High Resolution Estimates of Methane Emissions (by sector) Using TROPOMI and AVIRIS-NG Aircraft data

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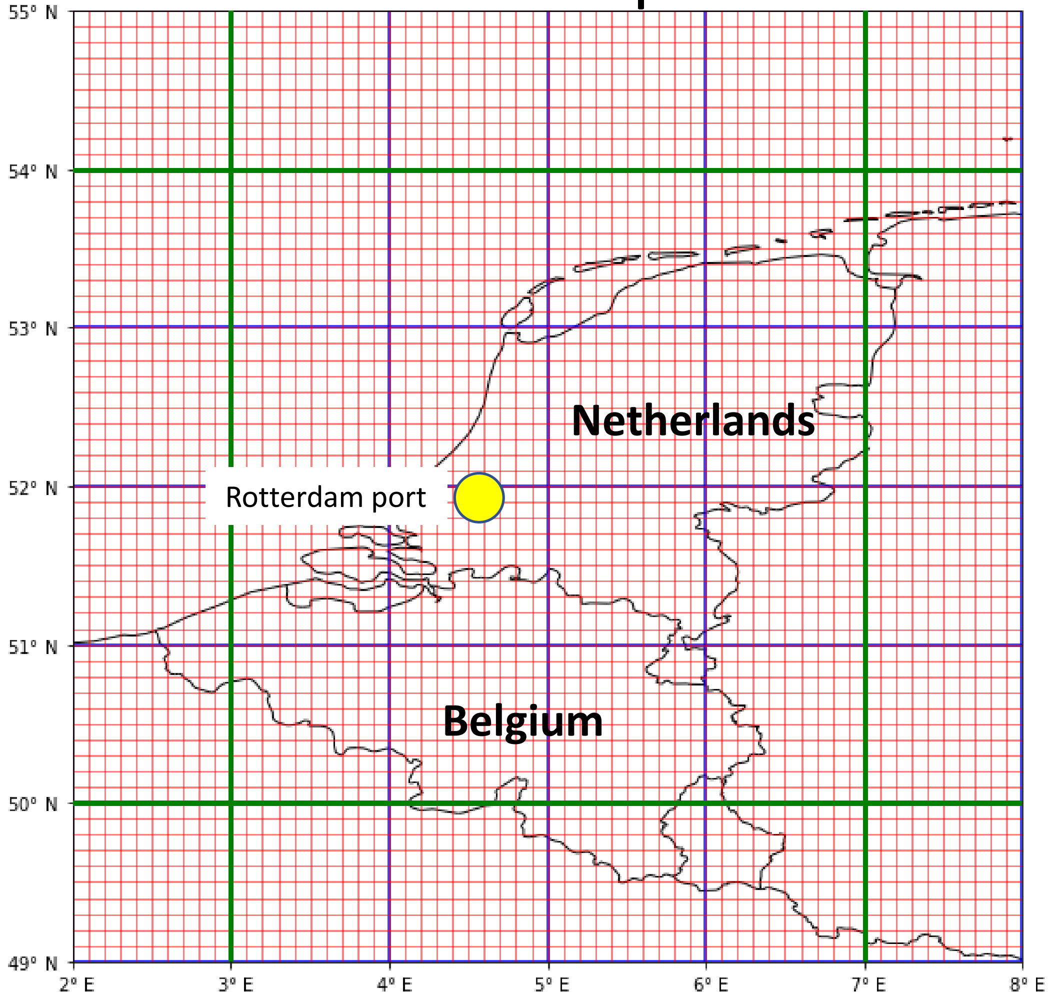
California Institute of Technology

Image: Cusworth et al. (2021)

Resolution of Emissions Versus Typical Satellite Based Fluxes

4° vs 1° vs 0.1° Spatial Grid



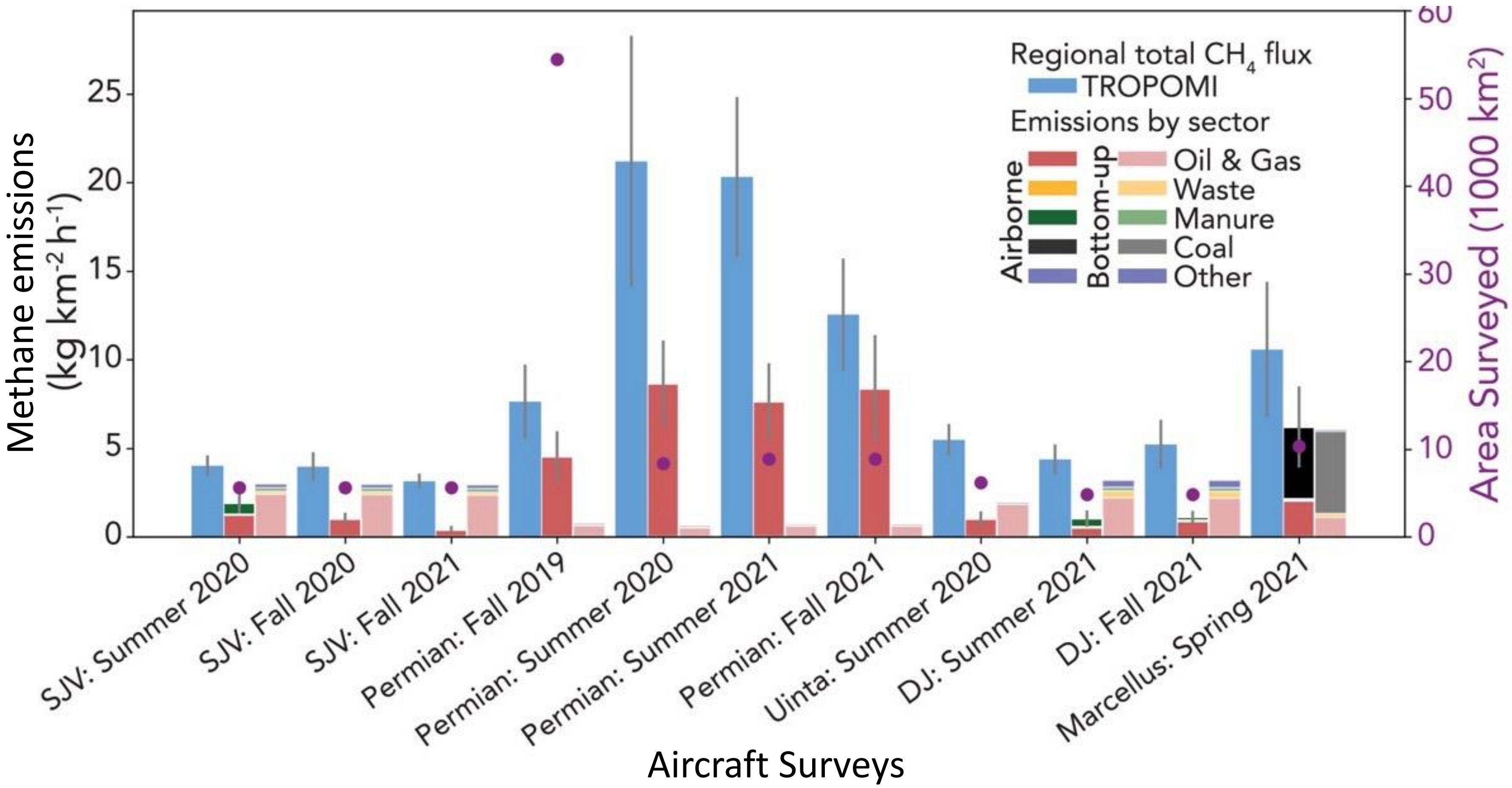
Resolution of Methane Fluxes from Satellite ~0.5-4 degrees depending on sampling

Facility to urban emissions are generally 0.01 to 0.1 degree spatial scale

Motivation: Estimate emissions at sub-degree scales

High Emitters at Small Scales Have Outsized Impact on Regional Fluxes

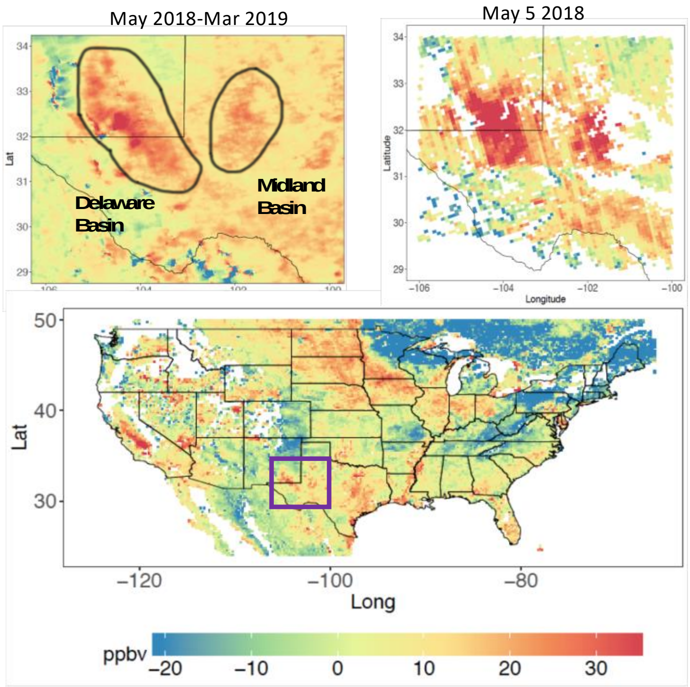
Emissions from each surveyed basin (Cusworth et al., 2022 *PNAS)*



