Global methane budget and trend in 2010-2017: comparative and joint inversions of suborbital (ObsPack) and satellite (GOSAT) observations

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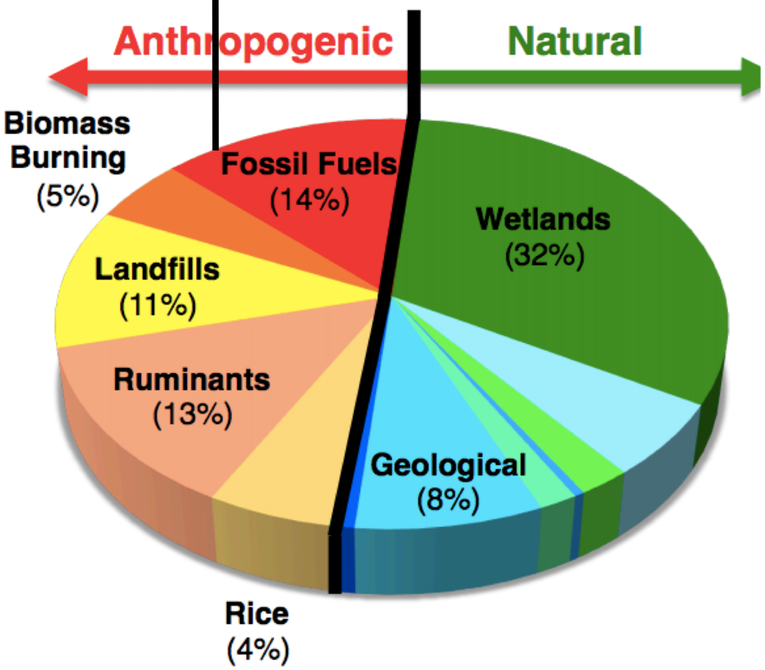
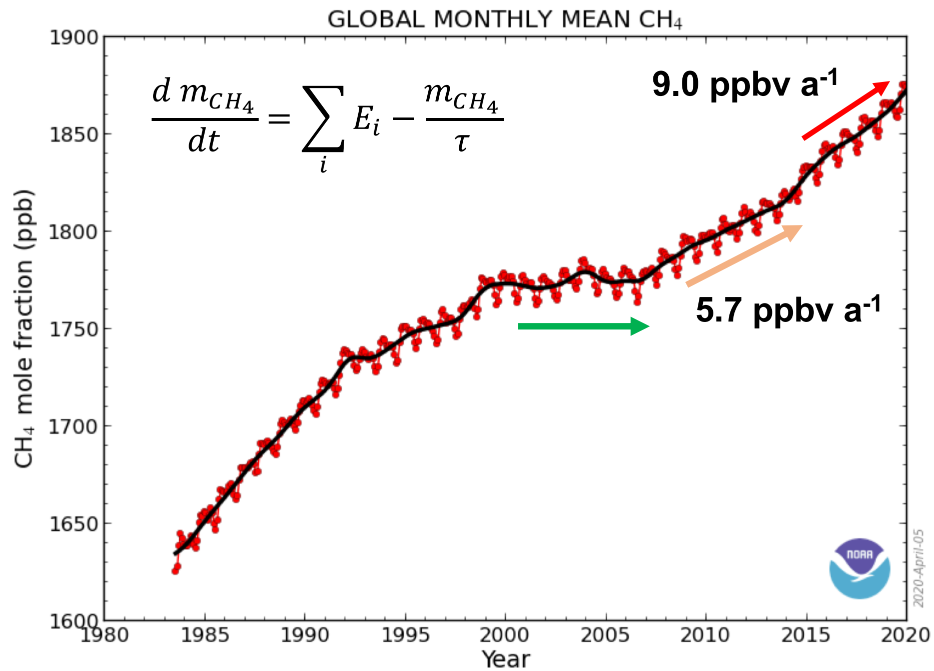
Ongoing efforts to understand methane budget and trend

Sources
~550 ± 60 Tg a^{-1}

Sinks
OH, soil uptake ….

