Reconciling satellite and in-situ estimates of North American methane emissions during the unconventional gas boom of 2009–2012

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With Data, Code, and Input from:

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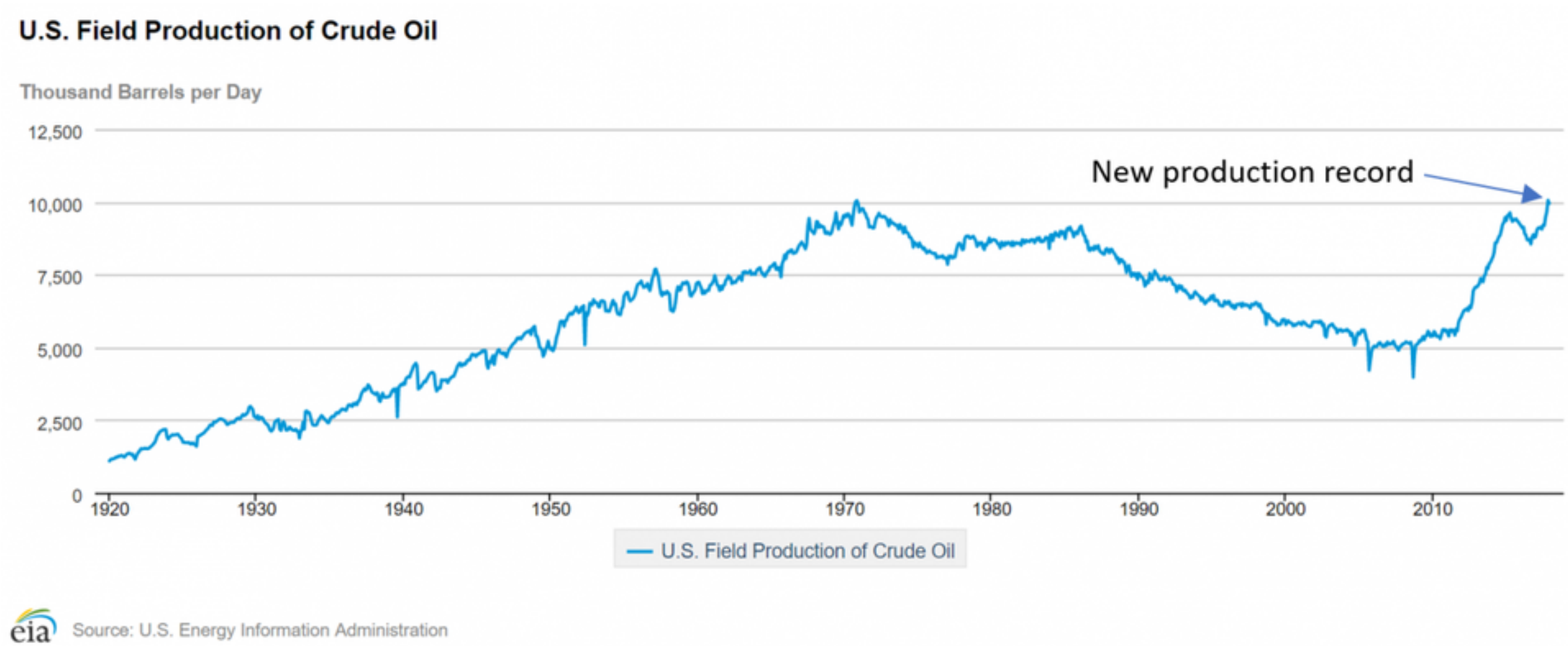
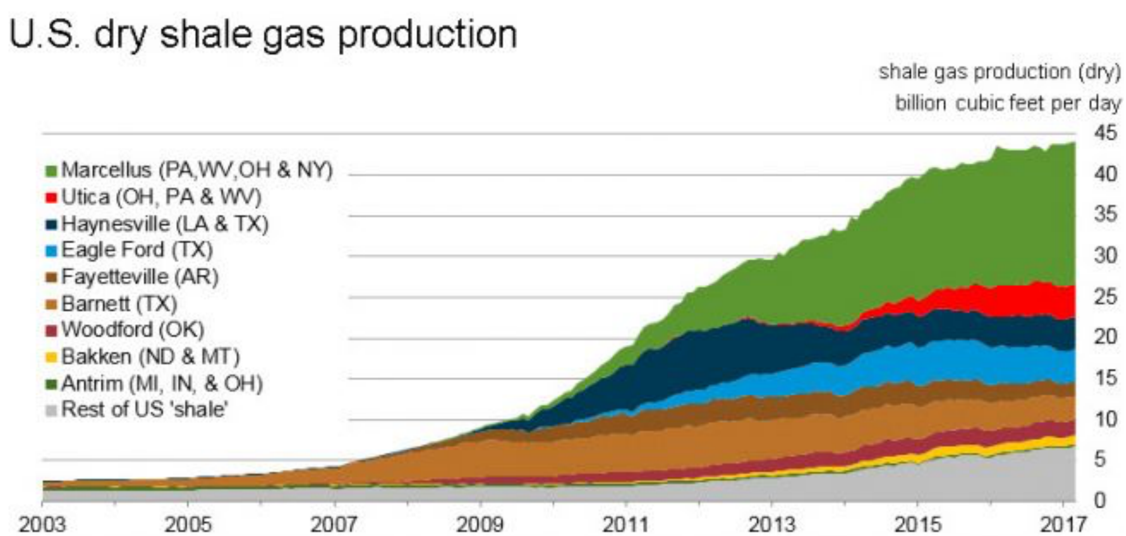
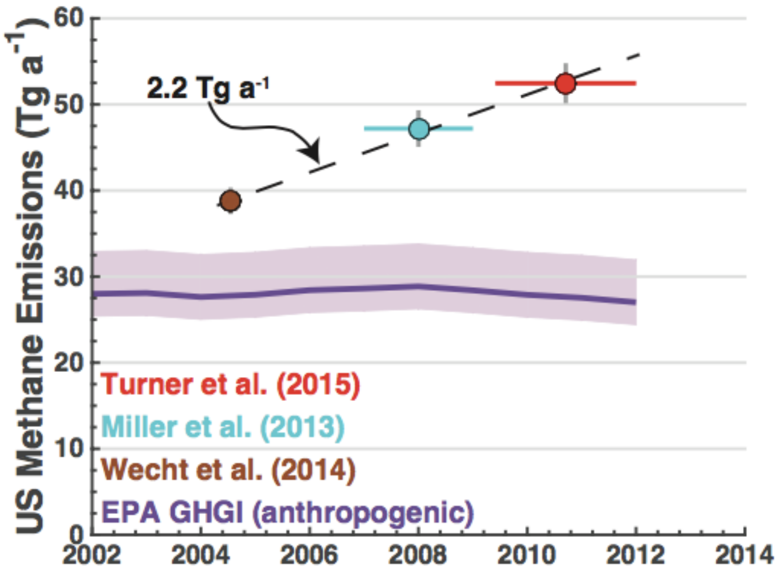
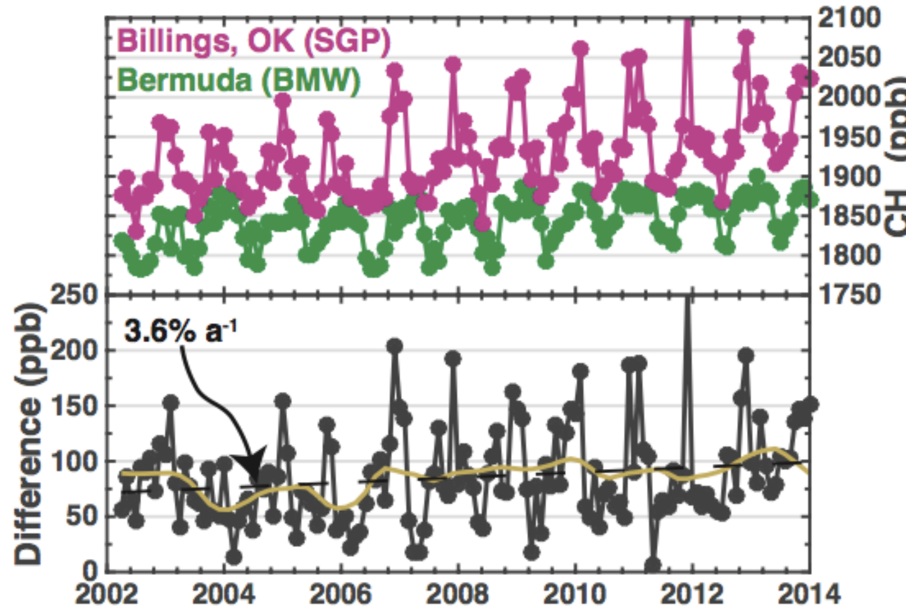
The US experienced the “shale gas revolution” 2007-2015
due to a combination of horizontal drilling and hydraulic fracturing.
Was this accompanied by significantly increased methane emissions?