Objective: Quantify Emissions with Satellite Data and High Resolution Plume Mapping data

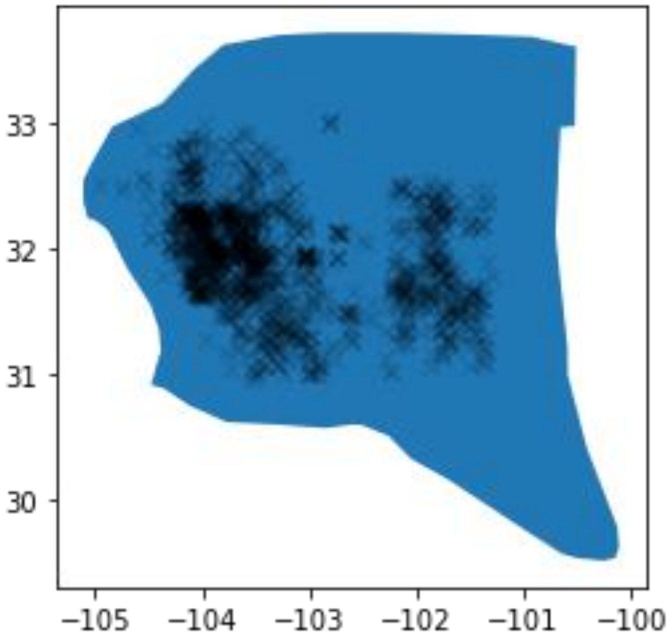
Satellite data can provide constraints on regional fluxes with some information about sources within a region
Plume mapping instruments provide high-resolution estimates of emissions
The combination should therefore provide a more complete picture

Test Case: Use TROPOMI estimates of methane emissions over Permian



Zhang et al. 2020, Cusworth et al. 2021, Nesser et al. In Preparation

Combine with aircraft estimates from AVIRIS-NG



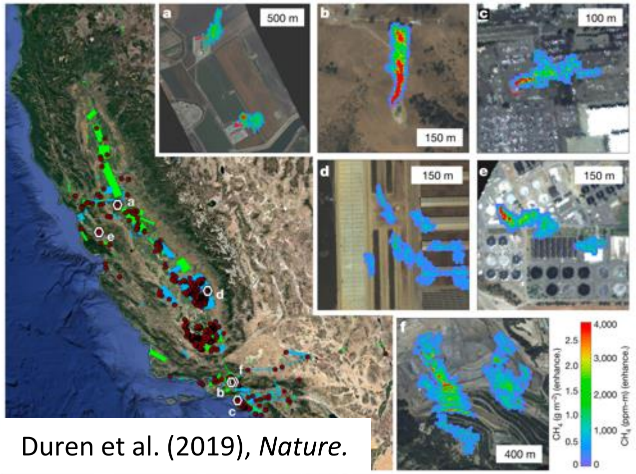
Cusworth et al. 2022

Lots of Current and New High-Res Instruments!

Detection limit

5 kg/h — 100 kg/h — 2000 kg/h

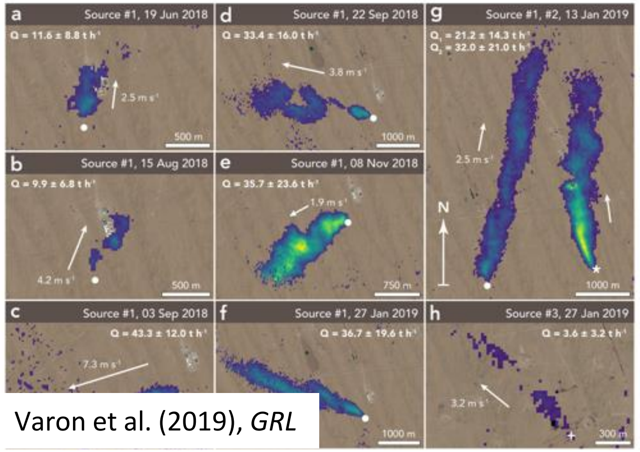
Aircraft



Duren et al. (2019), *Nature.*

Dedicated satellites

GHGsat



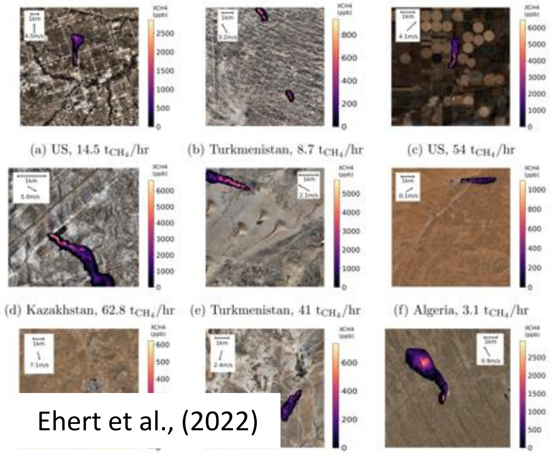
Varon et al. (2019), *GRL*

CARBON MAPPER

MethaneSAT™

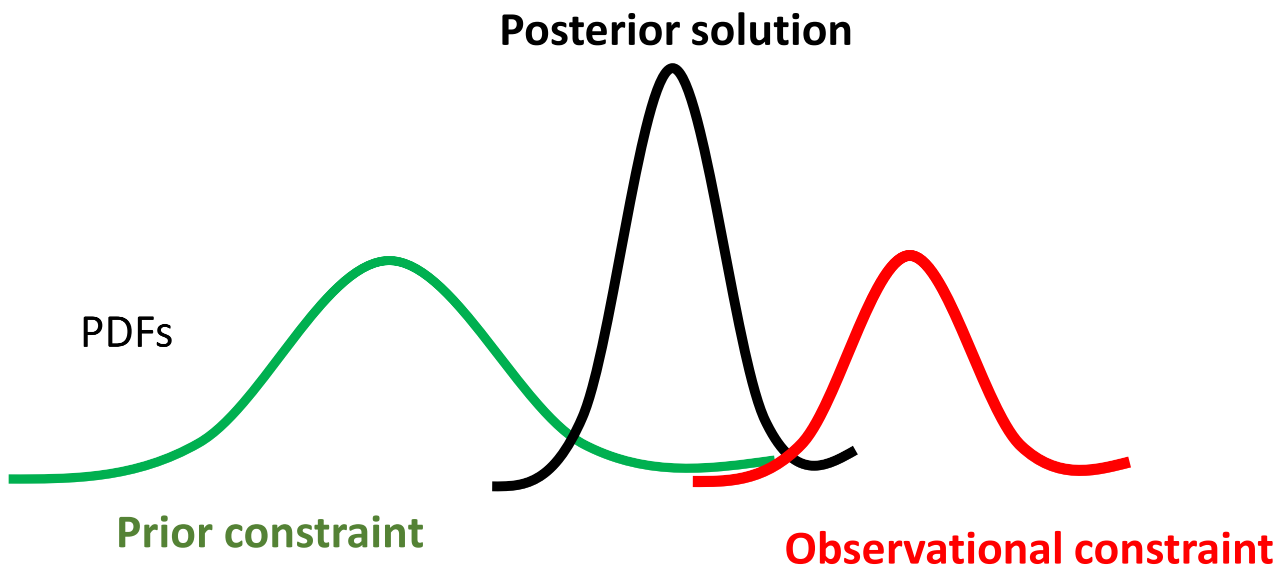
More satellites!

Sentinel-2



Ehert et al., (2022)

Bayesian Approach for Estimating Emissions



$$J(\boldsymbol{z}) = (\mathbf{z} - \hat{\mathbf{z}})\ \hat{\mathbf{Z}}\ (\mathbf{z} - \hat{\mathbf{z}})\ + \left(\mathbf{y_p} - \mathbf{M_p}\ \mathbf{z}\right)\ \boldsymbol{S_p}\ \left(\mathbf{y_p}\ - \mathbf{M_p}\ \mathbf{z}\right)$$

$\mathbf{z}$: Emission vector.

$\hat{\mathbf{z}}$: Prior emission vector or from prior solution using satellite data

$\hat{\mathbf{Z}}$: Prior error matrix.

$\mathbf{y_p}$: Observations vector.

