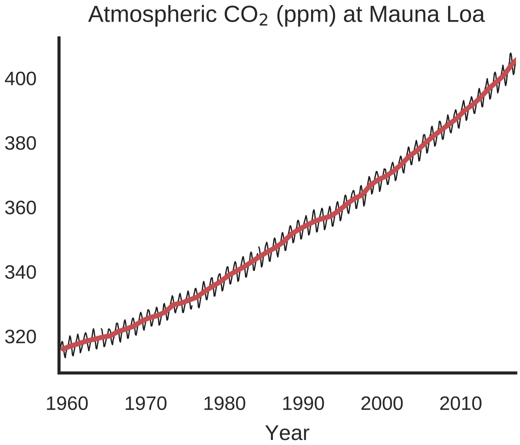


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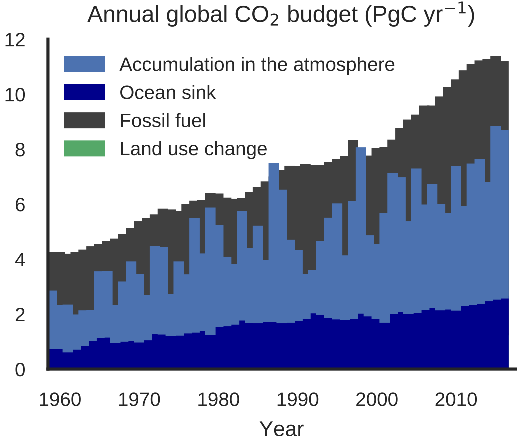


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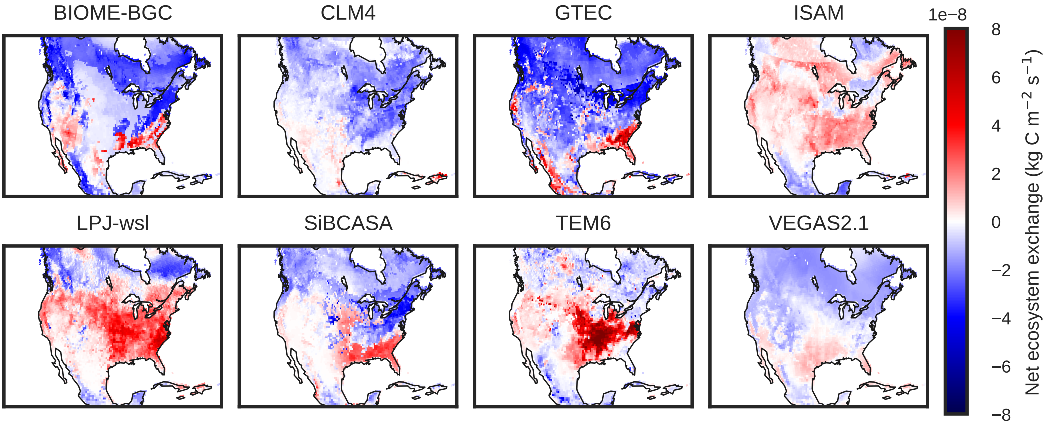
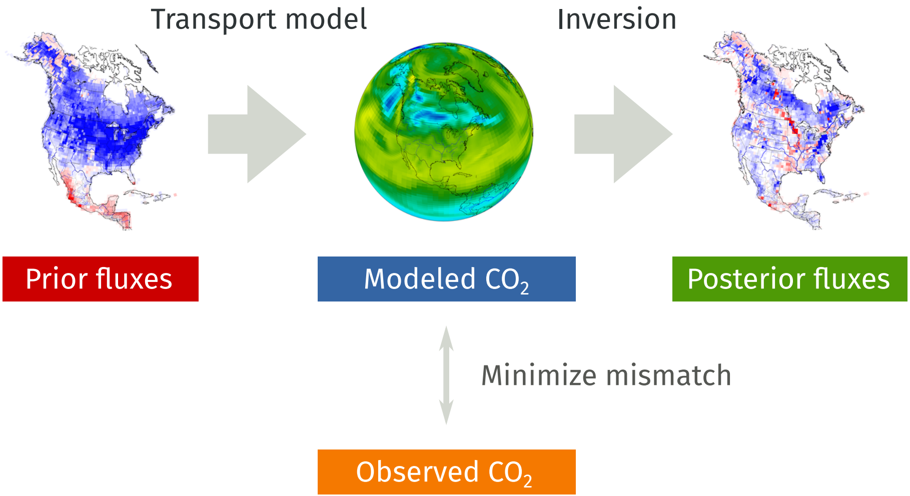
# Regional $CO_2$ fluxes from the terrestrial biosphere are highly uncertain

