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European Methane Flux Estimates Using the Community Inversion Framework

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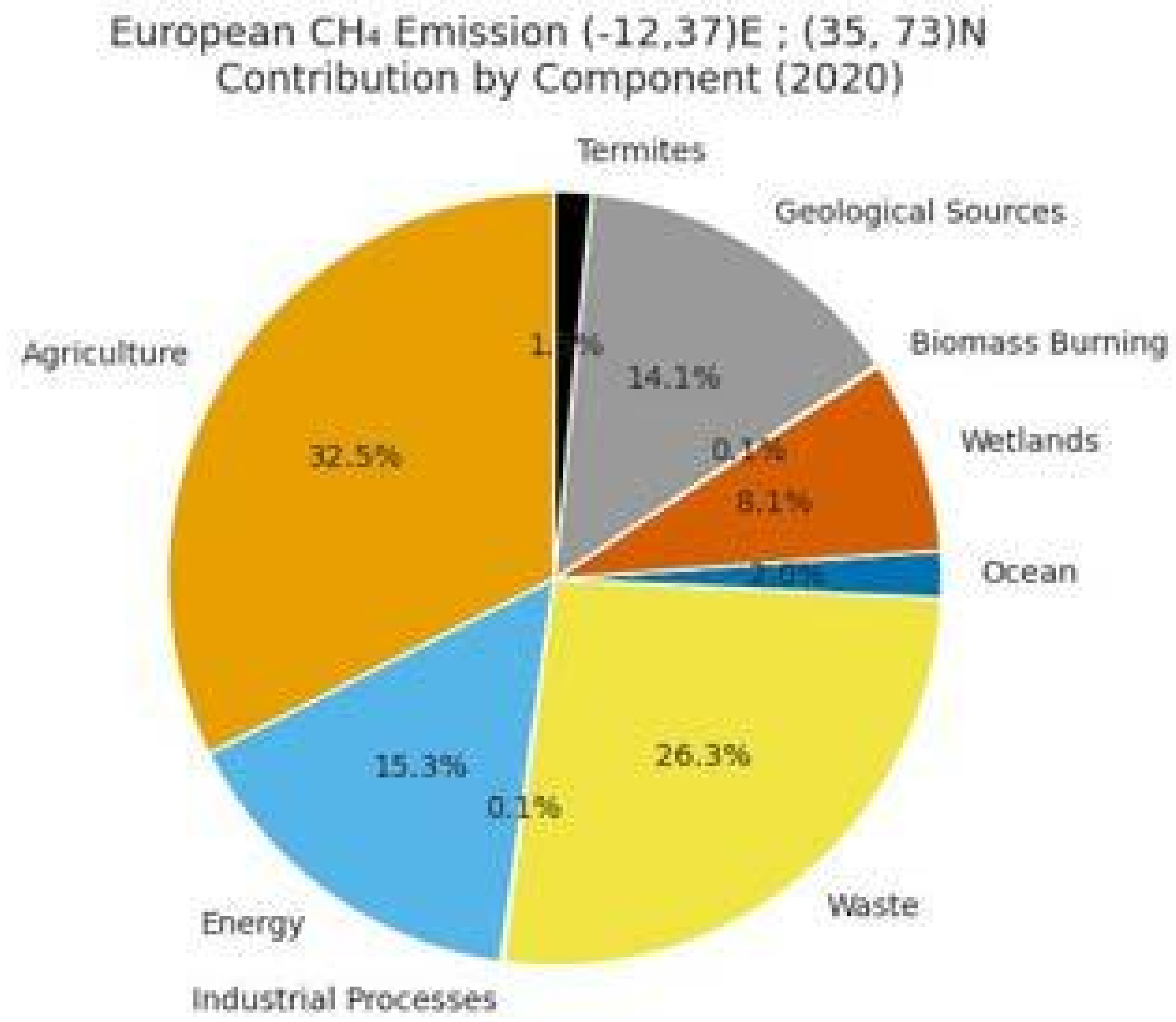
Background

- Methane is the second-largest contributor to climate change
- Responsible for ~30% of the global temperature increase
- To limit warming to 1.5^{0}C, emissions must peak before 2025 and drop 43% by 2030 *(European climate law)*
- Methane is the most effective short-term greenhouse gas to reduce, offering rapid climate response to emission cuts.
- CH_4 levels rose 12% in the 2010s vs. 2000s *(Saunois et al., 2025)*
- CH_4 estimates are uncertain due to:
    - Limited observations
    - Incomplete emission source maps
    - Transport model errors



(our inversion prior)

Our objectives:

✓ Generate high-resolution CH_4 inversion estimates for Europe

✓ Provide CH_4 emission estimates for ET27 + 3 countries with uncertainties

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Prior Datasets

component	source	Spatiotemporal resolution	Glob/EU est. Tg
Agriculture	GAINS for EU27 + 3 and EDGARv8 otherwise	0.1^0 x 0.1^0 Monthly	134.1/11.74
Energy	GAINS for EU27 + 3 and EDGARv8 otherwise	0.1 x 0.1 Monthly	120.4/5.6
Industrial process	EDGARv8	0.1 x 0.1 Monthly	0.55/0.03
Waste	GAINS for EU27 + 3 and EDGARv8 otherwise	0.1 x 0.1 Monthly	87.8/9.5
Ocean	Weber et al. (2019)	1 x 1 climatology	9.3/0.7
Wetland	JSBACH–HIMMELI /LPX for global	0.1 x 0.1 Monthly	119.3/2.9
Fire	GFED4s1 (Van Der Werf et al. 2017)	0.25 x 0.25 Monthly	11.4/0.03
Geological	Etiope et al. (2019) global scaled to 23Tg	1 x 1 Climatology	21.1/5.1
Termite	Climatology (Saunois et al. 2020)	1 x 1 Climatology	9.9/0.6

