How well can inverse analyses of high-resolution satellite data resolve heterogenous methane fluxes?

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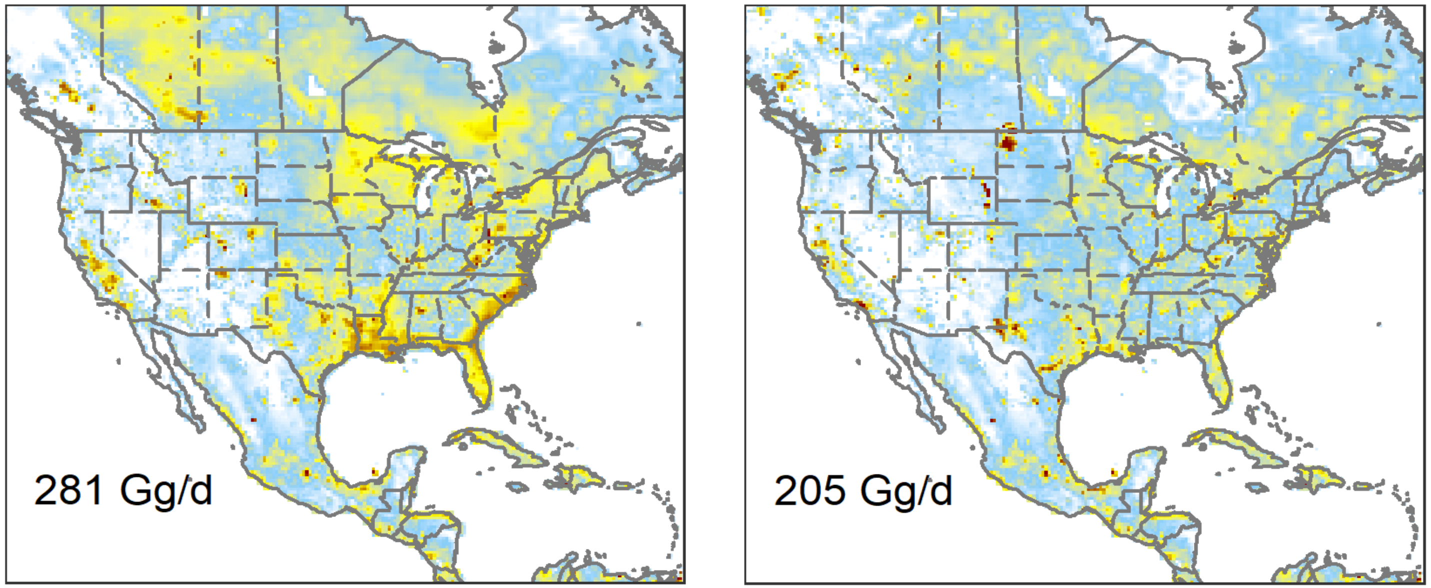
TROPOMI

How well do we understand the methane budget?

Global totals are best constrained. Large uncertainties in regional/sectoral distributions.

GEPA + WetCHARTs ensemble mean



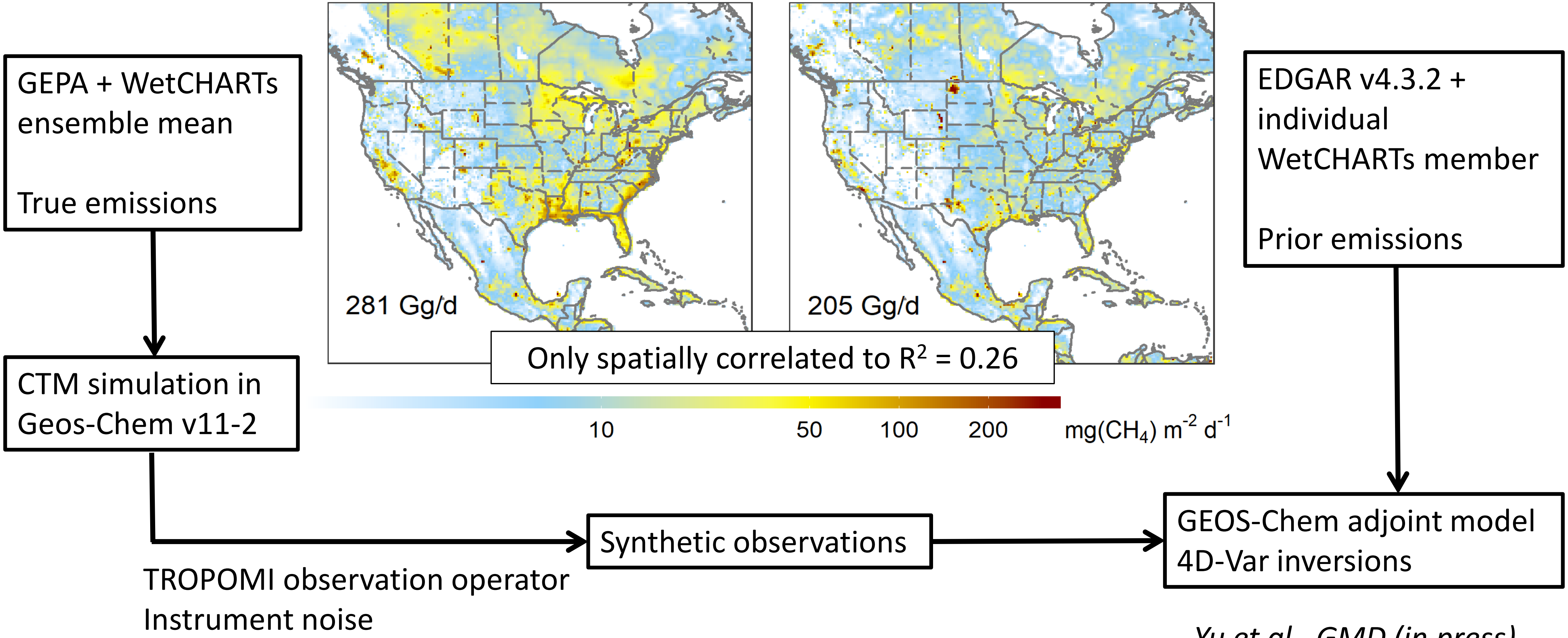
EDGAR v4.3.2 + individual WetCHARTs member