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




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

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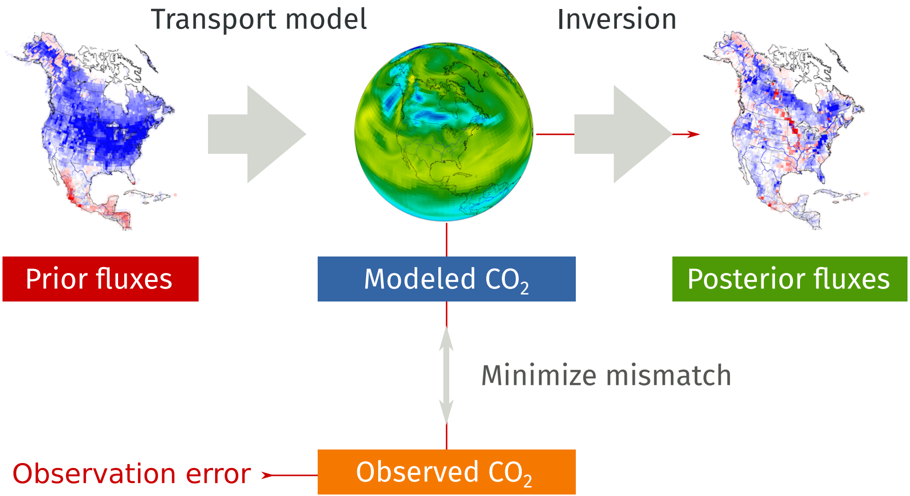



Images from CarbonTracker [https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/]

**How do observation representativeness errors affect $CO_2$ inversions?**

**How can we deal with such uncertainties?**

# Constraining $CO_2$ fluxes using a regional ensemble Kalman Filter system

Based on the **Advanced PSU EnKF system**

Atmospheric transport model: **WRF-Chem**

Atmospheric $CO_2$ and scaling factors for fluxes are added to the state vector:

$$\mathbf{x} = \begin{bmatrix} \mathbf{U} \\ \mathbf{V} \\ \vdots \\ \mathbf{CO_2} \\ \boldsymbol{\lambda} \end{bmatrix}$$

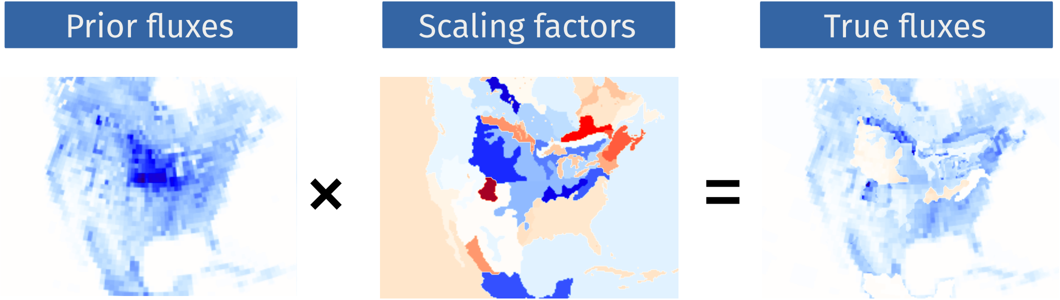
$$F_{CO_2}(x, y, t) = \lambda(x, y) \cdot F_{CO_2}^{\text{prior}}(x, y, t)$$

where

$F_{CO_2}$ are $CO_2$ fluxes

$F_{CO_2}^{\text{prior}}$ comes from a vegetation model (CASA)

