Regional CO_2 inversion through ensemble-based simultaneous state and parameter estimation

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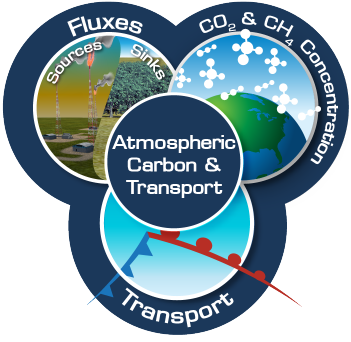
This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 958927, the Swedish National Space Agency (2021-00149) and Biodiversity and Ecosystem services in a Changing Climate (BECC)

Background



Atmospheric Carbon and Transport (ACT)–America

@PennState

Funded by NASA

CO_2 Human Emissions

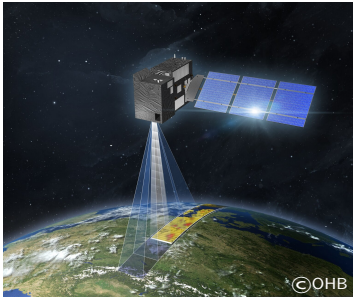
CoCO2

Prototype system for a Copernicus CO_2 service

CO_2 Human Emissions (CHE)
Copernicus CO_2 (CoCO2)

@LundUniversity

Funded by EU H2020



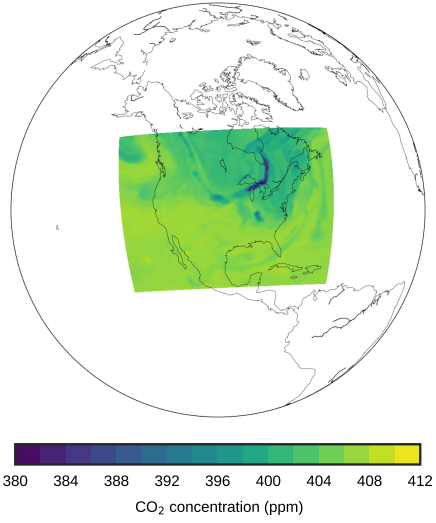
Monitoring anthropogenic CO_2 emissions from space
AVENGERS

@Chalmers

Funded by the Swedish National Space Agency and EU

Modeling system

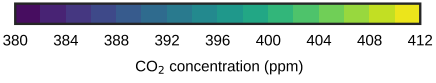
Development of a new regional CO_2 data assimilation system: TRACE



TRACE Regional Atmosphere–Carbon Ensemble system:

- Online atmospheric transport modeling using WRF-Chem
- Assimilation of meteorological observations to improve the modeled atmospheric transport
- Ensemble-based simultaneous state and parameter estimation (ESSPE) approach