Only spatially correlated to R^2 = 0.26

New high-resolution satellite instruments such as TROPOMI offer an unprecedented opportunity to quantify methane emission variability

XCH_4

We present a set of observing system simulation experiments (OSSEs)
in GEOS-Chem 4D-Var adjoint inversions to evaluate:
1) the capability of high-resolution satellite measurements to resolve heterogenous methane fluxes,
2) the challenges in optimizing methane fluxes through high-resolution inverse analyses.



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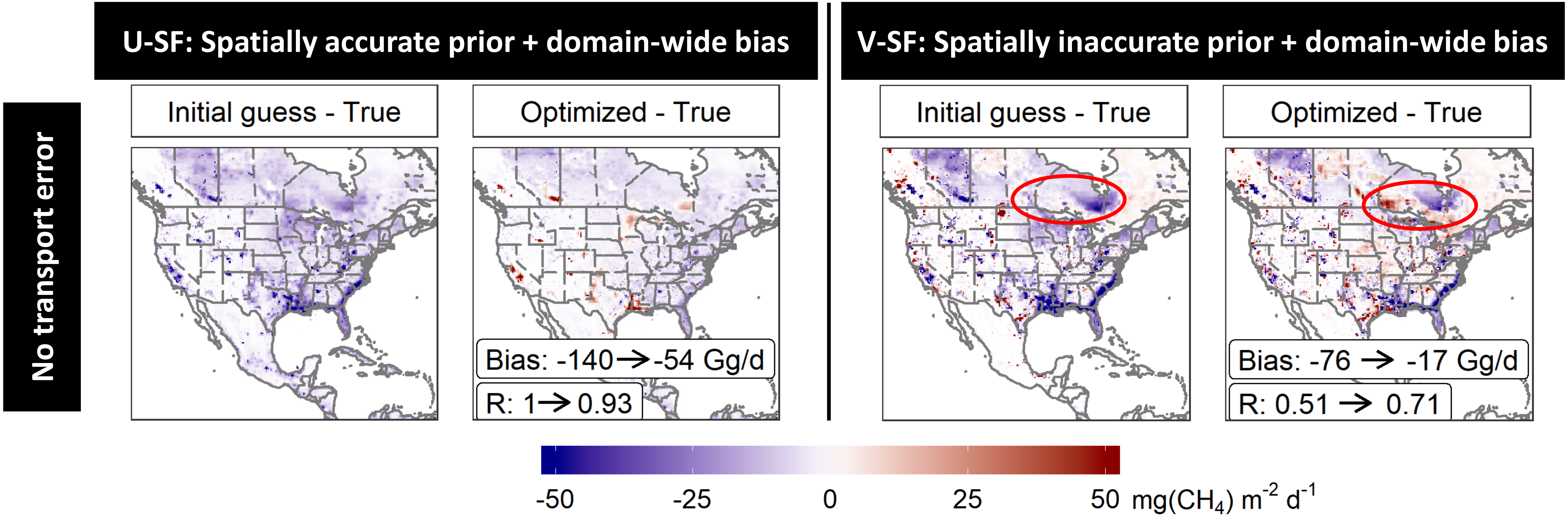
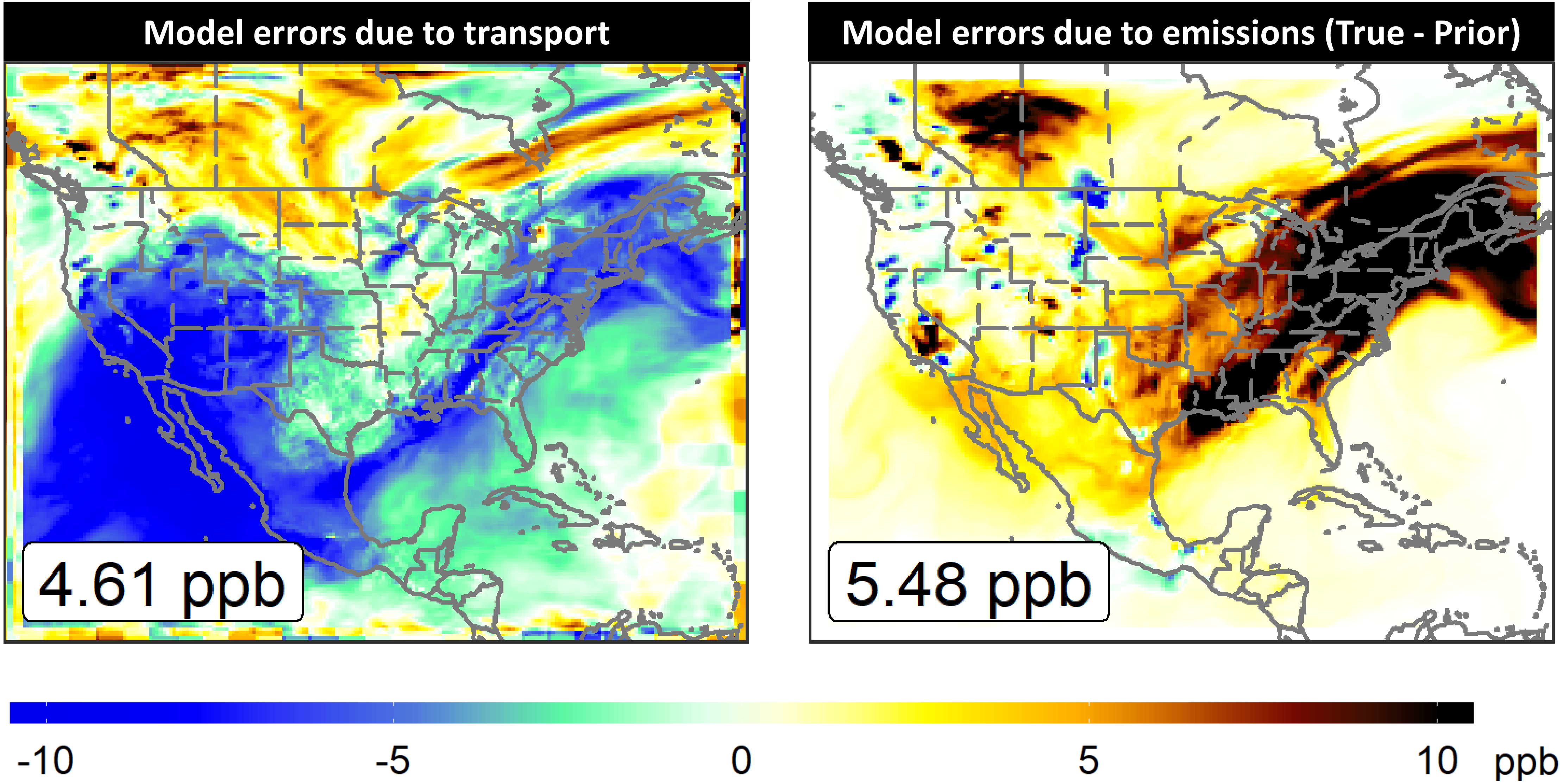
Domain-wide prior bias leads to over-correction of large sources



