

INTRODUCTION

Rising atmospheric methane concentrations are a major long-term driver of global warming. The Global Methane Pledge (GMP), now endorsed by more than 150 countries, commits signatories to reducing anthropogenic methane emissions by 30% by 2030 relative to 2020 levels. Despite this commitment, methane emissions across South Asia remain poorly constrained owing to sparse in situ observations and the complexity of rapidly evolving regional emission sources.

Satellite observations of the column-averaged dry-air mole fraction of methane (XCH₄) from instruments such as TROPOMI and GOSAT-1/2 now provide dense spatial coverage across the region. Combined with prior information, including satellite-derived methane hotspot inventories, these measurements enable more robust source attribution and improved quantification of methane emissions at high spatial and temporal resolution.

METHODS

To estimate methane emissions from XCH₄ observations, we employ a refined Local Ensemble Transform Kalman Filter (LETKF) framework (Lunt et al., 2021) coupled to the nested GEOS-Chem model at 0.25° × 0.3125° resolution over South Asia. The LETKF uses an ensemble to represent flux uncertainties and localization to suppress spurious long-range correlations, yielding the posterior flux estimate flux $\bar{x}^a$:

$$\bar{x}^a = \bar{x}^b + X^b \cdot \tilde{P}^a \cdot (Y^b)^T R^{-1} \cdot (y^o - \bar{y}^b)$$

$\bar{x}^b$: Mean prior (background) flux; X^b : flux perturbation ensemble; y^o : Satellite XCH₄ observations; R represents their error covariance; $Y^b = H(X^b)$: Projection of flux ensemble in the XCH₄ observation space, which is calculated by using GEOS-Chem model to simulate methane transport over South Asia; $\bar{y}^b$ mean prior model XCH₄ observation $\tilde{P}^a = [(Y^b)^T R^{-1} Y^b + (k - 1)I]^{-1}$ is the local analysis error covariance matrix estimated in the ensemble space.

EXPERIMENT

We conduct experiments to test effectiveness of TROPOMI observations in constraining top-down flux estimates over South Asia:

Observations: TROPOMI XCH₄ retrievals (WFMD v2.0; Schneising et al., 2026)

Atmospheric transport model: Nested GEOS-Chem v14.1 over South Asia (0.25° × 0.3125°)

Boundary conditions: Global GEOS-Chem simulation (2.0° × 2.5°) driven by posterior fluxes from Feng et al. (2022)

Prior fluxes: Posterior methane emissions from Feng et al. (2022)

State vector and ensemble design

XCH₄ observations alone cannot fully resolve source-specific emissions at high spatial resolution. We therefore use prior error covariance information to reduce the dimensionality of the inversion. Singular value decomposition (SVD) is applied to the prior covariance matrix, retaining the leading 1,000 modes, which explain >92% of the total flux uncertainty. A 100-member ensemble is generated from random combinations of these modes and used within the LETKF framework. Figure 1d shows the prior uncertainty, SVD eigenvalue spectrum, and reconstructed uncertainty.

