Constraining regional-scale CO_2 fluxes using a coupled meteorological–carbon ensemble Kalman filter

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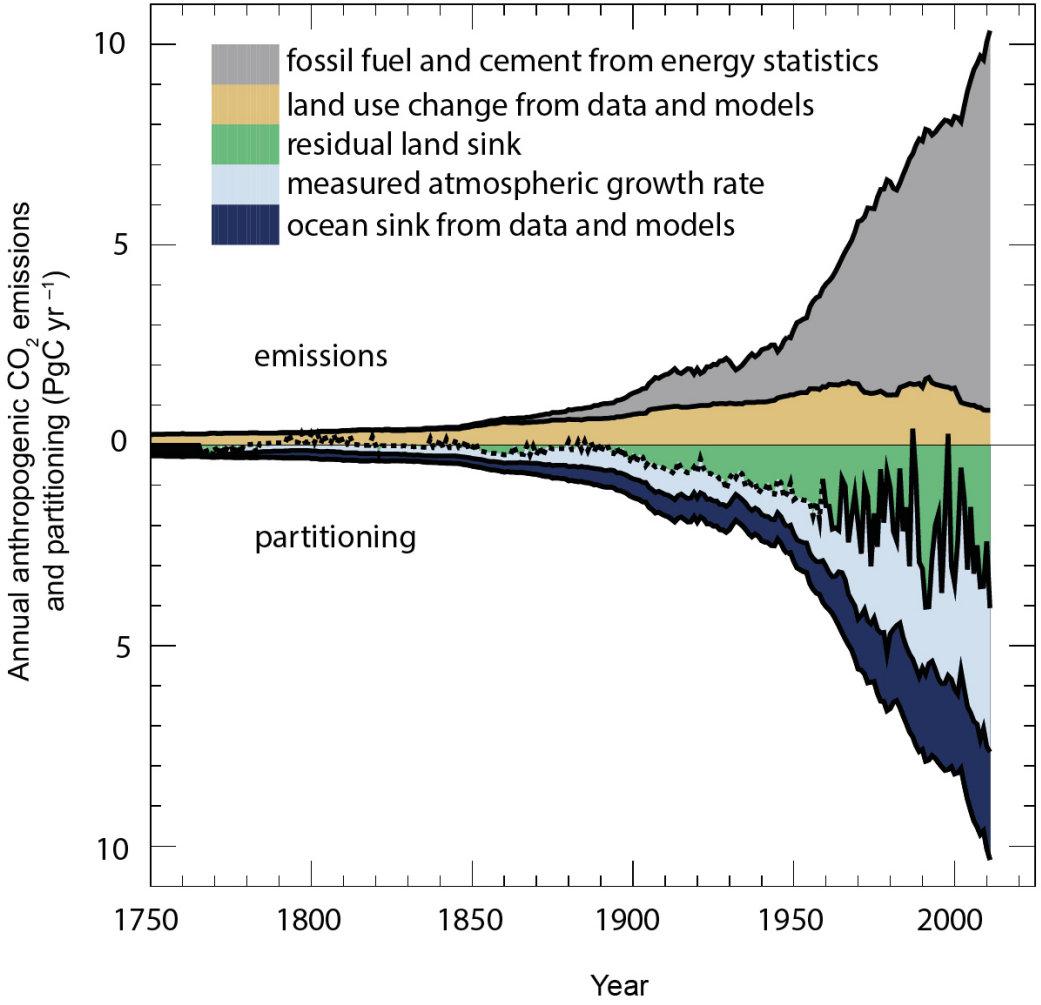
Goal: Estimate land sources and sinks of CO_2



CO_2 emissions due to human activity:

Fossil fuel

Land use change

CO_2 uptake by:

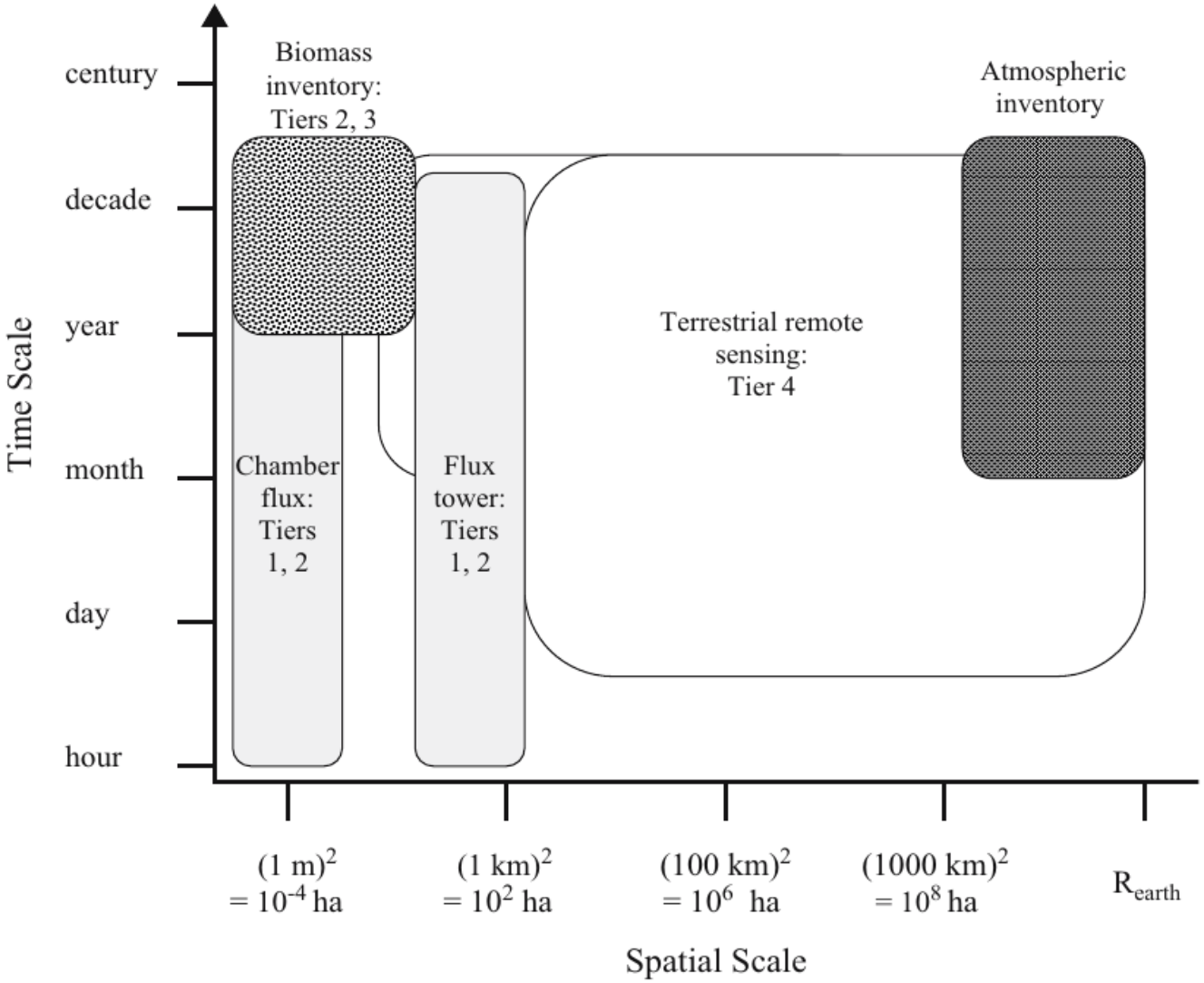
Land

Atmosphere

Ocean

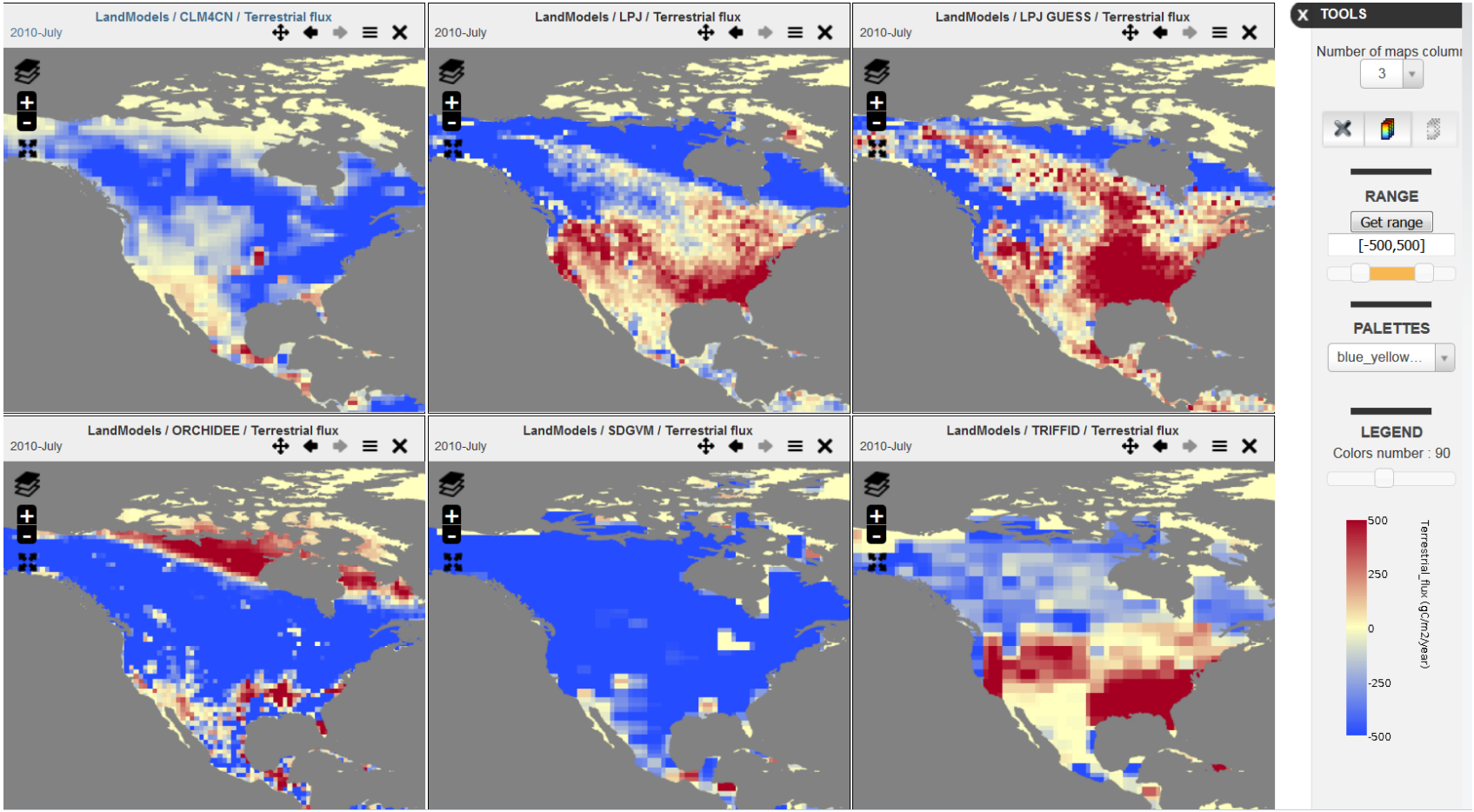
Annual human CO_2 emissions and their partitioning between land, atmosphere and ocean [IPCC 2014]