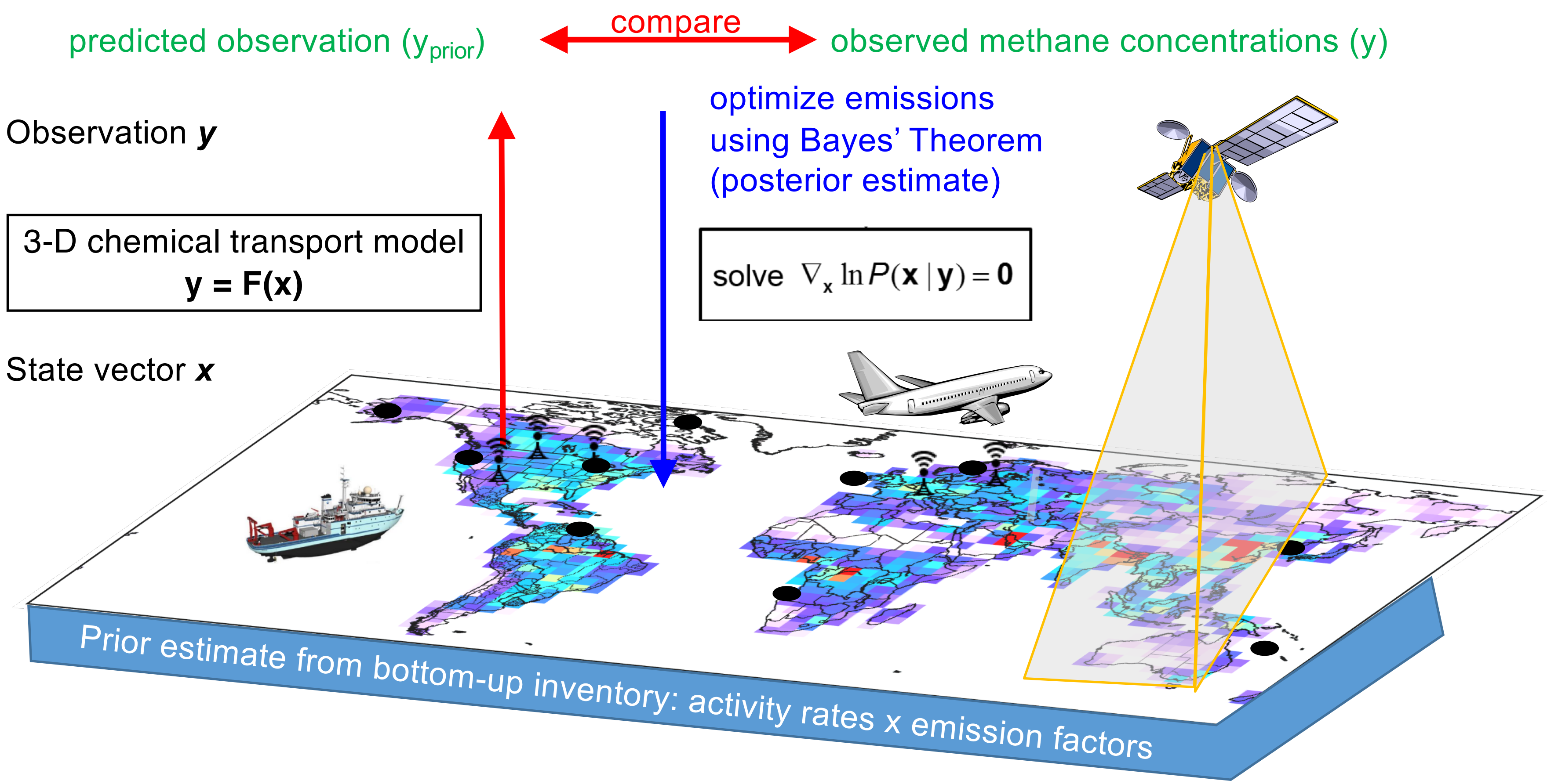
$$CH_4 \xrightarrow[\text{Tropospheric OH: 89\%}]{\text{Lifetime 9.1±0.9 years}} CO_2$$