Development of a new regional CO_2 data assimilation system: TRACE



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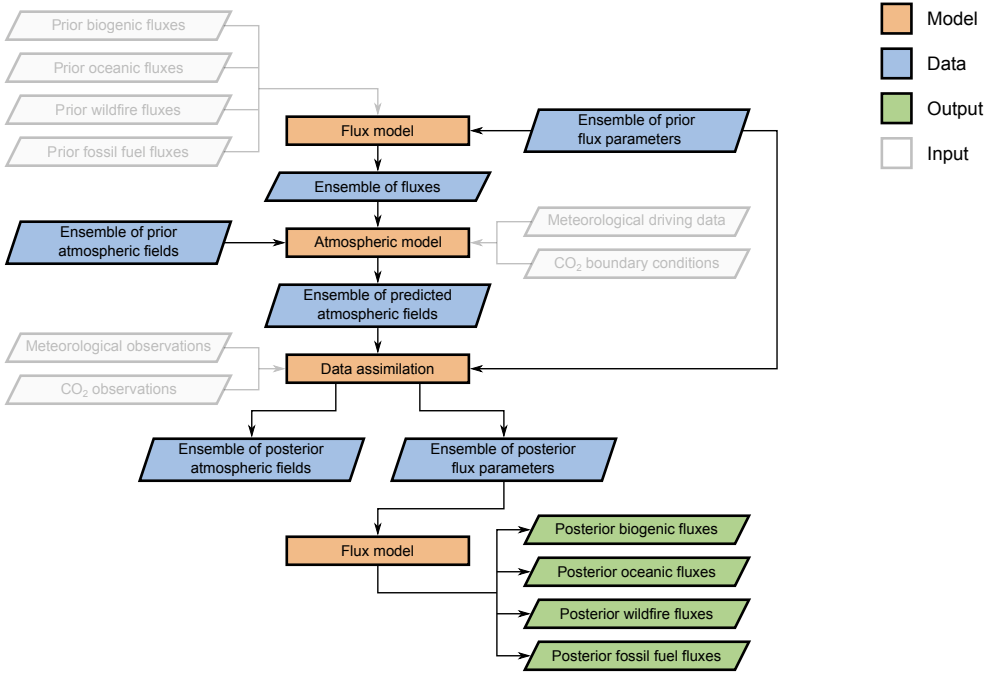
Prior biogenic fluxes
Prior oceanic fluxes
Prior wildfire fluxes
Prior fossil fuel fluxes
Flux model
Ensemble of prior flux parameters
Ensemble of fluxes
Ensemble of prior atmospheric fields
Atmospheric model
Meteorological driving data
CO_2 boundary conditions
Ensemble of predicted atmospheric fields
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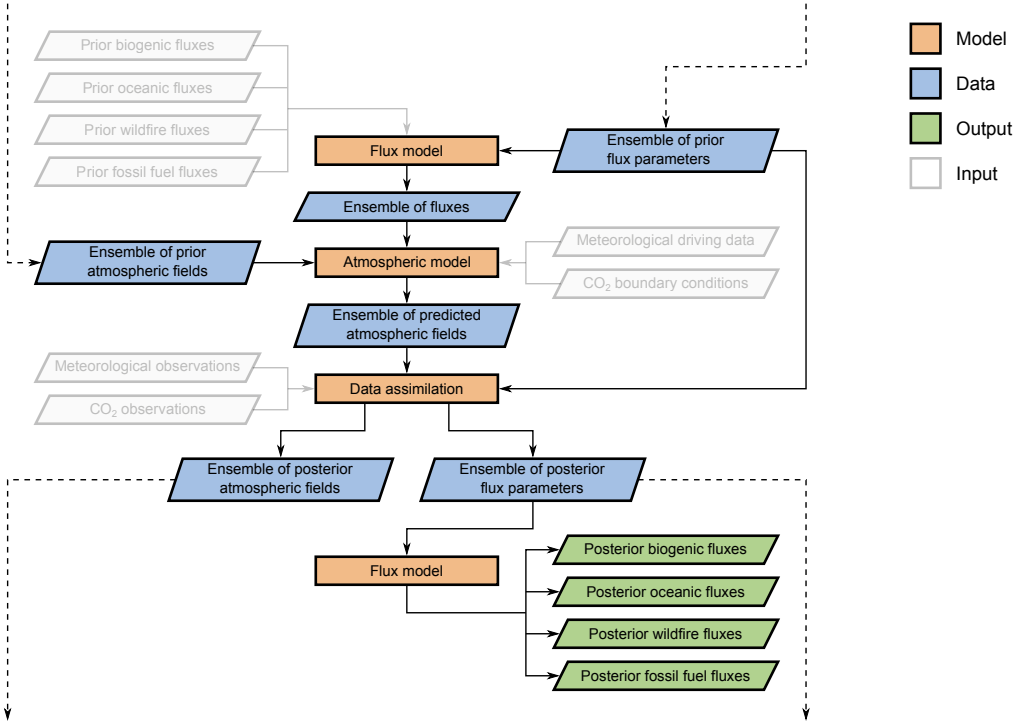
Model
Data
Output
Input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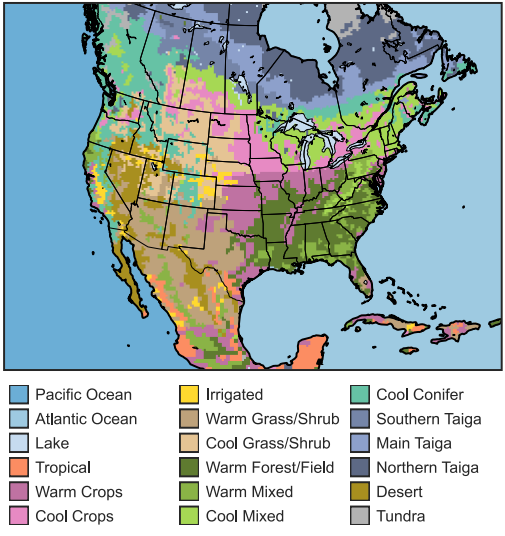
Flux model

The total surface CO_2 fluxes F are given by:

$$
\begin{aligned}
F(x,y,t) = \quad & s_{\text{bio}}(x,y,t) \cdot F_{\text{bio}}(x,y,t) + \\
& s_{\text{ocn}}(x,y,t) \cdot F_{\text{ocn}}(x,y,t) + \\
& s_{\text{ff}}(x,y,t) \cdot F_{\text{ff}}(x,y,t) + \\
& s_{\text{fire}}(x,y,t) \cdot F_{\text{fire}}(x,y,t)
\end{aligned}
$$