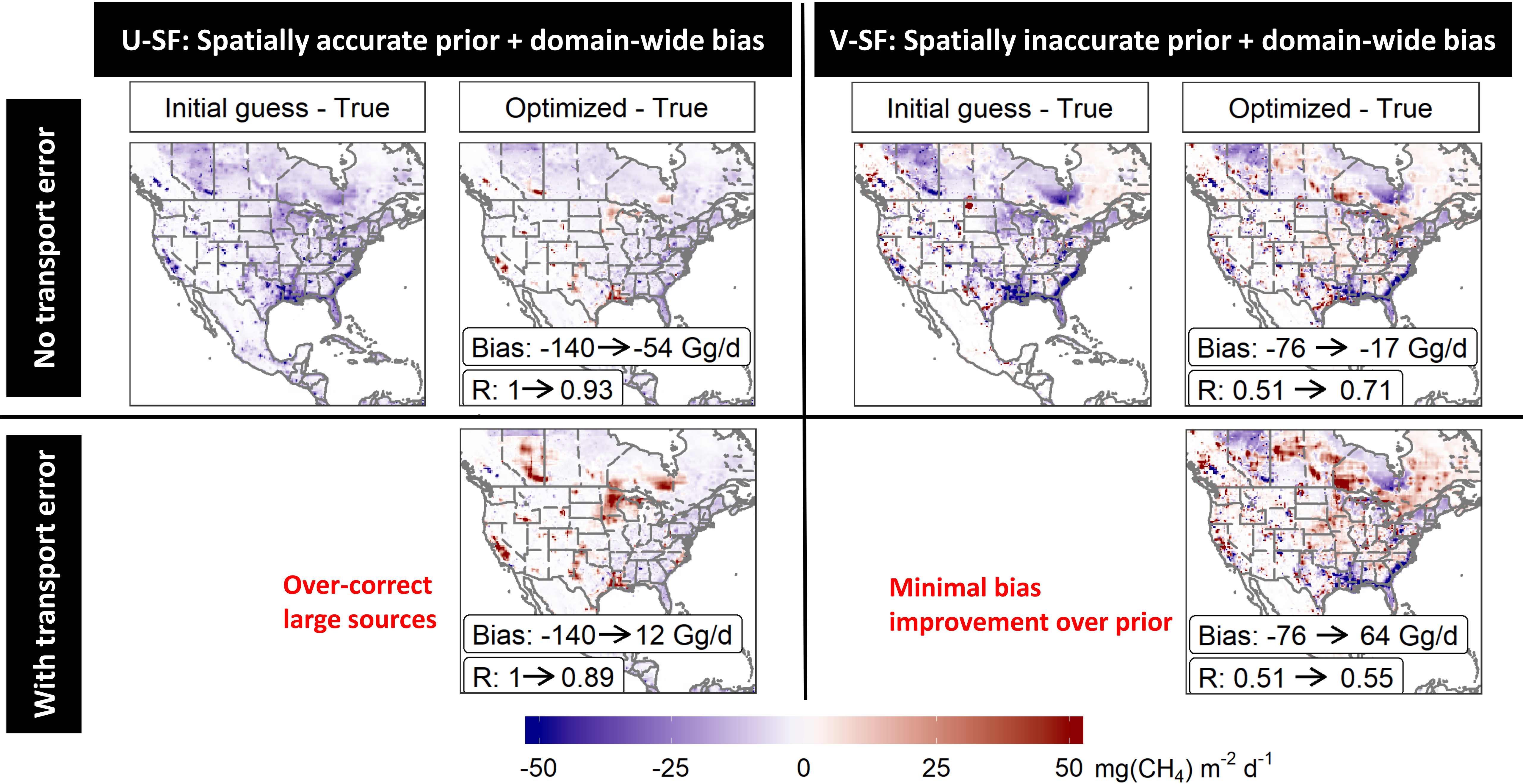
Inversions can improve emission estimates at 25-km scale.

