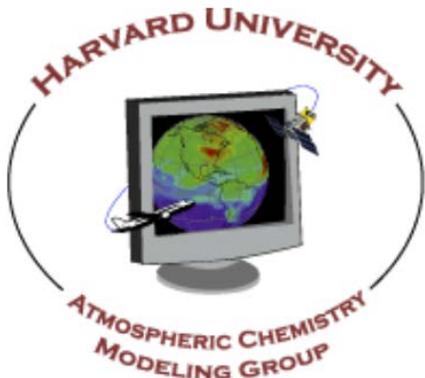


Global methane budget and trends in 2010-2017: complementarity of inverse analyses using in situ and satellite observations

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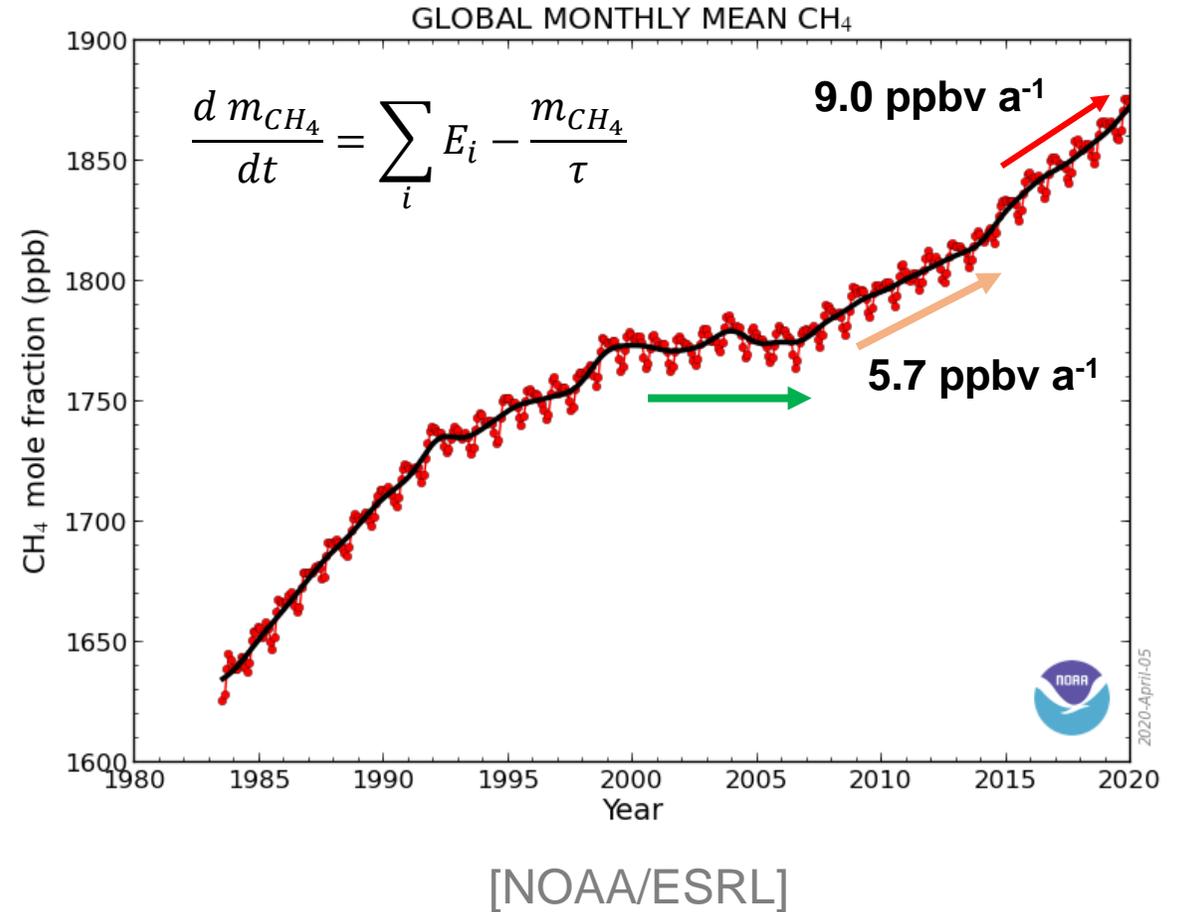
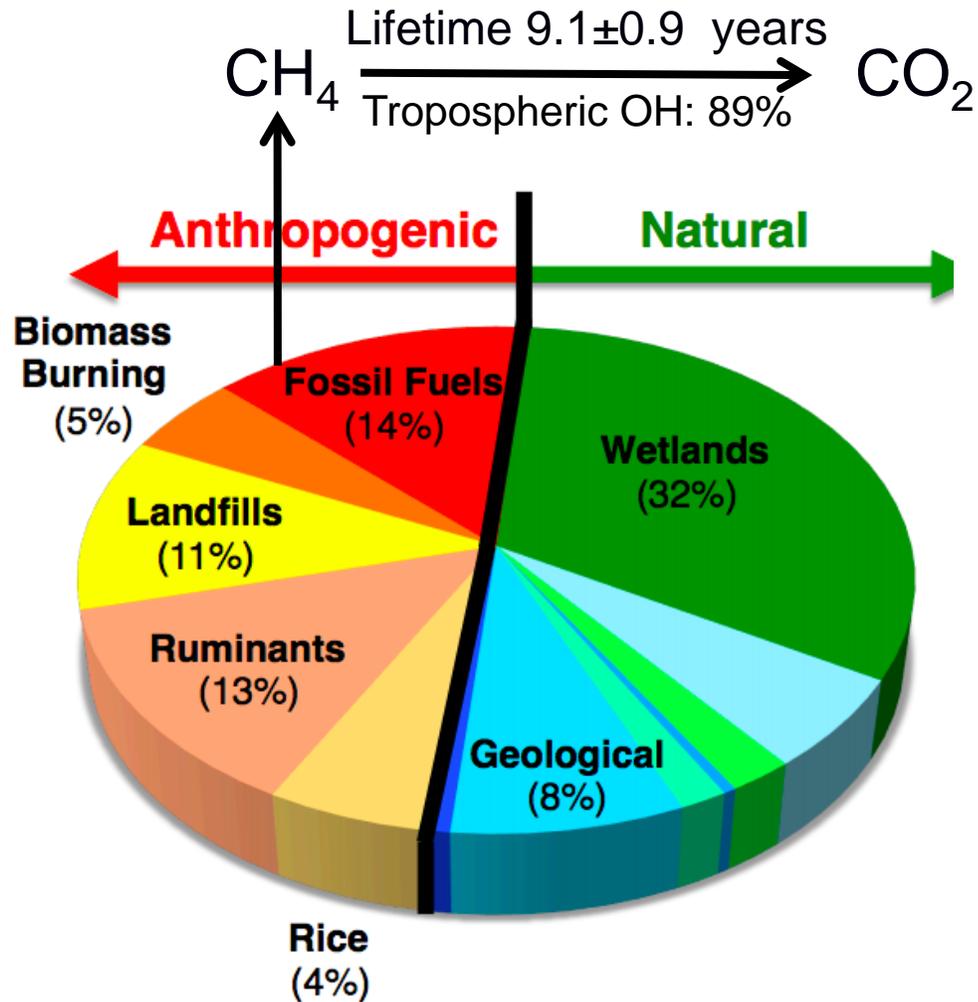