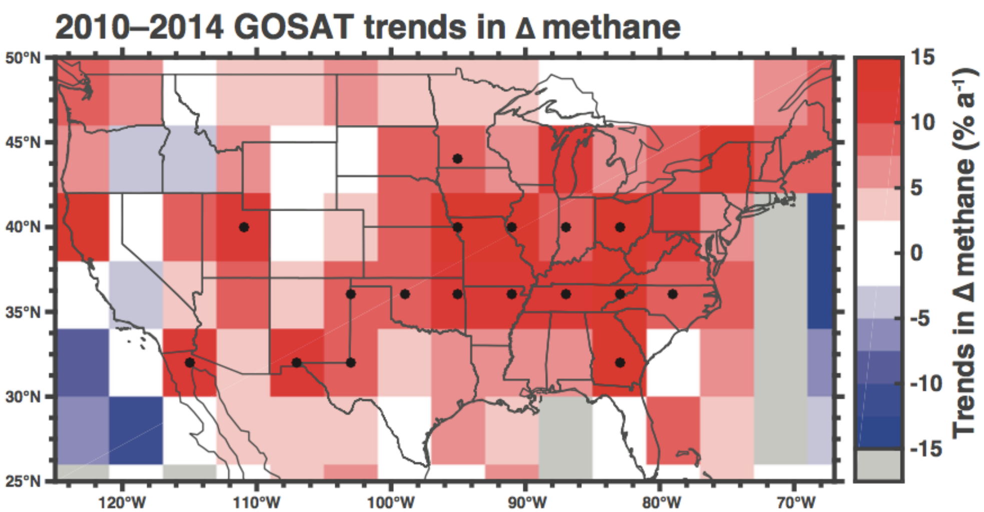




Turner et al. (2016) suggested a 30% increase in US emissions 2004-2014.







If this trend is correct, it would account for 30-60% of the renewed global trend

But Bruhwiler et al., (2017) made several poignant critiques.

In order to carefully assess trends in US methane emissions:

- a consistent inversion framework should be used to compare different periods (and data types).
- boundary conditions should be constructed in a way that avoids aliasing emissions trends.
- The seasonal sampling bias of GOSAT should be considered.

Here, we perform an analysis aimed at satisfying these points.

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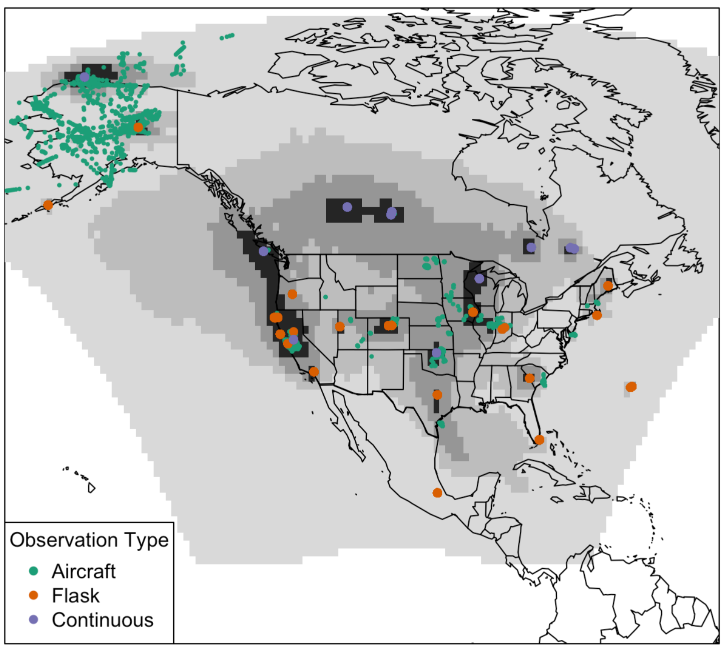
We analyzed observations using the CarbonTracker-Lagrange CH_4 inverse modeling system.

- 10 day back trajectories through 10km WRF fields (AER)
- GOSAT influence simulated with 23 levels
  weighted by pressure, averaging kernel, and water vapour
- Daily resolved geostatistical inverse model

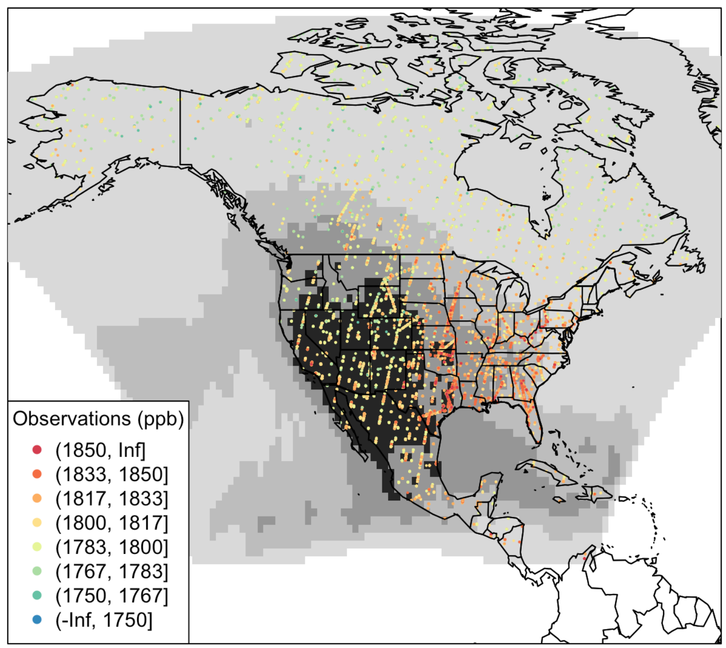
In-Situ, Flask, Aircraft (NOAA Obspack)



Surface observations selected:

- 11am - 3pm
- longer time series
- no complex terrain

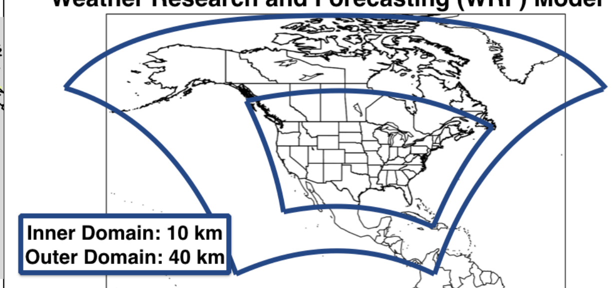
GOSAT RemoteC Proxy 2.3.7



GOSAT observations selected:

- Passed all quality flags
- No glint

Weather Research and Forecasting (WRF) Model



Optimized and run by AER
Thomas Nehkorn and Marikate Mountain

Contours Contain X% of Footprint

25% 50% 75% 100%

Our inversion system minimizes the geostatistical cost function:

Jacobian

model-data mismatch error covariance

drift coefficients

prior error covariance

$$p\left(\mathbf{s},\boldsymbol{\beta}|\mathbf{z}\right) \propto \exp\left[\overbrace{-\frac{1}{2}(\mathbf{z}-\mathbf{Hs})\mathbf{R}^{-1}(\mathbf{z}-\mathbf{Hs})}^{\text{observational constraint}}\overbrace{-\frac{1}{2}(\mathbf{s}-\mathbf{X}\boldsymbol{\beta})\mathbf{Q}^{-1}(\mathbf{s}-\mathbf{X}\boldsymbol{\beta})}^{\text{prior information}}\right]$$

observations (background corrected)

emissions state vector

matrix of predictors

(Michalak et al., 2004)

We solve a linear model of prior information.
This ensures that the prior is not influencing the trend.

We use the L-BFGS-B algorithm to solve the emissions under the constraint that they are non-negative.

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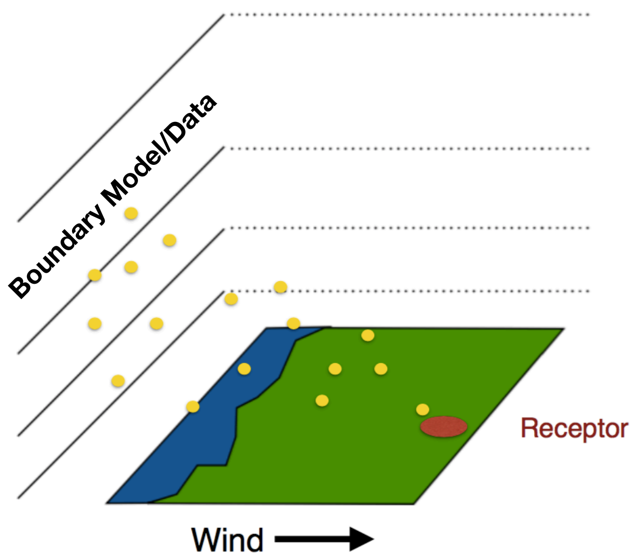
Background concentrations are usually evaluated in one of the following ways:

Empirical/model offline model

Use separate data/model
at the inversion system boundary

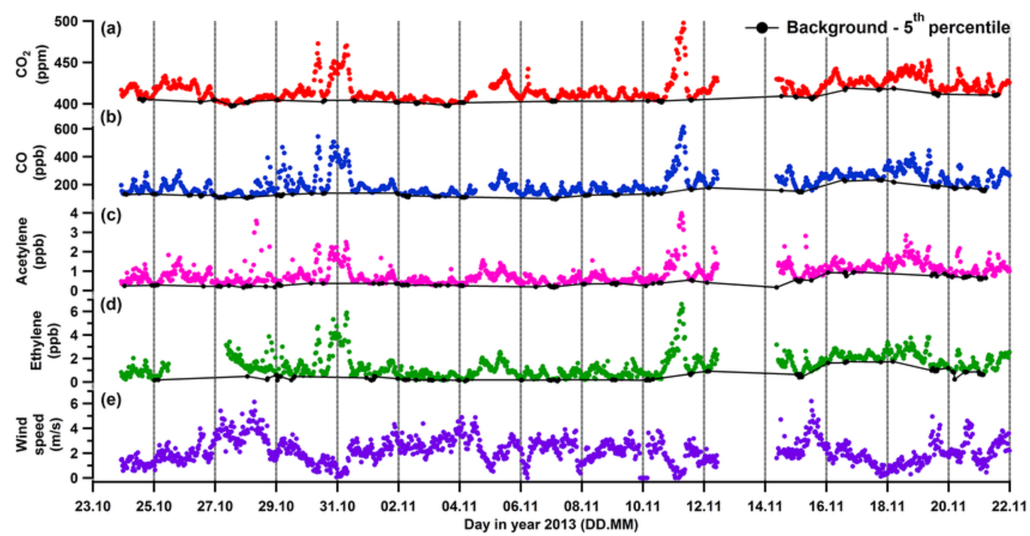


Works great for surface data
GOSAT mean enhancement for USA is 11ppb
Stratospheric errors/biases are problematic

Statistical

Use the clean-air data as
background concentrations

Example: Ammoura et al., 2015



GOSAT would need to be binned spatially
Many regions have no clean air (e.g. Texas)

We created a hybrid method

The background is estimated using a *quantile regression*.

A quantile regression is a linear model of data,
but instead of predicting the mean, it predicts a quantile q.

The quantile regression minimizes:

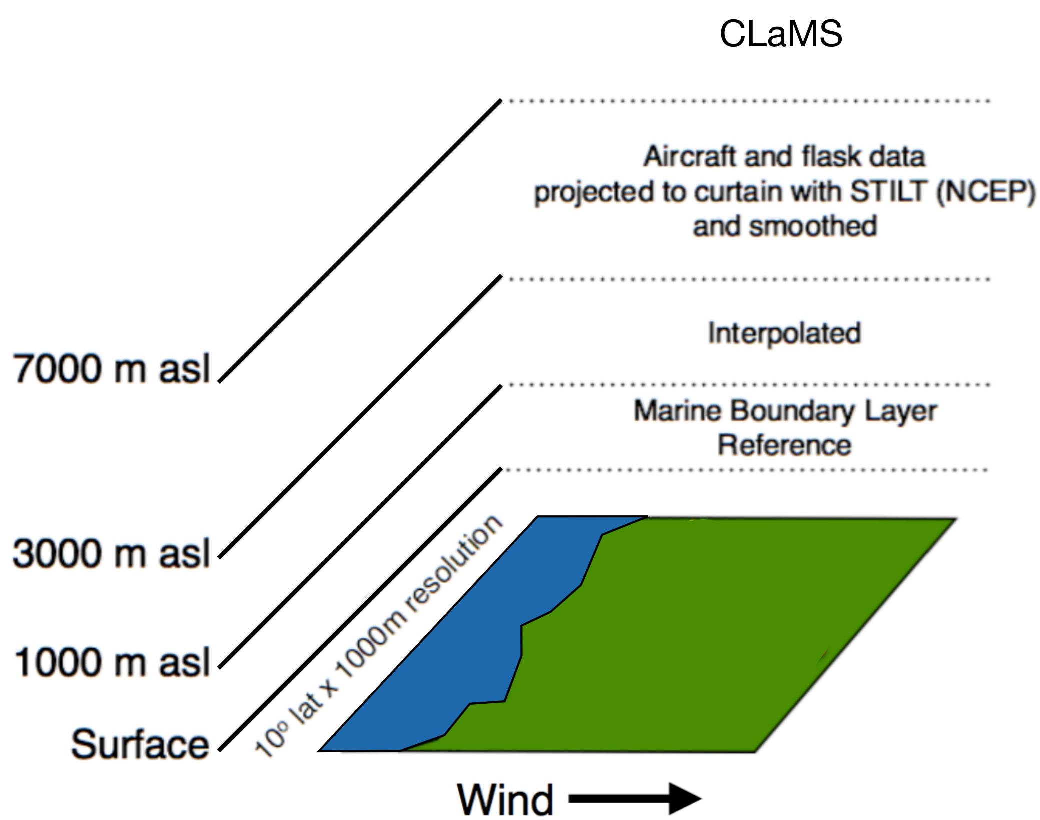
$$Q(\beta_q) = \sum_{i|y_i < x_i\beta} q|y_i - x_i\beta| + \sum_{i|y_i \geq x_i\beta} (1-q)|y_i - x_i\beta|$$