# $CO_2$ fluxes are constrained through scaling factors

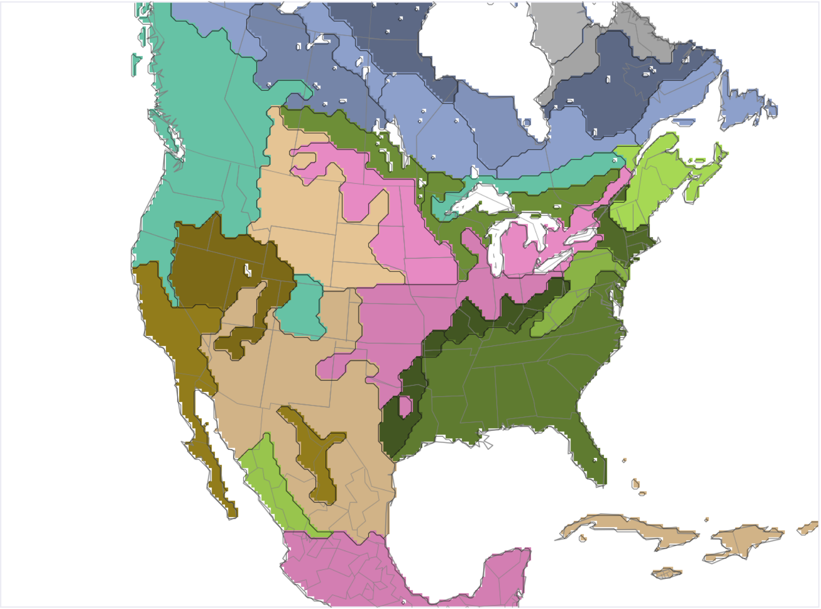



Assume that the true fluxes can be obtained by scaling the prior fluxes by a set of scaling factors $\boldsymbol{\lambda}$

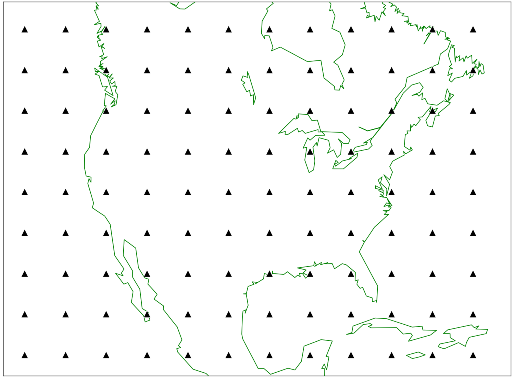
$\Rightarrow$ Reduces degrees of freedom from $F_{CO_2}(x, y, t)$ to $\lambda$(ecosystem) (regularization)

Further assume that $\lambda$s vary by ecosystem and are constant on subseasonal time scales

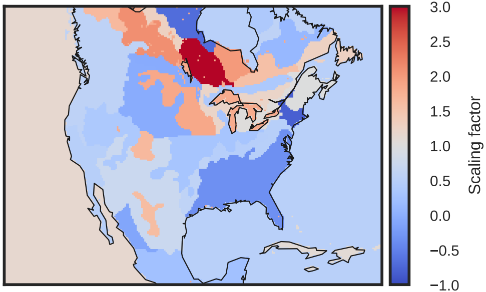
# $CO_2$ fluxes are constrained through scaling factors