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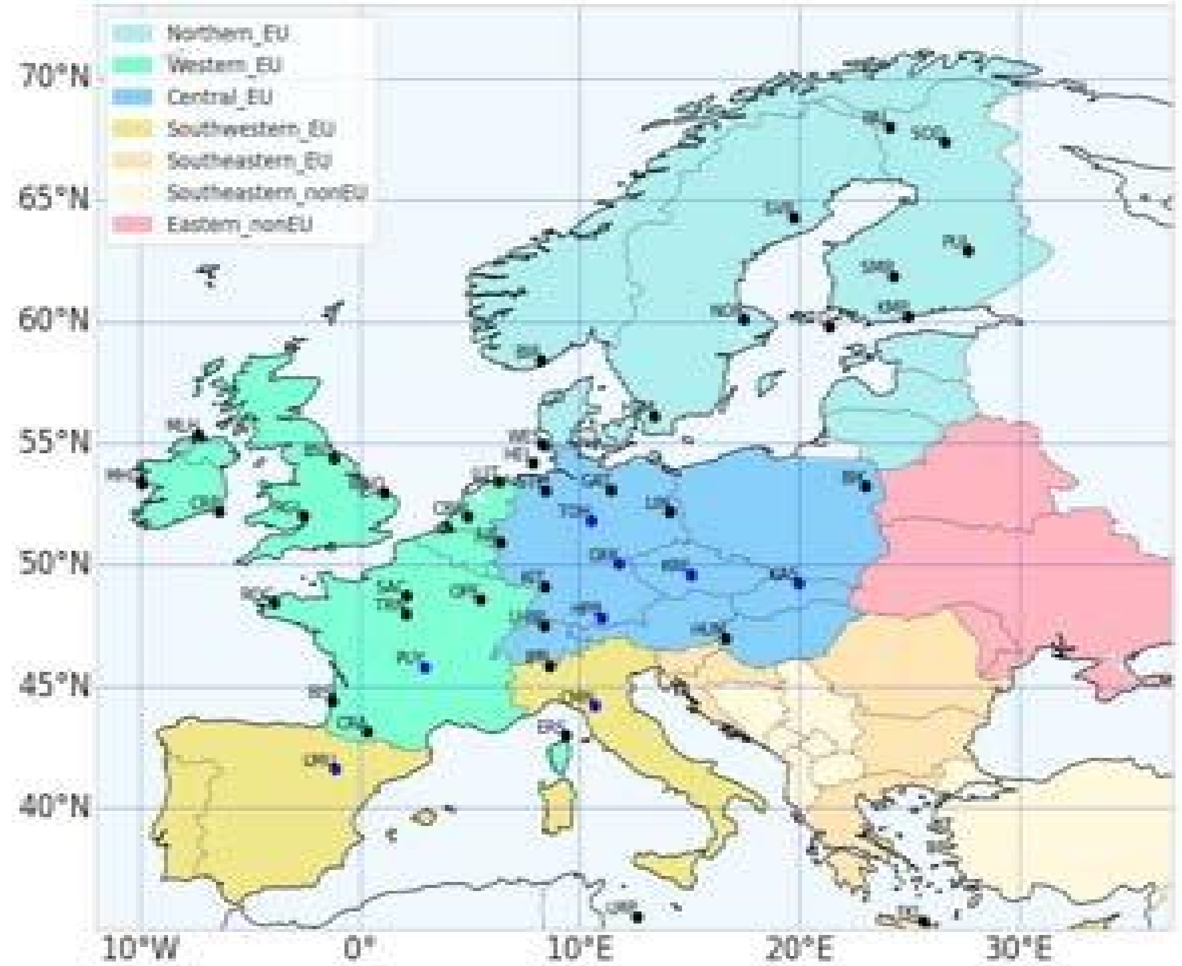
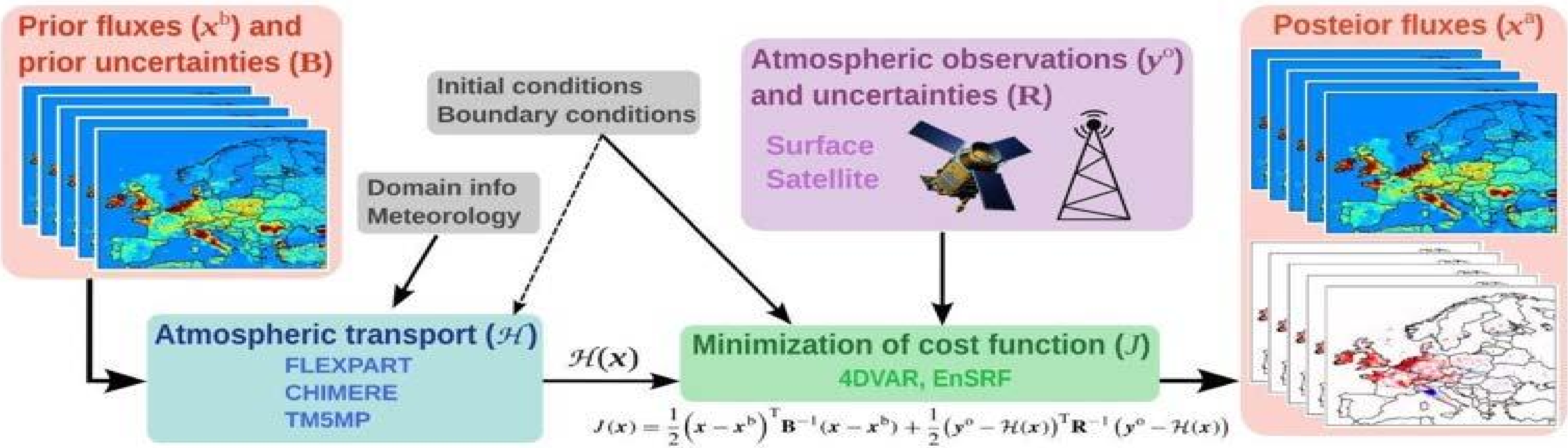
Observation Network



- Annual mean prior CH_4 emissions: ~36.2 Tg in 2020
- Assimilated data from 46 in-situ stations *(ICOS RI et al., 2024)*.
- CAMS daily mean CH_4 used as background
- ERA5 wind fields used to drive FLEXPART

Inversion setup

- Inversion Framework: Community Inversion Framework (CIF; *Berchet et al., 2020*)
- Transport Model: FLEXPART (*Pisso et al., 2019*)
- Inversion Method: 4D-Var using M1QN3 optimizer
- Source–Receptor Relationship (SRR) at a spatial resolution: 0.2° × 0.2°