Ongoing efforts to understand global methane budget and trends

Sources
 $\sim 550 \pm 60 \text{ Tg a}^{-1}$

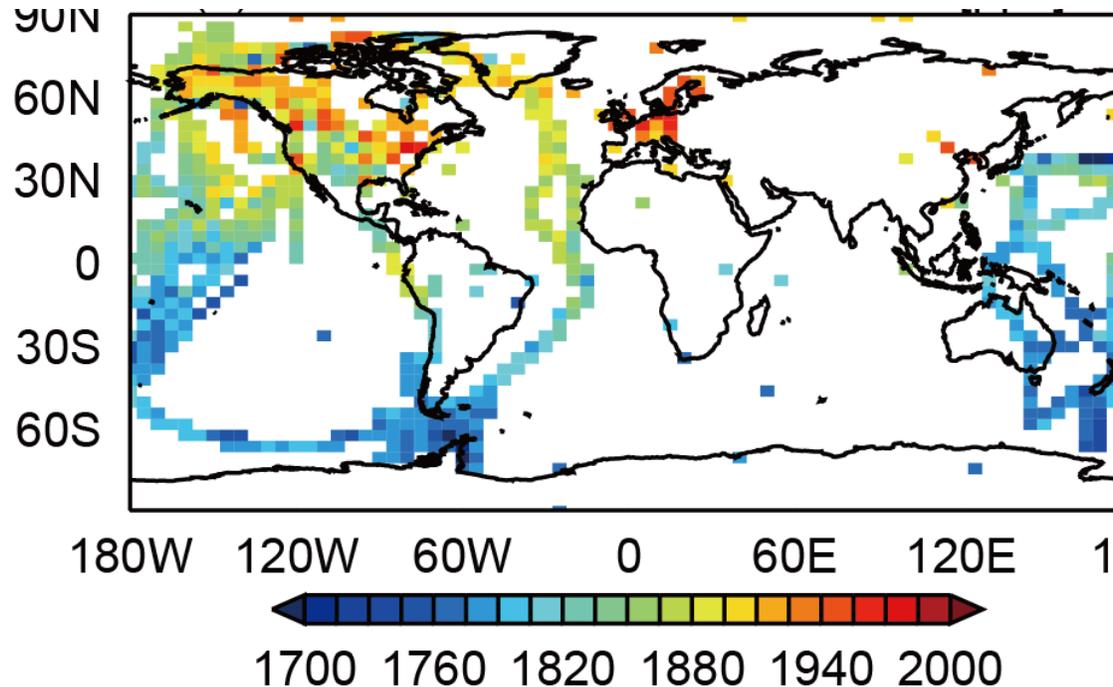


Sinks
 OH, soil uptake

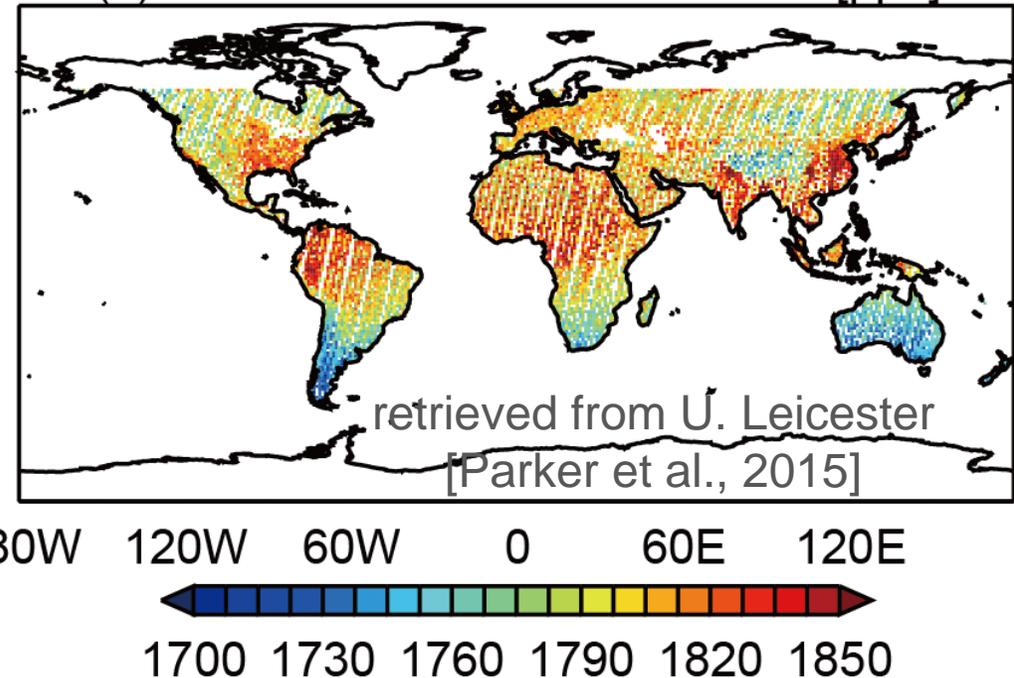


Comparing suborbital and satellite observations in inversion

In situ (suborbital) methane from ObsPack, 2010-2017
(surface, tower, shipboard, aircraft)



GOSAT measurements of, 2010-2017
atmospheric methane column



Pros: accurate, sensitive to surface flux

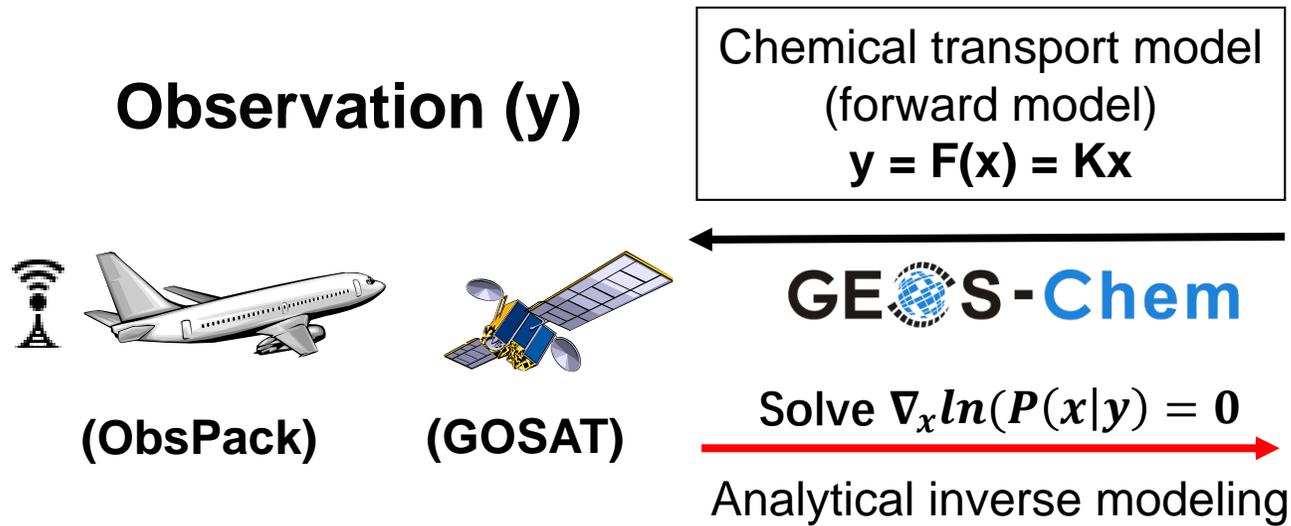
Cons: spatial sparsity

Pros: massive, global coverage

Cons: errors associated with retrieval

Are ObsPack (in situ) and GOSAT (satellite) observations consistent and complementary/redundant in inversion?