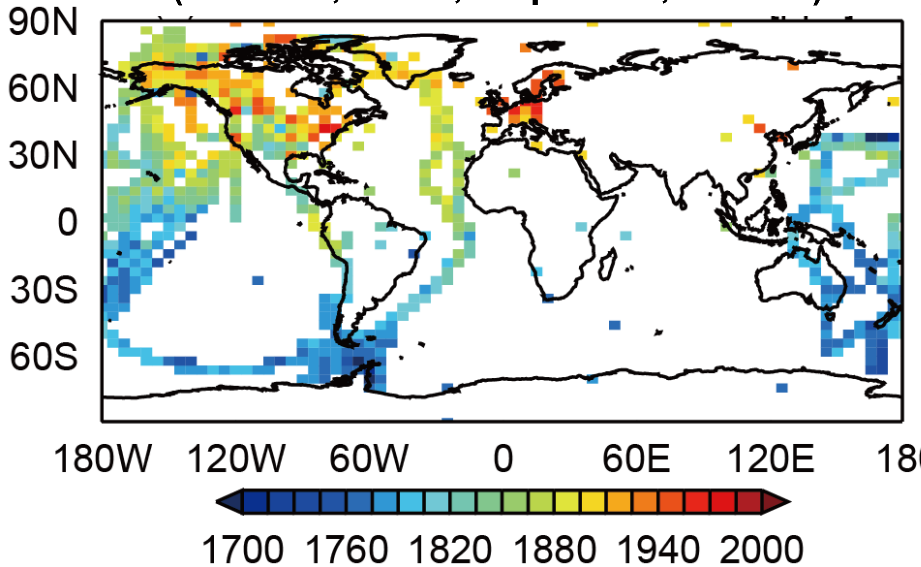
[NOAA/ESRL]

Inversion analyses to interpret methane budgets

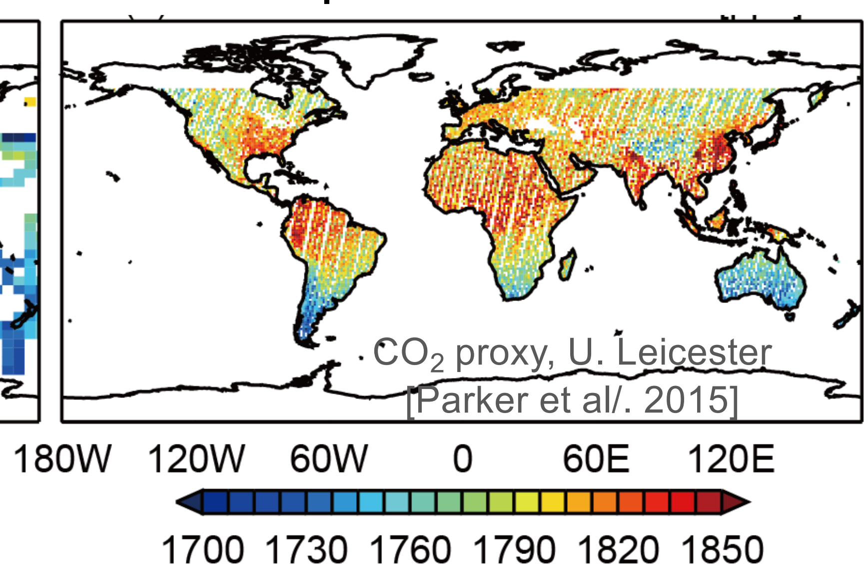


Comparing suborbital and satellite observations in inversion

ObsPack methane from NOAA, 2010-2017
(surface , tower, shipboard, aircraft)



GOSAT measurements of, 2010-2017
atmospheric methane column



Pros: accurate, sensitive to surface flux
Cons: sparse

Pros: massive, global coverage
Cons: errors associated with retrieval

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

Method: analytical inversion of ObsPack and GOSAT observations

Observation (y)

(ObsPack) **(GOSAT)**

Chemical transport model
(forward model)
y = F(x) = Kx

GEOS-Chem

Solve $\nabla_x ln(P(x|y)) = 0$

Analytical inverse modeling

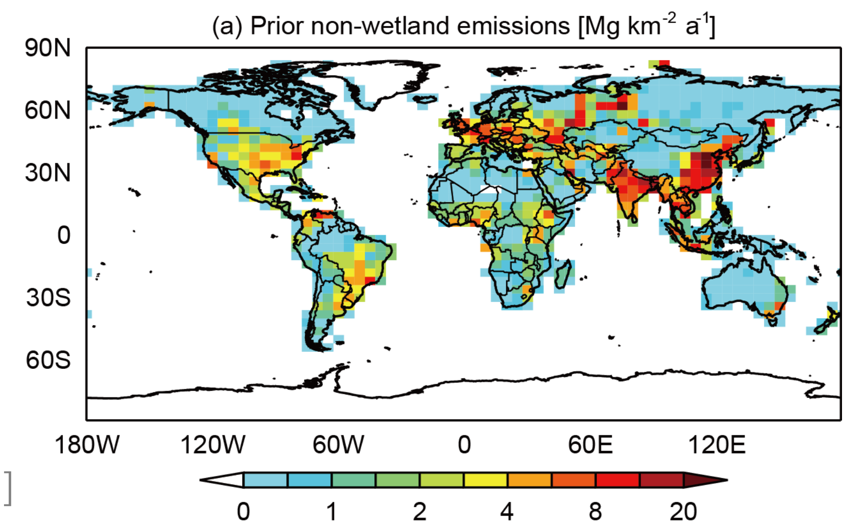
State vectors (x), Methane emission and loss, n=3378