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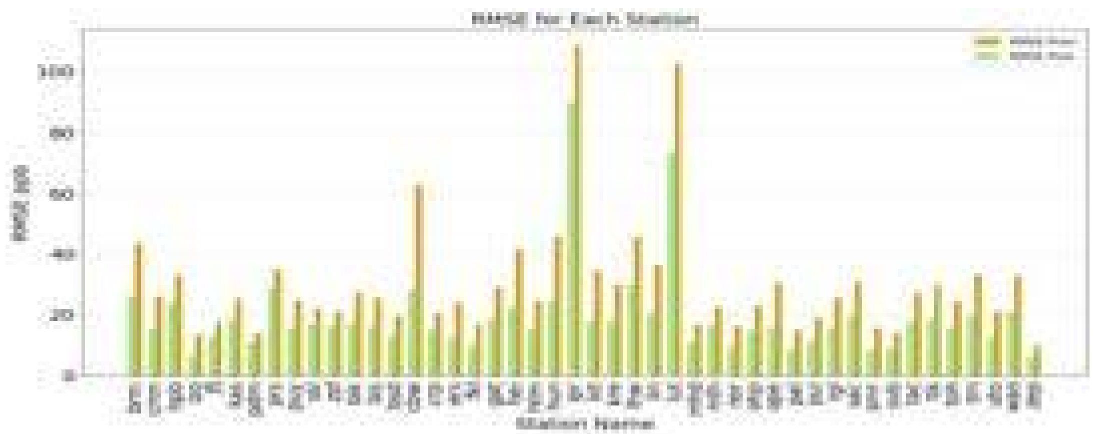
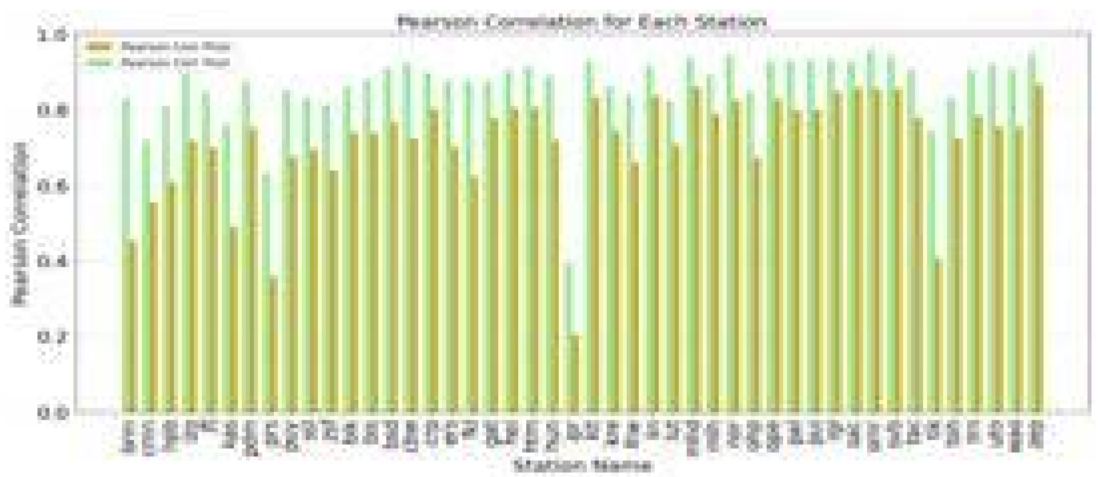
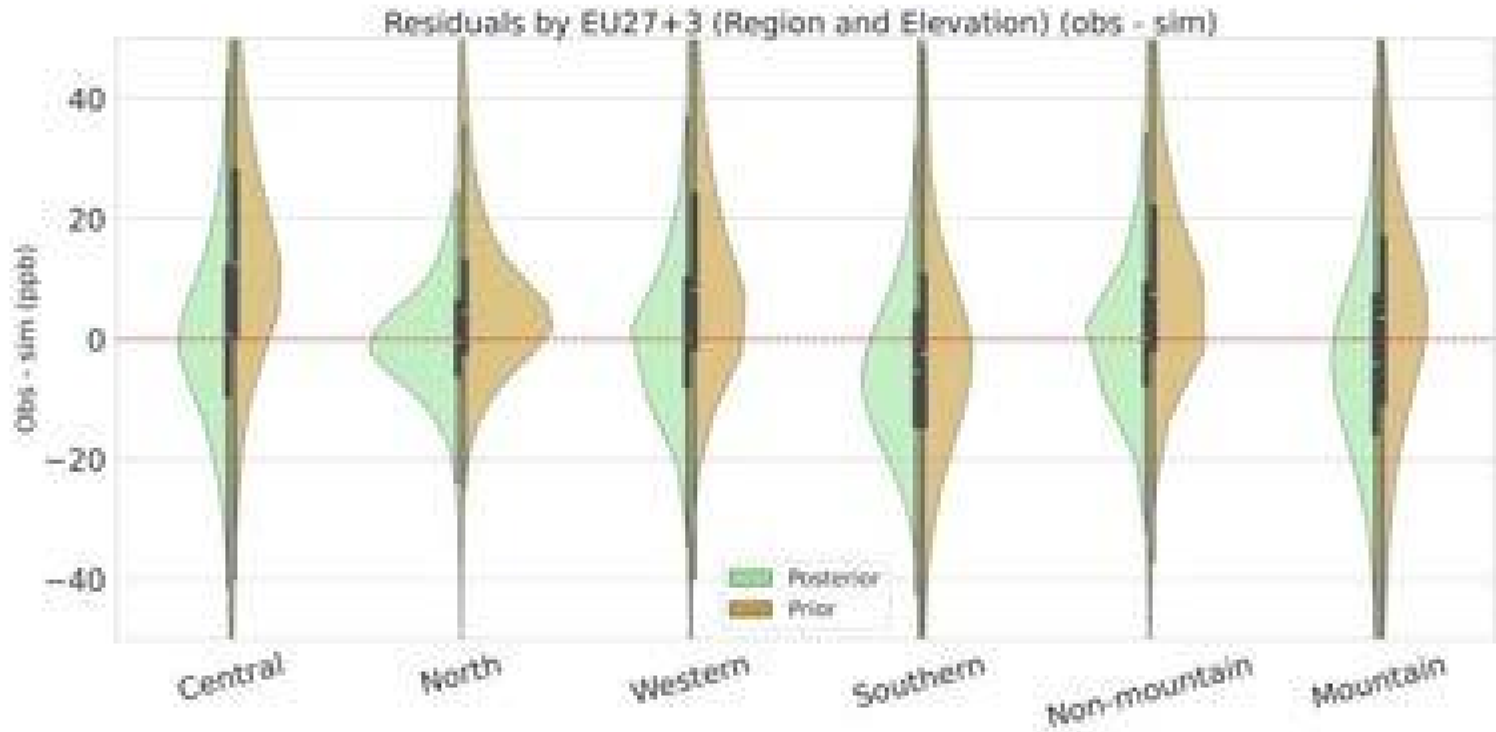
CH_4 Inversion Results