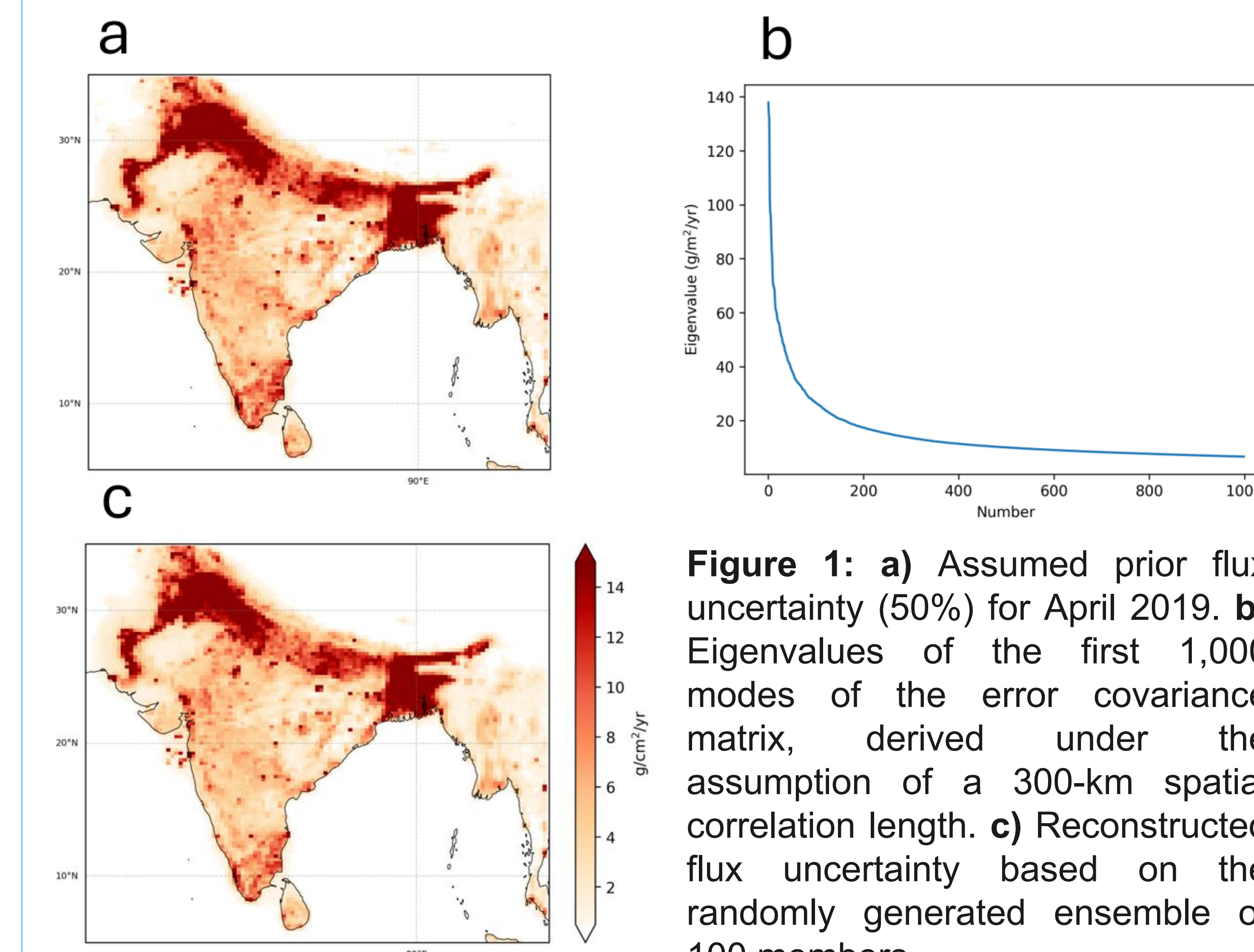


Figure 1: a) Assumed prior flux uncertainty (50%) for April 2019. b) Eigenvalues of the first 1,000 modes of the error covariance matrix, derived under the assumption of a 300-km spatial correlation length. c) Reconstructed flux uncertainty based on the randomly generated ensemble of 100 members.

RESULTS

Figure 2 shows preliminary results from our assimilation of TROPOMI XCH₄ retrievals during April 1-10, 2019