Missing emissions mis-assigned to large, nearby sources.

Model methane biases due to transport error can be as large as those due to emissions



Transport error mis-assigned to large sources

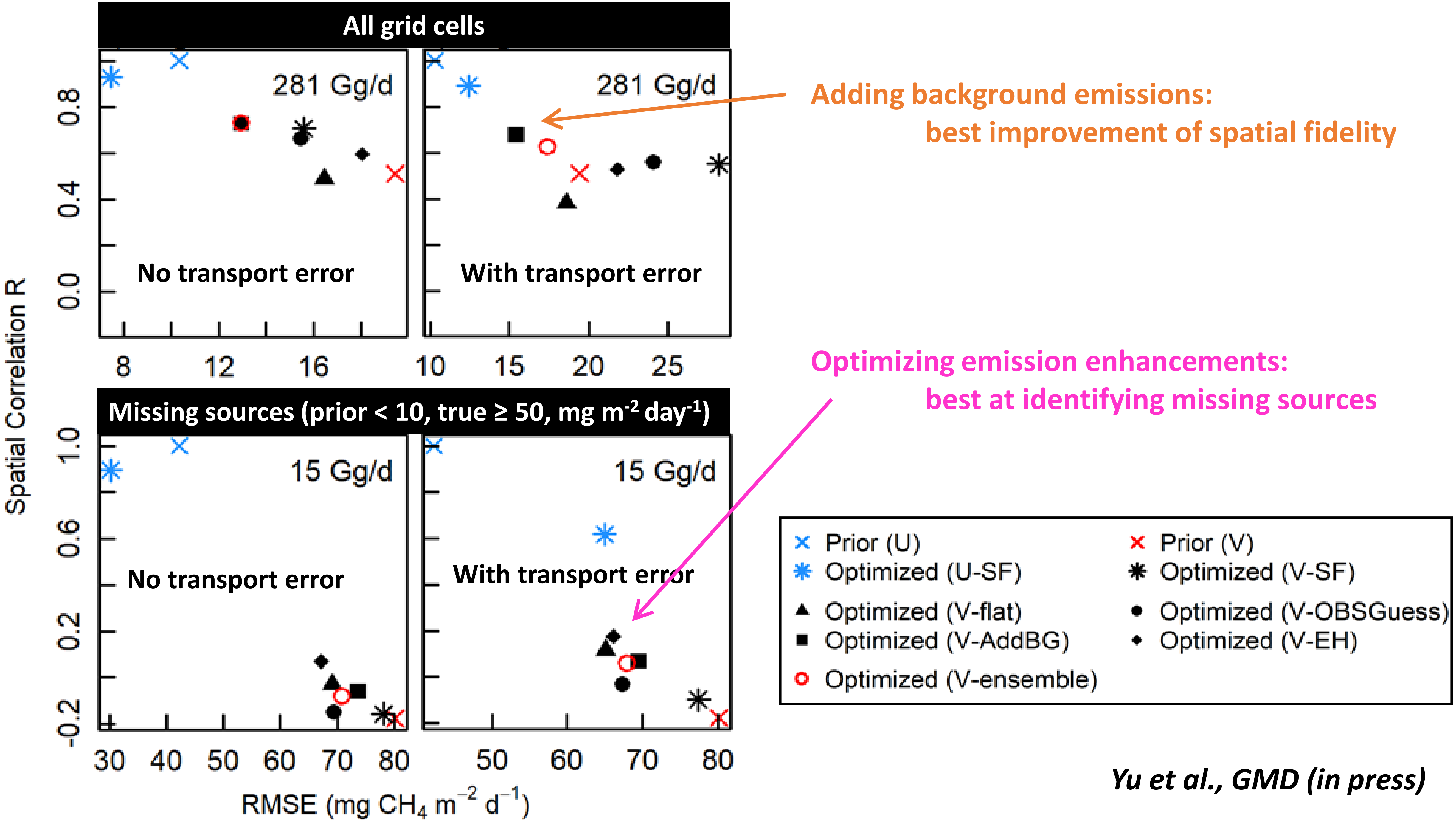


Alternative inversion methods to overcome limits of classical scale-factor approach