Modeled and Observed concentration

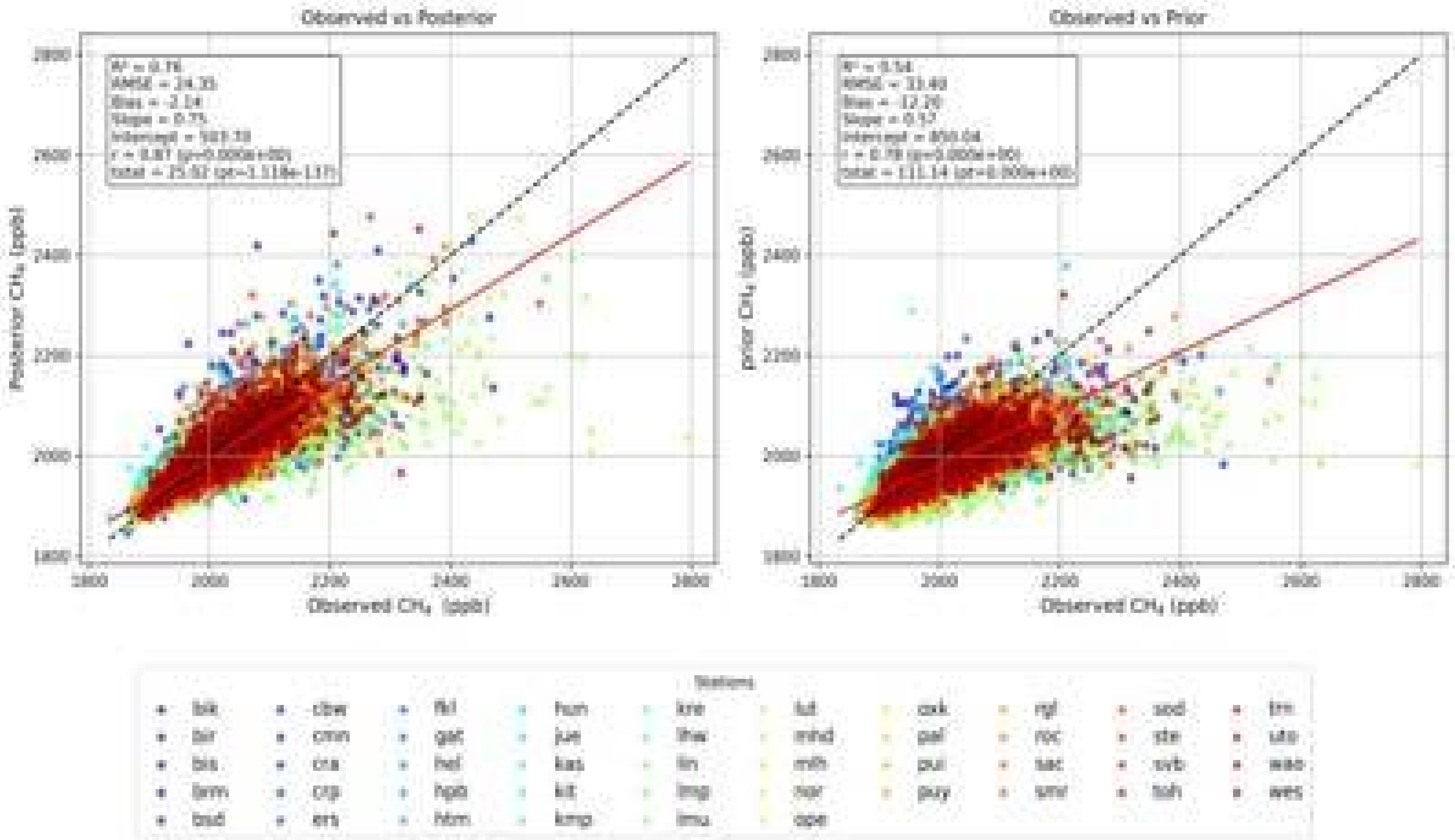






- Improved posterior alignment across stations; weaker performance at IPR, PRS , and LUT
- Regional categories show reduced residual spread vs. prior, except South, where bias slightly increased
- Posterior residuals more clustered for non-mountain stations; medians near zero, smaller spread