# How well can we constrain $CO_2$ fluxes using atmospheric $CO_2$ observations?

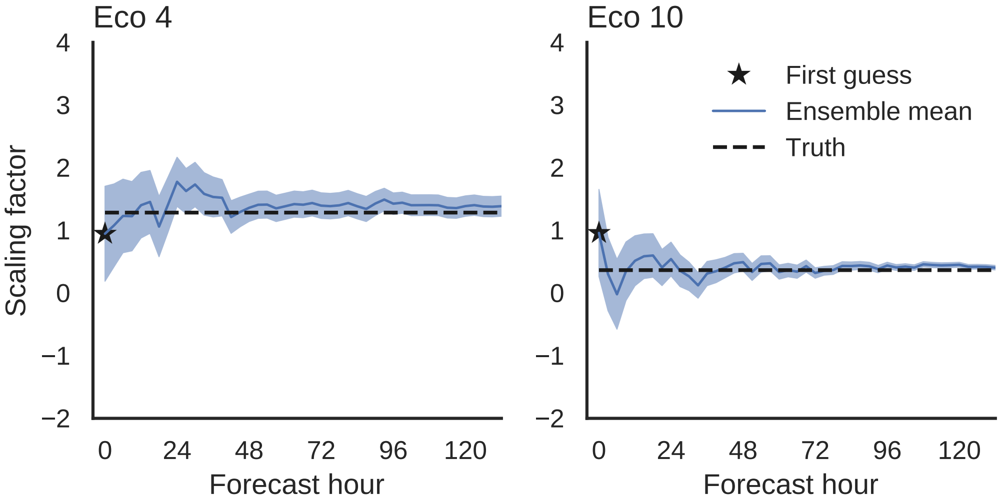


$CO_2$ observation at 100 m every 540 km




"True" scaling factors, $\lambda_k \sim \mathcal{N}(1, 0.8)$

# If all assumptions are met, $CO_2$ fluxes can be well constrained



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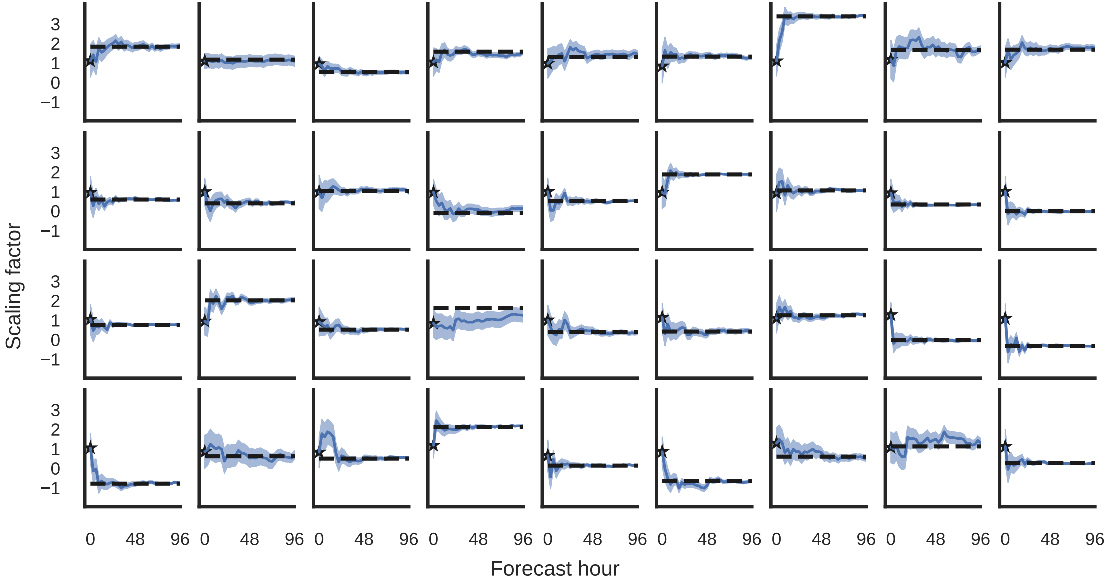

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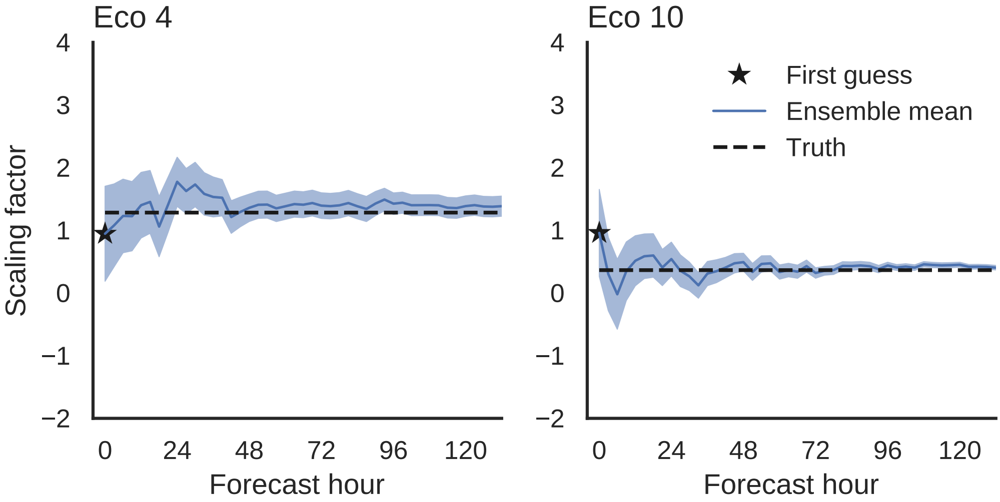