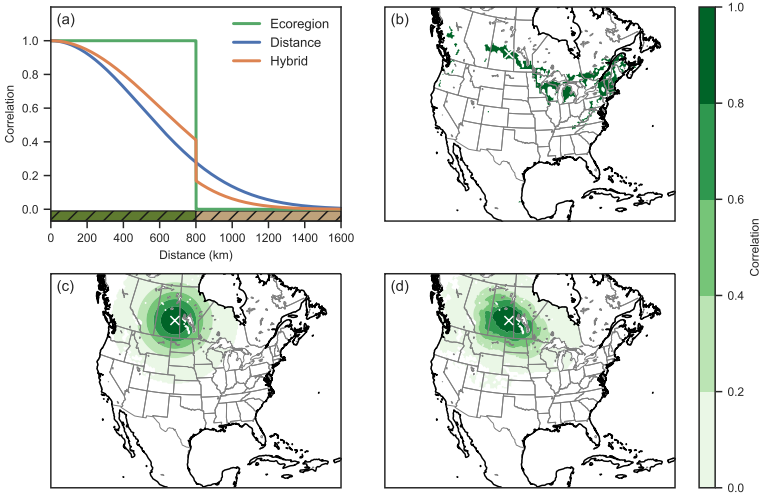
s_x are scaling factors for prior fluxes (F_x)

(Here we used prior fluxes from CT2019B)



Ecoregions based on Olsen (1985) classification

Flux parameter errors

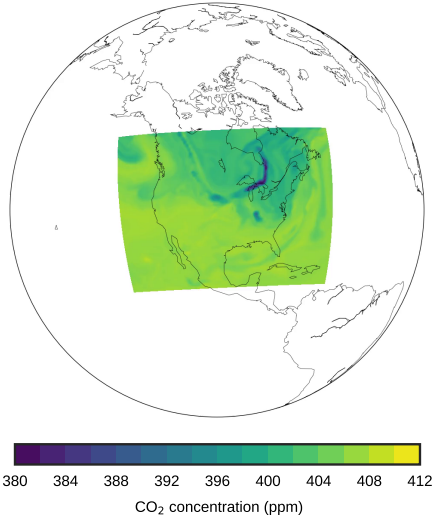


Different specifications for flux parameter error correlations:

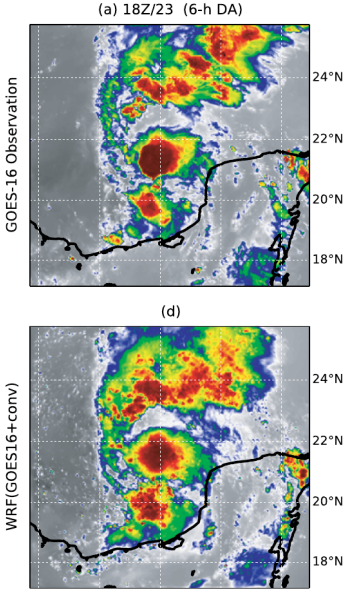
- **Ecoregion**-specific parameters
- **Distance**-based decay
- **Hybrid** between distance and ecoregion

Atmospheric model

- WRF-Chem 3.6.1
- Modified to allow an ensemble of tracers in a single model run
- Driven by ERA-Interim (newest version uses ERA5)
- CO_2 lateral boundary conditions from CT-NRT v2017 and CT2019B (now also possible with CAMS)
- Currently 27 km horizontal resolution and 60 vertical layers



Data assimilation



(Zhang et al. 2019 BAMS)

- Based on the PSU WRF EnKF system
- Deterministic ensemble square root filter
- Mature system for numerical weather prediction
- For CO_2 inversions, the state vector is augmented to include CO_2 concentrations and flux parameters:

$$\boldsymbol{x} = \begin{bmatrix} \vdots \\ \boldsymbol{CO_2} \\ \boldsymbol{s}_{\mathrm{x}} \end{bmatrix}$$

- Flux parameters forecast using a persistence model

Localization and inflation

Localization

Spatial localization (Gaspari-Cohn function)

Radius of influence: 5,400 km

Inflation

Relaxation to prior perturbations (Zhang et al. 2004):

$$\mathbf{x}'^{a} \leftarrow (1-\alpha)\mathbf{x}'^{a} + \alpha\mathbf{x}'^{b}$$

Relaxation to initial perturbations (Chen et al. 2023):

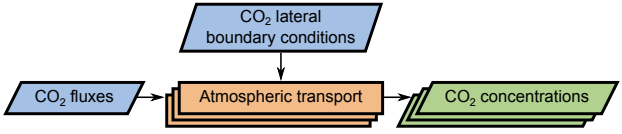
$$\mathbf{s}'^{a} \leftarrow \mathrm{sgn}(\mathbf{s}'^{a}) \cdot \left[(1-\beta)\cdot \mathrm{abs}(\mathbf{s}'^{a}) + \beta \cdot \mathrm{abs}(\mathbf{s}'^{i})\right]$$