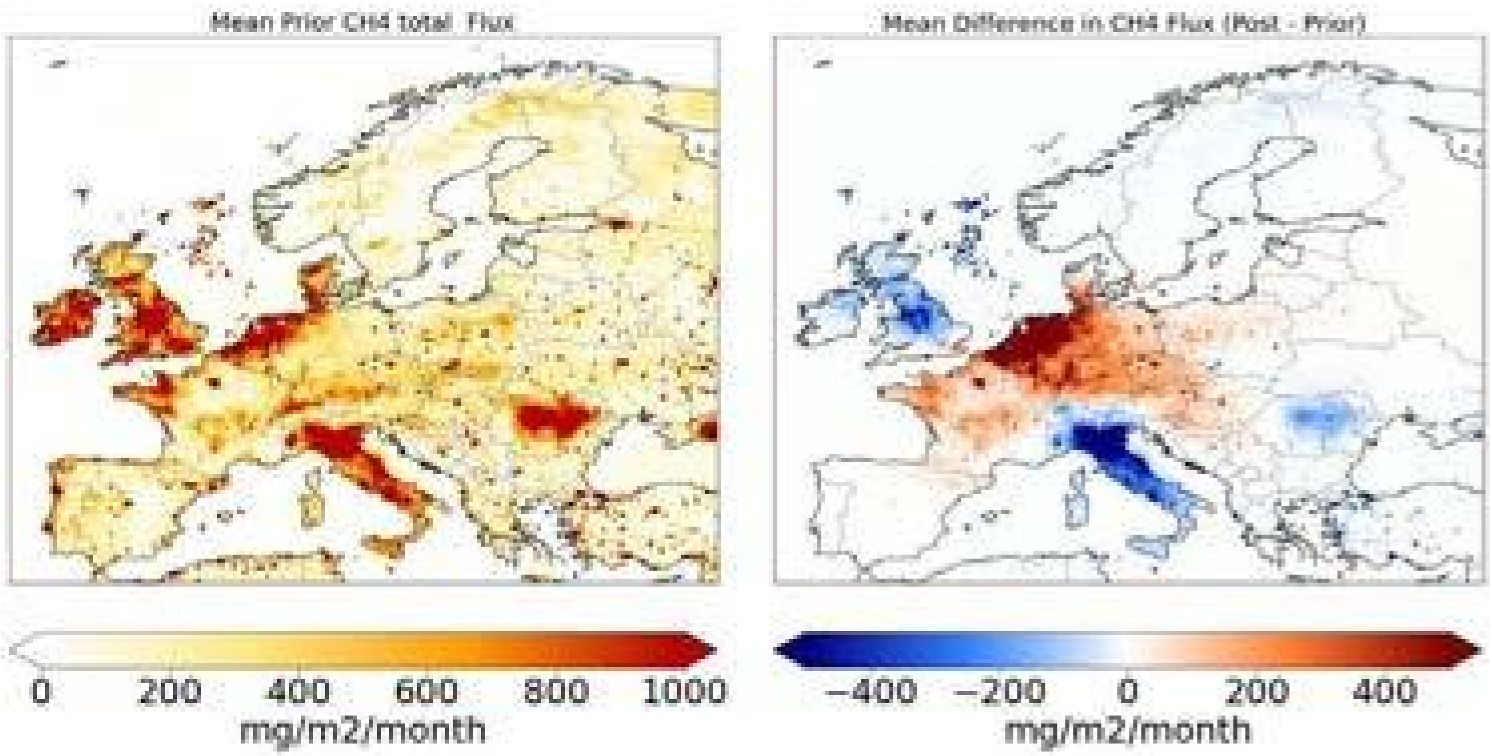
Modeled and Observed concentration

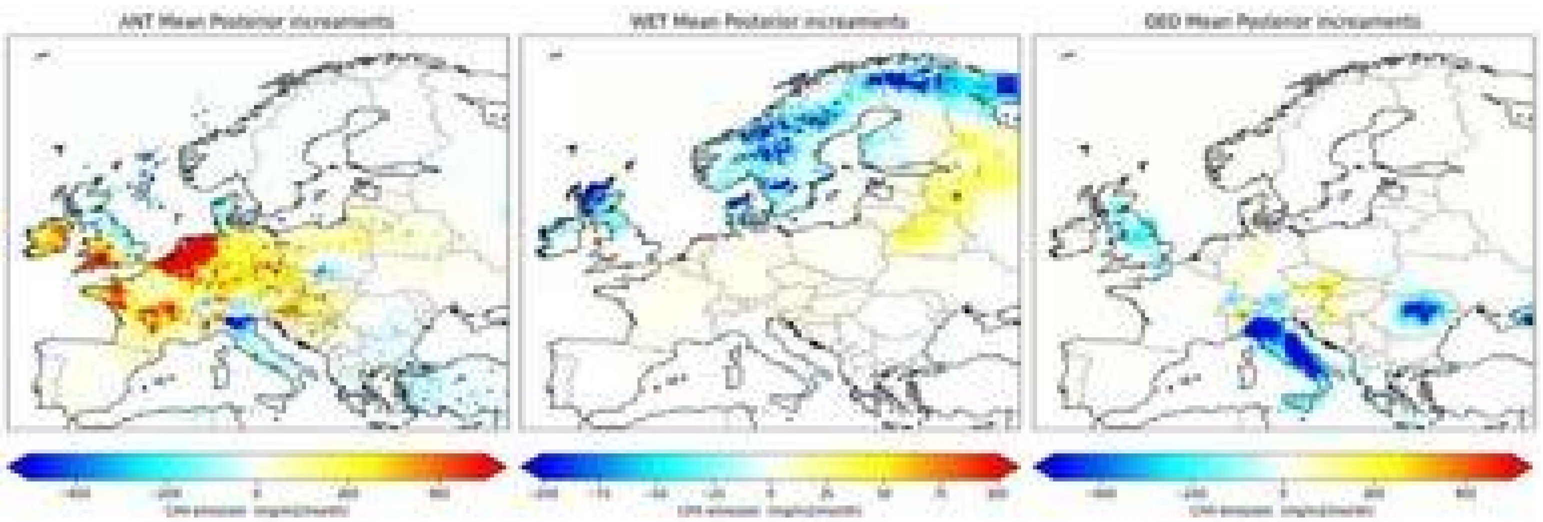


- R^2 improved from 0.54 to 0.76 (posterior)
- Higher accuracy: RMSE reduced from 33.4 to 24.35
- Less underestimation: Bias corrected from -12.20 to -2.18.
- Regression slope improved from 0.57 to 0.75, better responsiveness
- Paired t-test confirms smaller, more consistent deviation in posterior

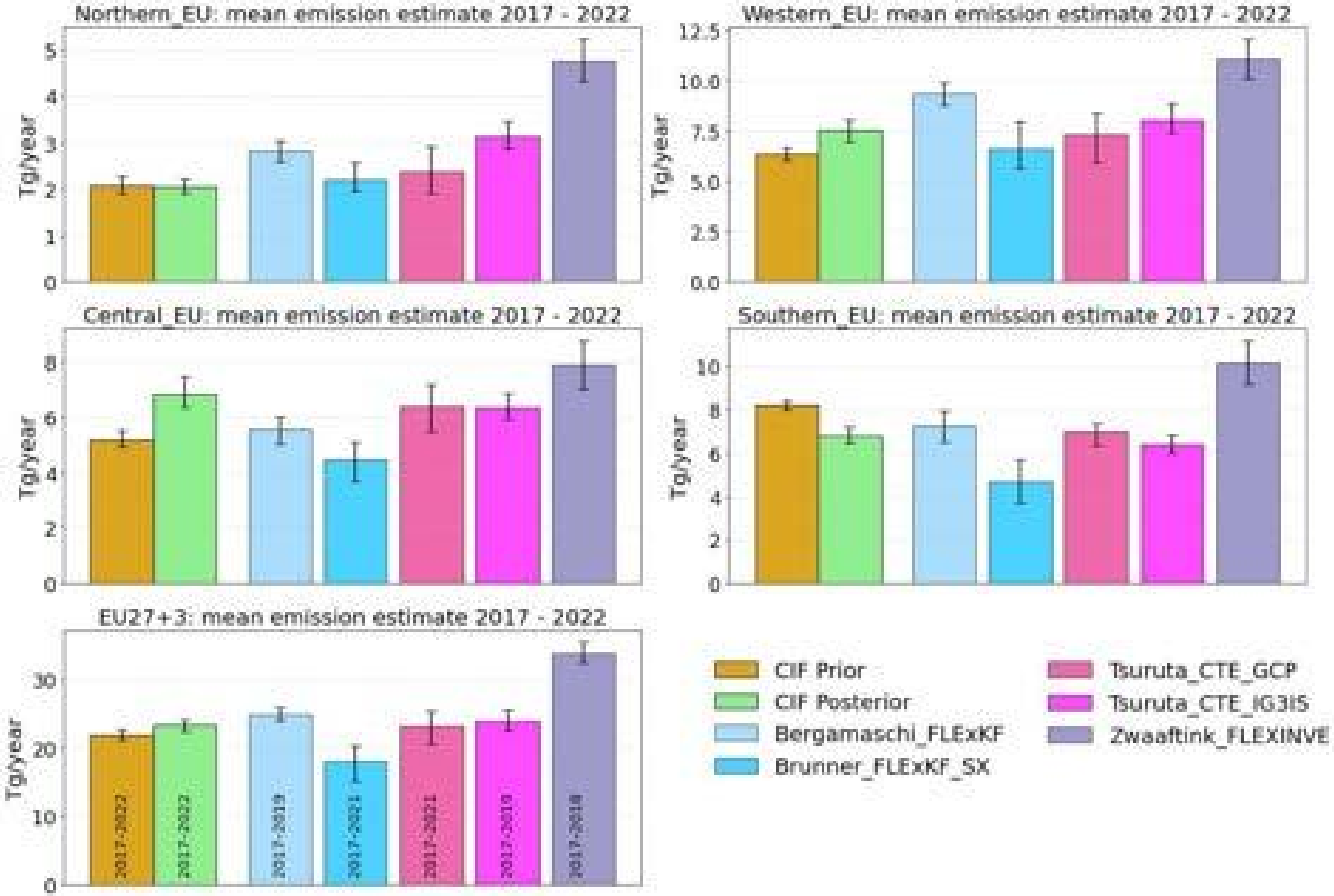
Fluxes adjustments

- Higher posterior CH_4 emissions in Benelux, Germany, and France
- Significant reductions in Italy, Romania, and the UK (likely due to overestimated geological priors)
- Modest overall mean difference across the study region
- Posterior aligns with prior in data-sparse areas (e.g., Iberian Peninsula)
- Slight reductions in Scandinavia