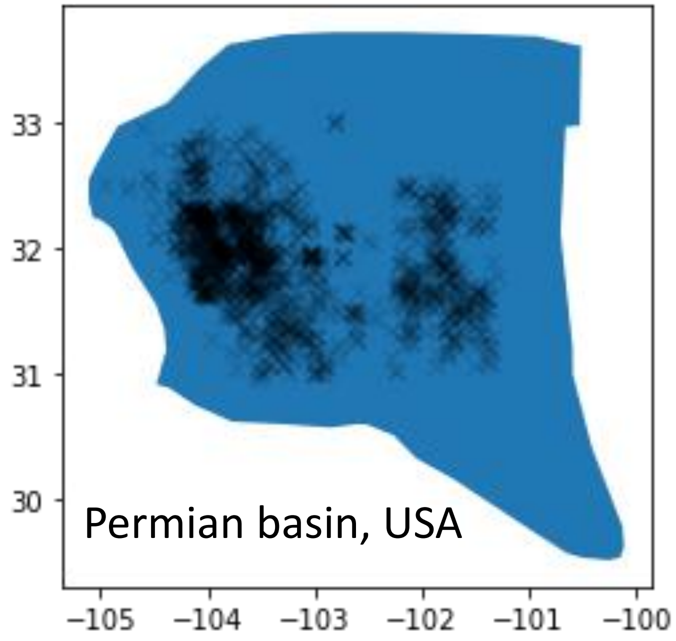
$\mathbf{S}_\mathrm{p}$: Observations error matrix.

$\mathbf{M_p}$: Mapping function realting emissions to observations.

Aircraft Observations of Methane Plumes

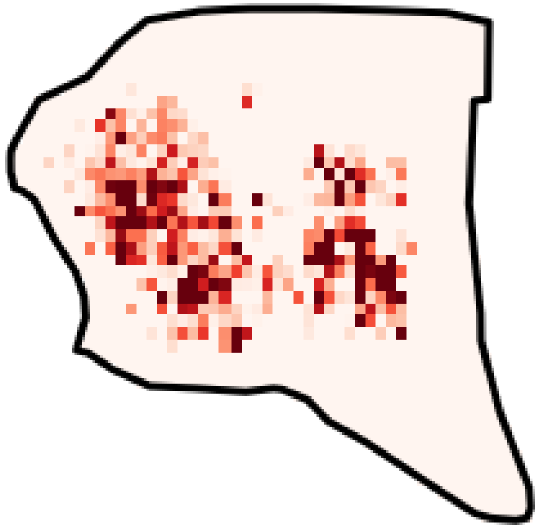
- We optimize inventory emissions (by sector) at 0.1 x 0.1 degree spatial resolution (scale which spans TROPOMI and aircraft)
- We assimilate AVIRIS-NG and GAO plume data and Sentinel-5p satellite data.
- Emission Errors from aircraft/plume results are based on reported errors for individual emissions / sqrt(N)

Plume detection sites

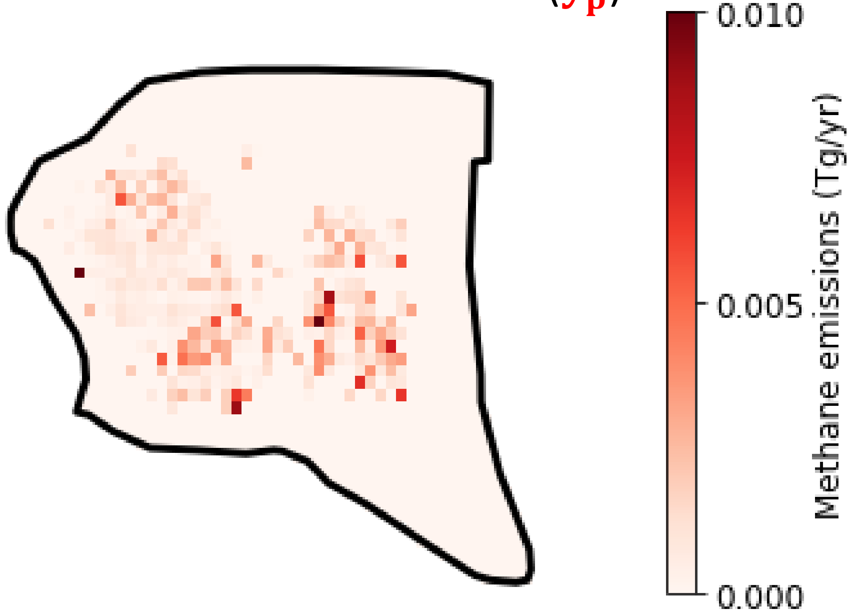


Plume observations for assimilation

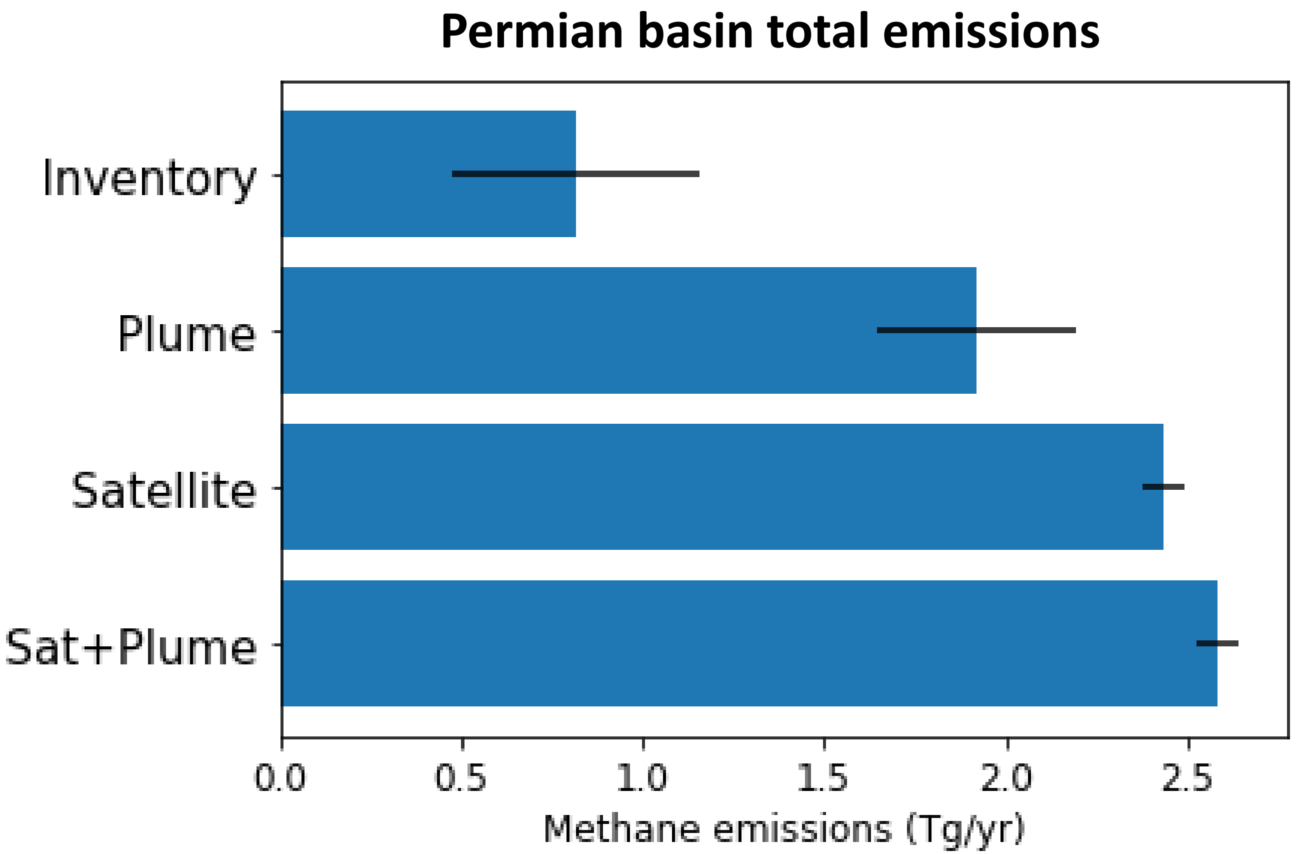
Gridded source rates ($\mathbf{y_p}$)



Gridded source rates Errors ($\mathbf{y_p}$)