Our Variables:

x_2 Stratospheric contribution from CLaMS

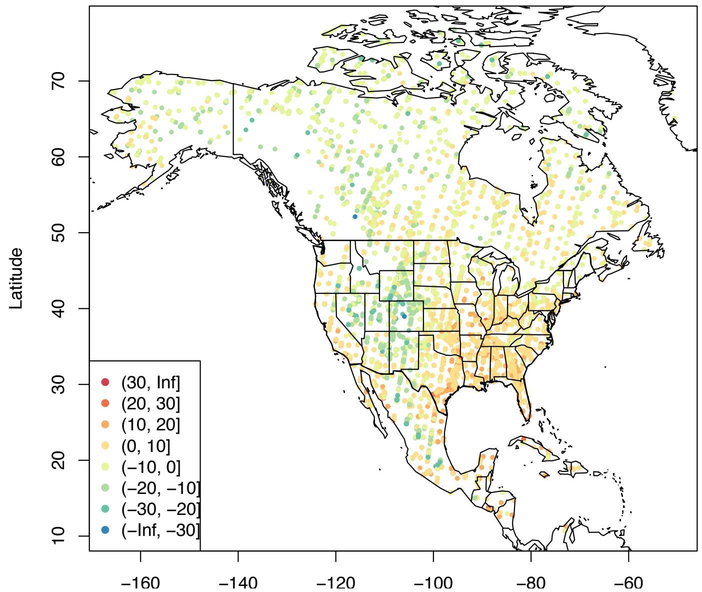
x_1 Tropospheric contribution from NOAA Marine Boundary Reference/ Aircraft and Flask

x_0 Intercept

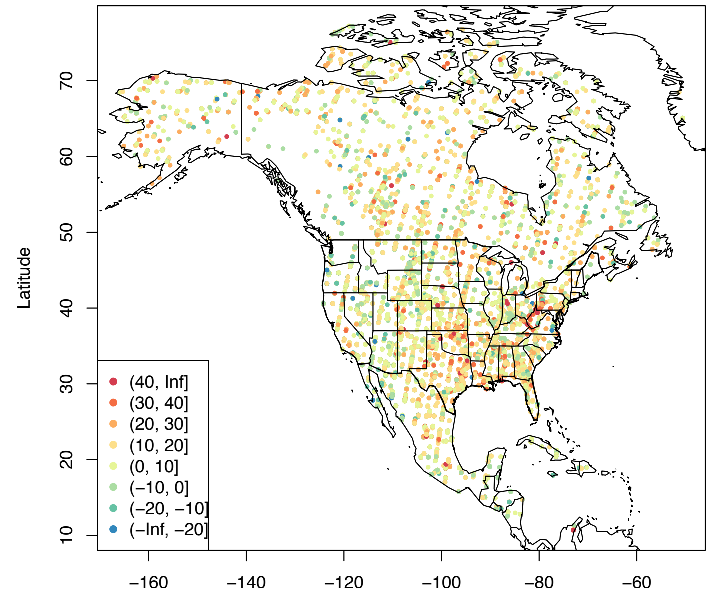


The quantile regression produces a clear signal, and has good residuals in time and latitude

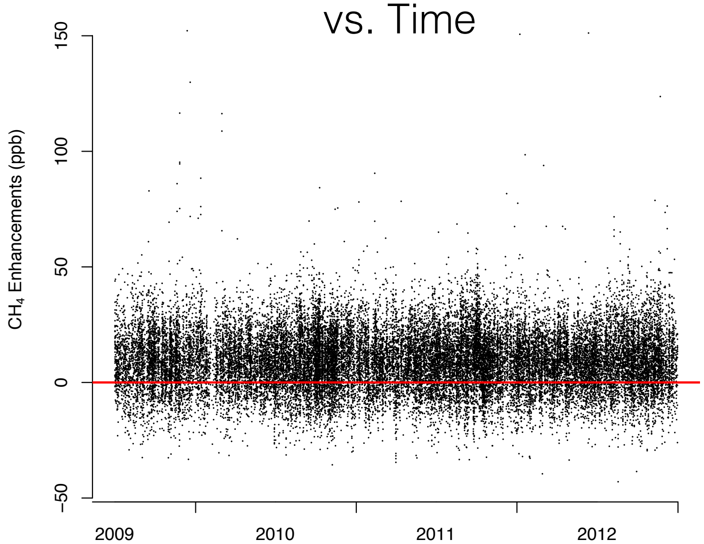
De-seasonalized and
de-trended background