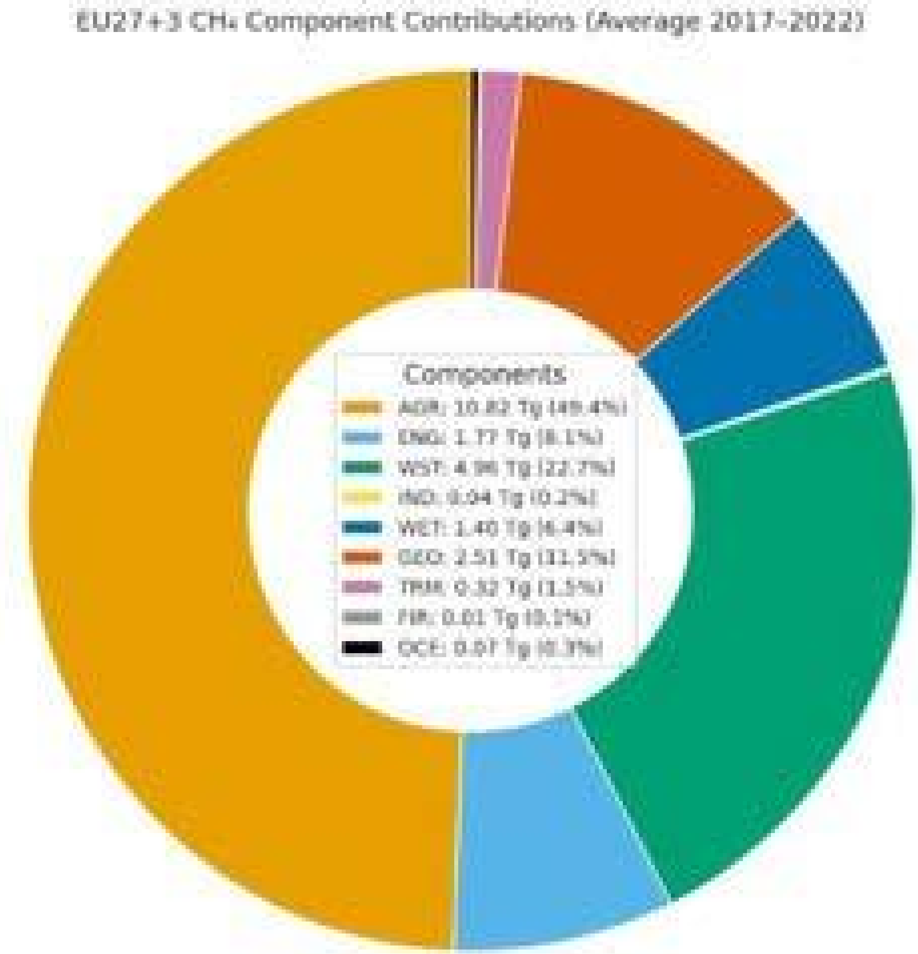




EU27+3 and sub-regional Emission



- **EU27+3:** Closer to other estimates, with regional differences.
- **Posterior mean:** 23.28 (22.27 - 24.14 Tg/yr (6.56% from prior)



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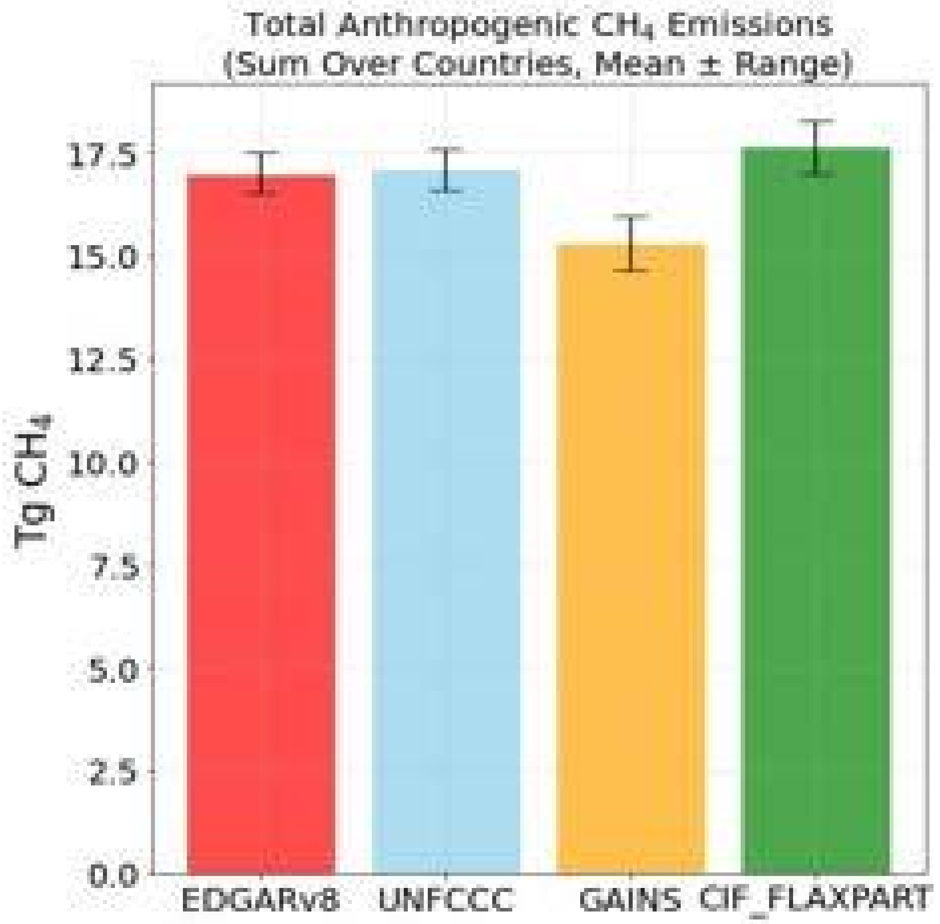
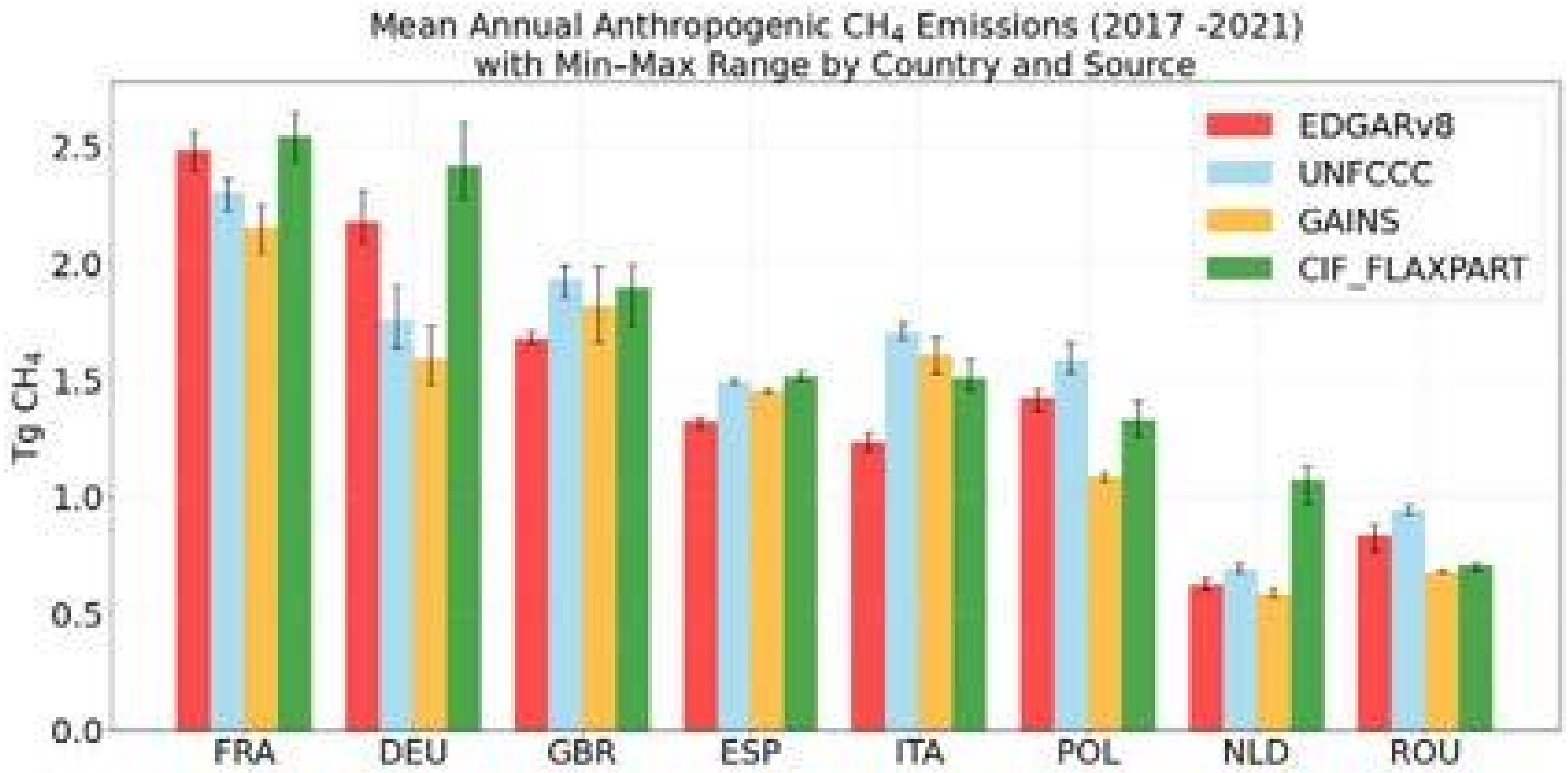
EU27+3 Anthropogenic Methane Emissions