CO_2 fluxes are difficult to measure at regional to global scales



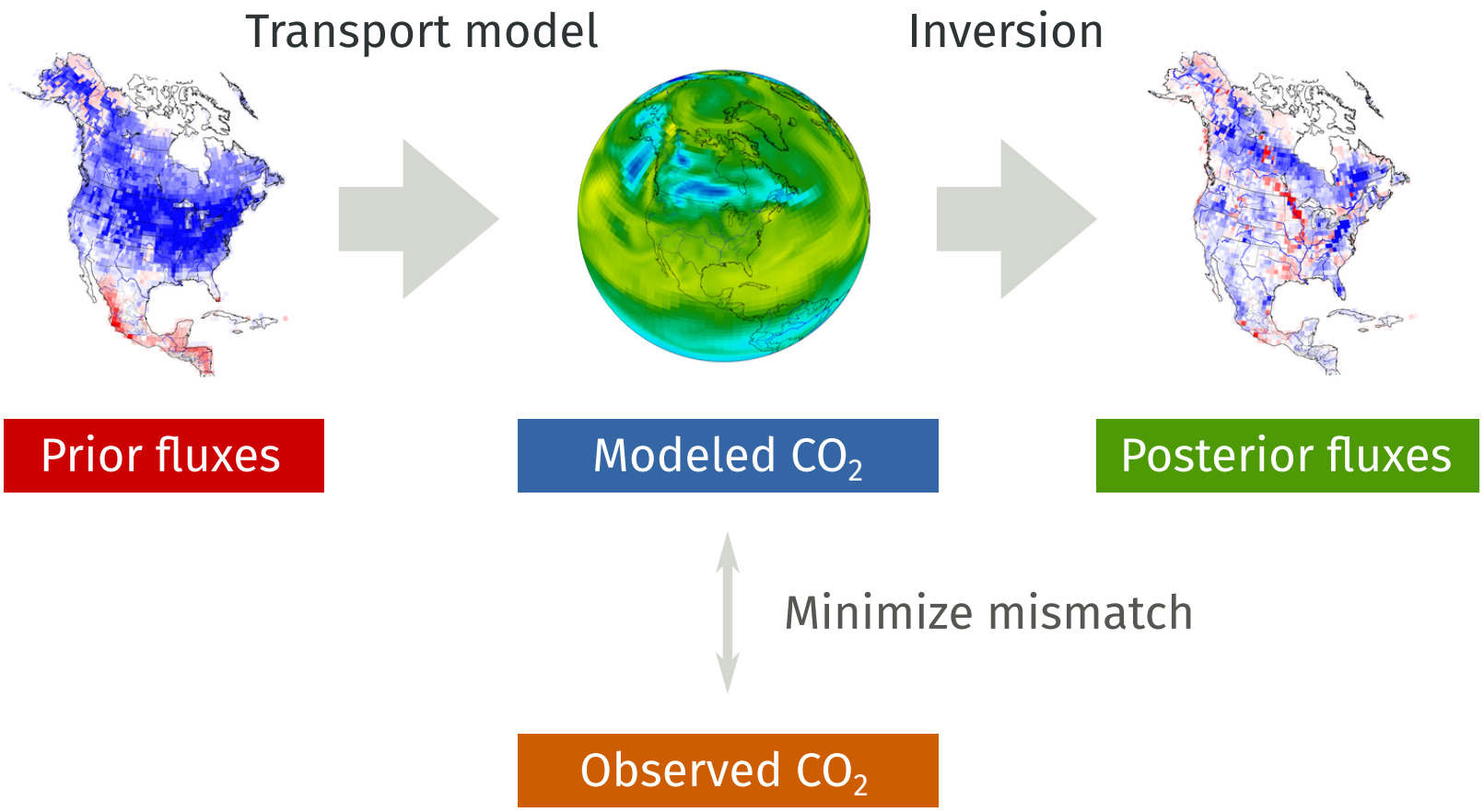
Spatial and temporal scales of CO_2 flux measurements [Davis 2008]

Process-based models show large regional-scale differences



Monthly mean biospheric CO_2 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):

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

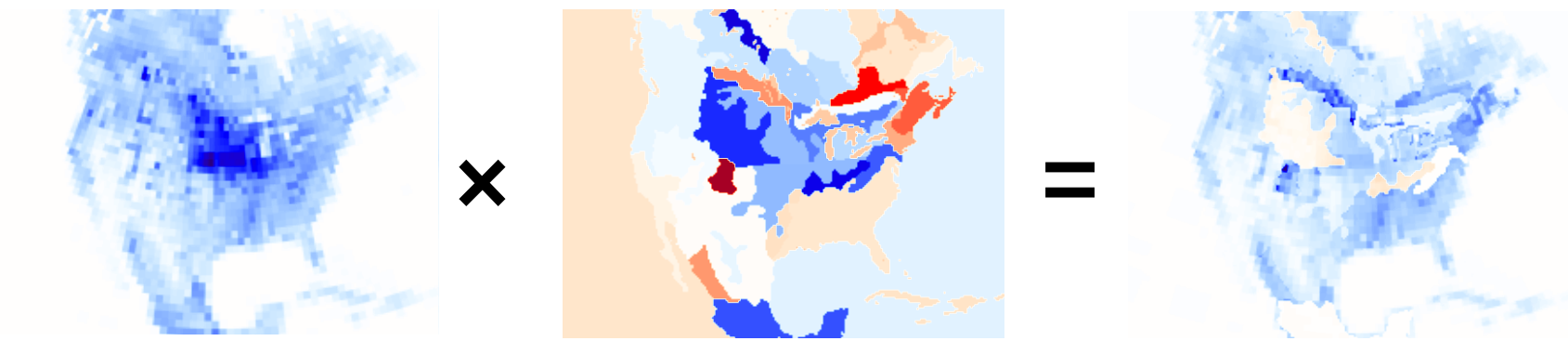
$$CF_{\text{true}}(t, x, y) = \lambda_{\text{true}}(x, y) \times CF_{\text{prior}}(t, x, y)$$

CF: Carbon Fluxes

CF_{prior} from a vegetation model (CASA)

Optimize a set of scaling factors

Prior fluxes | Scaling factors | True fluxes

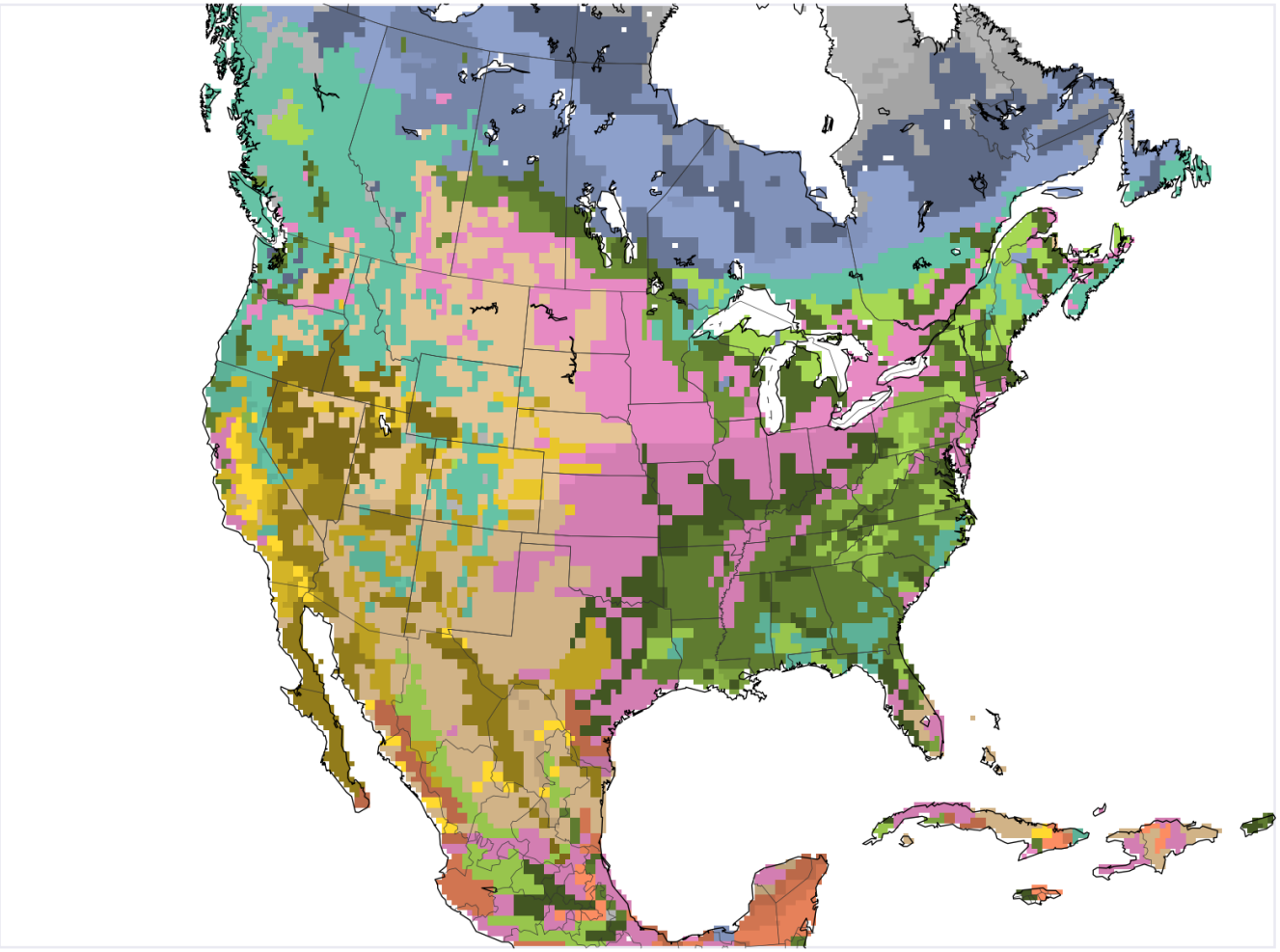


Assume that the true fluxes can be obtained by scaling the prior fluxes by a set of scaling factors $\boldsymbol{\lambda}$

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

$$\boldsymbol{\lambda}_{t+1} = \mathcal{M}(\boldsymbol{\lambda}_t) = \mathbf{I}\boldsymbol{\lambda}_t$$