Integrated Emissions from AVIRIS and TROPOMI



Inversions

Plume = Inventory + Plume

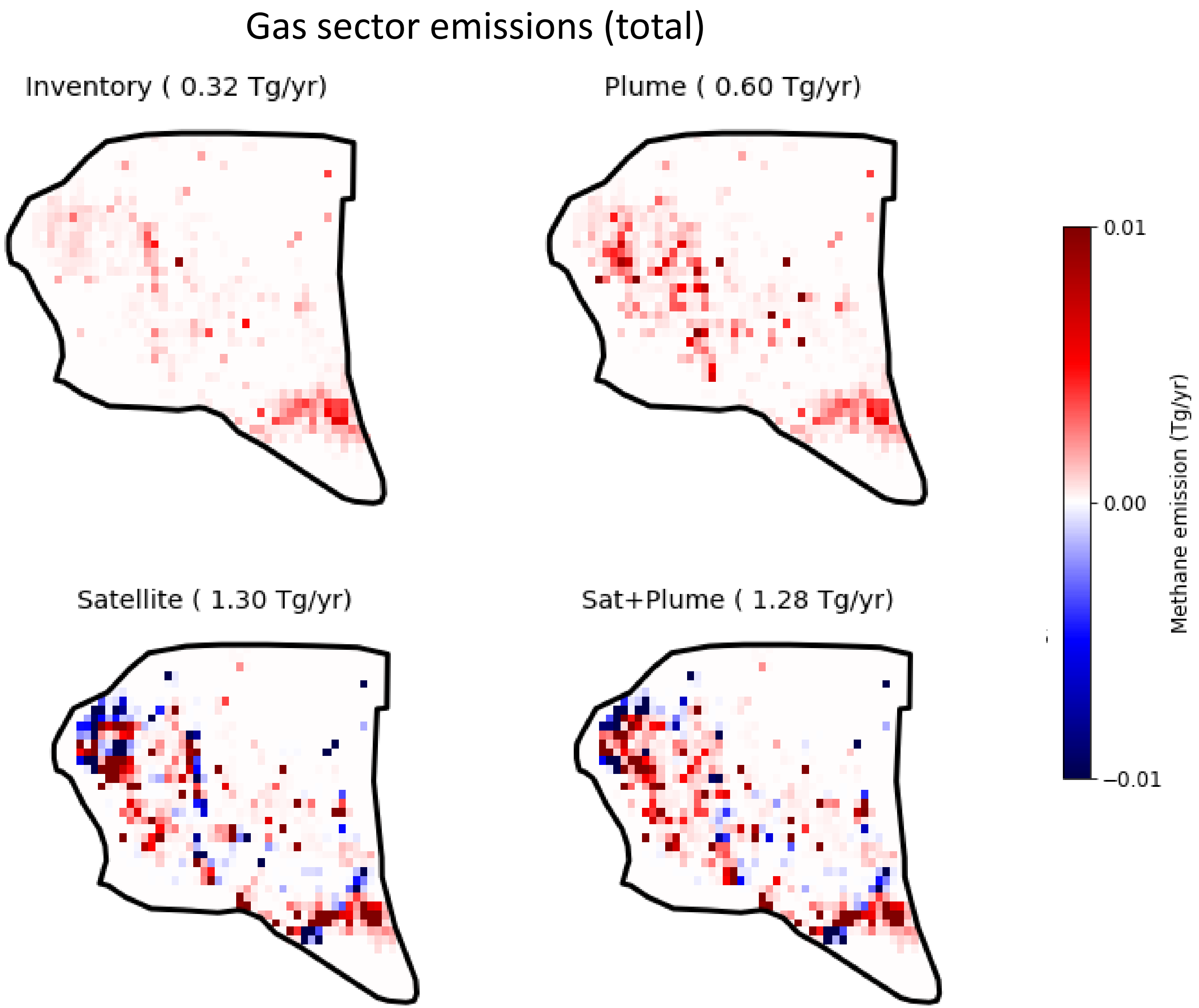
Satellite = Inventory + Satellite

Sat+Plume = Inventory + Satellite + Plume

- The plume assimilation increases emissions by ~2.5x
- Assimilating plume with satellite data has little impact on total but substantial impact on distribution

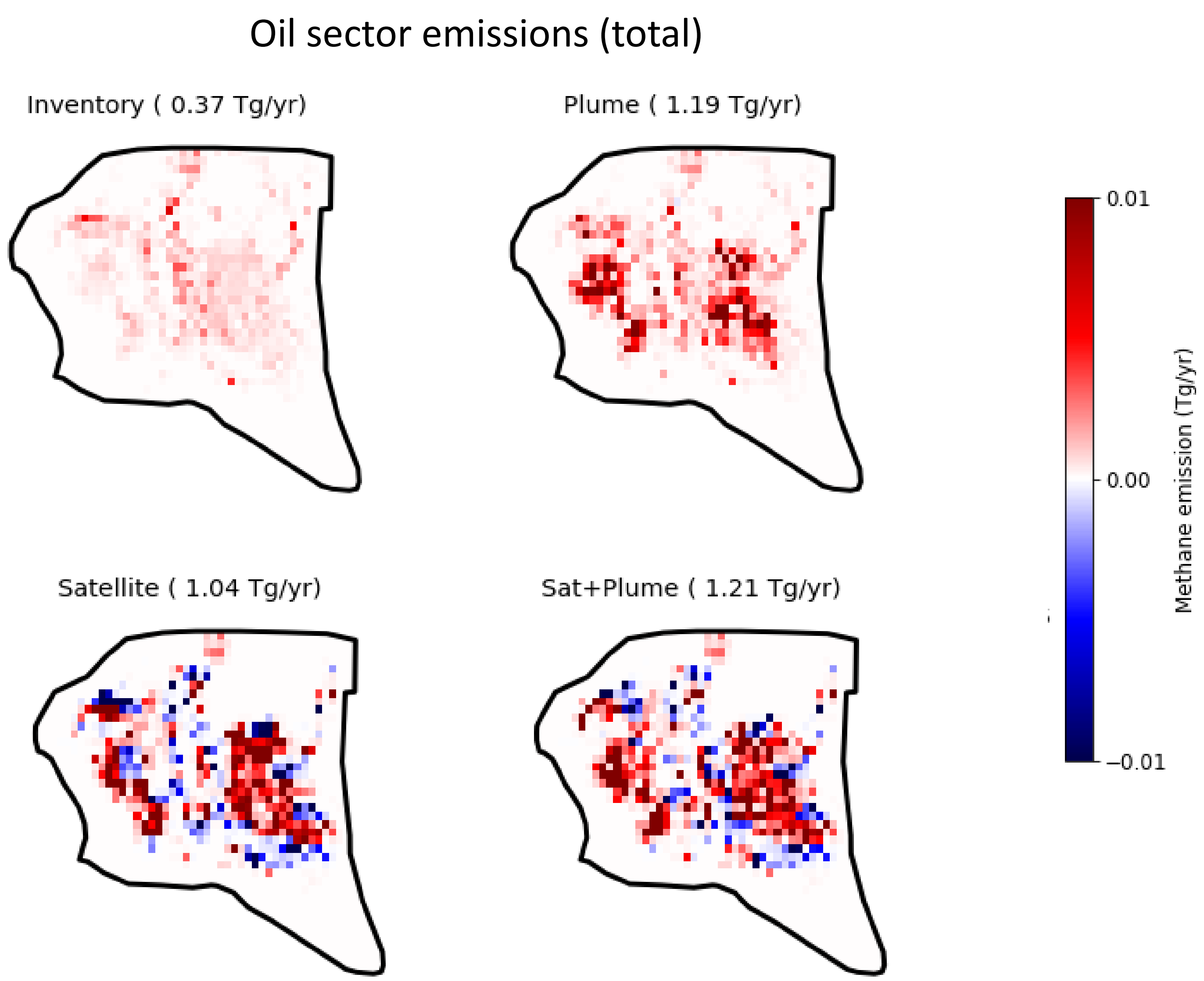
Plume Assimilation Results

- Plume assimilation doubles the inventory emissions.
- Plume assimilation reduces “dipoles” in the satellite inversion, but keeps the total emission similar.



Plume Assimilation Results

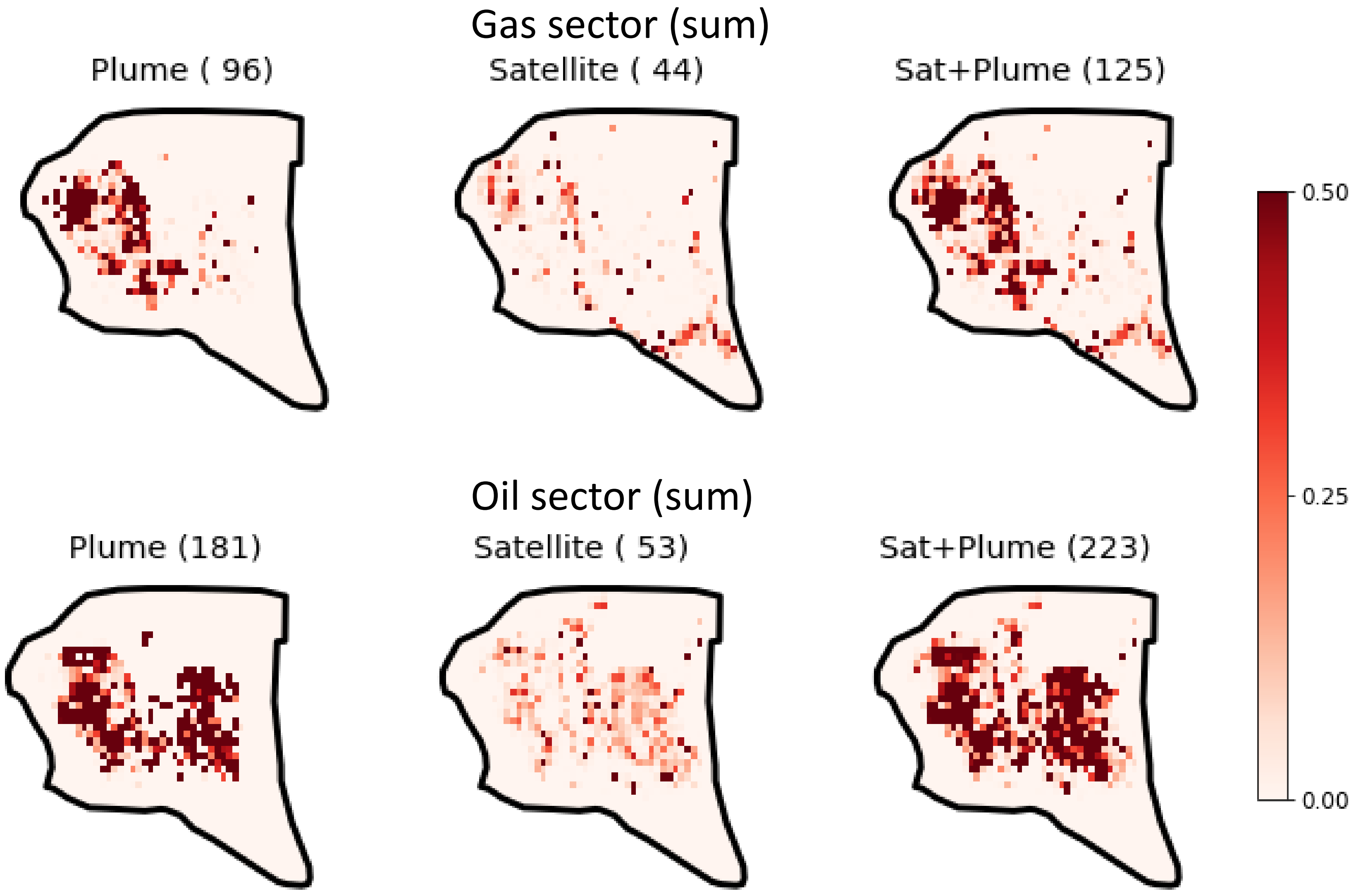
- ➢ Spatial patterns of inventory and plume observations match, so the Plume increases the oil emissions more than the gas emissions.