Method: analytical inversion of ObsPack and GOSAT observations



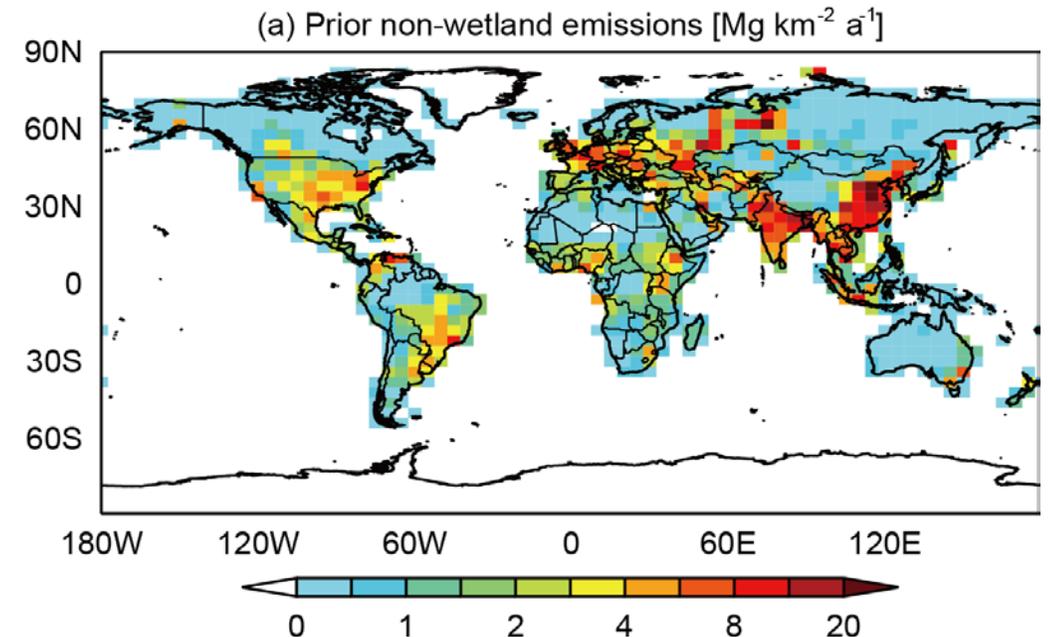
State vectors (x)

- mean non-wetland emissions on $4^\circ \times 5^\circ$ grid for 2010-2017
- trends of emissions for 2010-2017, gridded
- Monthly wetland emissions in 14 subcontinental regions
- Annual hemispheric OH concentrations

□ **Prior estimates:** GFEI for fuel emission; EDGAR v4.3.2 for global others; GEPA; WetCHARTs for wetland; No trends in 2010-2017.

□ **Analytical inversion:** Yielding closed-form posterior error \hat{S} and averaging kernel sensitivity A