- 2010-2017 mean non-wetland methane emissions and trends on 4°x5° grid
- Monthly wetland emissions in 14 subcontinental regions
- Annual hemispheric OH concentrations

Prior estimate of emission (533 Tg a^{-1})

- GFEI oil/gas/coal emission inventory (consistent with UN report)
- Gridded EPA for US
- EDGAR v4.3.2 for others
- WetCHARTs wetland from JPL
- No trends in 2010-2017.

[Scarpelli et al., 2020, Maasakkers et al., 2016; Bloom et al., 2017]



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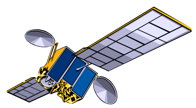

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Solution of $\nabla \boldsymbol{x}\ \boldsymbol{ln}(\boldsymbol{P}(\boldsymbol{x}|\ \boldsymbol{y})=\boldsymbol{0}$ by minimizing the cost function

$$J(\boldsymbol{x}) = (\boldsymbol{x}-\boldsymbol{x_A})^T \boldsymbol{S_A}^{-1}(\boldsymbol{x}-\boldsymbol{x_A}) + \boldsymbol{\gamma}(\boldsymbol{y}-\boldsymbol{Kx})^T \boldsymbol{S_O}^{-1}(\boldsymbol{y}-\boldsymbol{Kx})$$

- Analytical solution $\quad \hat{\boldsymbol{x}} = \underbrace{\boldsymbol{x_A}}_{\text{Prior}} + \underbrace{\boldsymbol{G}(\boldsymbol{y}-\boldsymbol{Kx_A})}_{\text{Correction to prior based on observation}}$ $\quad$ where $\boldsymbol{G} = \left(\boldsymbol{\gamma K^T S_O}^{-1}\boldsymbol{K} + \boldsymbol{S_A}^{-1}\right)^{-1}\boldsymbol{\gamma K^T S_O}^{-1}$

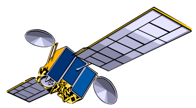
- Yielding closed-form posterior error $\hat{\boldsymbol{S}}$ and averaging kernel sensitivity $\boldsymbol{A}$ in analytical solution:

$$\hat{\boldsymbol{S}} = \left(\boldsymbol{\gamma K^T S_O}^{-1}\boldsymbol{K} + \boldsymbol{S_A}^{-1}\right)^{-1} \qquad \boldsymbol{A} = \frac{\partial \hat{\boldsymbol{x}}}{\partial \boldsymbol{x}} = \boldsymbol{I_n} - \hat{\boldsymbol{S}}\boldsymbol{S_A}^{-1} \longrightarrow$$

Quantify the capability of the observation system to constrain the state vector.

Method: analytical inversion of ObsPack and GOSAT observations

Observation (y)