Assume spatial covariances in λ depend on ecoregions



- Regularization
- Use additional information about fluxes from external source

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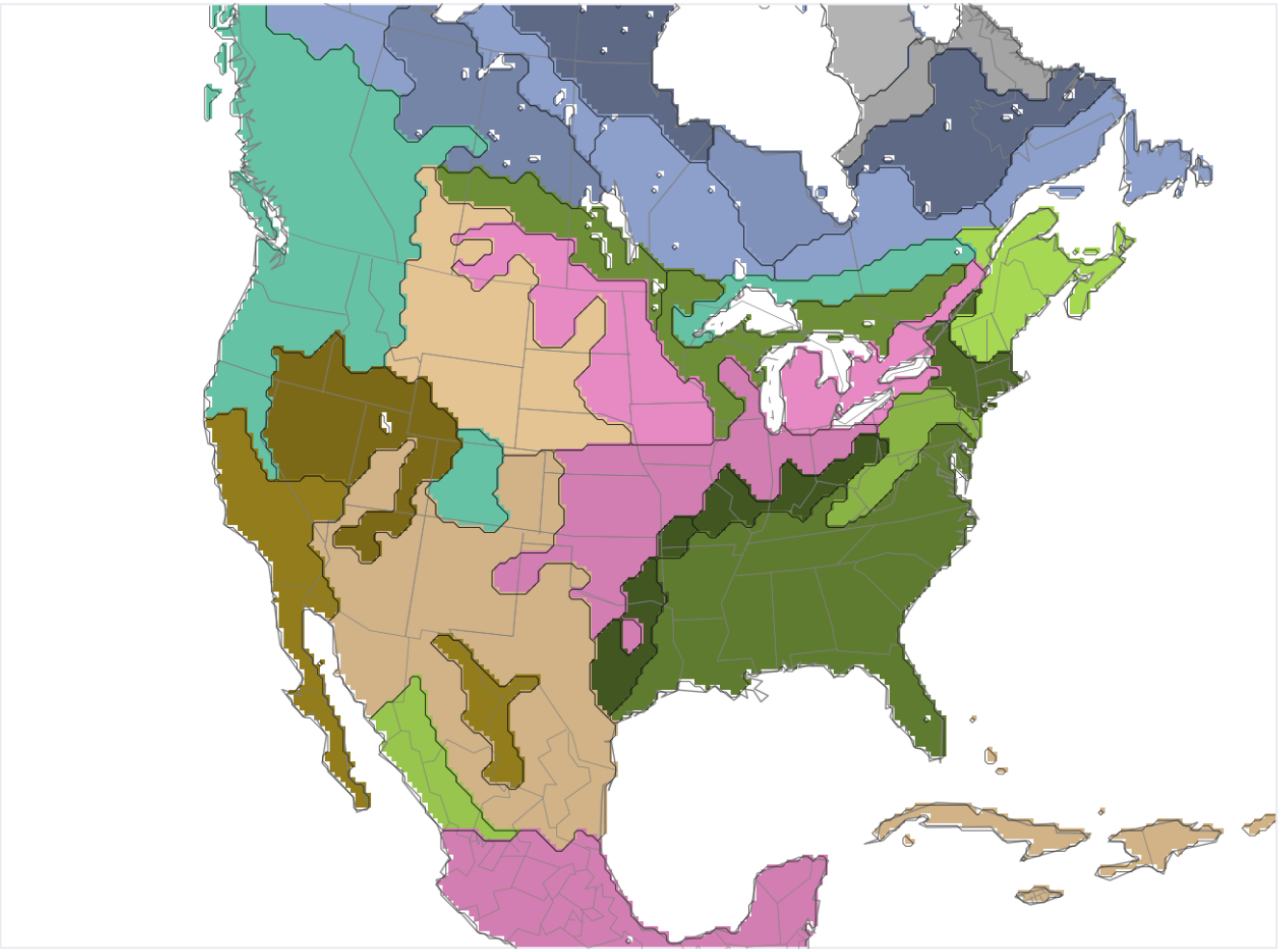


- Regularization
- Use additional information about fluxes from external source

How is atmospheric CO_2 linked to CO_2 flux perturbations?

Ensemble sensitivity experiment

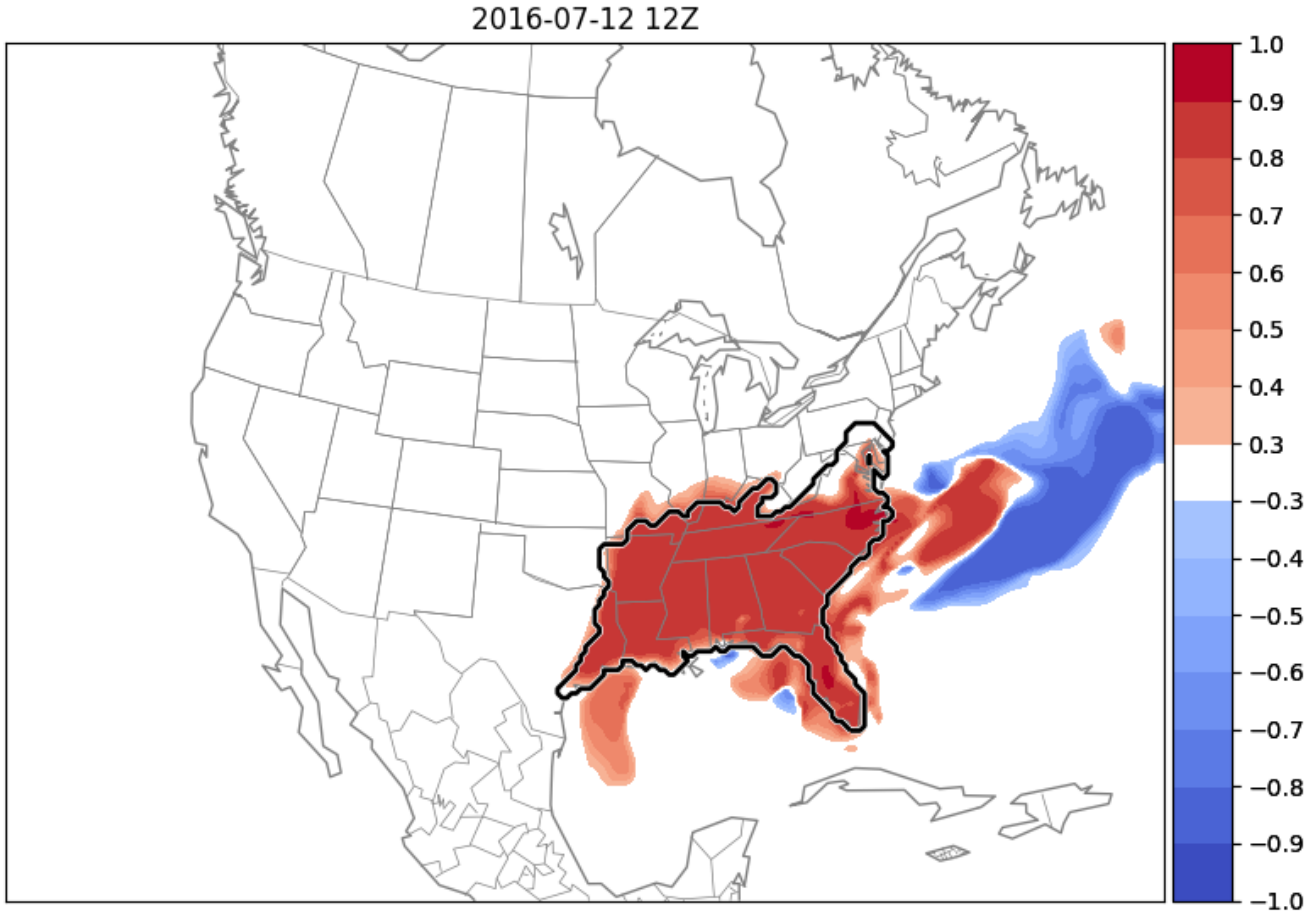
200 ensemble members with perturbed fluxes according to:

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

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

All members have the same atmospheric transport

Flux signals are generally constrained to within ecoregions



Ensemble correlation between λ and CO_2 at 100 m

$$CF = \lambda \times CF_{\text{prior}}$$

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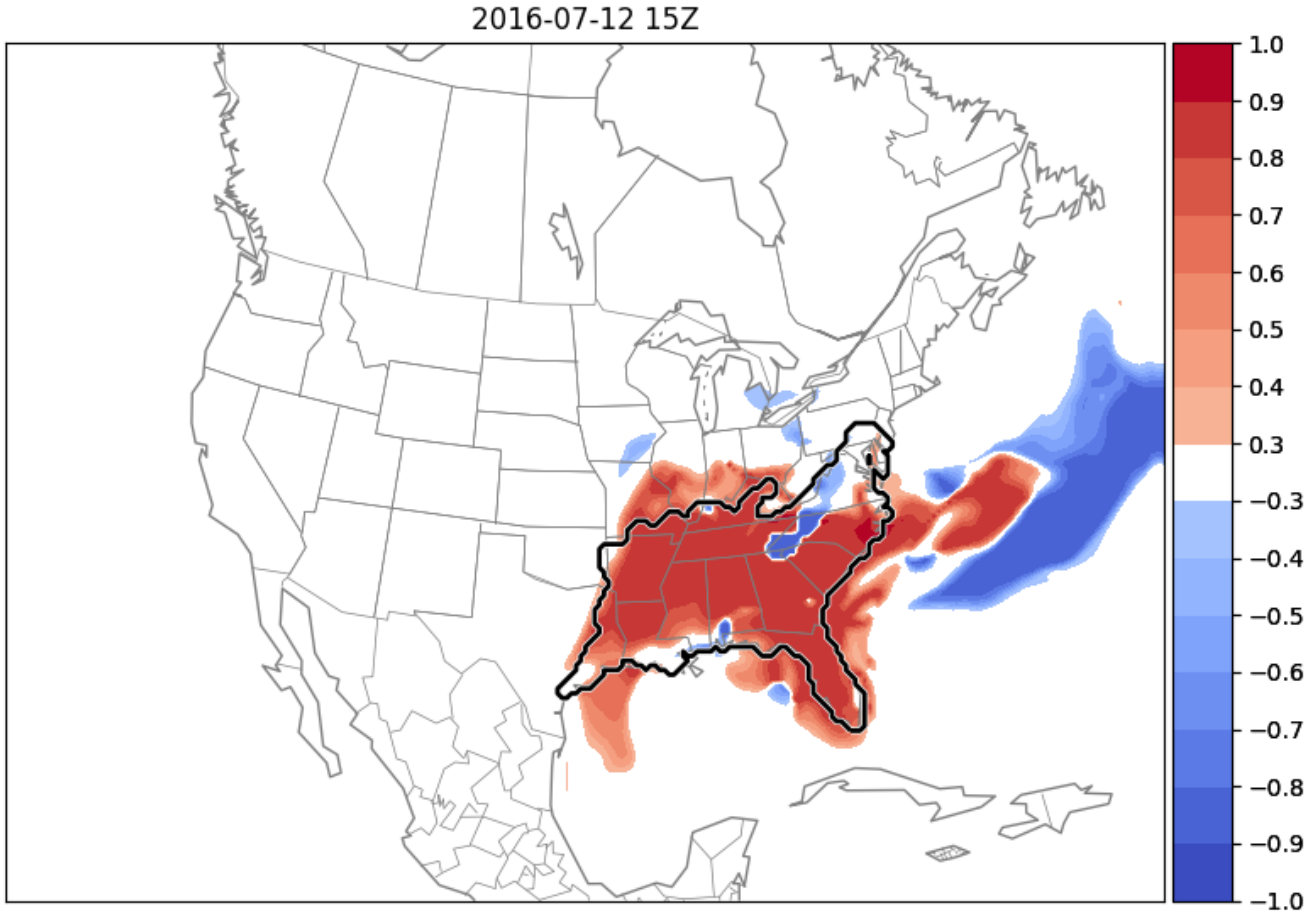