$\boldsymbol{s}$: scale factors; $\boldsymbol{x}$: emissions

Base-case SF	$\boldsymbol{x} = \boldsymbol{s} \circ \boldsymbol{x_a}$	
Flat prior	$\boldsymbol{x} = x_{a\_ave}\, \boldsymbol{s}$	Identify constraints solely from TROPOMI without bottom-up knowledge
Background increment	$\boldsymbol{x} = \boldsymbol{s} \circ (0.5\, \boldsymbol{x_a} + 0.5\, x_{a\_ave})$	Identify missing sources
Observational guess	$\boldsymbol{x} = \boldsymbol{s} \circ (\boldsymbol{x_a} + \boldsymbol{x_{ObsGuess}})$	Resolve and optimize emission hotspots
Enhancement	$\boldsymbol{x} = x_{inc}\, \boldsymbol{s} + \boldsymbol{x_a}$	Identify missing sources

Yu et al., GMD (in press)



Adding background emissions: best improvement of spatial fidelity

Optimizing emission enhancements: best at identifying missing sources

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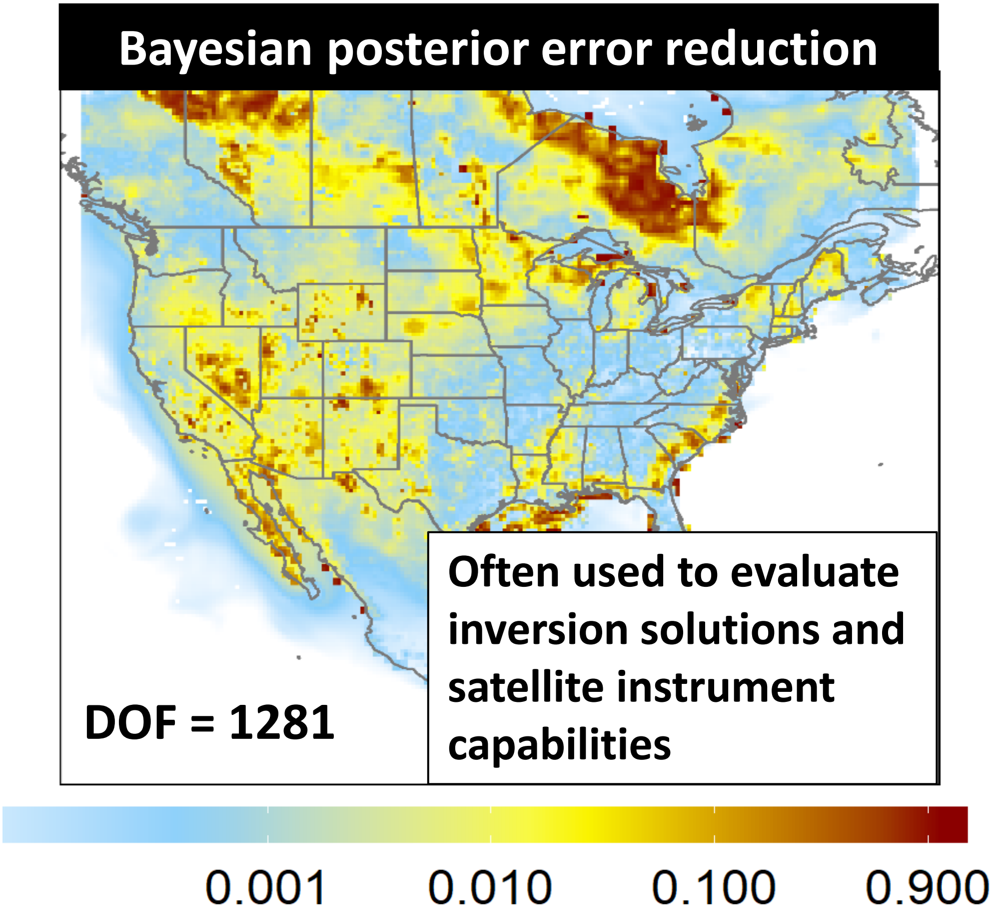
High Bayesian posterior error reduction does not necessarily imply better flux estimates