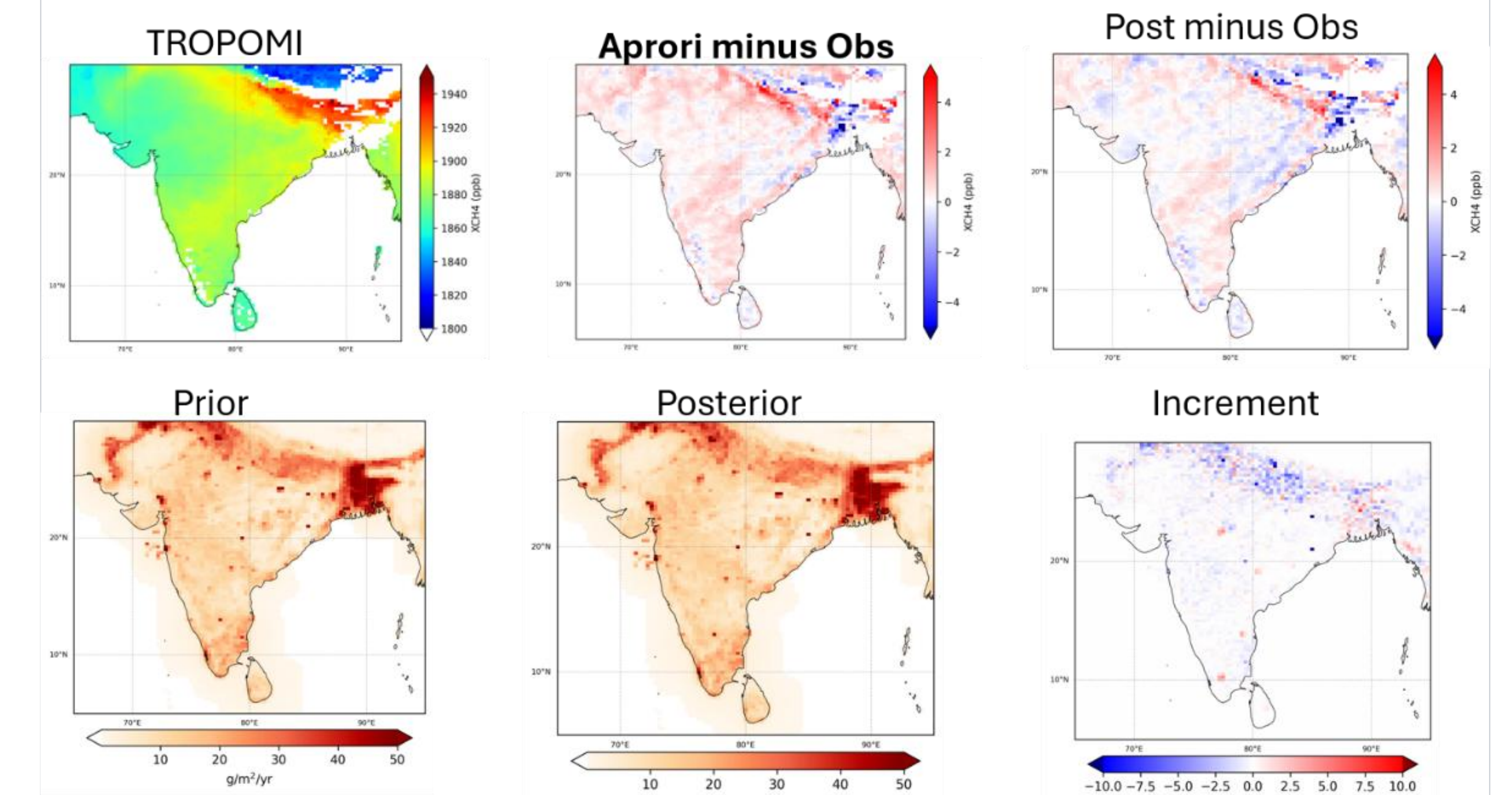


Figure 2: Top Panels: Comparison of TROPOMI XCH₄ and prior posterior GEOS-Chem simulations in April 2019; Bottom Panels: Comparison of prior and posterior methane emissions

DISCUSSION

- LETKF is an efficient and flexible tool for quantifying methane emissions by assimilating dense space-based XCH₄ observations over South Asia.
- Ongoing research aims to incorporate additional prior information, such as satellite-detected emission hotspots, to further improve flux estimates.

REFERENCES

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ACKNOWLEDGEMENTS

This study is funded by the ESA project ‘Methane Emissions: Testing, Reporting and Implementing Common practises using Satellites’.