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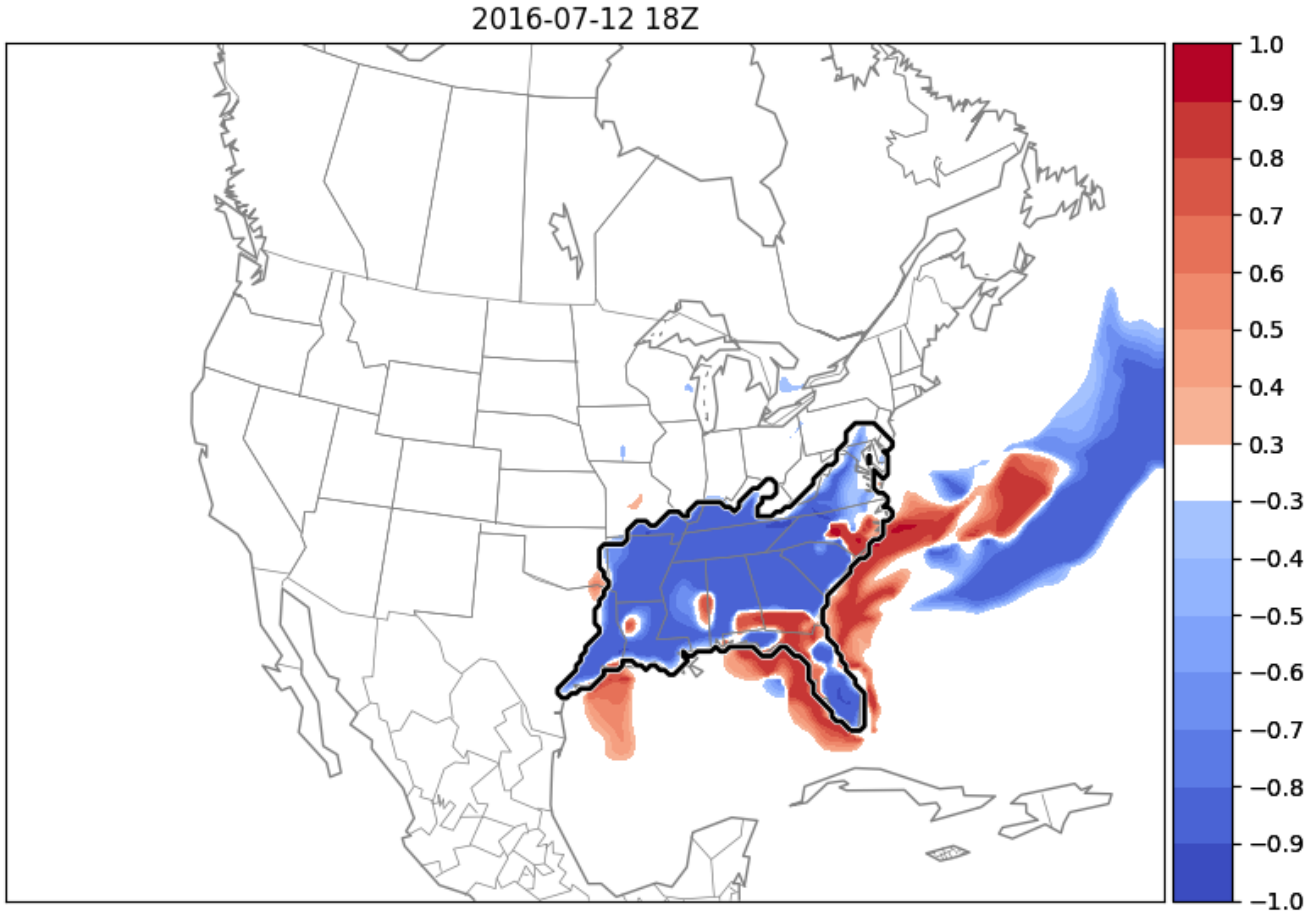

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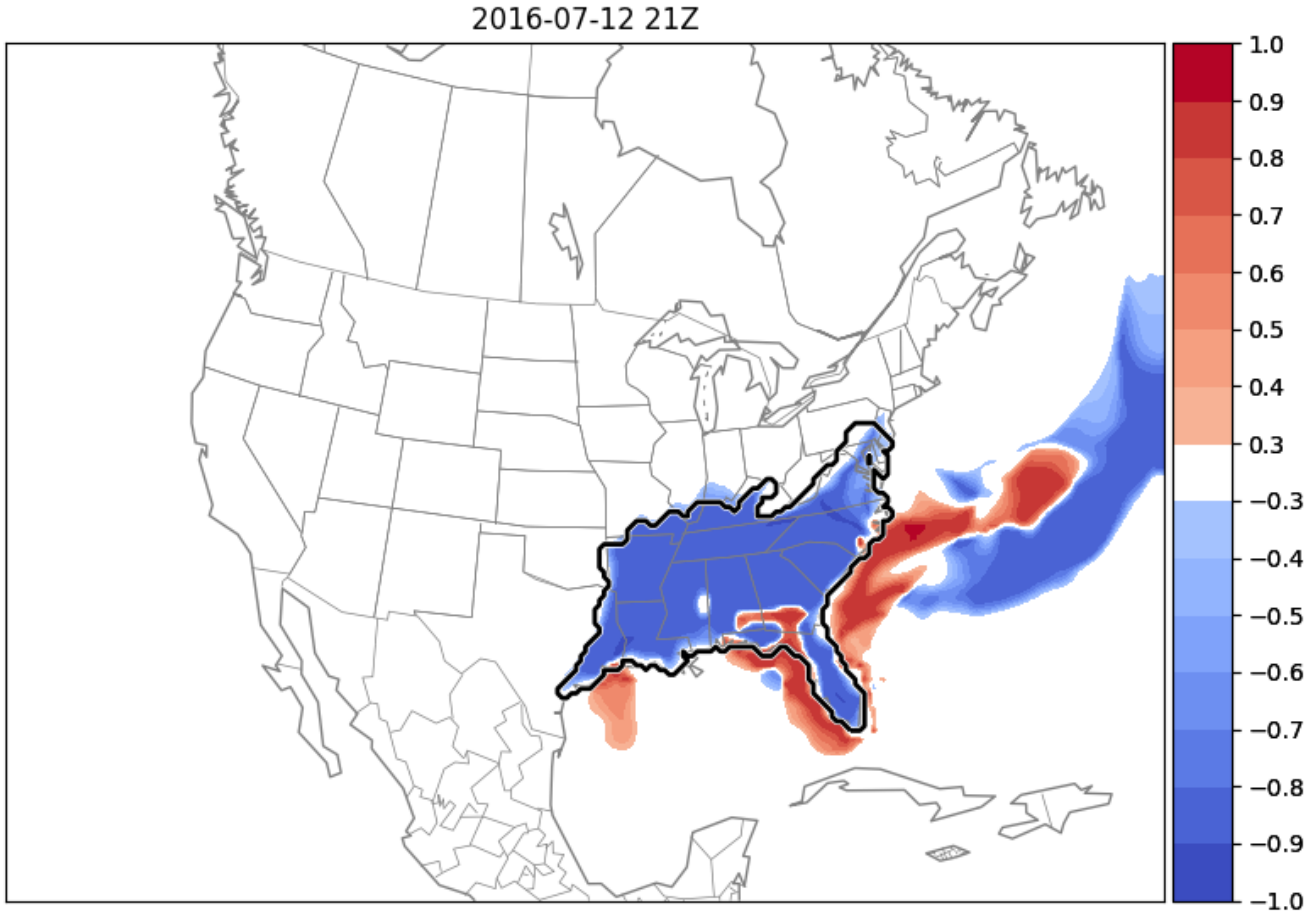

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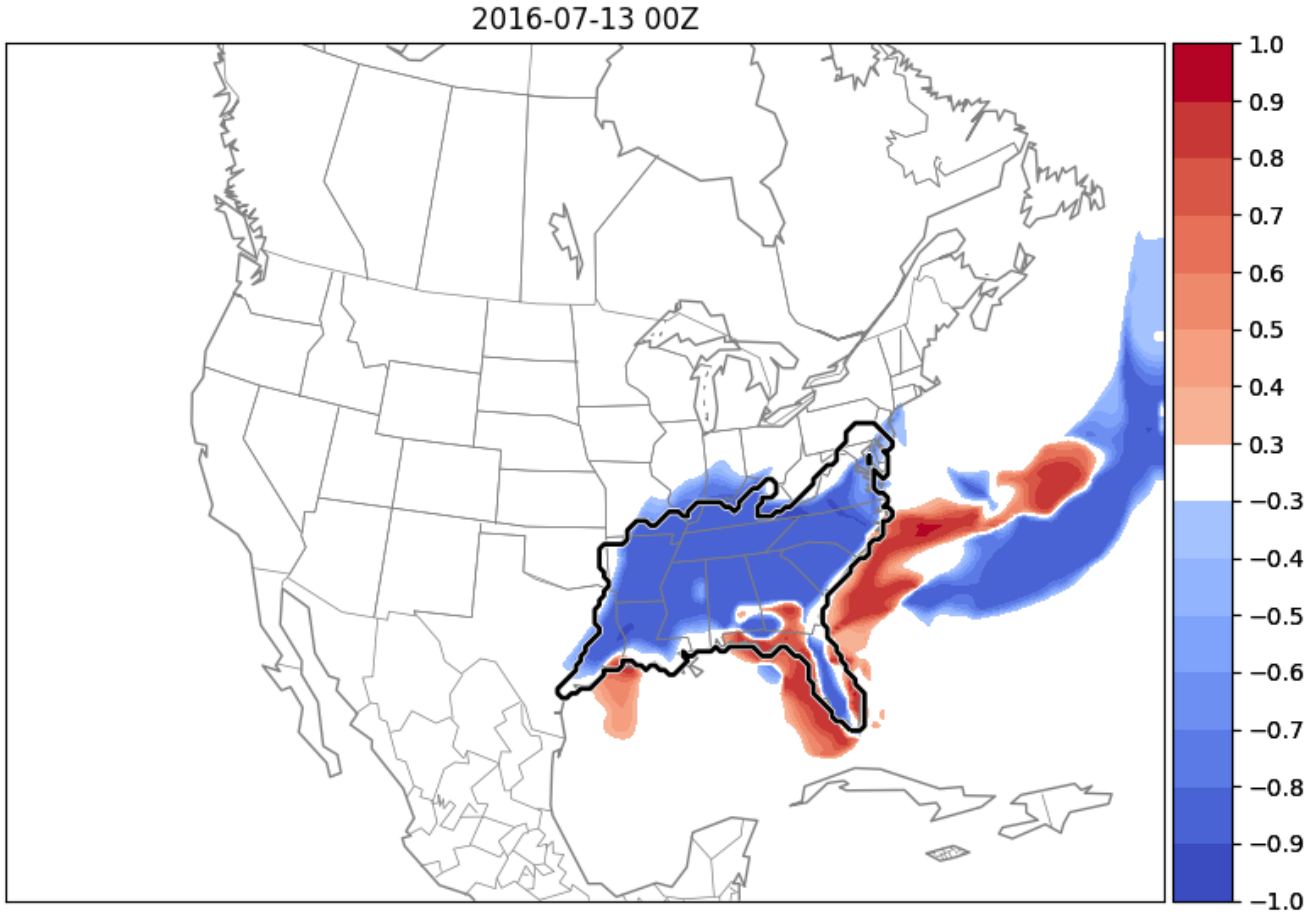