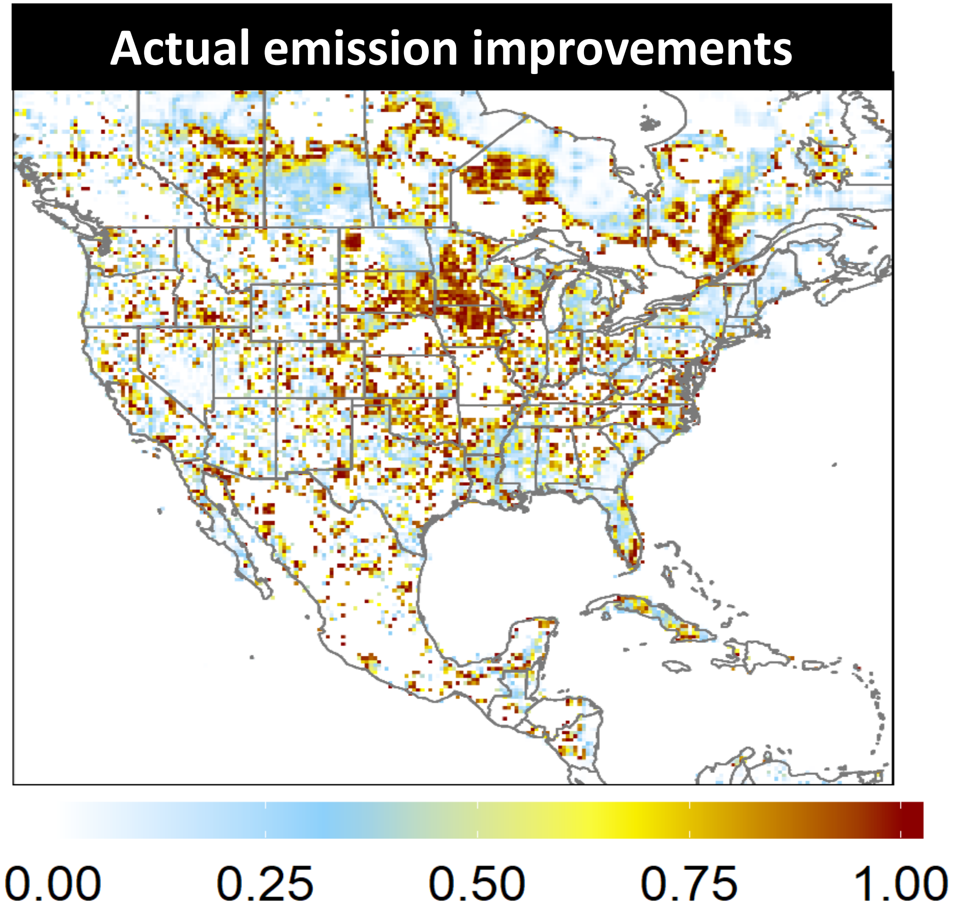
Error reduction analyses are useful for observing system characterization, but have no relationship to the spatial accuracy of posterior emissions