Plume Assimilation Results

- The satellite inversion's constraint is distributed over all emissions sectors, while the plume observations constrain only the oil and gas sectors.
- For oil sector, the spatial pattern between inventory and plume observations match, so DOFS is larger for oil (181) that gas (96) sector.

Degrees of Freedom for Signal (DOFS)



Summary

- Combined satellite-aircraft based estimates provide improved picture of emissions within a region
- TROPOMI provides total emissions estimate with partial constraint on facility scale emissions
- AVIRIS-NG provides constraint on facility scale emission
- Need sufficient plume measurements to establish error characteristics
- General Bayesian approach applicable to combinations from upcoming plume-mappers (e.g. Carbon Mapper / GHGSAT) + wide field measurements (e.g. Sentinel 5P / 5, CO2M, GEOCARB, MethaneSat, GOSAT—GW)

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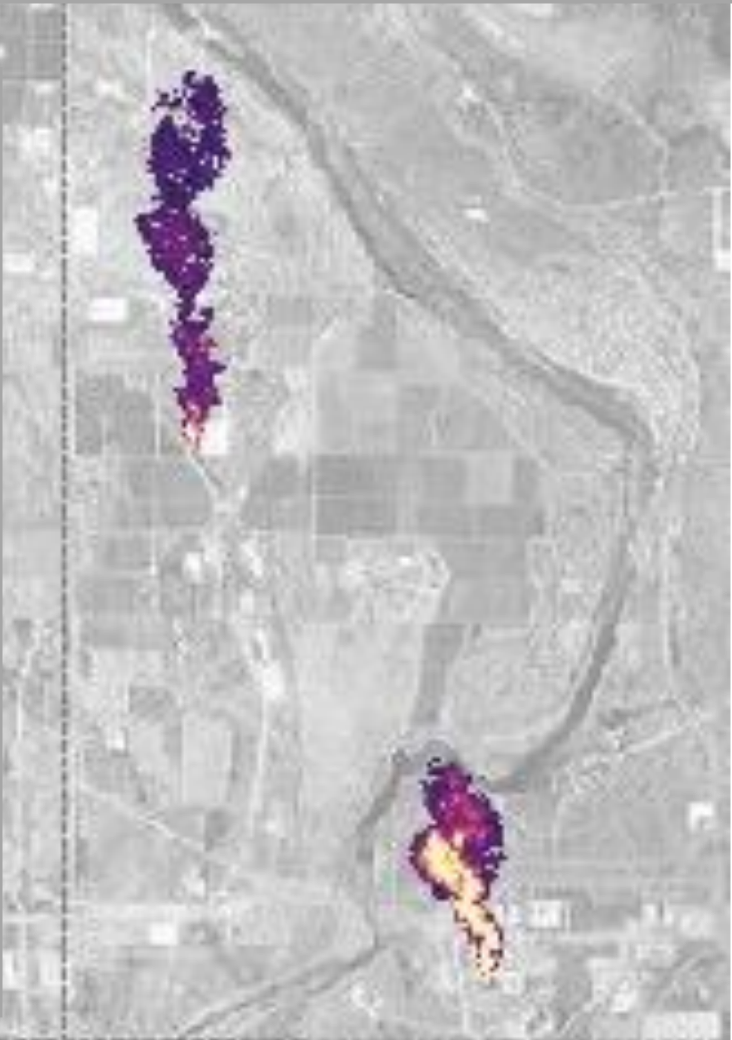

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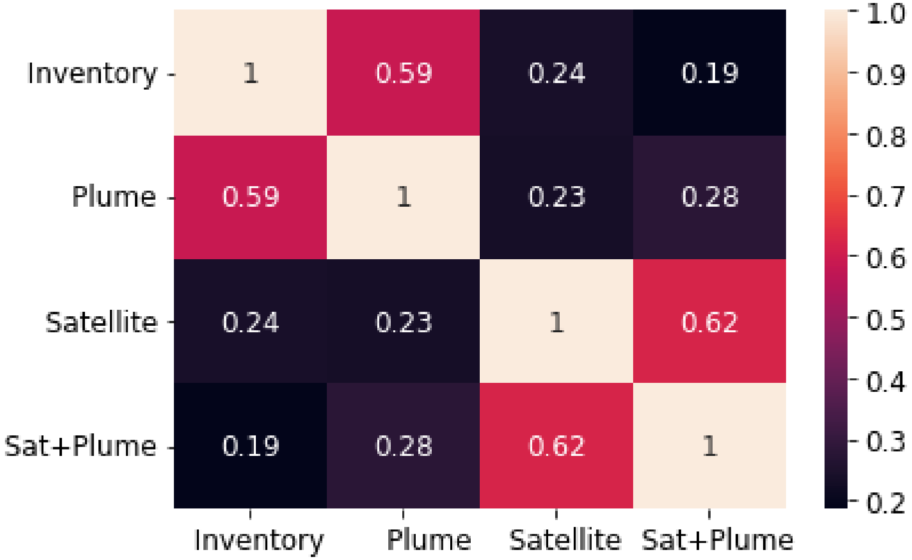
Image: Cusworth et al. (2021)