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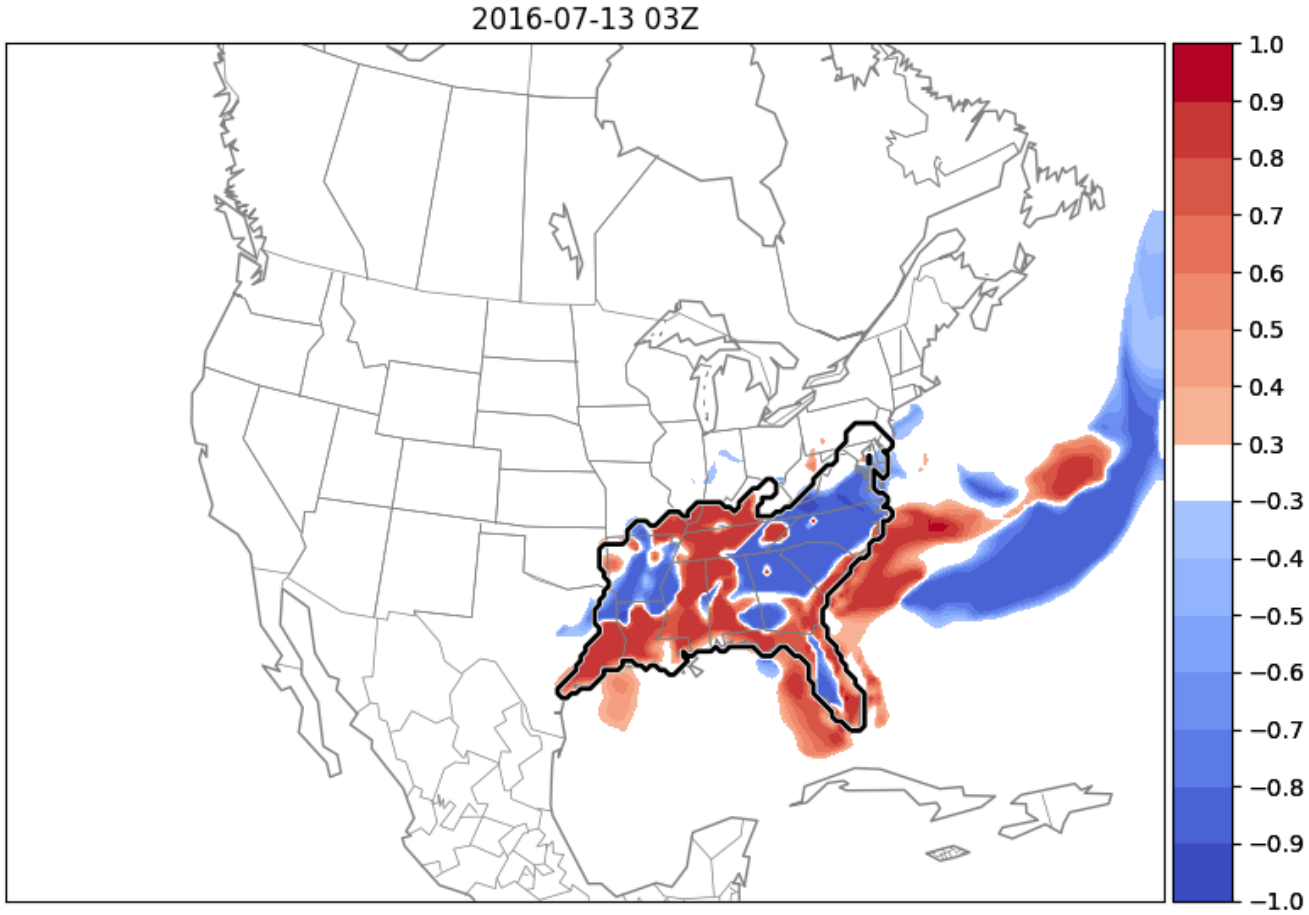

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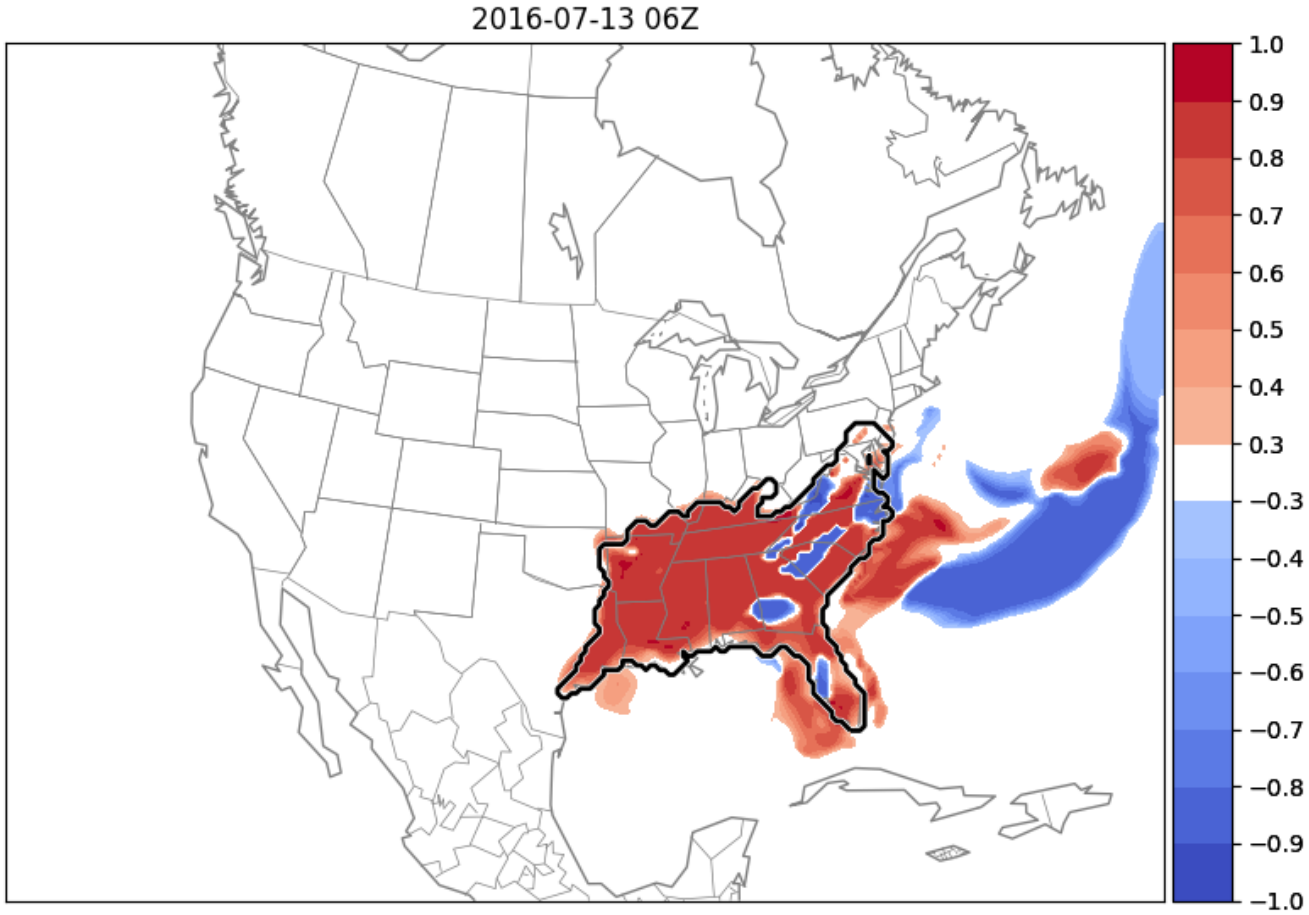
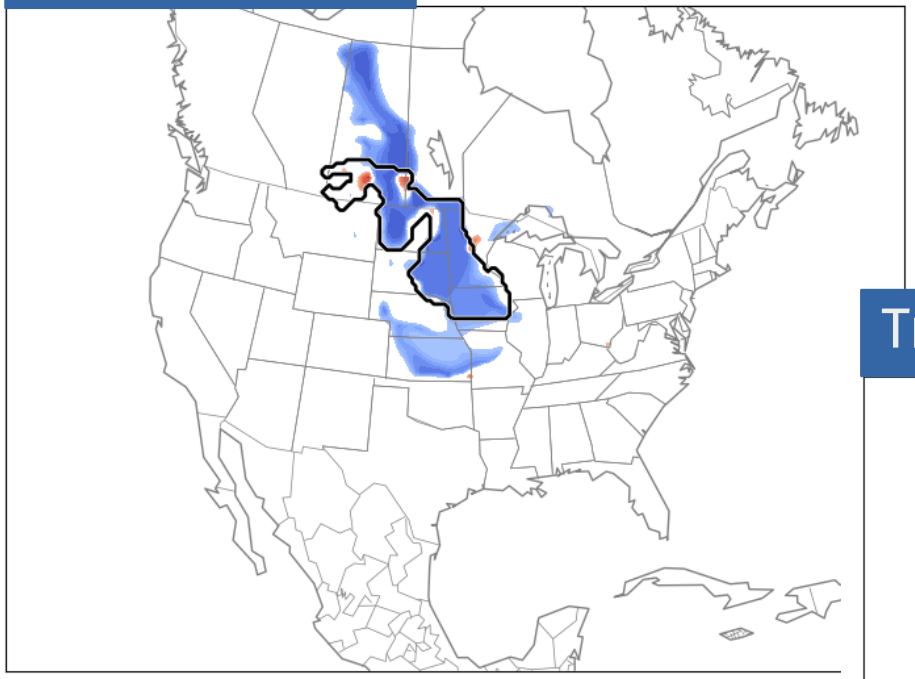