$$\rho_{est}(i) = 1 - S_{opt}(i,i)/S_a(i,i)$$

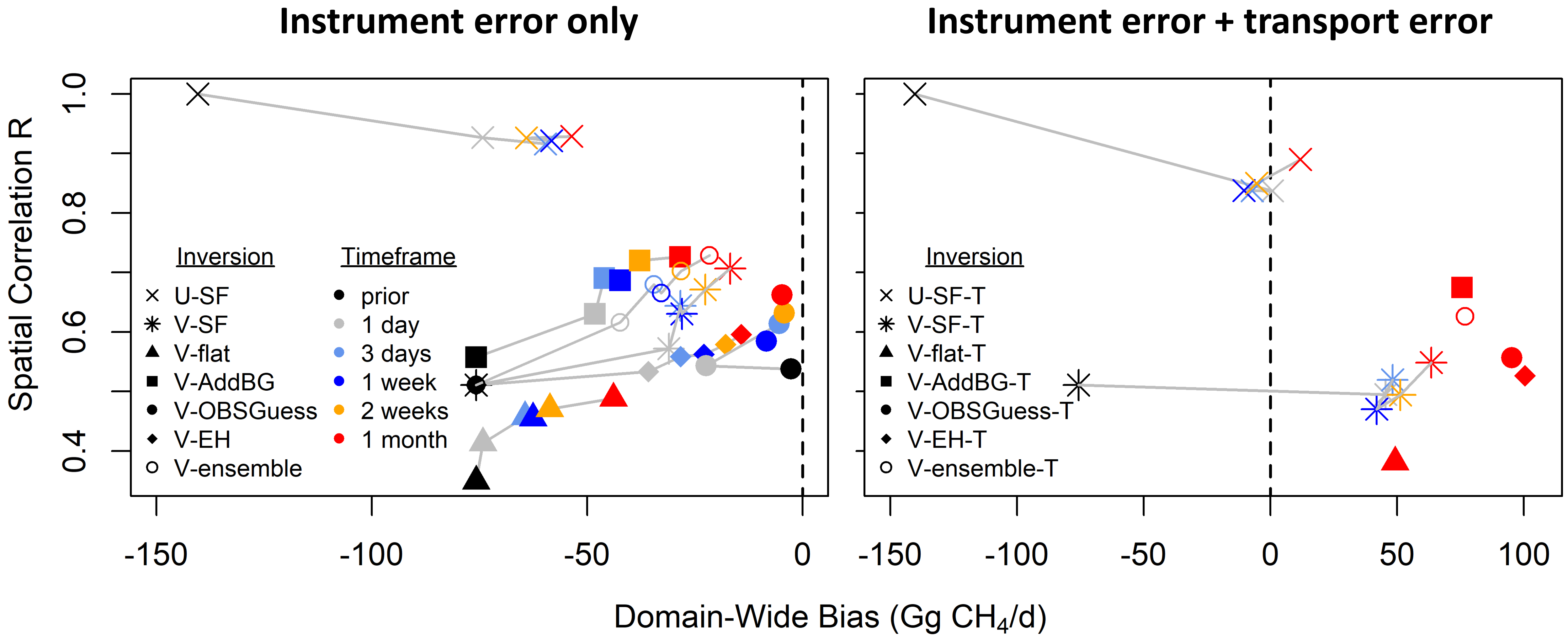
≠

R = 0.07



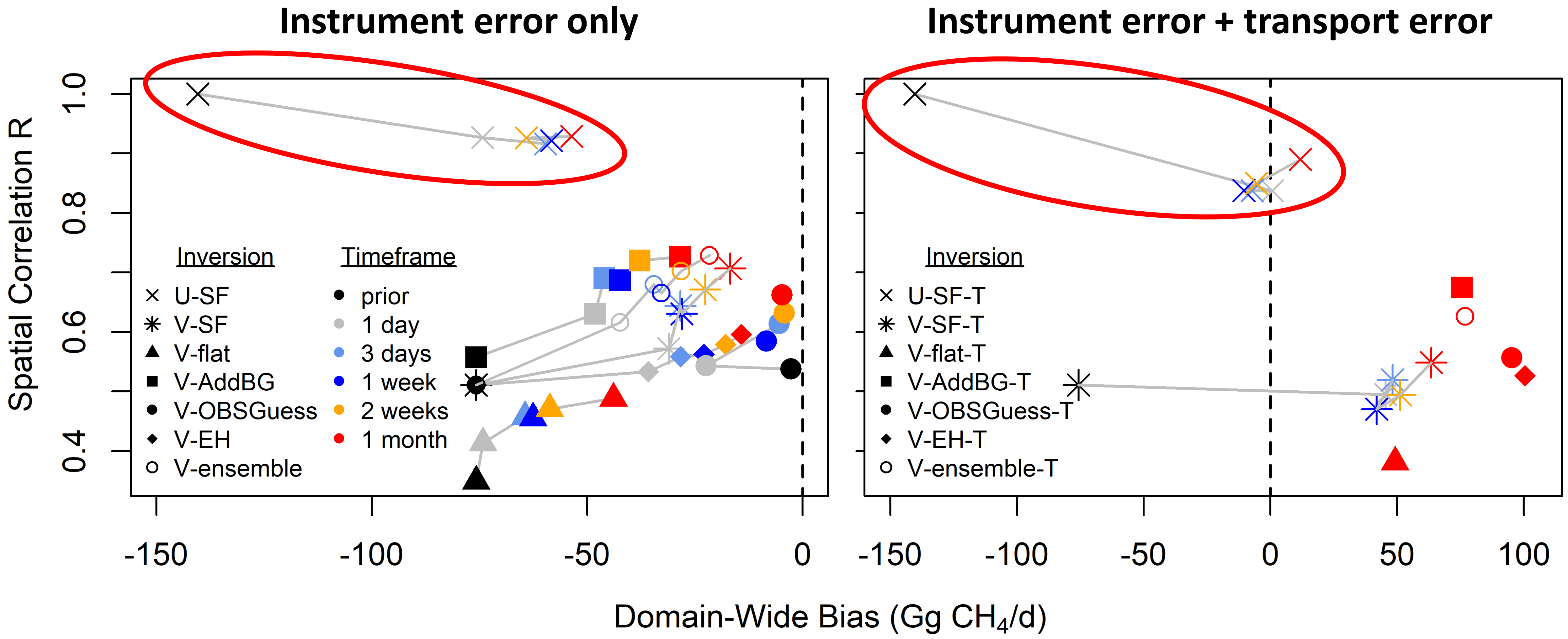
$$\rho_{true}(i) = 1 - \left(\hat{x}(i) - x_{true}(i)\right)^2 / \left(x_a(i) - x_{true}(i)\right)^2$$

Alternative timeframes yield consistent messages



With spatially accurate prior emissions, inversions can improve emission magnitude estimates at 25 km.
With accurate model transport, additional observations can progressively improve spatial emission estimates.
When both spatial emission errors and transport errors are present, results are strongly degraded.