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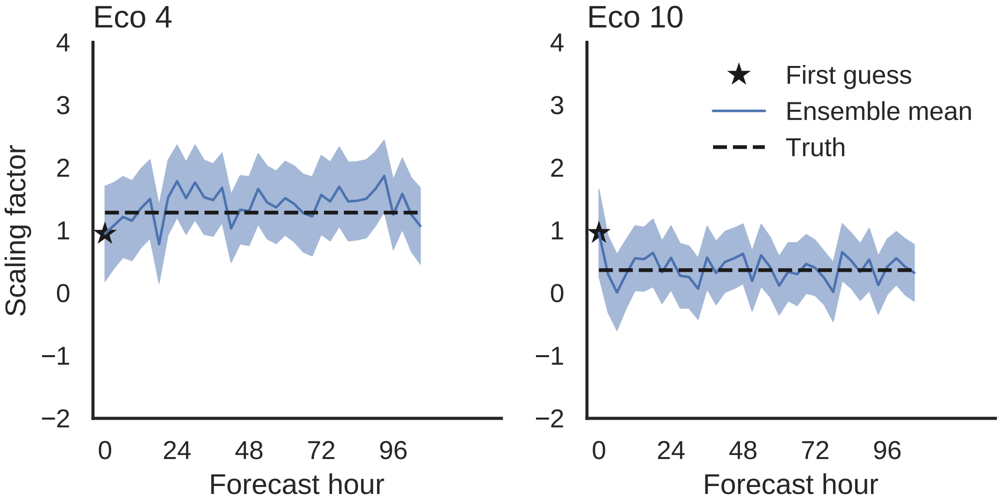
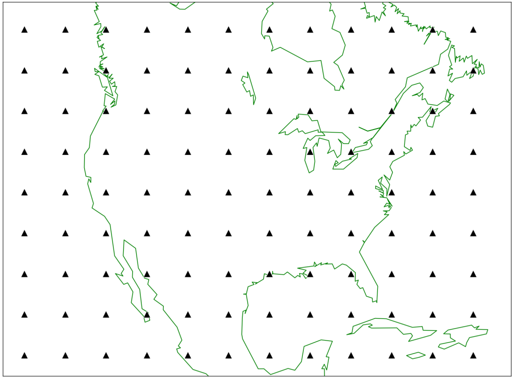
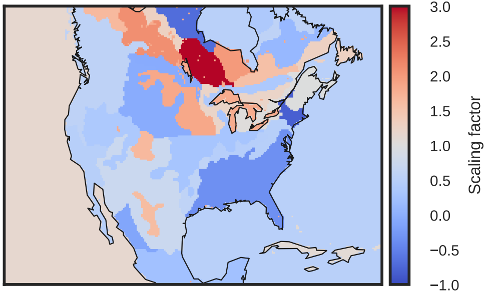



Relax scaling factor perturbations to initial perturbations to maintain spread

# How do noise from unresolved scales influence the inversion results?



$CO_2$ observation at 100 m every 540 km




Add 50 % noise ($L = 100$ km) to truth

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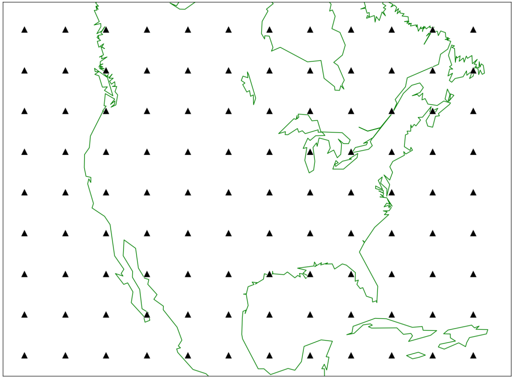

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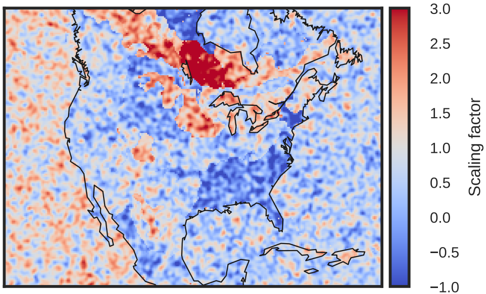