Ensemble correlation between λ and CO_2 at 100 m

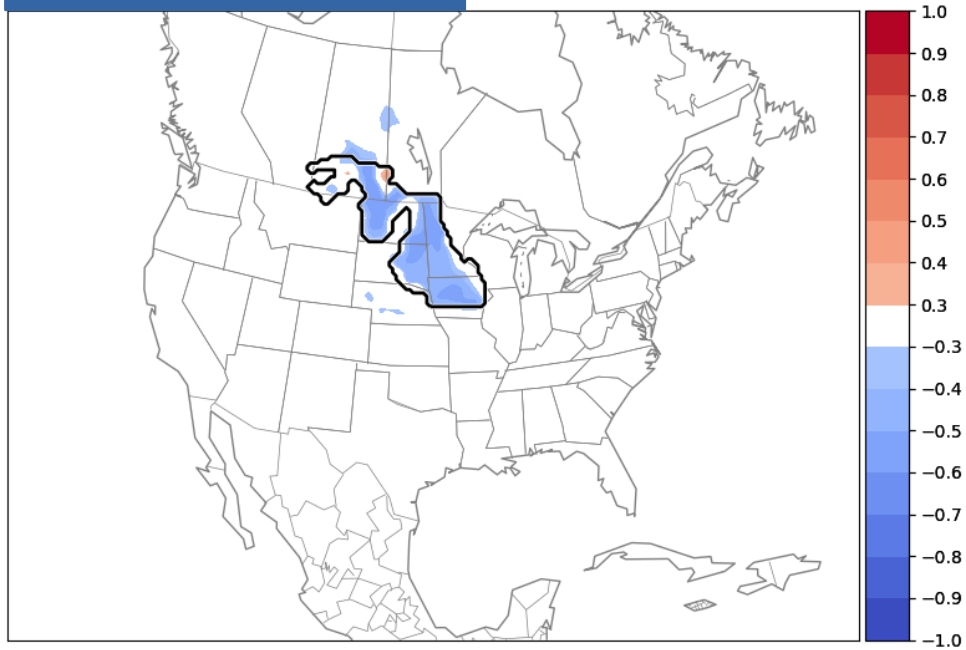
$$CF = \lambda \times CF_{\text{prior}}$$

Transport errors further reduce ensemble correlations

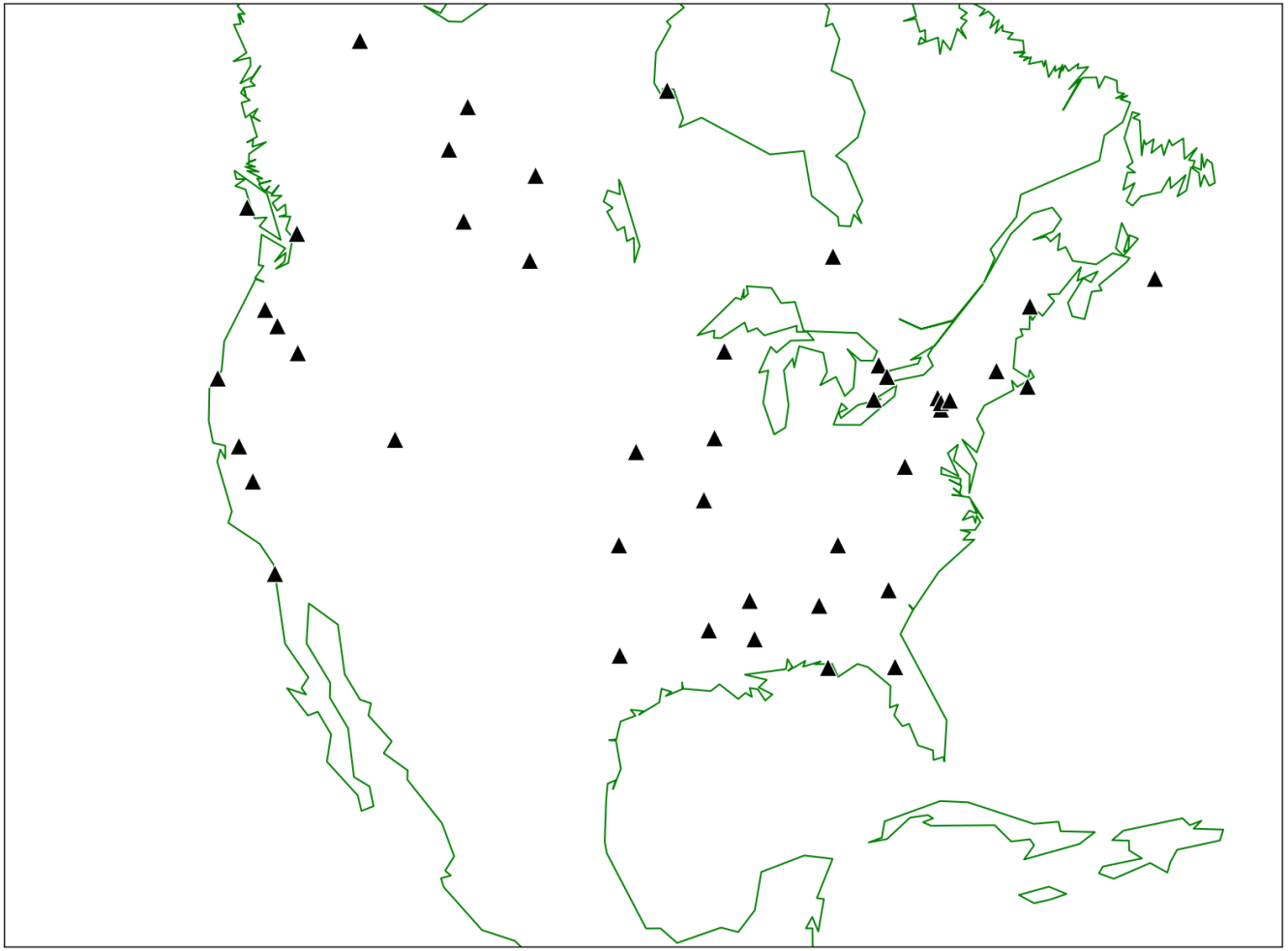
True transport



Transport errors

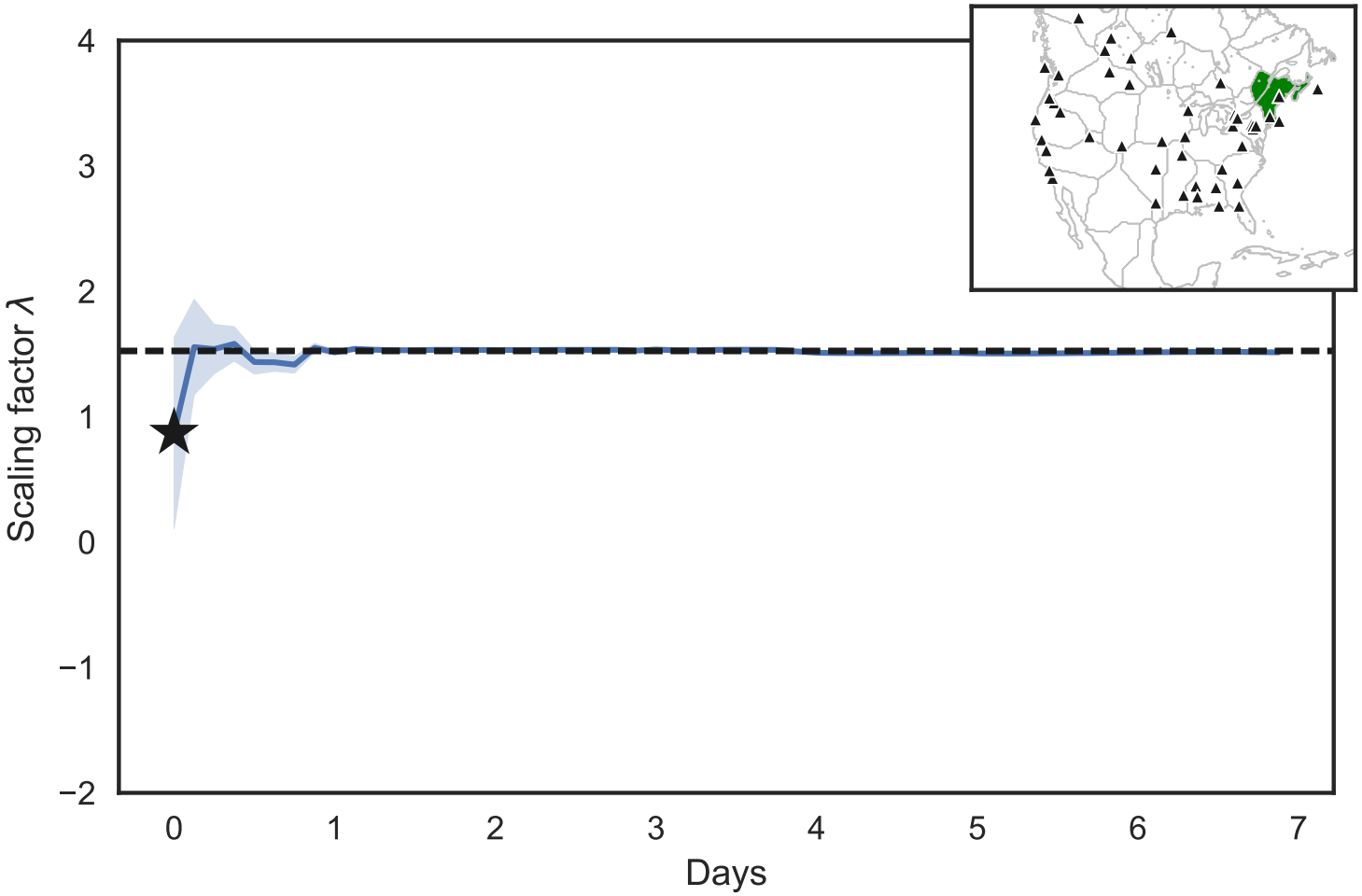


Can we constrain CO_2 fluxes with the current operational observation network?