Thanks you

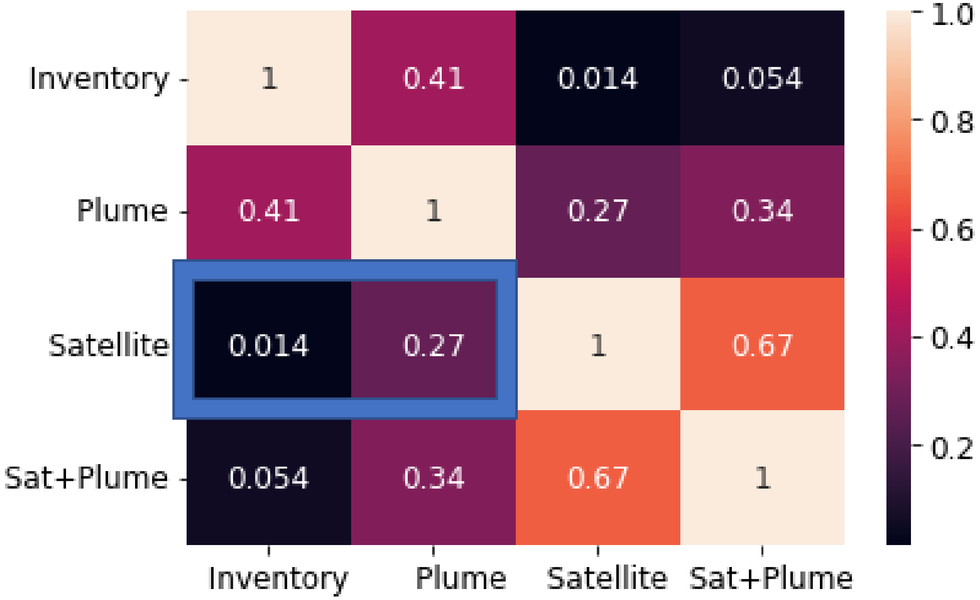
End of the presentation

Spatial correlations coefficients

Gas Sector



Oil Sector

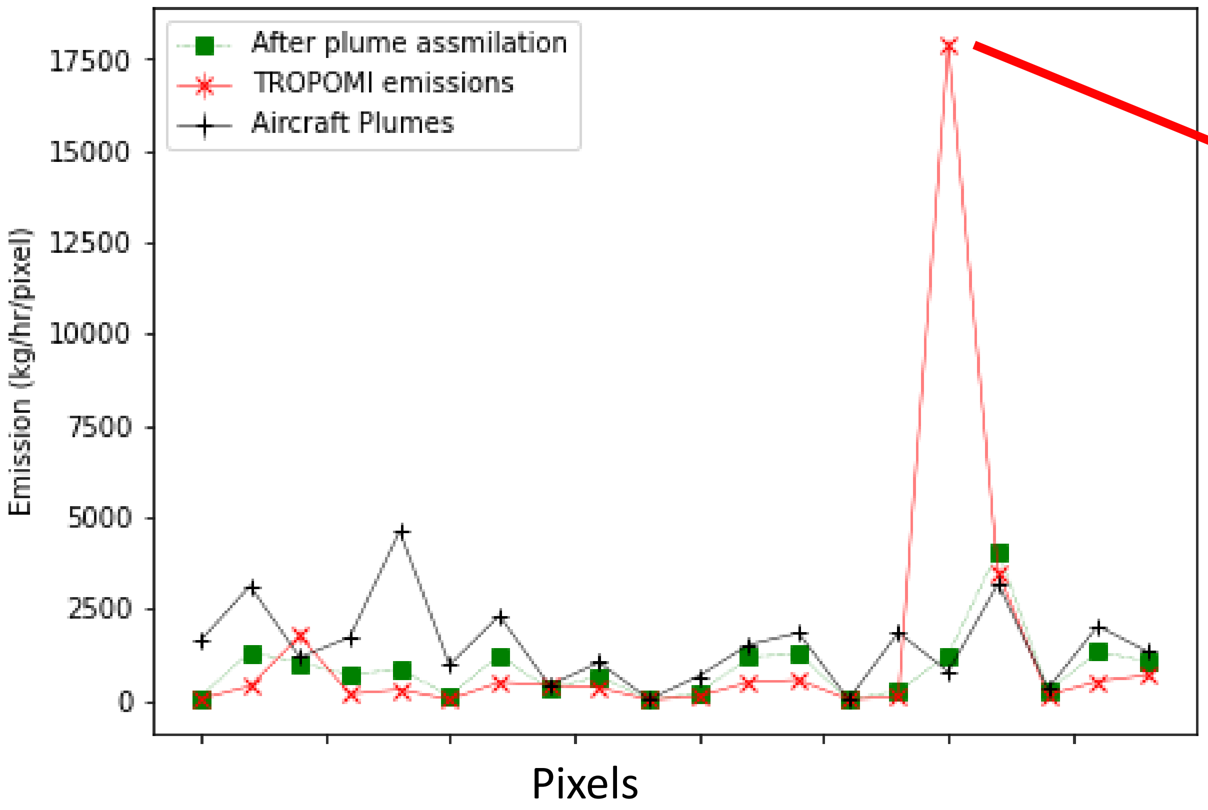


Validation of the Plume inversion with Satellite data:

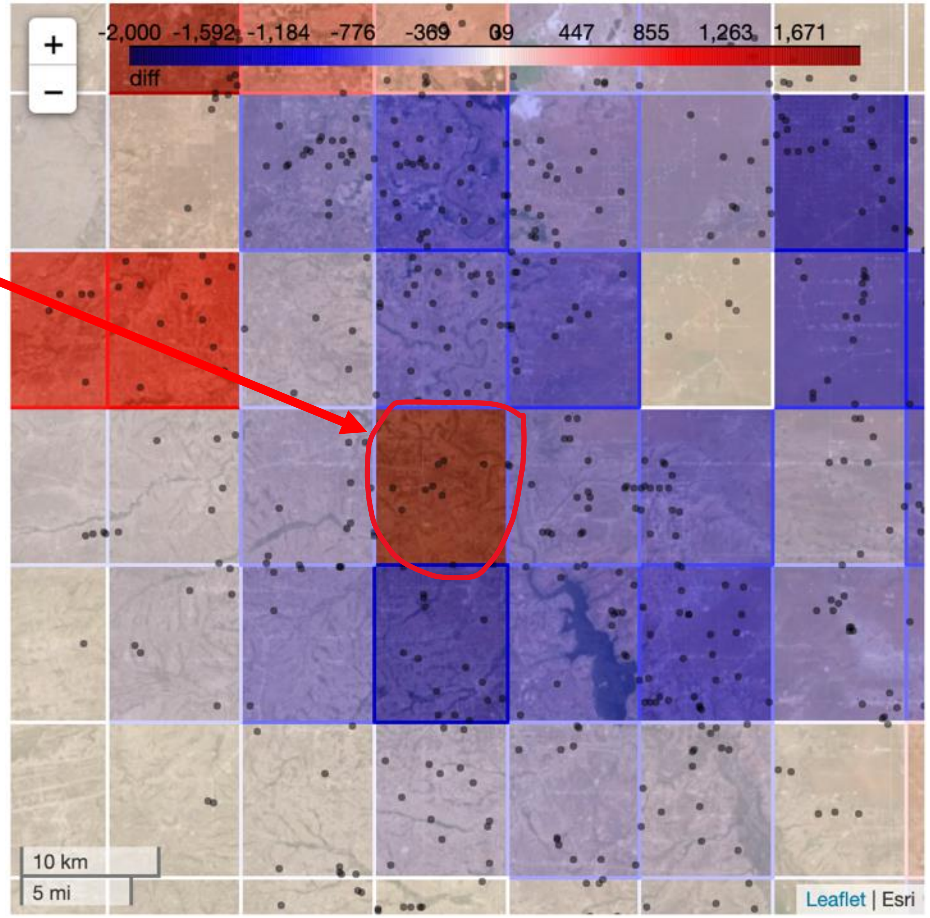
- For the oil emissions, the R with the Satellite inversion is better for the Plume inversion than for the Inventory. This shows that satellite data agrees with the spatial pattern information of the plume data.

Plume Assimilation Results

Emissions Adjustments



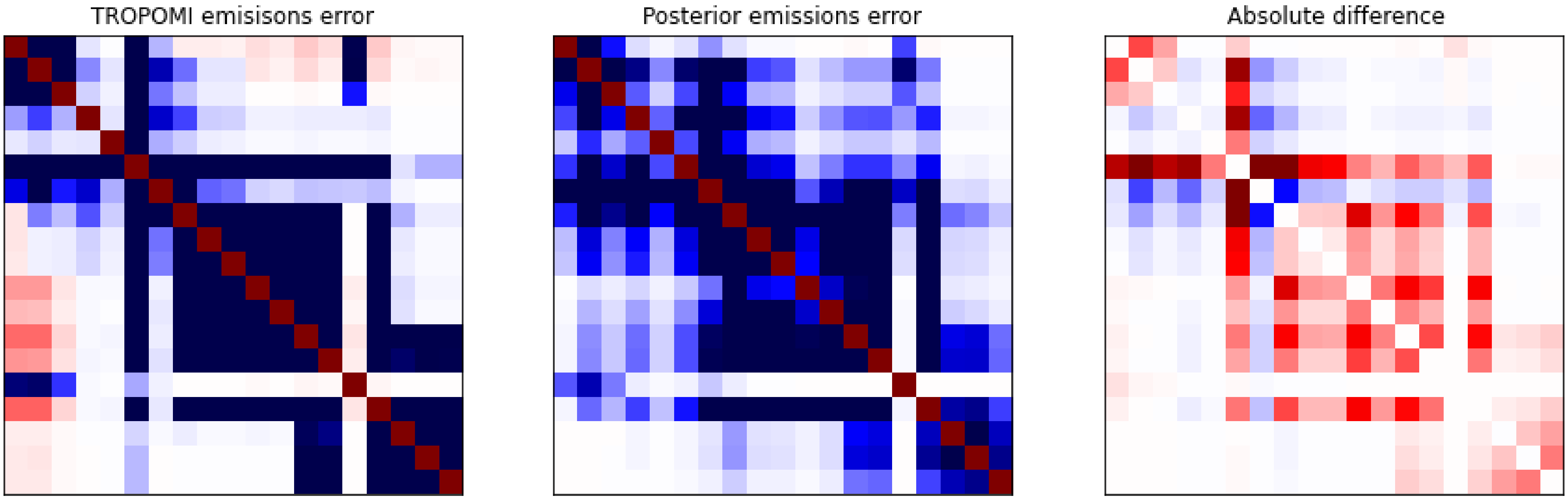
TROPOMI minus Aircraft Emissions



- Plumes in the high emissions pixel are not more than surrounding pixels, so the plume assimilation reduced the pixel's emissions.