Here $\alpha = 0.2$ and $\beta = 0.1$

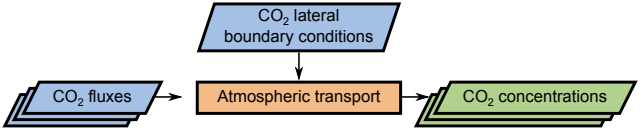
Forward simulations

Sensitivity experiments

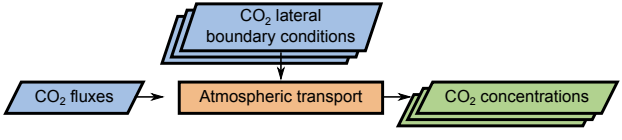
Transport (meteorological data assimilation)

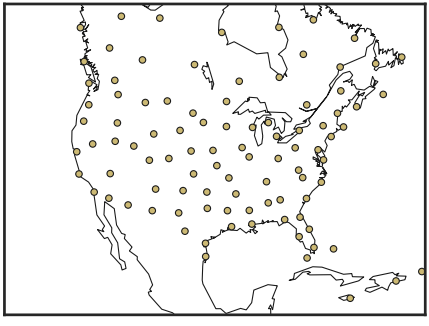


Flux (80%)



Background (4 global models)

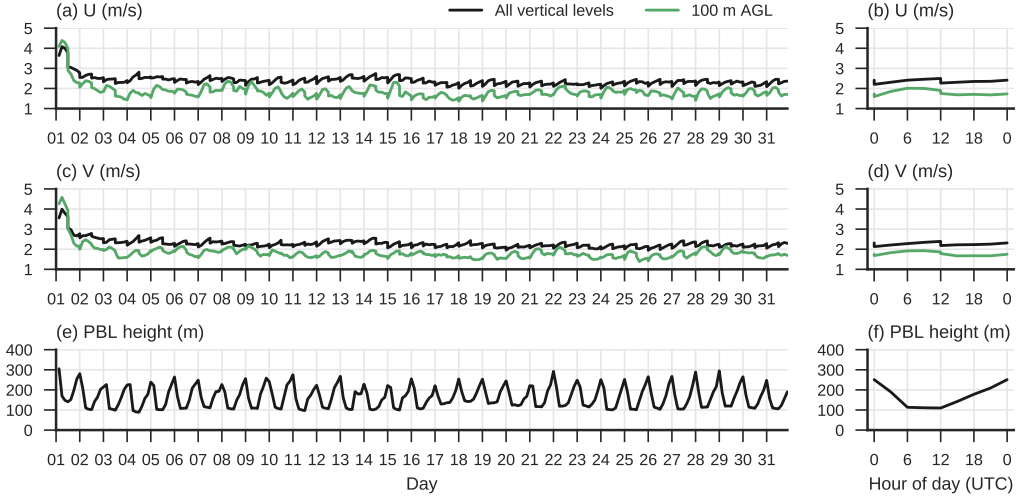




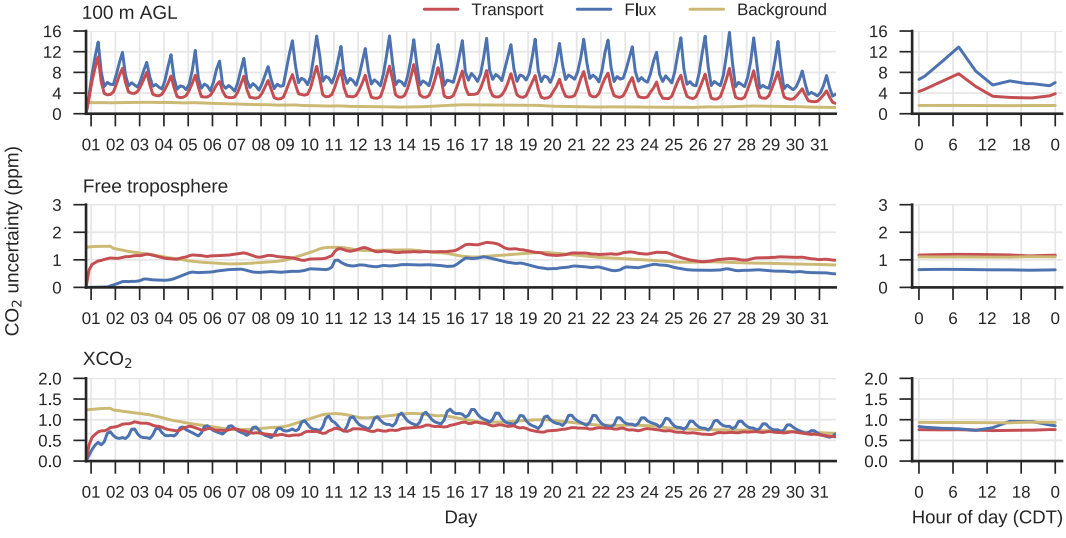
12-hourly synthetic rawinsonde observations assimilated to constrain atmospheric transport errors

(Chen et al. 2019 GRL)