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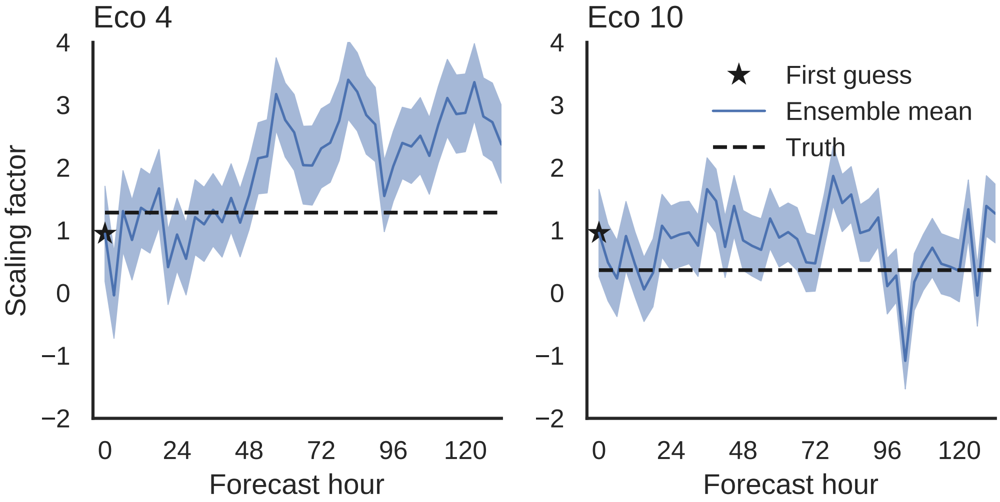
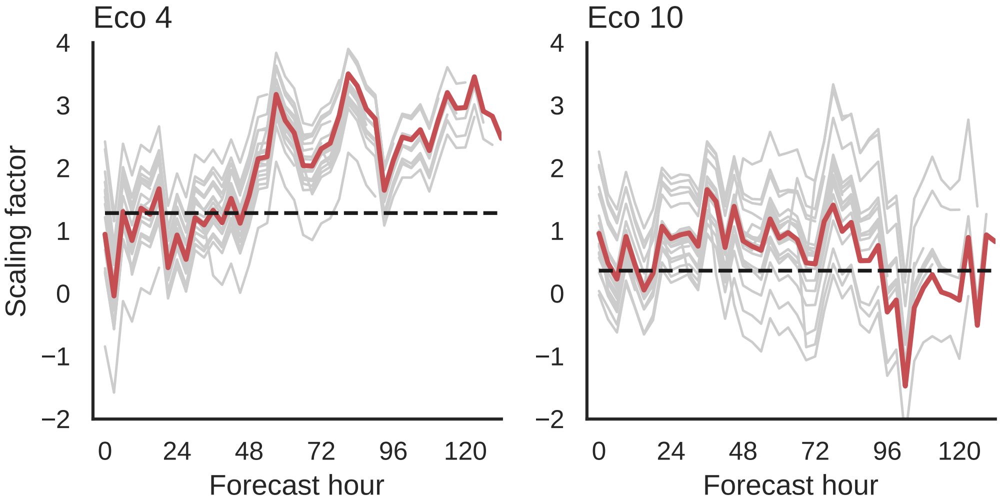
# Noise from unresolved scales can lead to significant biases



# 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

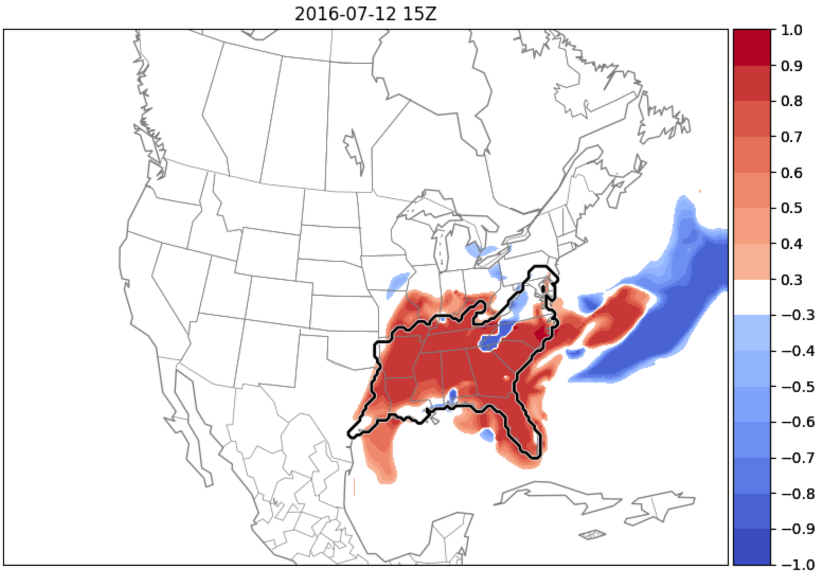
# References

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.

Le Quéré and Coauthors, 2018: Global Carbon Budget 2017, Earth Syst. Sci. Data, 10, 405-499. https://doi.org/10.5194/essd-10-1-2018

Dr. Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.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 ($F_{CO_2} = \lambda \cdot F_{CO_2}^{\text{prior}}$)

# Real $CO_2$ tower observation network