□ Conduct ObsPack-only, GOSAT-only, and GOSAT+ObsPack inversions

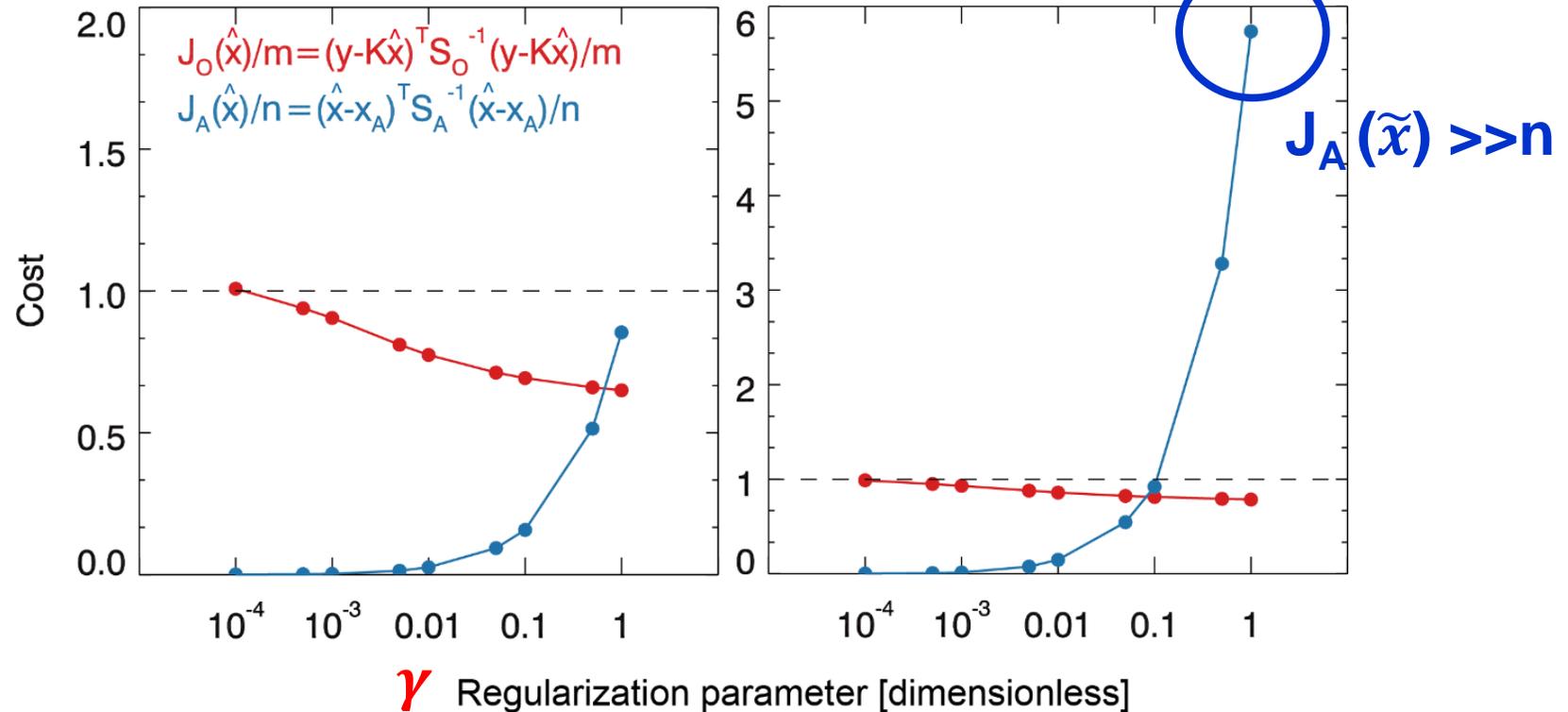


Weighting in situ and satellite observations in inversion

Cost function $J(x) = \underbrace{(x - x_A)^T S_A^{-1} (x - x_A)}_{J_A} + \gamma \underbrace{(y - F(x))^T S_O^{-1} (y - F(x))}_{J_O}$

(a) In situ

(b) GOSAT



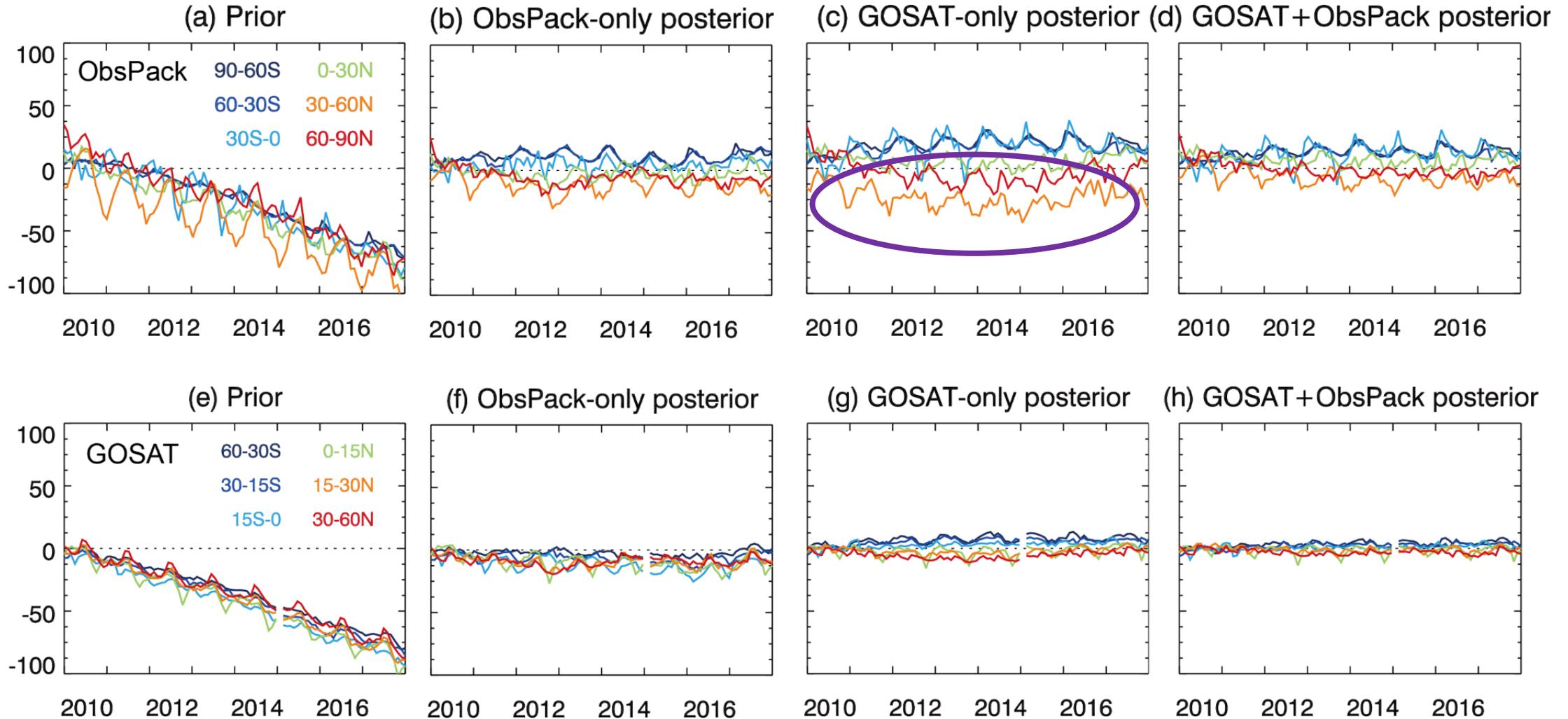
Ideally,
 $J_A \sim n$ (number of state vector)
 $J_O \sim m$ (number of observation)