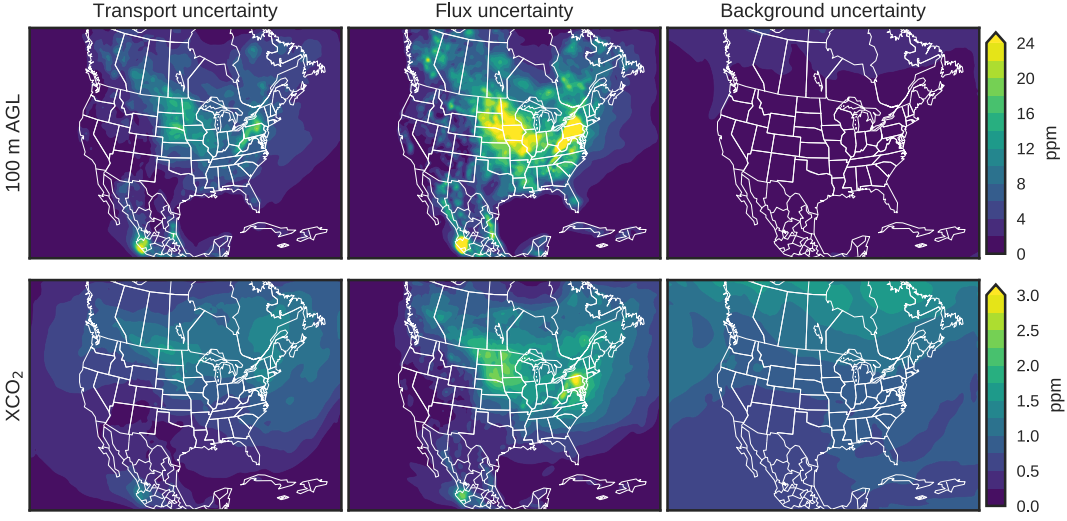
Flow-dependent atmospheric transport errors



Temporal evolution of CO_2 errors



Spatial variation of CO_2 errors



Inversions

Observing system simulation experiments

Focusing on July 2016

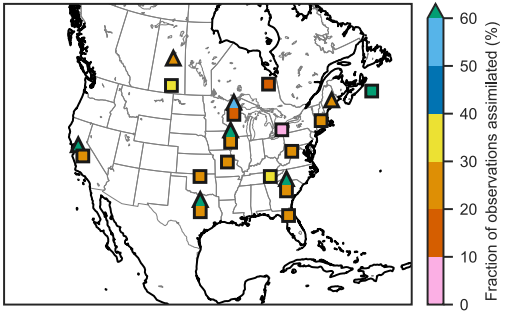
Assimilating 3-hourly synthetic CO_2 observations from ground-based network

Filter and fixed-lag smoother with a one-week window

0.8 and 0.4 uncertainty in land and ocean flux parameters, respectively

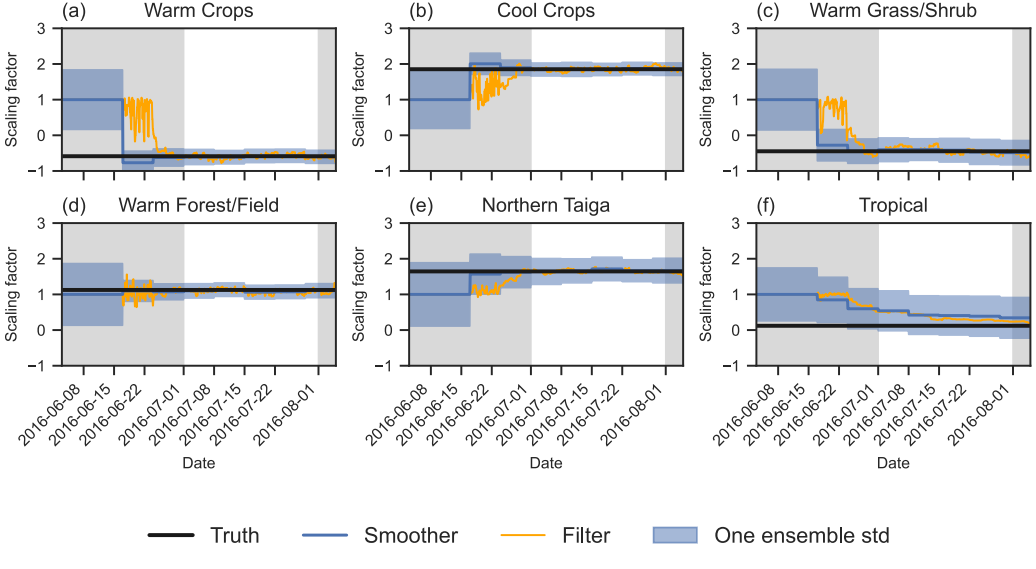
Two experiments:

- Ideal inversions with known errors
- Inversions with unknown errors

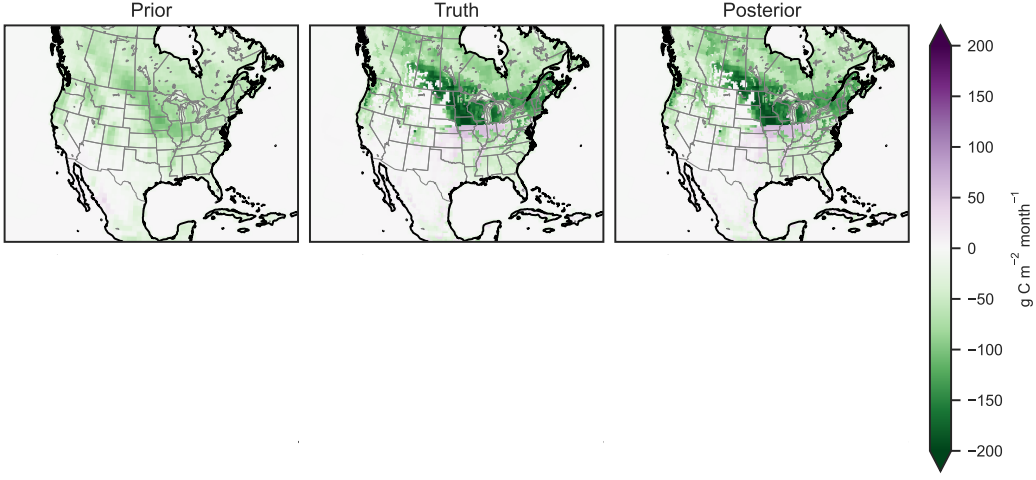


(Chen et al. 2023 JAMES)