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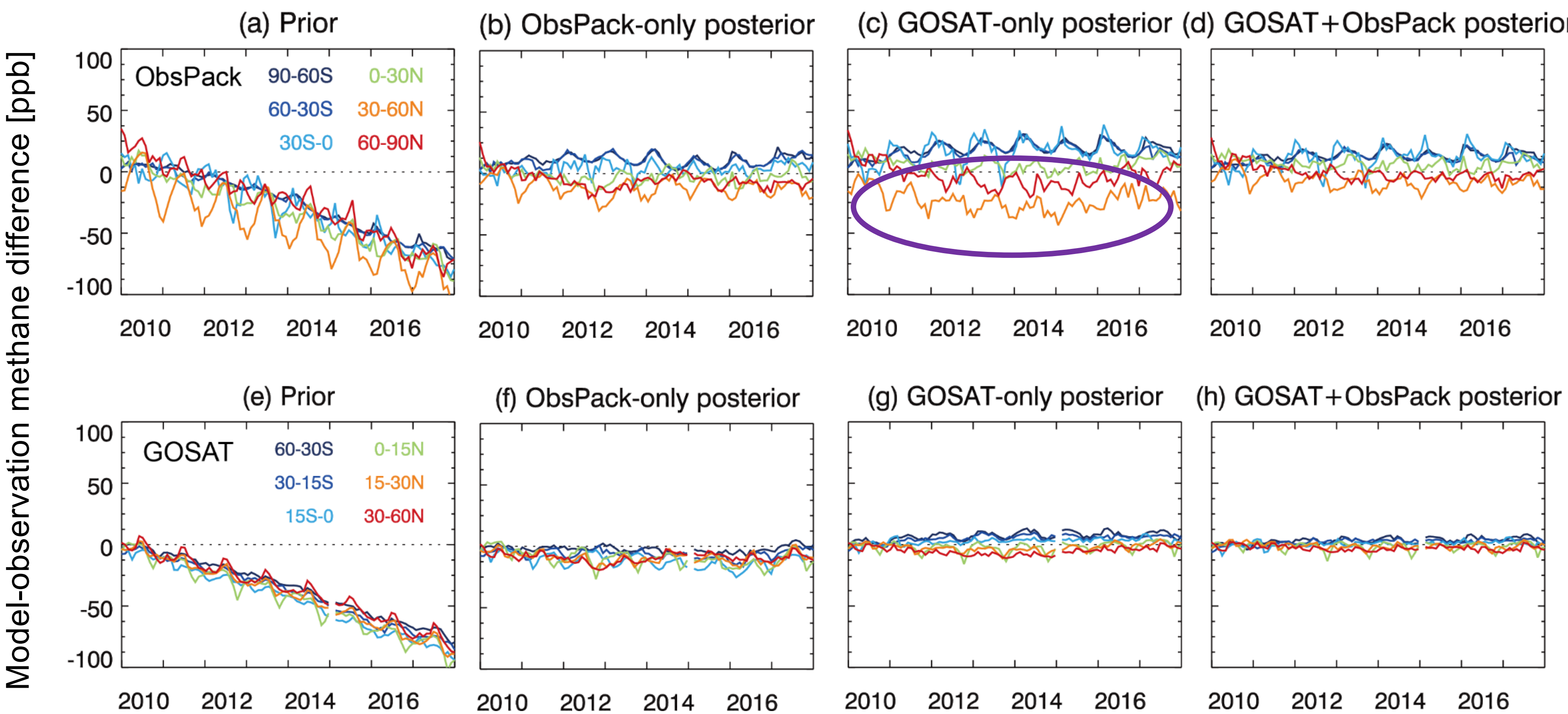
- ☐ Conduct <u>ObsPack-only</u>, <u>GOSAT-only</u>, and <u>GOSAT+ObsPack</u> inversions
- ☐ Analytical inversion with error characterization allows quantitative comparison of the <u>ObsPack</u> vs <u>GOSAT</u> information
- ☐ <u>GOSAT+ObsPack joint inversion</u> provides the "best" estimate of methane budget and trend

Posterior model fit to observations



- ☐ 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.

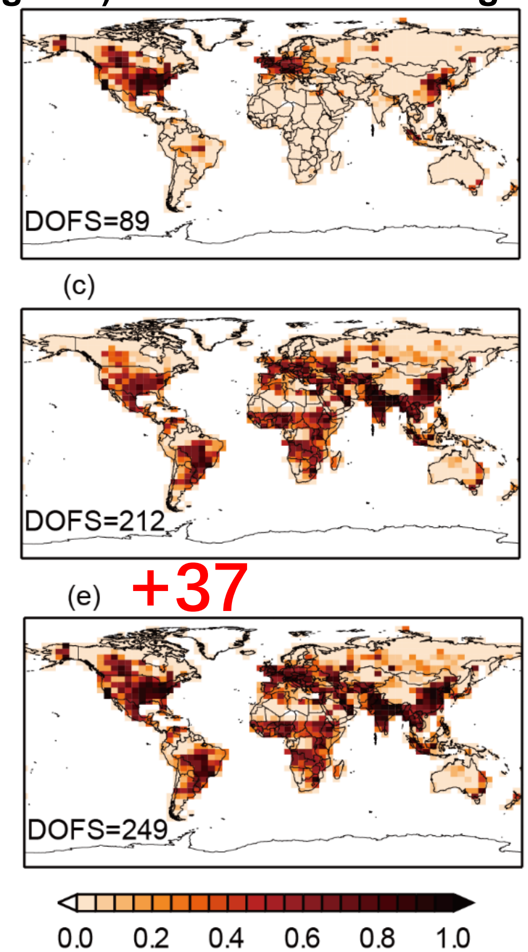
Ability of ObsPack vs. GOSAT to constrain anthropogenic emission