$\gamma = 1$ (no regularization) for ObsPack in situ observations

$\gamma = 0.1$ for GOSAT satellite observations

Evaluating posterior model fit to observations

Model-observation methane difference [ppb]



- ❑ Using either ObsPack or GOSAT is enough to constrain background methane and global methane budget imbalance (as it can fit observed trend).
- ❑ GOSAT could not fit ObsPack surface / tower observations that are sensitive to source.

Ability of ObsPack vs. GOSAT to constrain anthropogenic emission

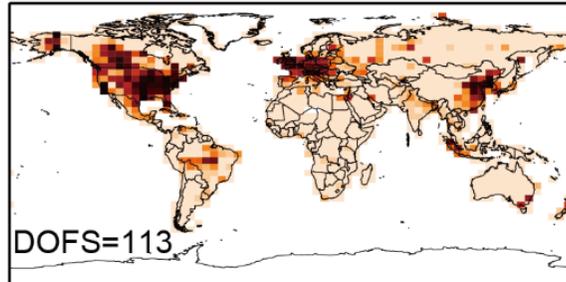
Averaging kernel sensitivities for non-wetland (anthropogenic) emissions on 1009 grid.

$$A = \frac{\partial \hat{x}}{\partial x} = I_n - \hat{S}S_A^{-1}$$

Averaging kernel sensitivities

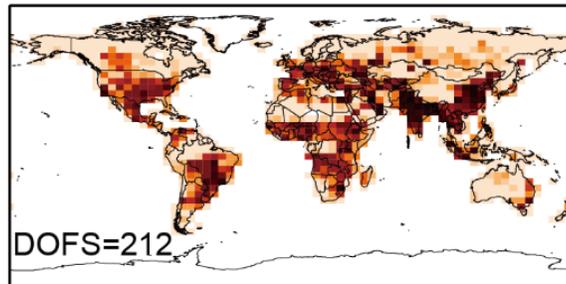
(a)

In situ-only inversion



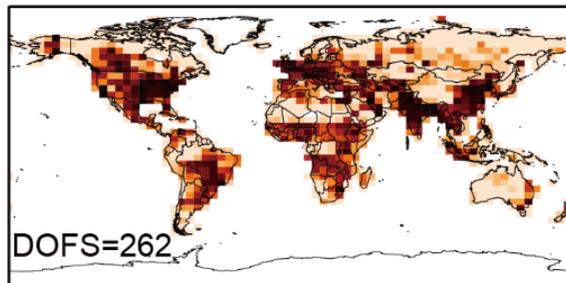
(c)

GOSAT-only inversion



(e)