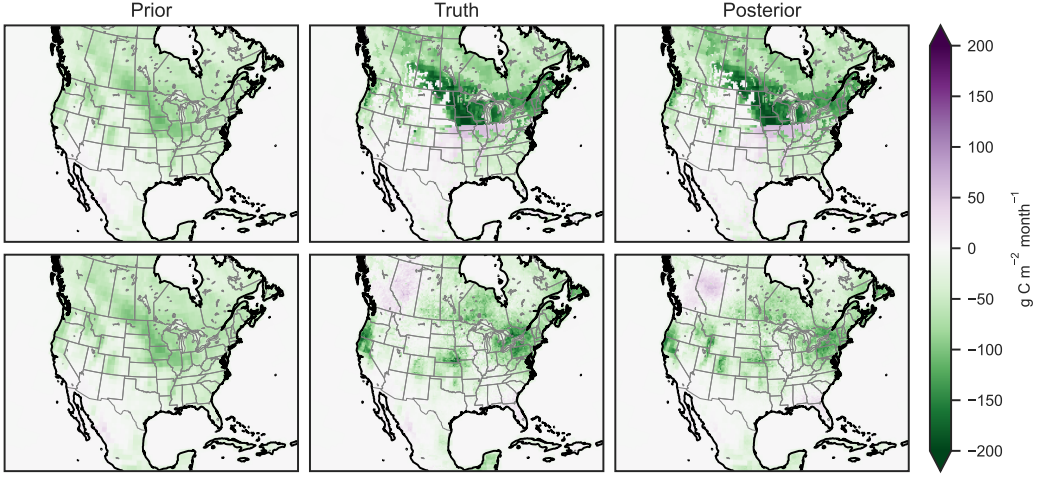
Inversions with known errors statistics



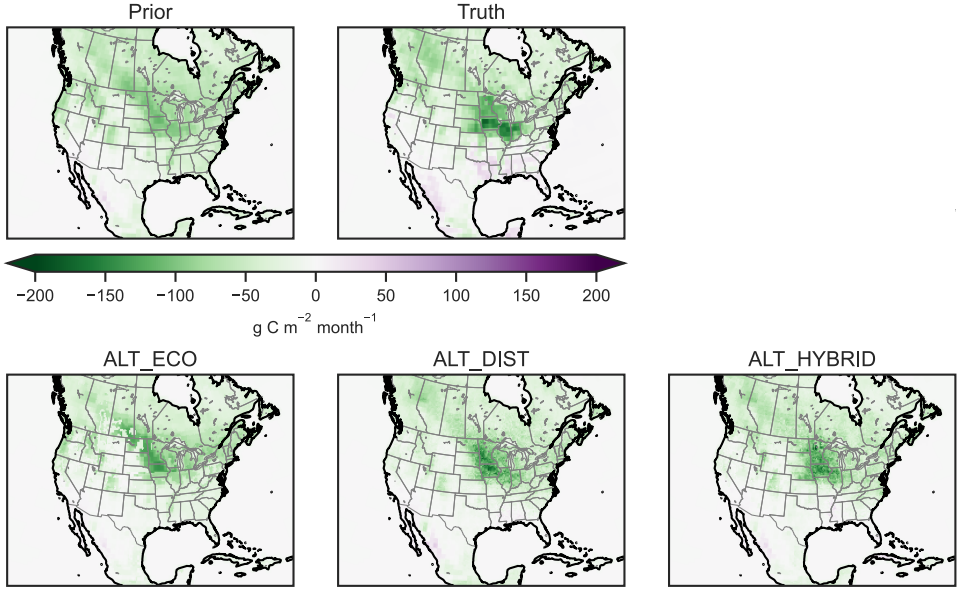
Inversions with known errors statistics



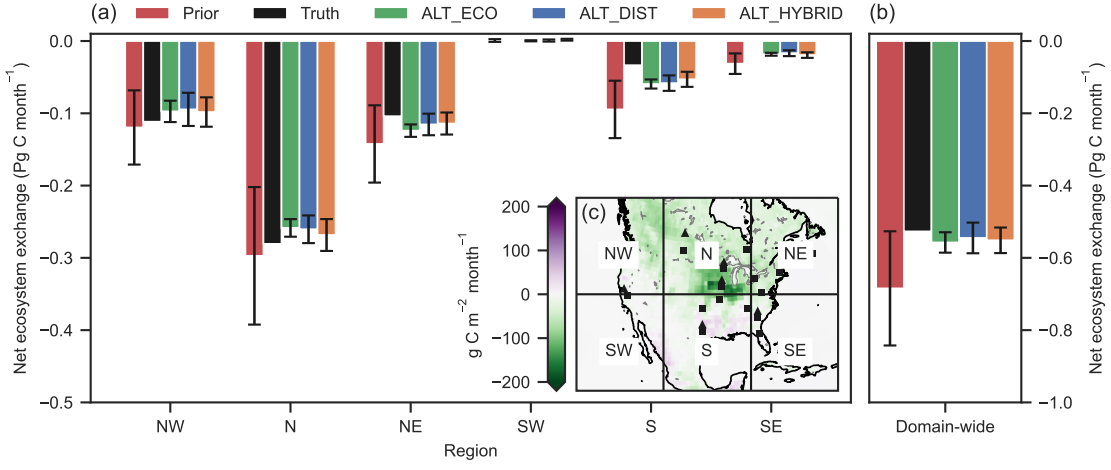
Inversions with known errors statistics



More realistic inversions with unknown errors

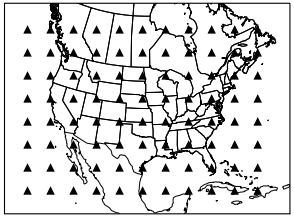


Regional fluxes and uncertainties

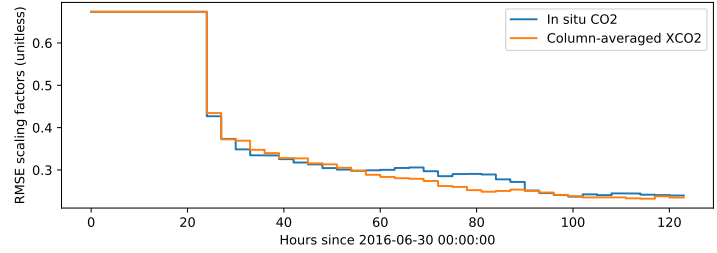


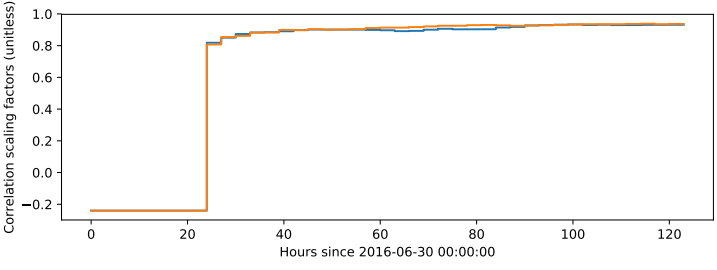
Future developments

Satellite XCO_2 and fossil fuel emissions

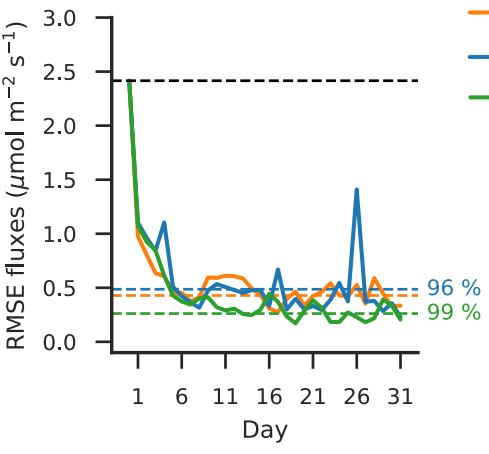


3-hourly synthetic in situ CO_2 (100 AGL) or XCO_2 observations every 540 km





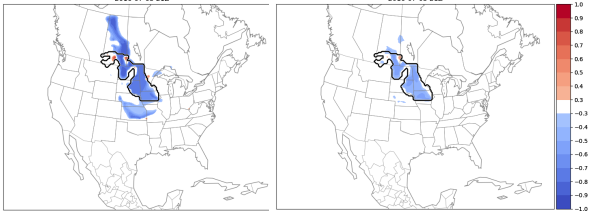
Atmospheric transport errors



Deterministic transport with relaxation

Deterministic transport with localization

Ensemble of transports



Conclusions

- Ensemble-based simultaneous state and parameter estimation (ESSPE) is a promising approach to enable the assimilation of large volumes of observations