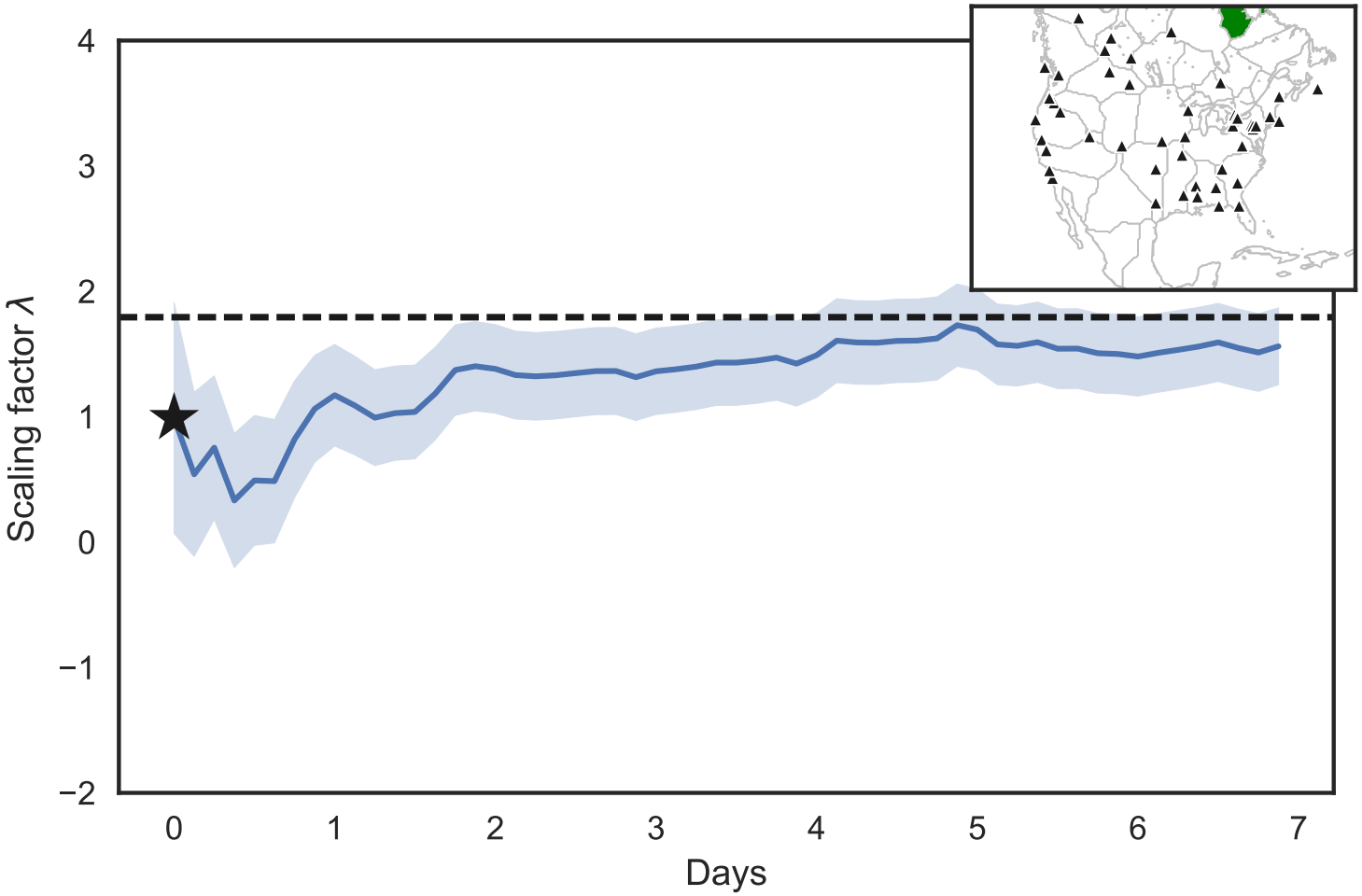
Assimilate ideal CO_2 tower observations every 3 hours using EnKF

With perfect knowledge about the transport, CO_2 fluxes can be well constrained



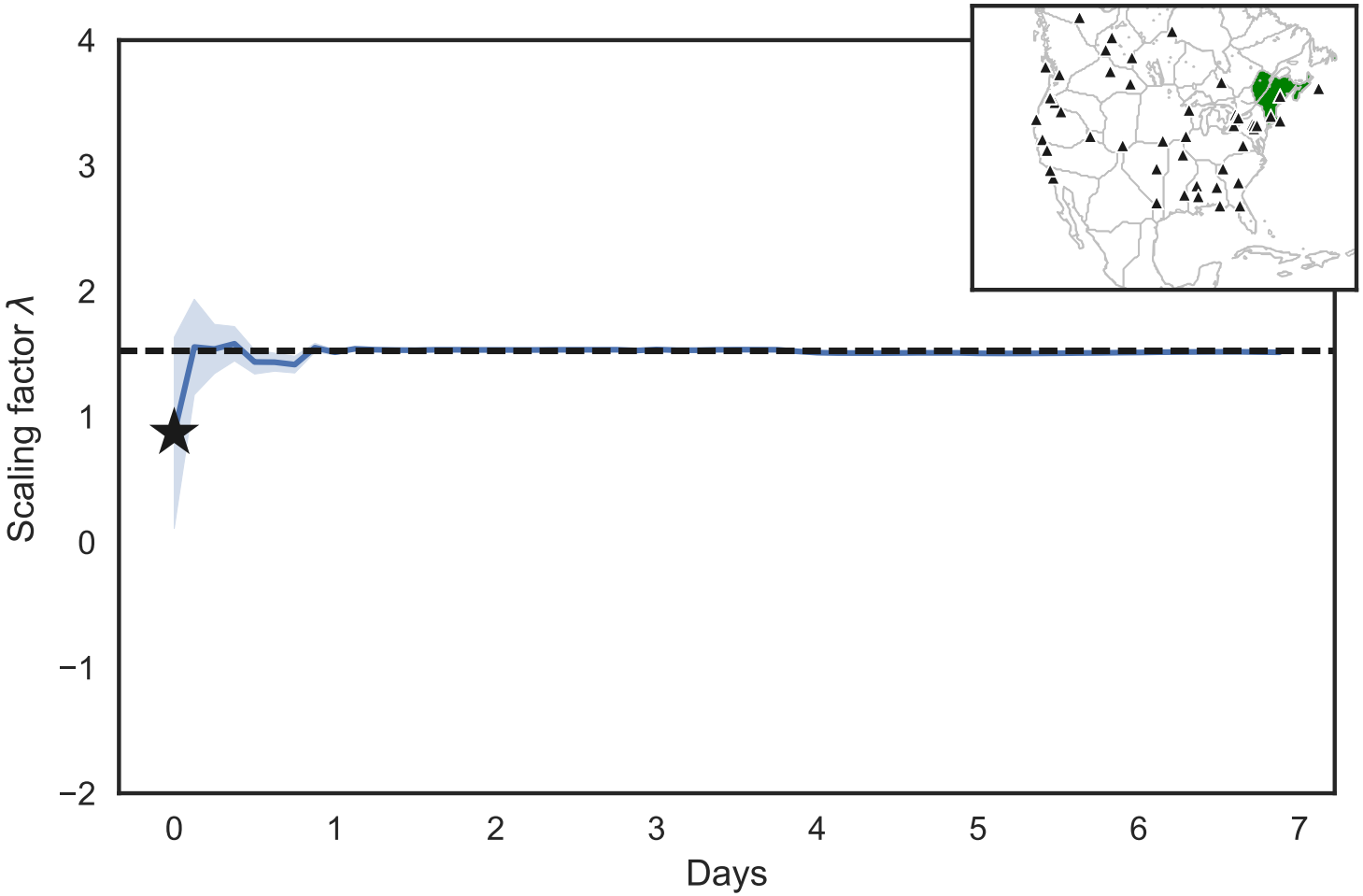
. . . in regions with many observations . . .

With perfect knowledge about the transport, CO_2 fluxes can be well constrained



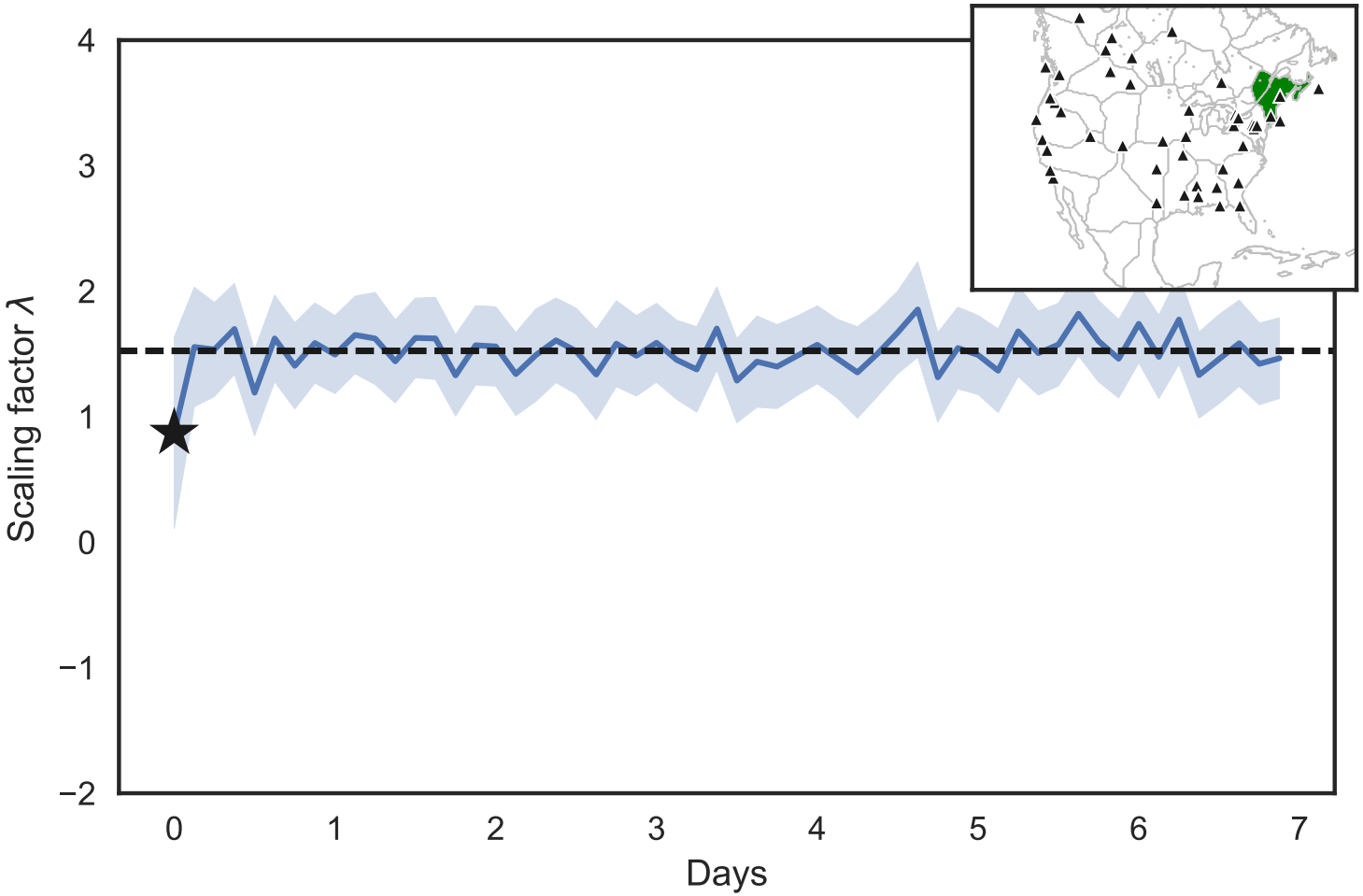
. . . and in regions remote from observations