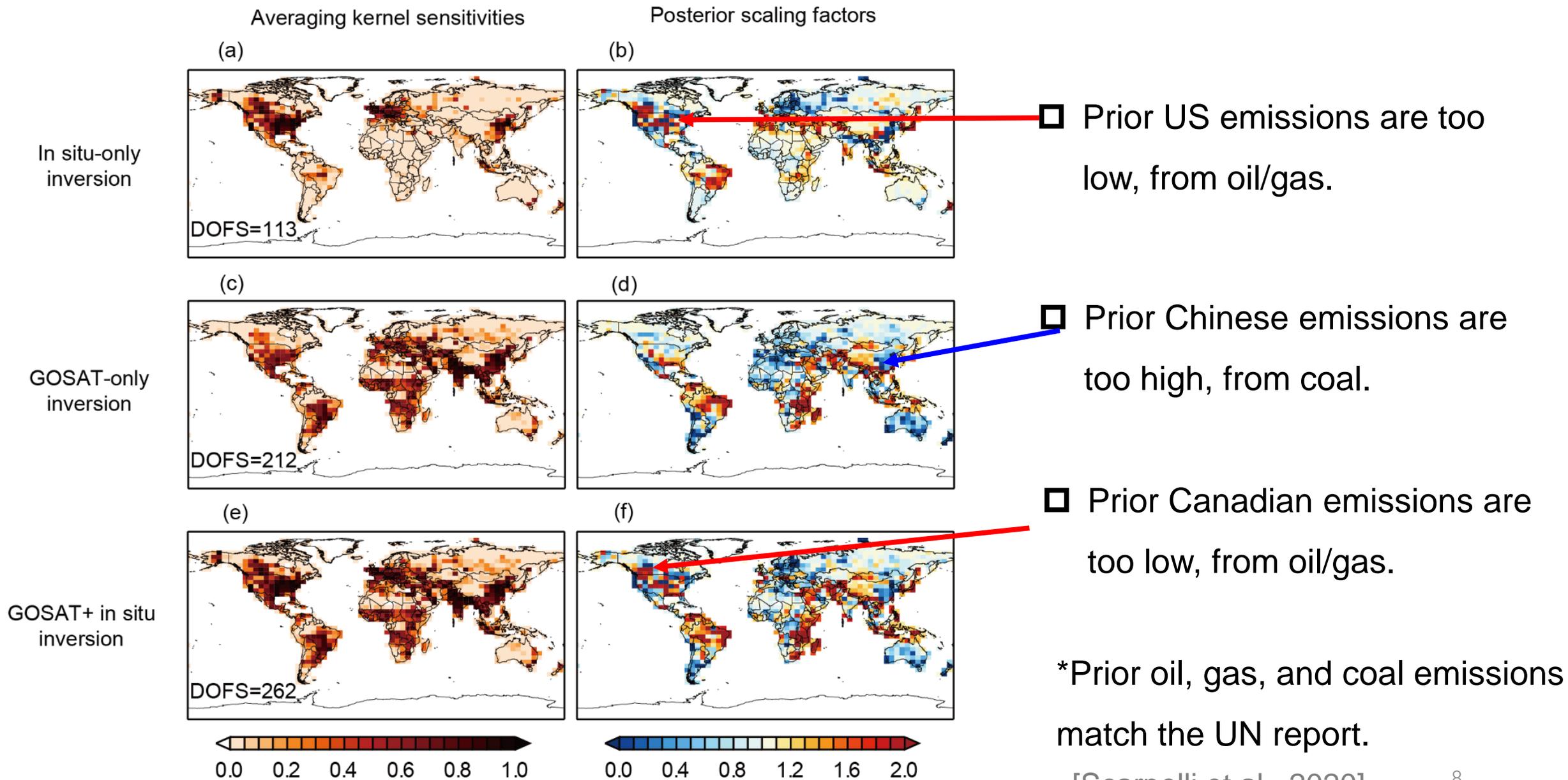
GOSAT+ in situ inversion



DOFS: Degree of freedom for signal, trace of (A), =1009 if fully constrained

- ❑ Globally, GOSAT provides more information than ObsPack. (DOFS=212 vs DOFS=113)
- ❑ ObsPack can add 50 (from 212 to 262) independent pieces of information (DOFS) to GOSAT (**complementarity**).
- ❑ GOSAT provides strong constraints in the tropics, ObsPack is valuable in northern middle and high latitudes (US, Canada, Europe, China).