- TRACE provides a platform for developing and testing ESSPE methods for coupled atmosphere–carbon data assimilation

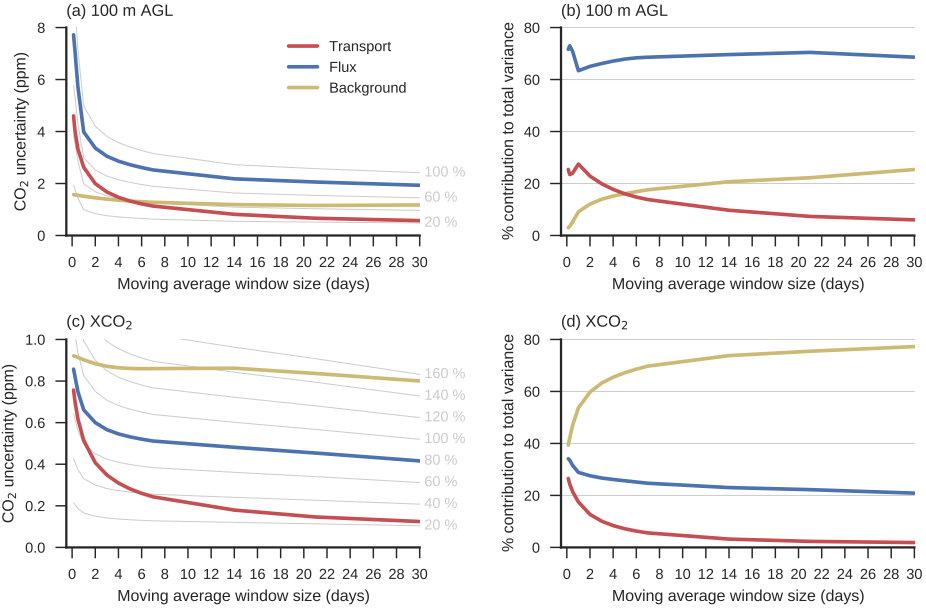
Chen, H. W., F. Zhang, T. Lauvaux, K. J. Davis, S. Feng, M. P. Butler, and R. B. Alley (2019): Characterization of regional-scale CO_2 transport uncertainties in an ensemble with flow-dependent transport errors. *Geophysical Research Letters*, **46**, 4049–4058, doi:10.1029/2018GL081341.

Chen, H. W., F. Zhang, T. Lauvaux, M. Scholze, K. J. Davis, and R. B. Alley (2023): Regional CO_2 inversion through ensemble-based simultaneous state and parameter estimation: TRACE framework and controlled experiments. *Journal of Advances in Modeling Earth Systems*, **15**, e2022MS003208, doi:10.1029/2022MS003208.

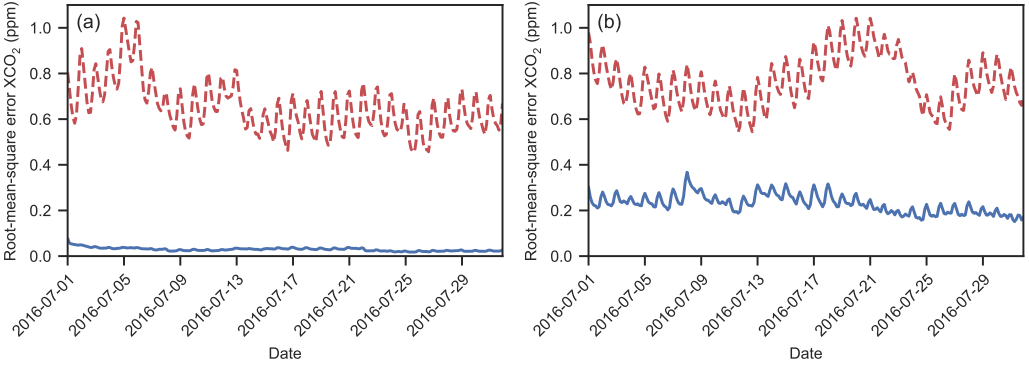
http://hanschen.org/publications

Extra

CO_2 errors at different temporal scales



XCO_2 in ideal inversions



Prior (red) and posterior (blue)

XCO_2 in ALT inversions