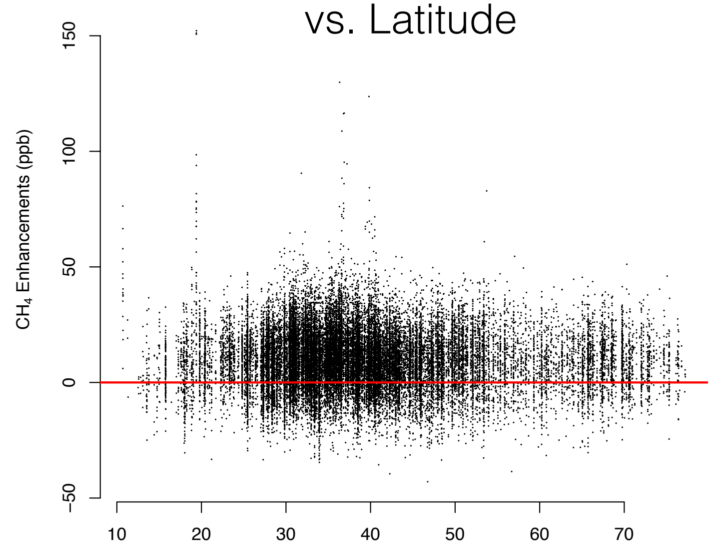
Observations - background



Observations - background
vs. Time

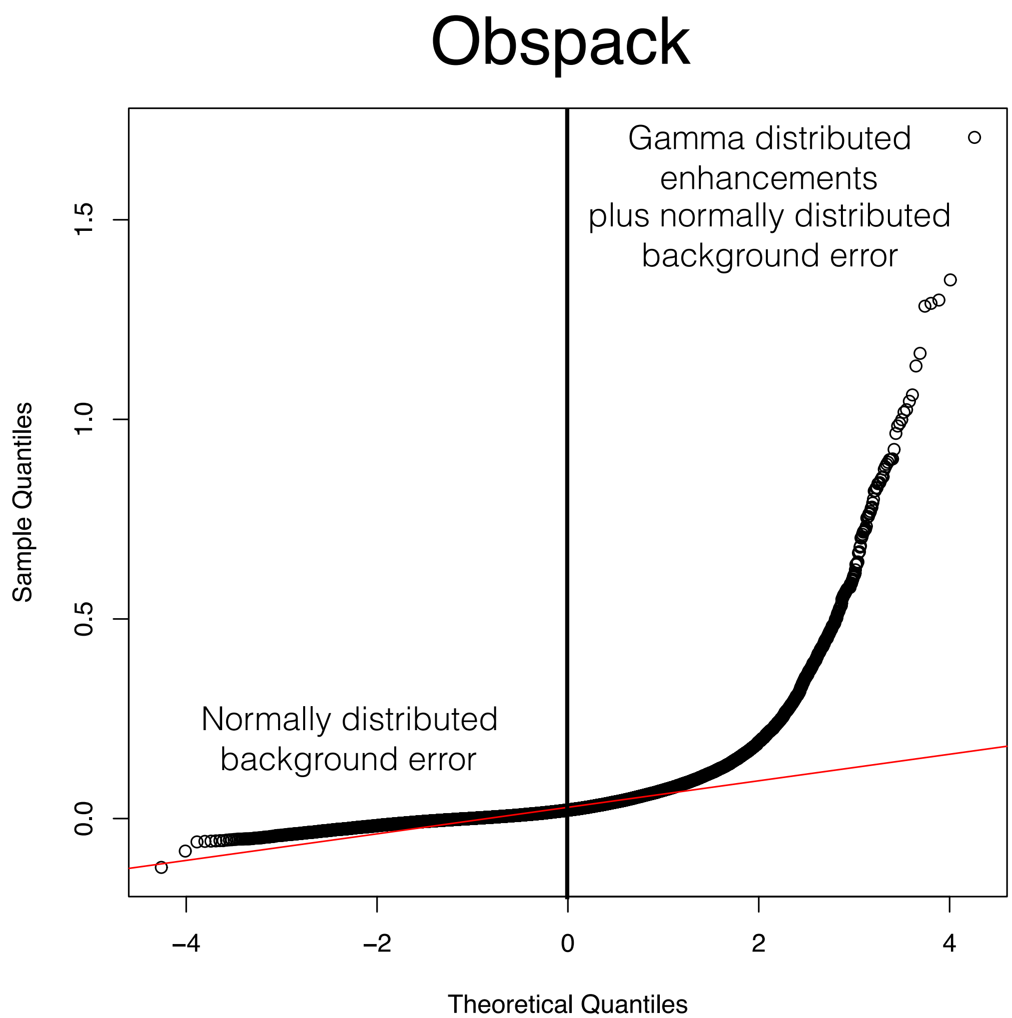


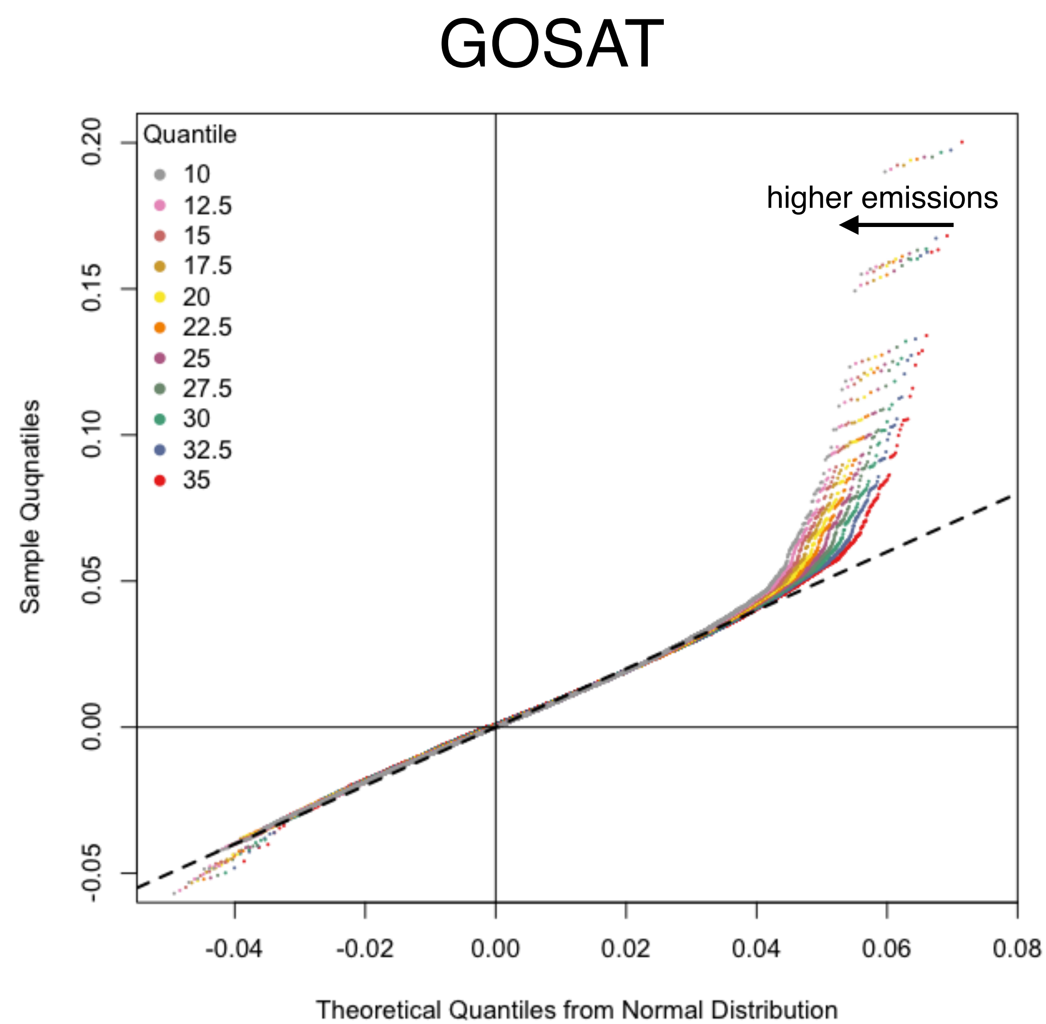
Observations - background
vs. Latitude



The positive skewness of the distribution of observations gives the strength of the signal.