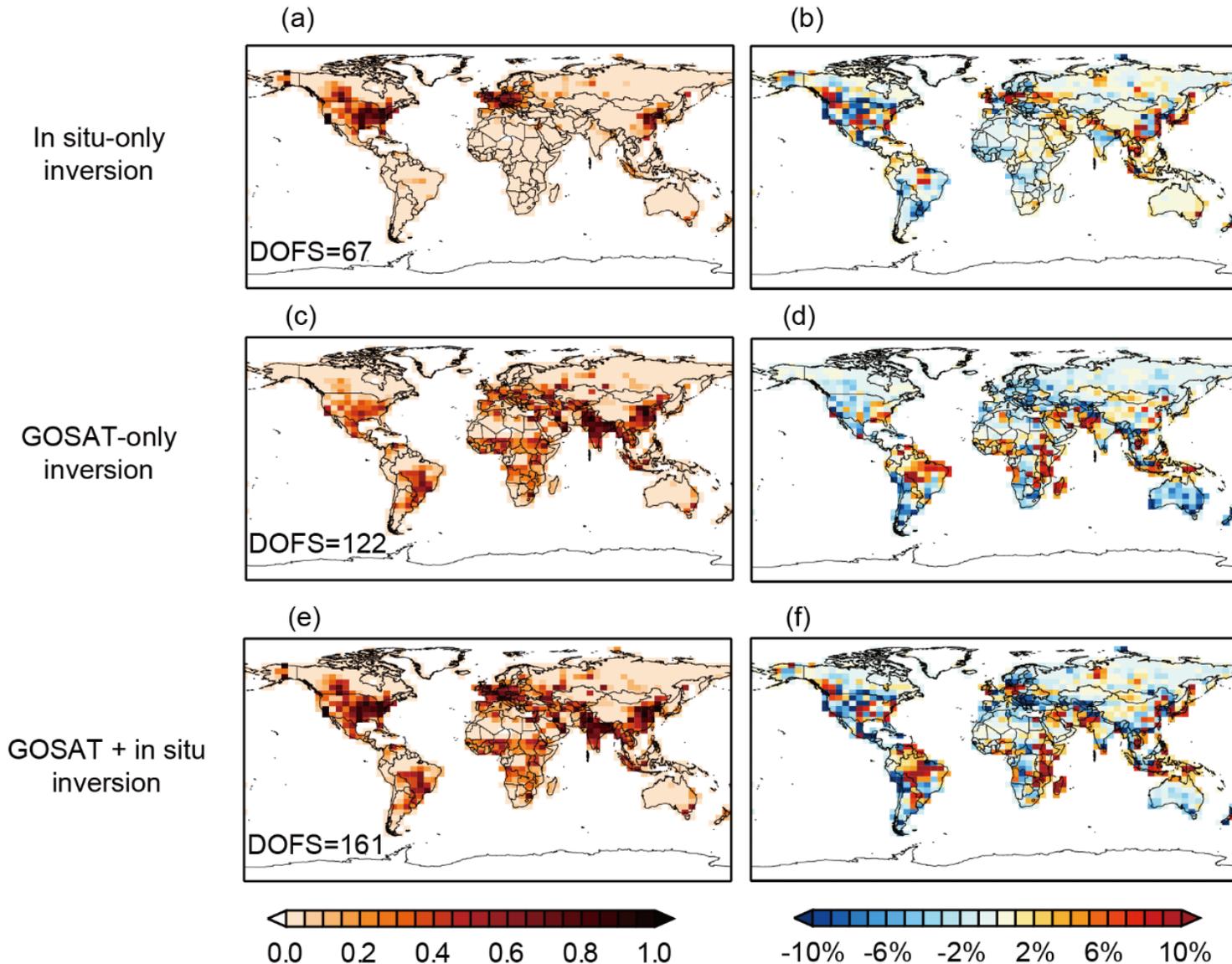
Posterior correction to prior anthropogenic emissions



Anthropogenic emission trends in 2010-2017

Averaging kernel sensitivities

Estimated trend [a^{-1}]



□ The joint inversion shows methane emission increases in the US ($\sim 0.4 \text{ Tg a}^{-2}$) and China ($\sim 0.1 \text{ Tg a}^{-2}$). Europe and Canada shows no trends.

□ Global non-wetland emissions increases by $1.7 \pm 0.6 \text{ Tg a}^{-2}$, information is mostly from GOSAT.

Global methane budget in 2010-2017

	Prior	ObsPack	GOSAT	GOSAT+ObsPack
Total sources [Tg a⁻¹]	533	515	504	551
Anthropogenic	344	359	333	371
Wetland emission	161	126	15	16
Fire emissions	14	15	16	16
Seep, termites	14	15	140	148
Total sinks [Tg a⁻¹]	540	494	478	528
OH oxidation	468	421	406	455
Other loss	73	73	72	73
Mean imbalance [Tg a⁻¹]	-7	21	26	23
Methane chemical lifetime [a]	10.6	11.9	12.5	11.2
<i>r</i> (methane emissions vs lifetime)	/	-0.53	-0.72	-0.68

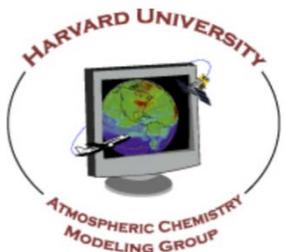
Equivalent to mean methane growth of 7.7~8.8 ppbv a⁻¹, compared to 7.2 ppb a⁻¹ in observation

Global Carbon Project: 538~593 Tg a⁻¹ in 2008-2017, 360 Tg a⁻¹ are anthropogenic sources.

- ❑ All inversions reproduce the mean methane budget imbalance.
- ❑ GOSAT+ObsPack provides the most consistent budget with literatures.

Take home messages

- GOSAT and ObsPack are complementary in the inversion. GOSAT information dominates the tropics, ObsPack is more important for northern mid-latitudes. ObsPack also helps to lower the error correlation between methane emissions and loss.
- GOSAT+ObsPack joint inversion finds:
 - underestimation of oil/gas emissions in US and Canada
 - overestimation of emissions in China (coal)
 - wetland emissions in North America are over estimated
 - oil/gas emissions are increasing in US
 - global methane emissions and loss are 551 and 528 Tg a⁻¹ in 2010-2017



Lu X., Jacob D., et al., Global methane budget and trend, 2010-2017: complementarity of inverse analyses using in situ (GLOBALVIEWplus CH₄ ObsPack) and satellite (GOSAT) observations, submitted to ACP, available at the Harvard ACMG website.