- EU27+3 level :
  - UNFCCC: 17.05 (17.59 - 16.58) Tg yr^{-1}
  - EDGARv8: 16.96 (17.51 - 16.51) Tg yr^{-1}
  - **Posterior: 17.59 (18.25 - 17.01) Tg yr^{-1}**

- Country-Level Differences vs UNFCCC:
  - BENELUX (+54%), Germany (+37%), France (+10%)
  - Romania (–25%), Poland (–16%), Italy (–11%)

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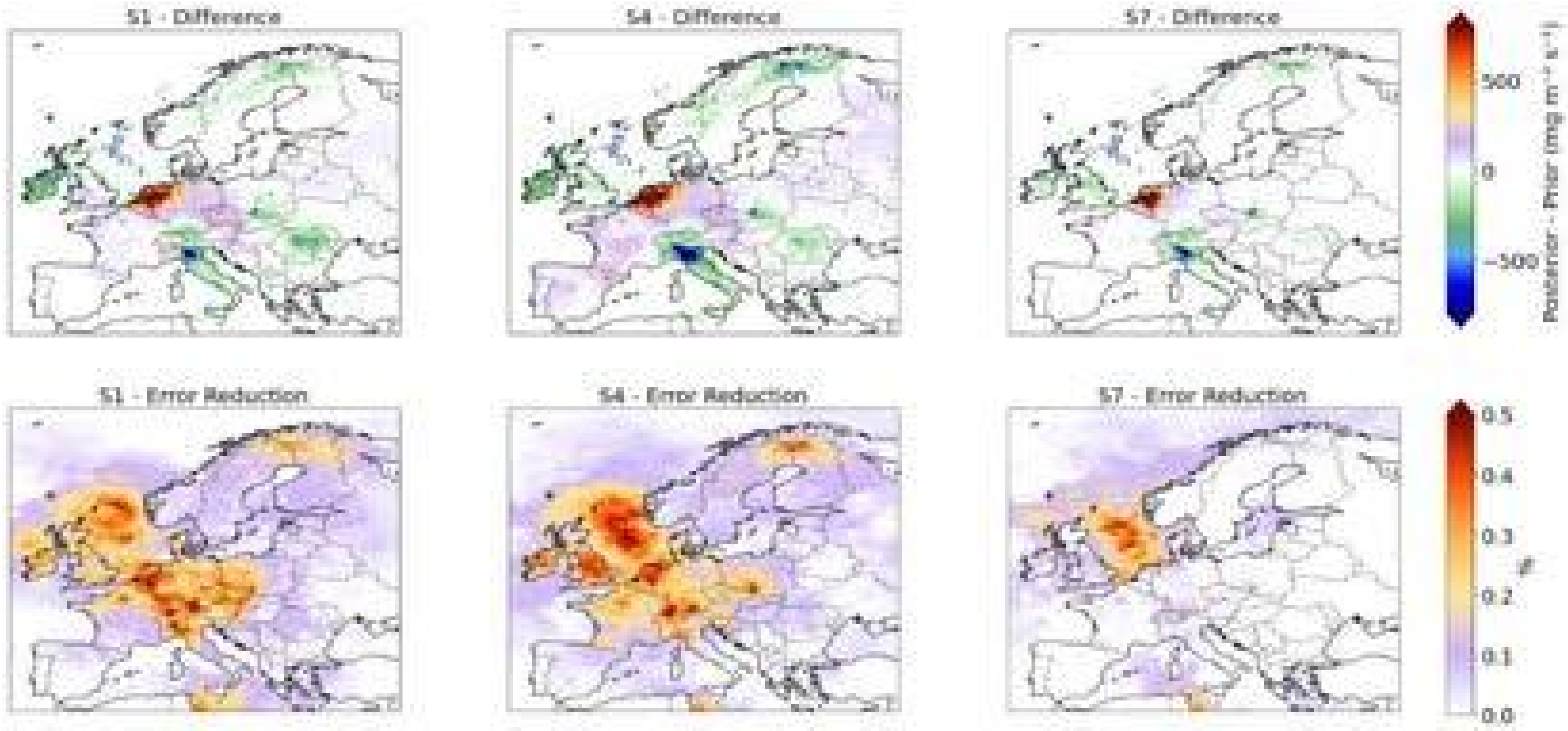
Inversion Sensitivity Experiment

Inv setup	Background	prior. unc.	bg. unc %	prior	Obs. density	corr. length	rel. height
CIF-FP-S1	CAMS	50%	5%	Prior 1	46	200/500	sample height
CIF-FP-S2	TM5MP						
CIF-FP-S3		100%					
CIF-FP-S4			0.5%				
CIF-FP-S5				Prior 2			
CIF-FP-S6					56		
CIF-FP-S7						50/500	
CIF-FP-S8						20/50	
CIF-FP-S9							model level



- Difference (posterior – prior) Error reduction for July 2021
- Significant error reduction in central, western EU
- Lower Model sensitivity S1–S3.
- Highly sensitive to background error, *addition of station* and correlation length