Q-Q plots

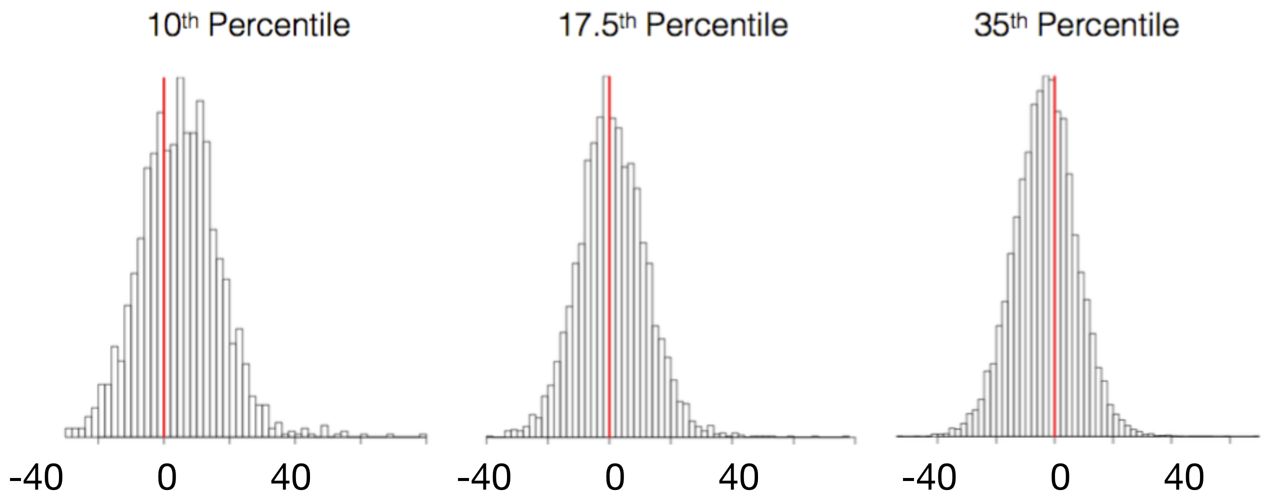


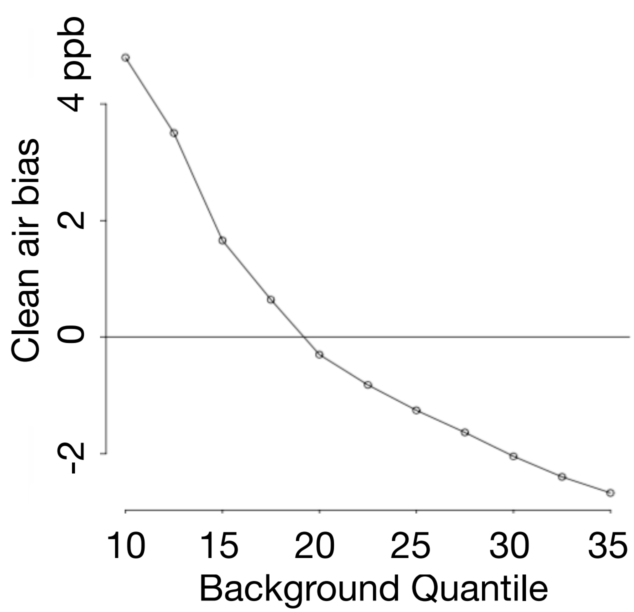


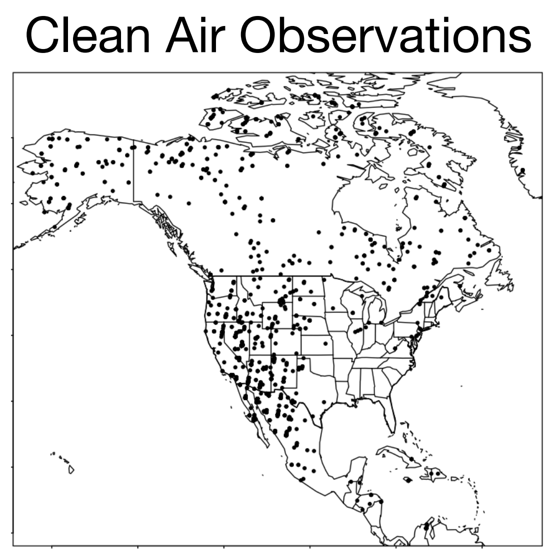
But how do we decide which quantile to use?

The correct quantile predicts clean air observations without bias

Look at observations with <1.5ppb enhancement.
Subtract the enhancement and calculate the mean.

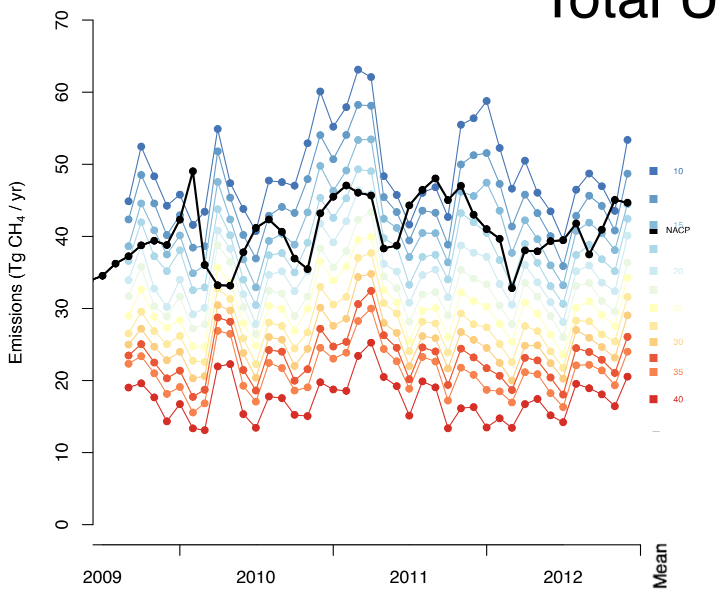


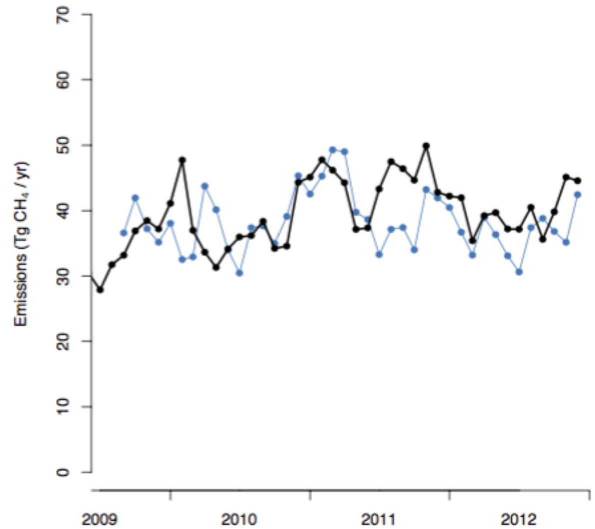




We find independent agreement between posterior emissions using GOSAT and Obspack data

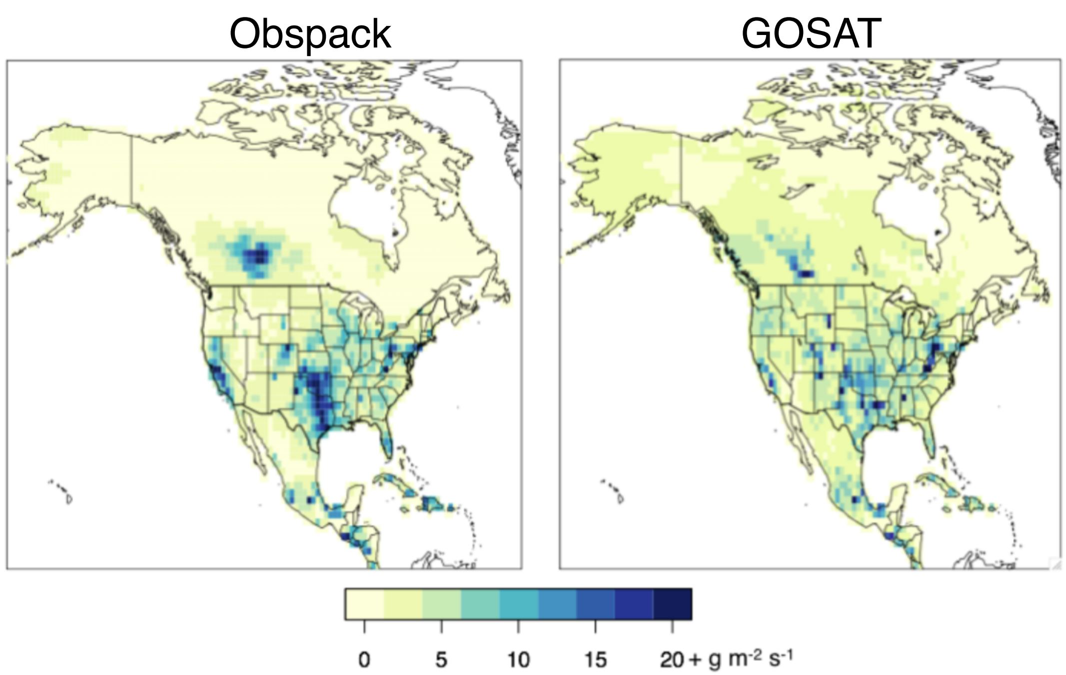
Total US Emissions





Black: Obspack: 41 ± 2 Tg/yr

Colors: GOSAT: 40 ± 3 Tg/yr



In order to carefully assess trends in US methane emissions:

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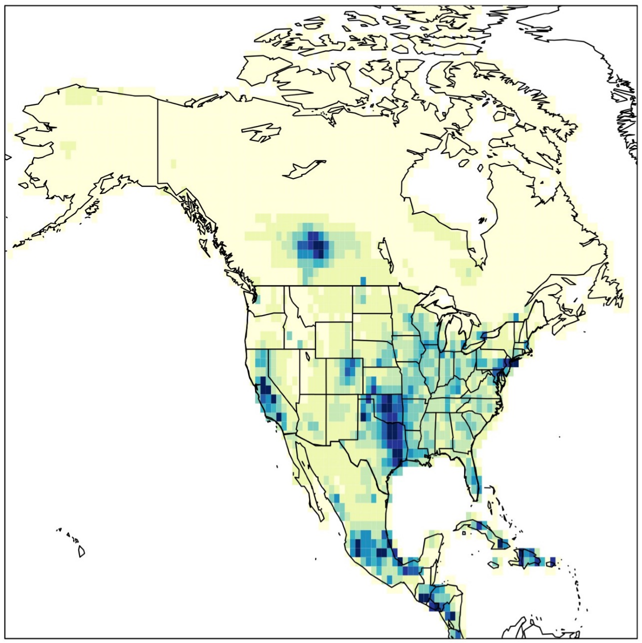
Does the seasonality of GOSAT sampling produce a bias?

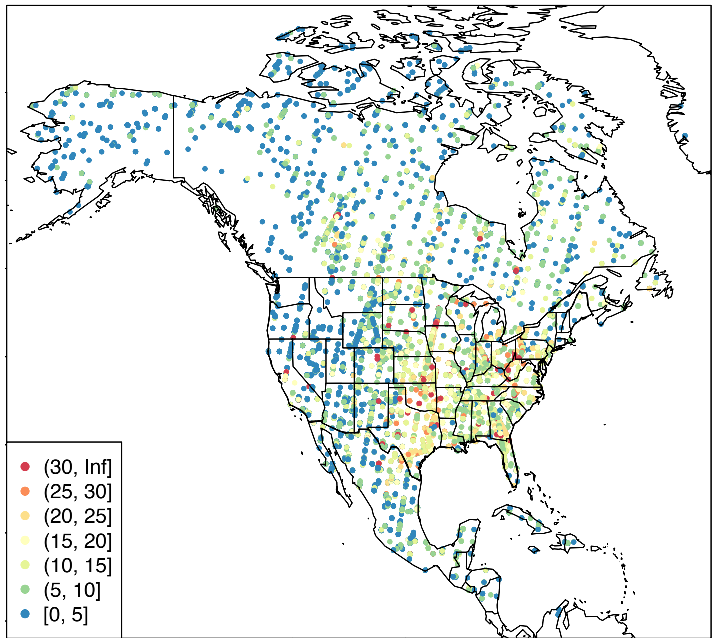
We run an OSSE inversion using the GOSAT footprints,
with perfect transport and backgrounds,
and target emissions given by the posterior of the NACP inversion.

NACP



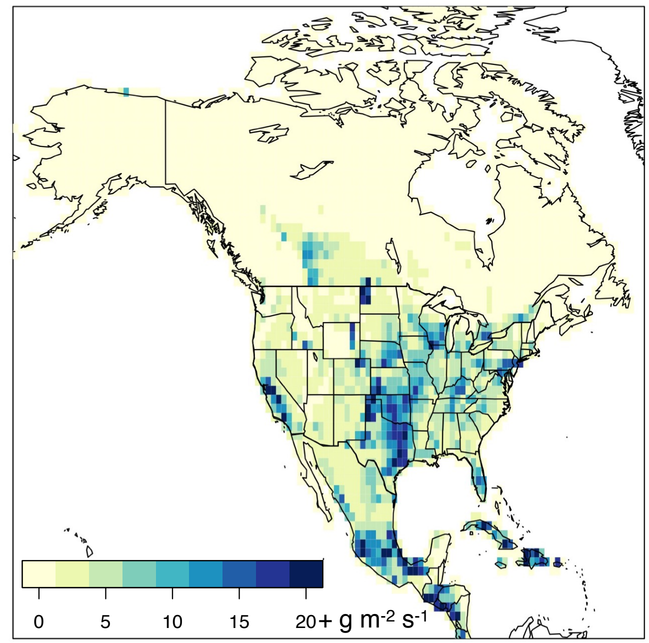
Assume these emissions (“target”)

GOSAT



Simulate these observations

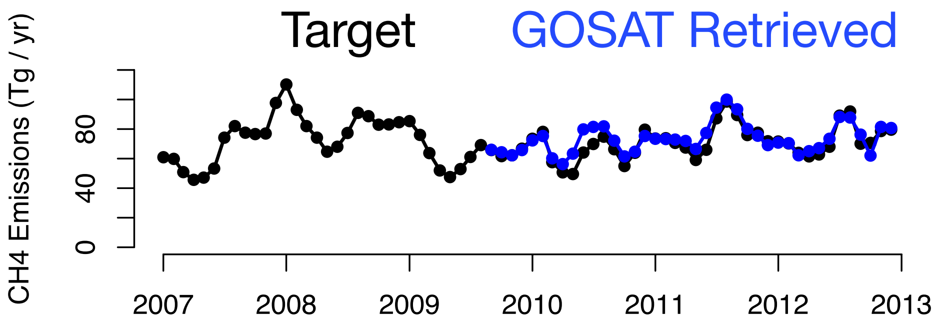
OSSE

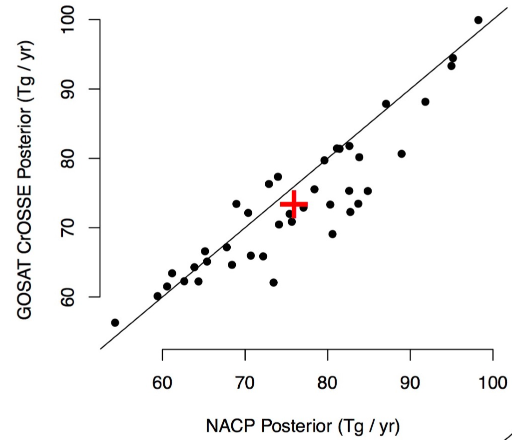


Retrieve these emissions

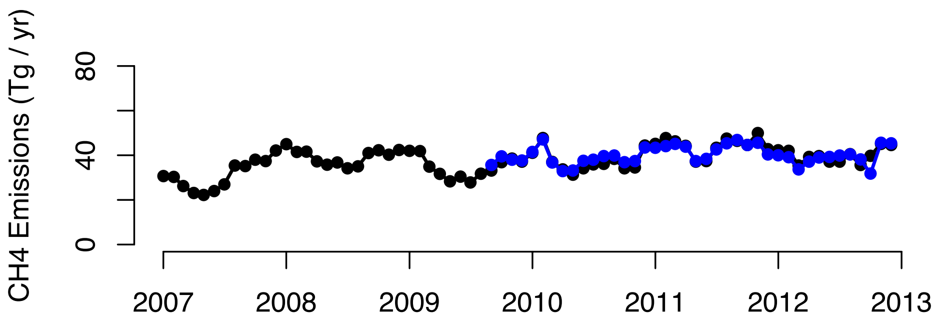
GOSAT does a good job of matching the budget