Plume Assimilation Results

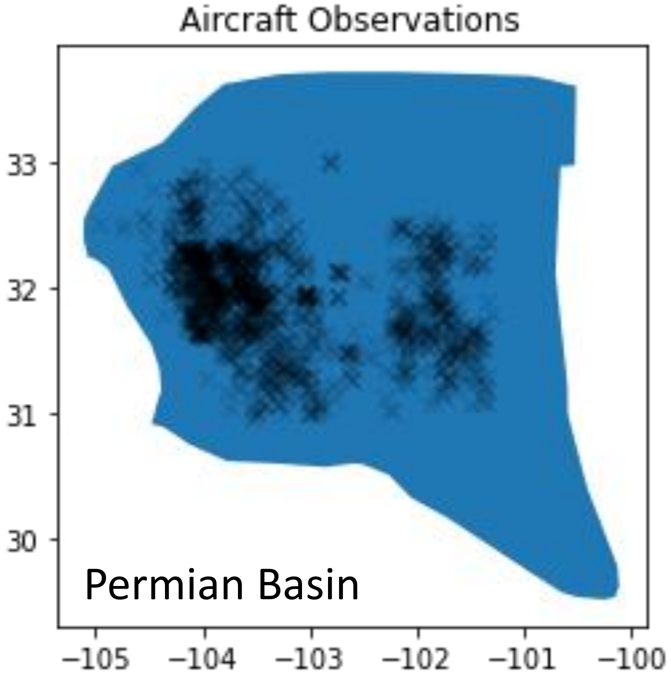
Error Correlation Matrices



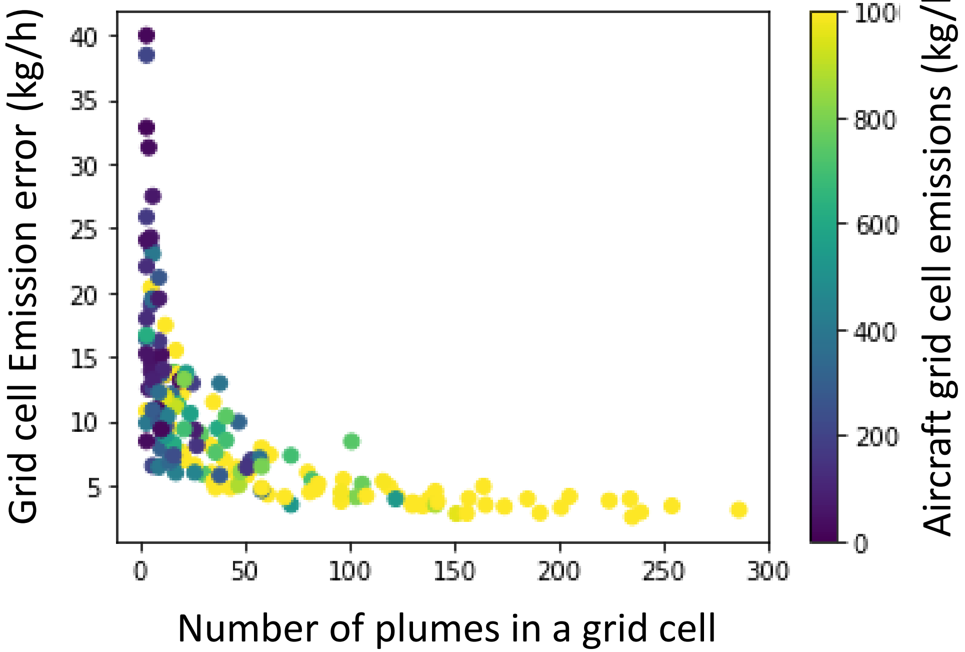
➢ Reduction in off-diagonal elements means better resolution of grid cell emissions.

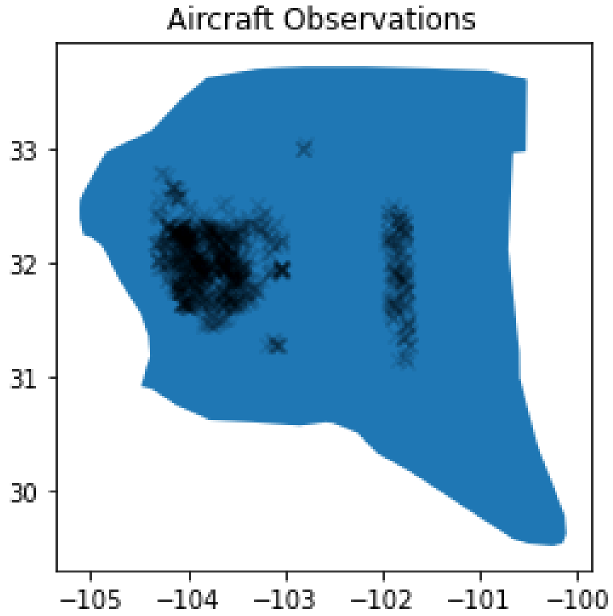
Aircraft Observations of Methane Plumes

Fall 2019 aircraft plume observations from Cusworth et al. (2021b)



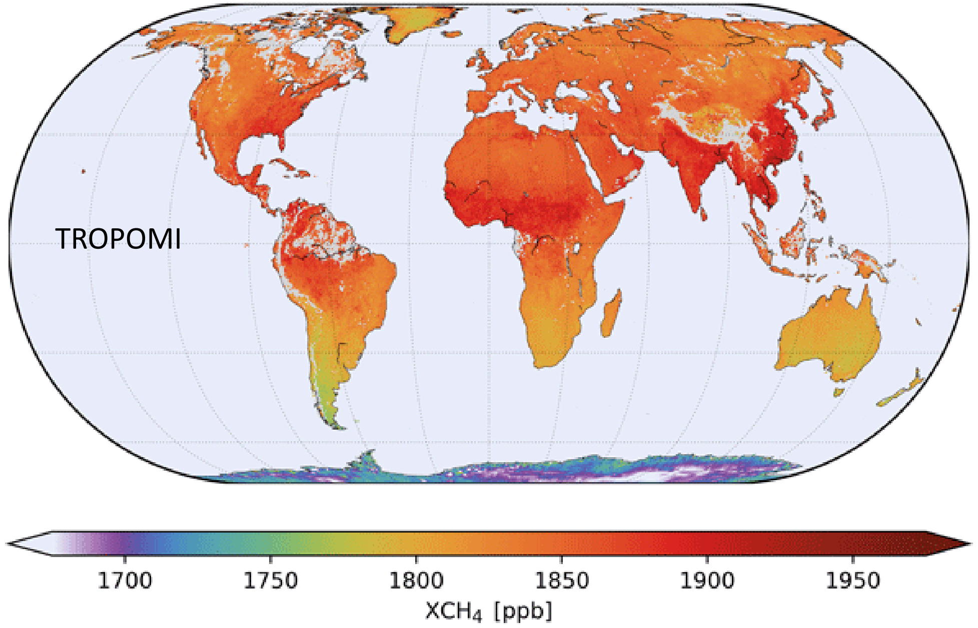
> 3 flights per location



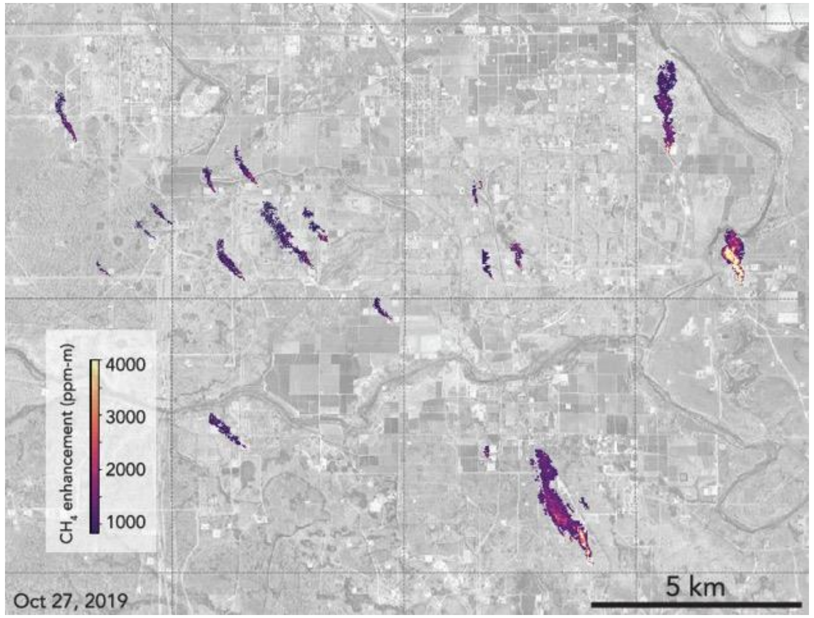


Concentration vs Plume Observations

Concentration Observations



Plume Detections



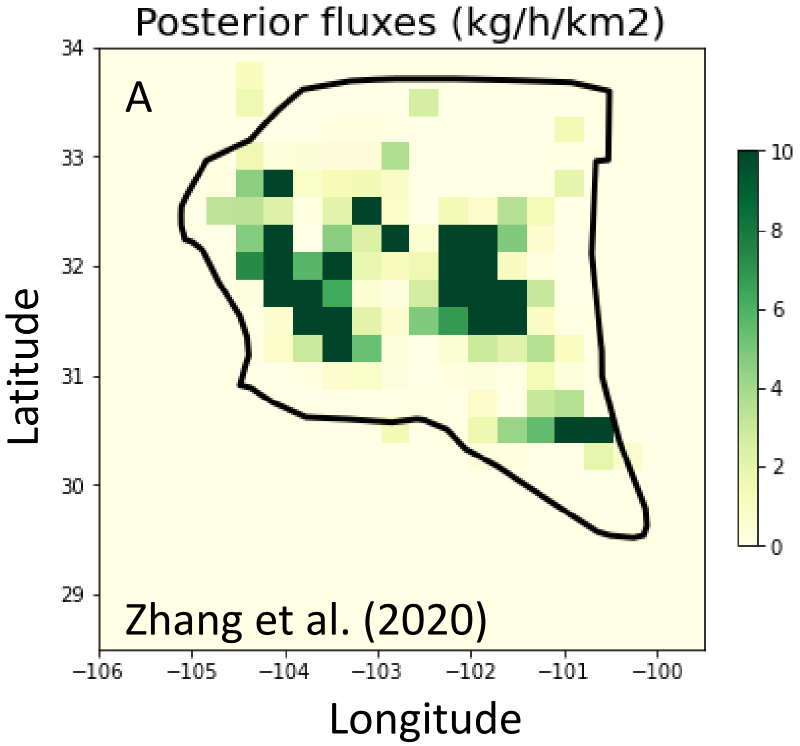
Cusworth et al. (2021)