Alternative timeframes yield consistent messages



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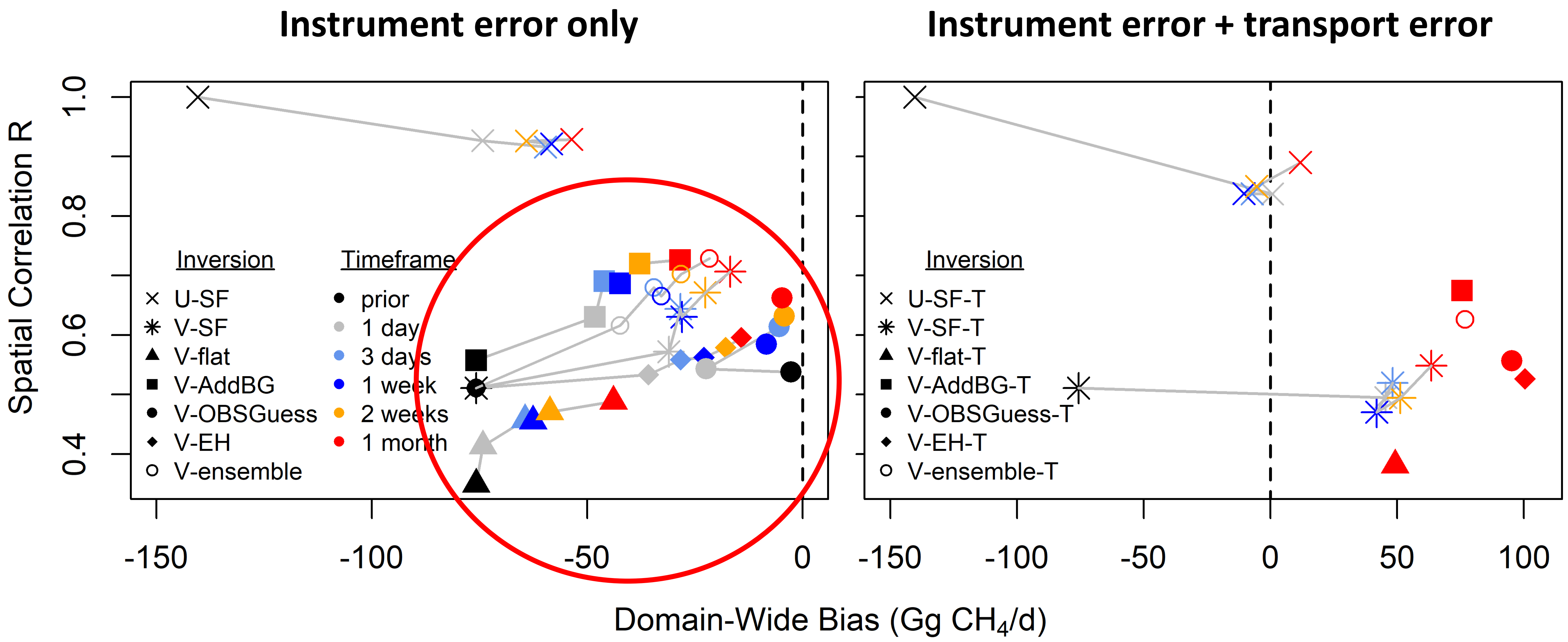

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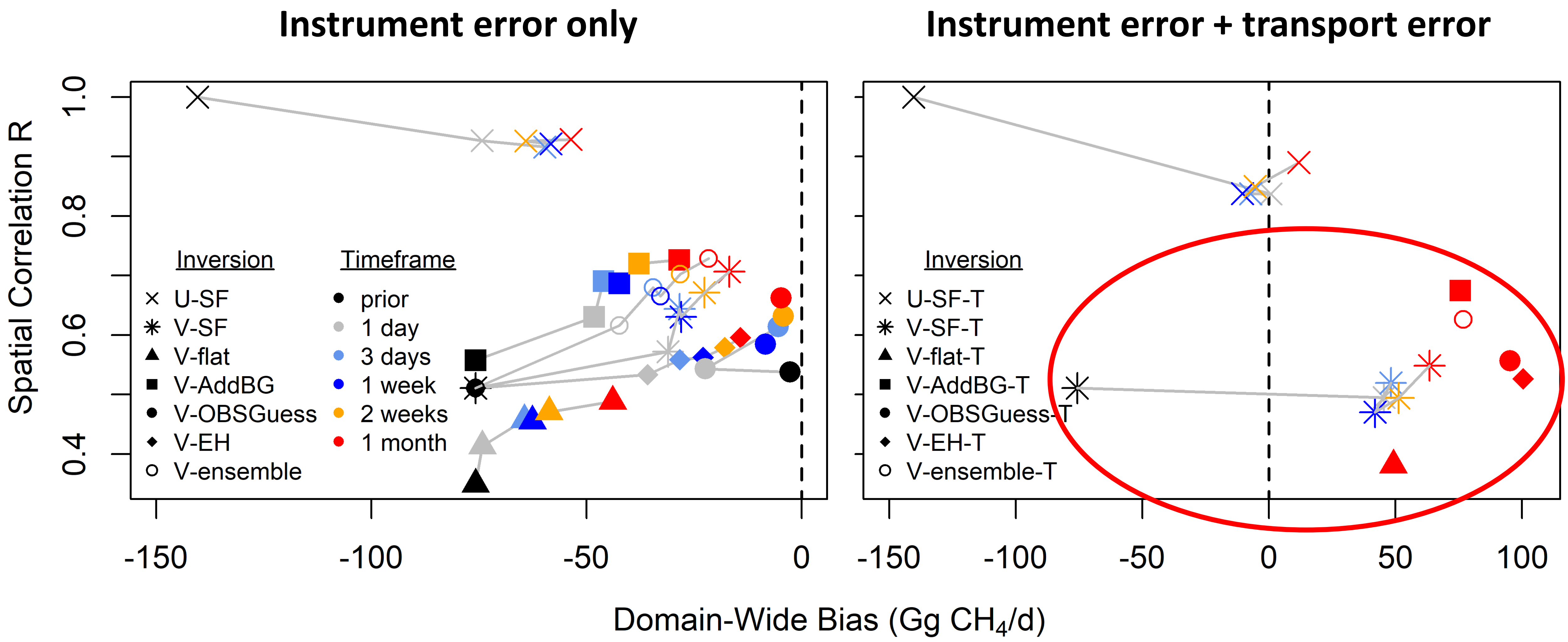

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Take home messages

We conducted Observing System Simulation Experiments to test how well inverse analyses of high-resolution satellite data (such as TROPOMI) can quantify methane emissions.

Inversions can improve monthly flux estimates at a 25-km scale even with a spatially biased prior or model transport errors, but results are strongly degraded when both errors are present.

Missing emissions are misassigned to large, nearby sources. Alternative formalisms (such as optimizing enhancements) have promise to mitigate this limitation.

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