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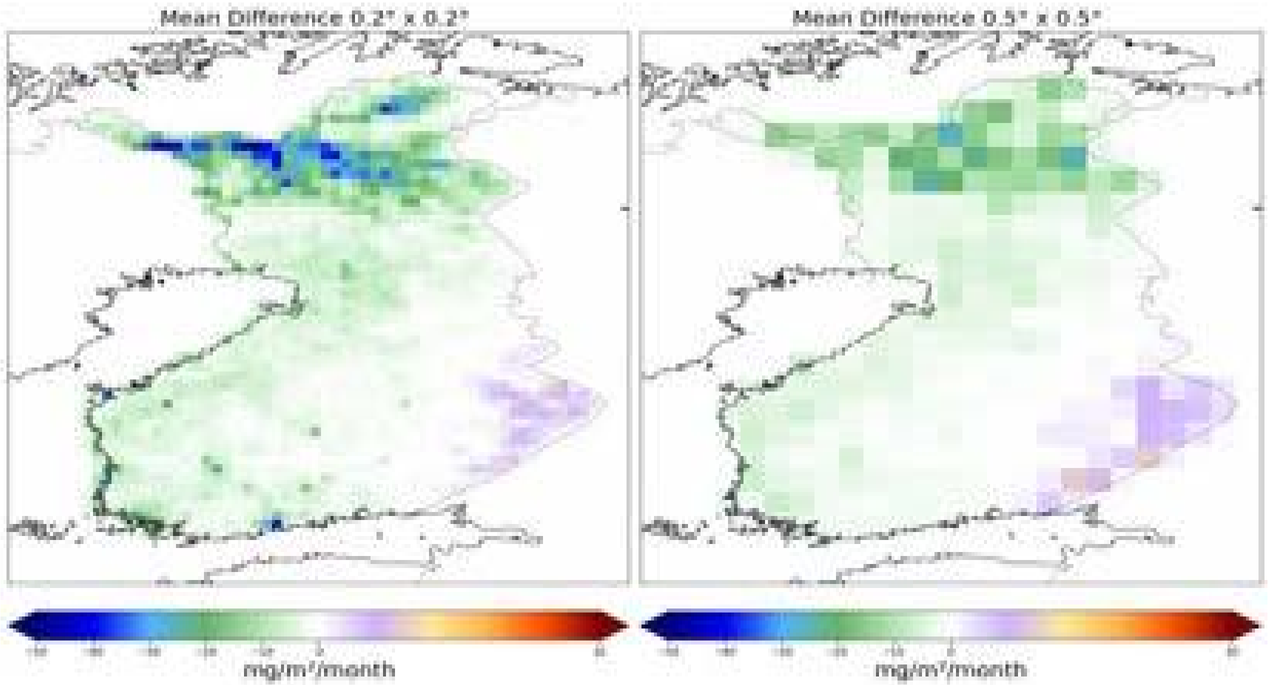
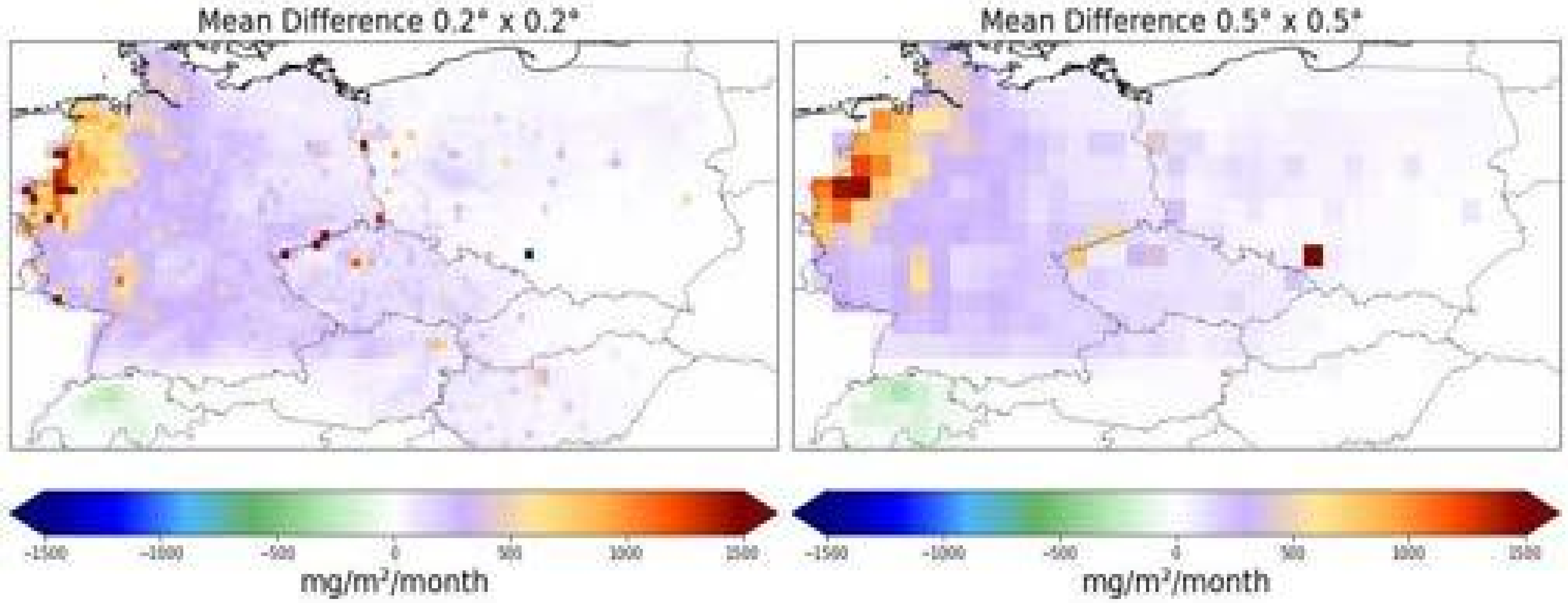
Advantages of Higher Resolution





- 0.2° × 0.2° (left) and 0.5° × 0.5° resolution (right).
- Improved spatial representation of emission adjustments

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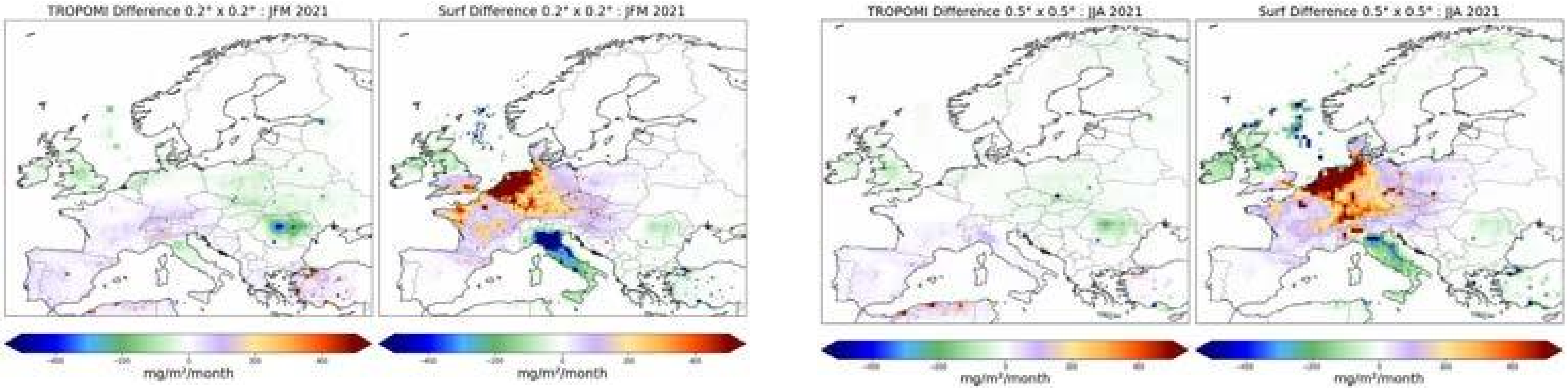
Satellite vs Surface Inversion: Preliminary Test Results



- Inversion with Bremen TROPOMI Retrievals:
- Slight adjustments in posterior flux, mostly resulting in reductions.
- TROPOMI inversion shows posterior reductions in emission hotspot regions: Benelux, Germany
- Low agreement with surface inversion

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Summery

- Improved Fit: Posterior estimates align better with observations than priors.
- Regional Offsets: Flux increases in some regions are offset by decreases in others.
- Consistency: Strong agreement at EU23+3 level with other inversions and UNFCCC reports; lower consistency at subregional/country level.
- Model Sensitivity: Results are highly sensitive to background error, station density, and correlation length.
- Resolution Impact: Higher resolution improves accuracy compared to coarse-resolution outputs.
- Satellite Comparison: Low agreement with satellite-based inversions.

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