Inflate ensemble perturbations to avoid filter divergence



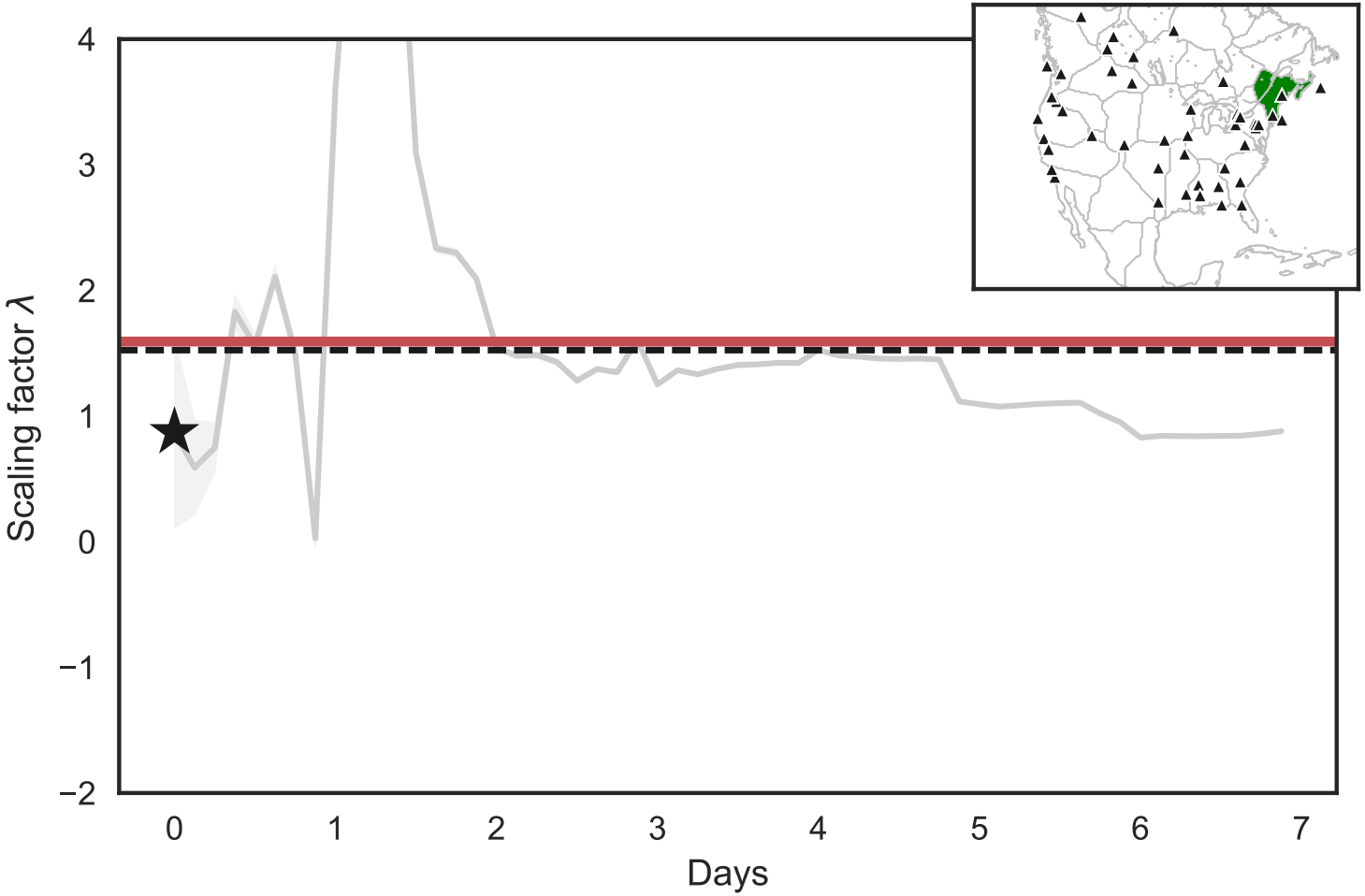
Ensemble perturbations relaxed back to initial perturbations to maintain spread

Inflate ensemble perturbations to avoid filter divergence



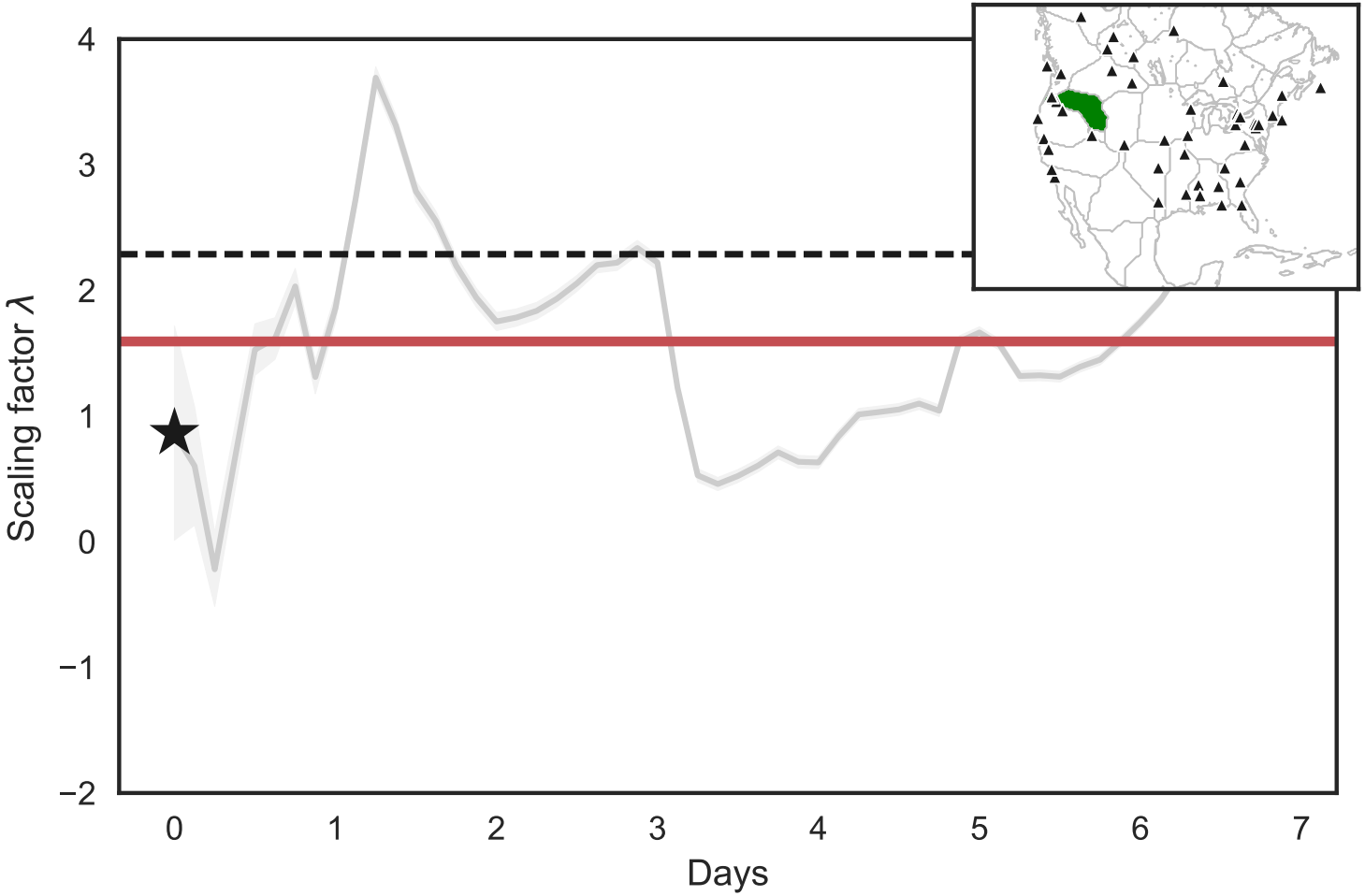
Ensemble perturbations relaxed back to initial perturbations to maintain spread

Transport errors can lead to non-converging results



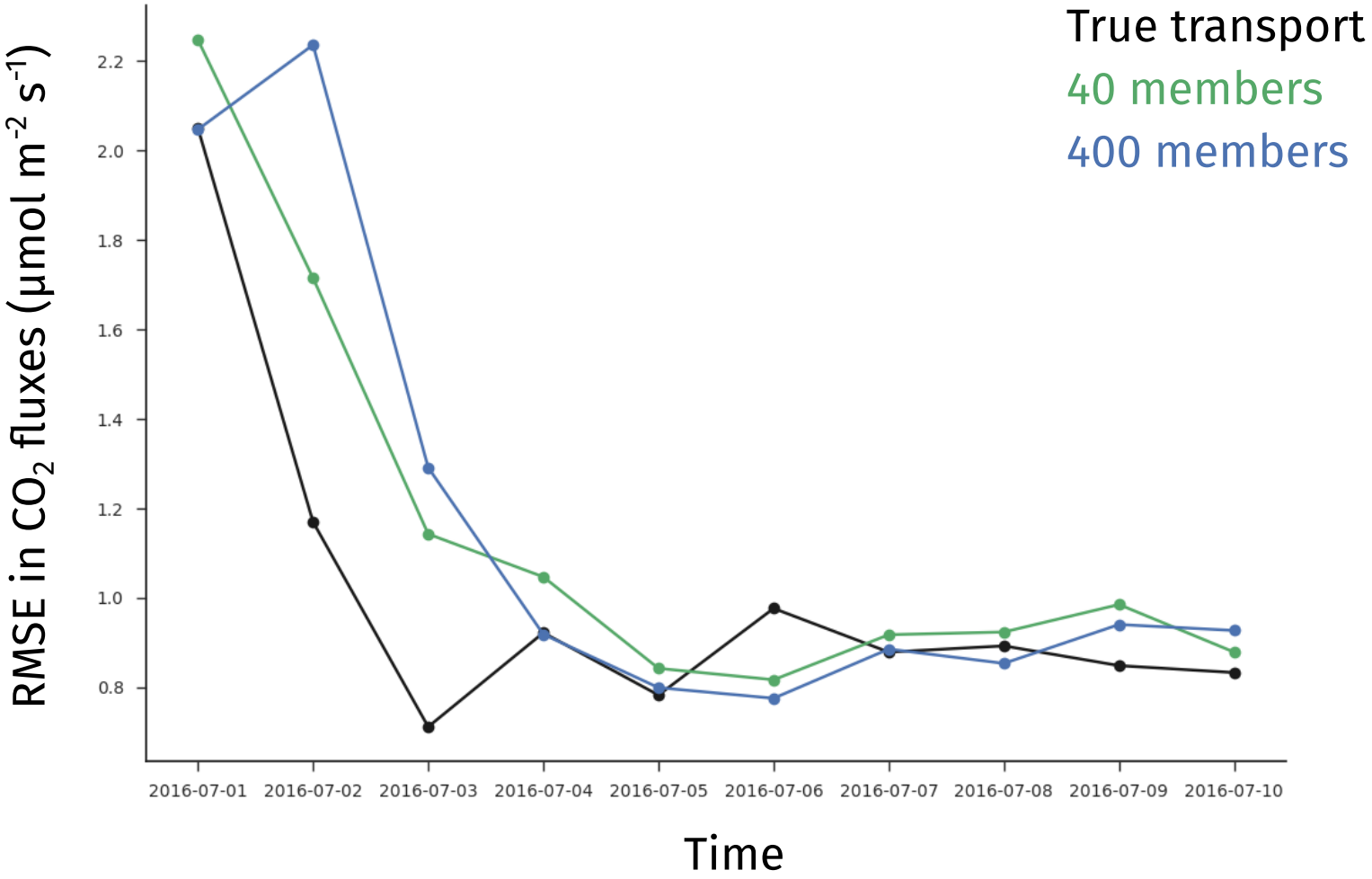
Sometimes we are lucky and the errors average out

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 CO_2 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