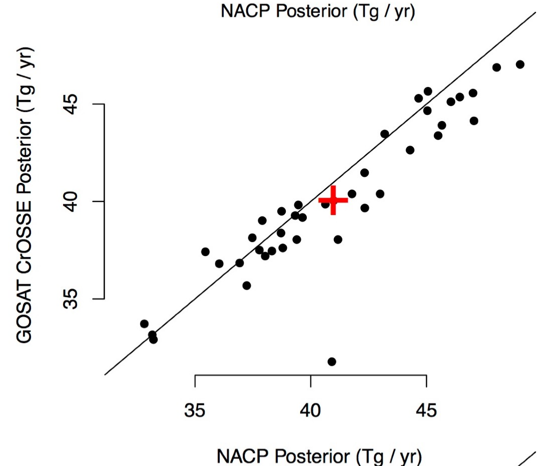
Whole Domain



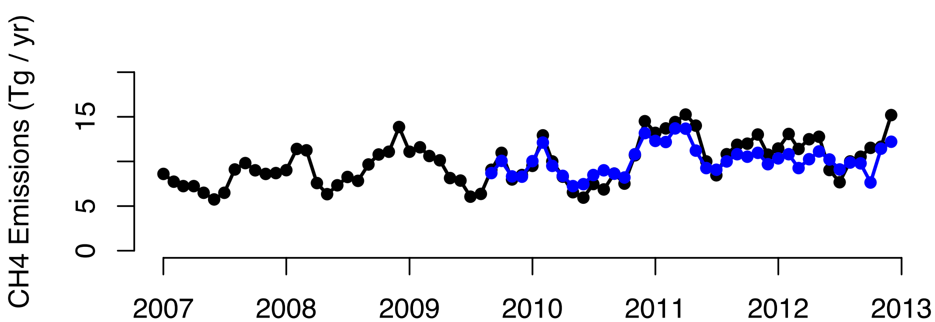


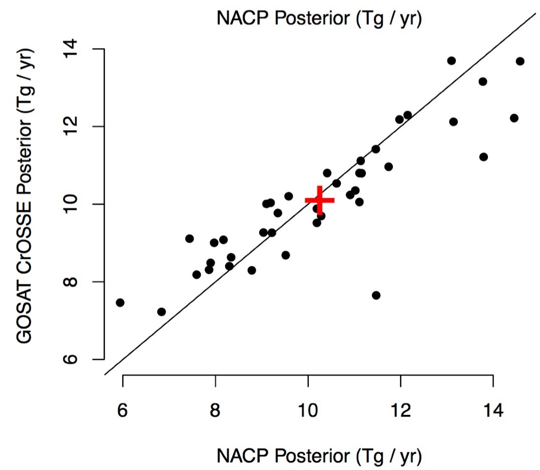
USA





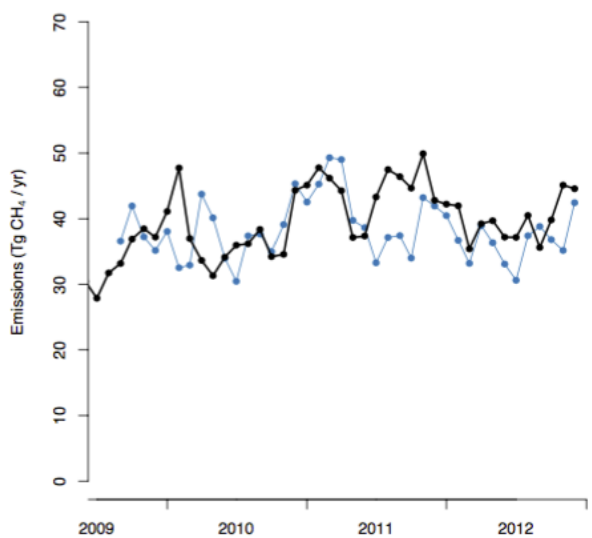
Texas/ Oklahoma

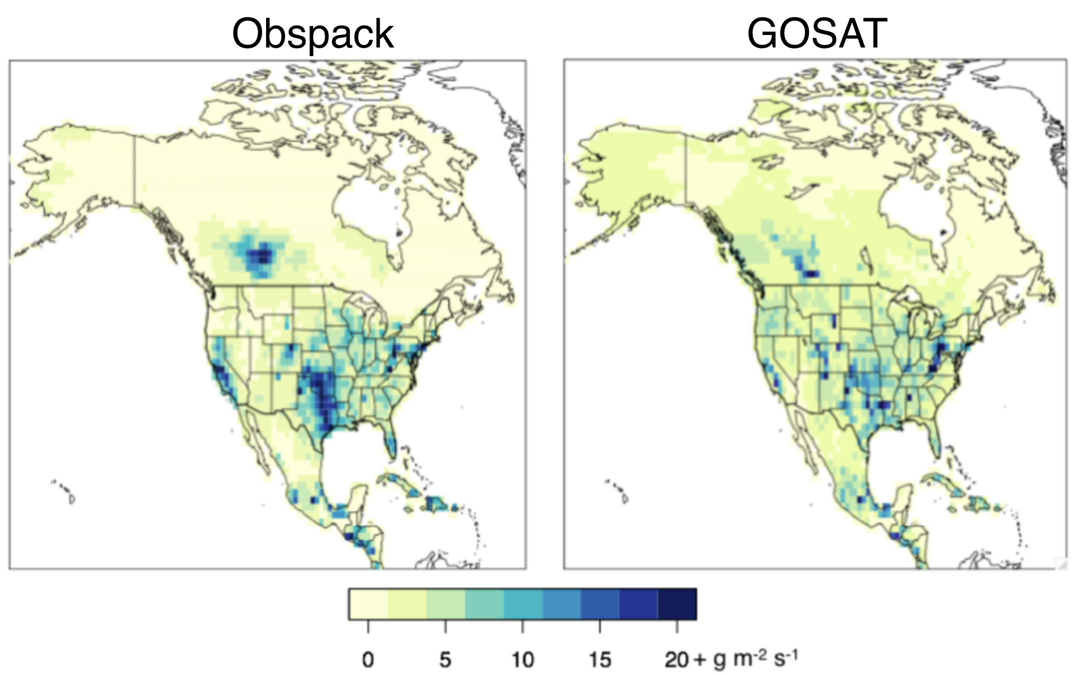




Conclusions

- We retrieved US methane emissions from GOSAT and Obspack with good agreement.
- Our inversion system does not produce a significant trend in US methane emissions for 2009 - 2012.
- 2013 and 2014 coming shortly.





Thanks!

Check out CarbonTracker-Lagrange at
esrl.noaa.gov/gmd/ccgg/carbontracker-lagrange/

And CarbonTracker at:
esrl.noaa.gov/gmd/ccgg/carbontracker/

Contact me at:
benmergui@g.harvard.edu

Error Parameters (Restricted Maximum Likelihood)

NACP

$$\sigma_{\mathrm{Q}} = 0.034\,\mu\mathrm{mol\ m^{-2}\ s^{-1}}$$
$$\phi_{\mathrm{l}} = 100\ \mathrm{km}$$
$$\phi_{\mathrm{t}} = 30\ \mathrm{days}$$
$$\sigma_{\mathrm{R}} = 30.6\,\mathrm{ppb}$$

GOSAT

$$\sigma_{\mathrm{Q}} = 0.05\ \mu\mathrm{mol\ m^{-2}\ s^{-1}}$$
$$\phi_{\mathrm{l}} = 100\ \mathrm{km}$$
$$\phi_{\mathrm{t}} = 30\ \mathrm{days}$$
$$\sigma_{\mathrm{R}} = 10\ \mathrm{ppb}$$