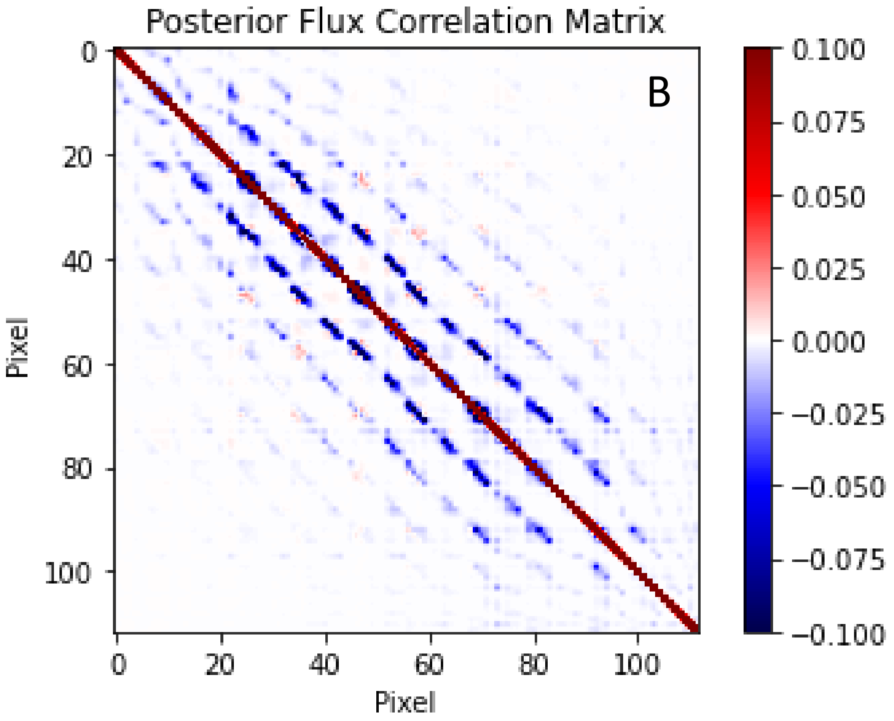
- <u>Gives spatial and temporal aggregates.</u>
- Less reliable at high spatial resolution. due to biases and resolution of CTM and observations.

- <u>Identify & monitor super-emitters.</u>
- Less reliable for spatial and temporal aggregates.

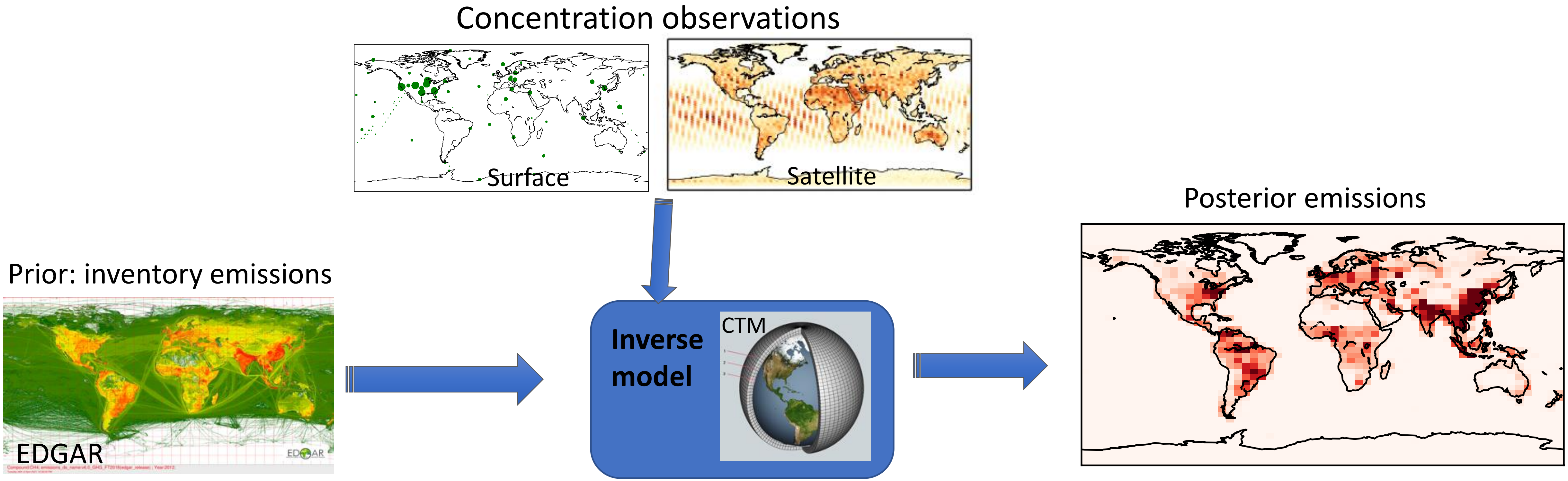
Posterior Error Matrix Issue

2019 TROPOMI inversion over Permian basin by Zhang et al (2020)



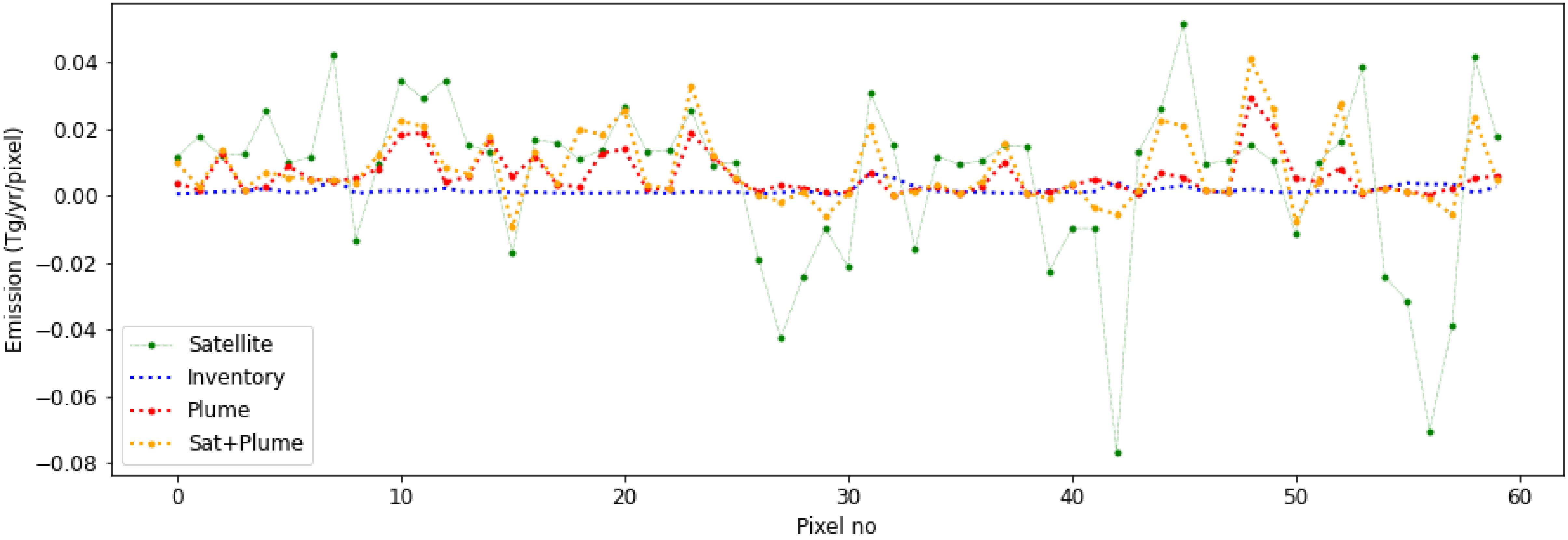


The G



- **Inverse models** combine the information from inventories and concentration observations.
- Problem: Loss of information due to resolution of transport models and observations.

Sum of Gas and Oil emissions for Select Pixels



- **The dipole effect** is causing negative emissions in the Satellite inversion. Adding plume data, (i.e., SatPLume inversion) the negative emissions up.