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

ObsPack-only inversion

GOSAT-only inversion

GOSAT+ObsPack inversion

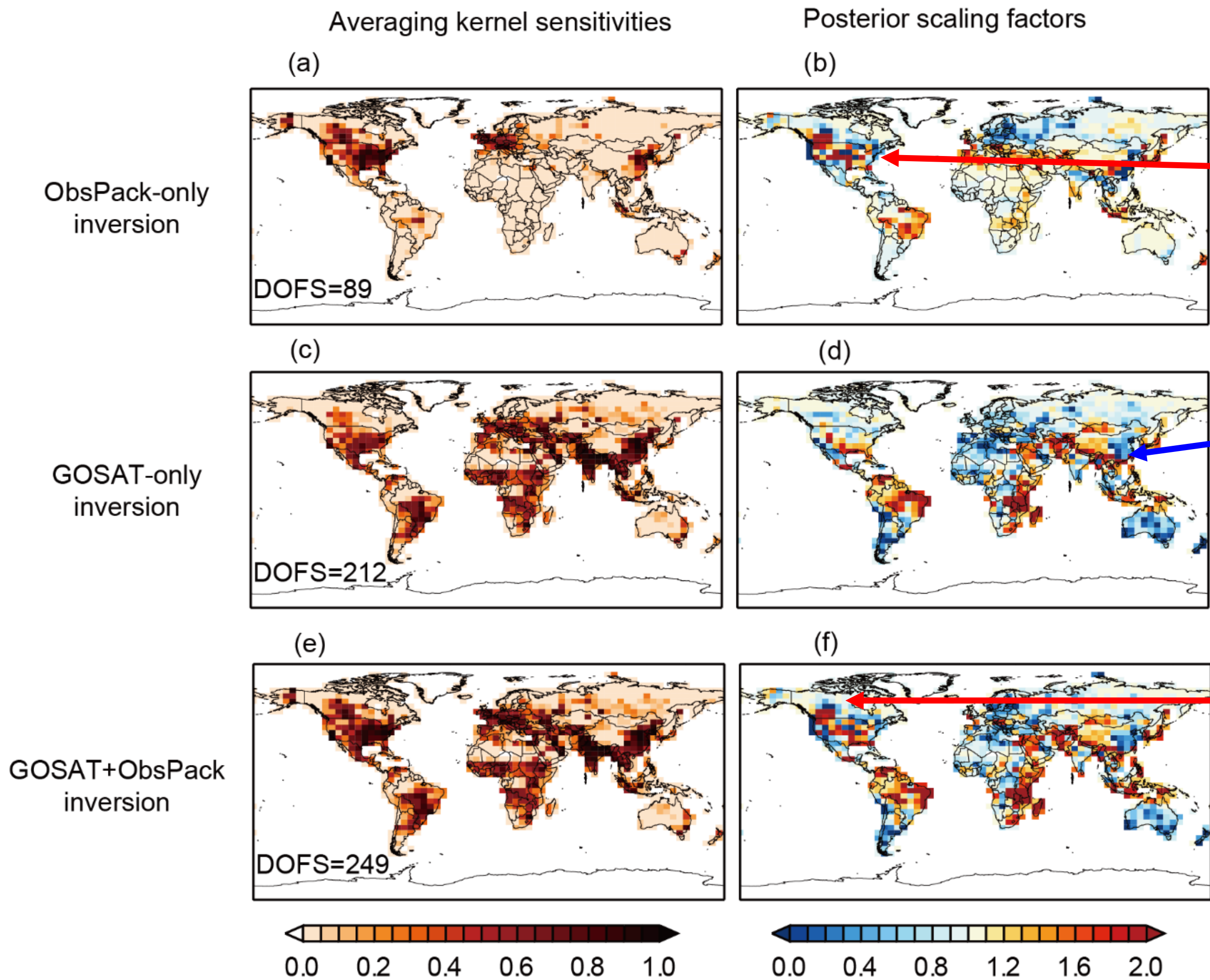


$$A = \frac{\partial \hat{x}}{\partial x} = I_n - \hat{S} S_A^{-1}$$

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

- Globally, GOSAT provides more information than ObsPack. (DOFS=212 vs DOFS=89)
- ObsPack can add 37 (249-212) independent pieces of information to GOSAT (complementarity).
- GOSAT provides strong constraints in the tropics, ObsPack can be valuable in northern middle and high latitudes (US, Canada, Europe, China).

Posterior correction to anthropogenic emissions

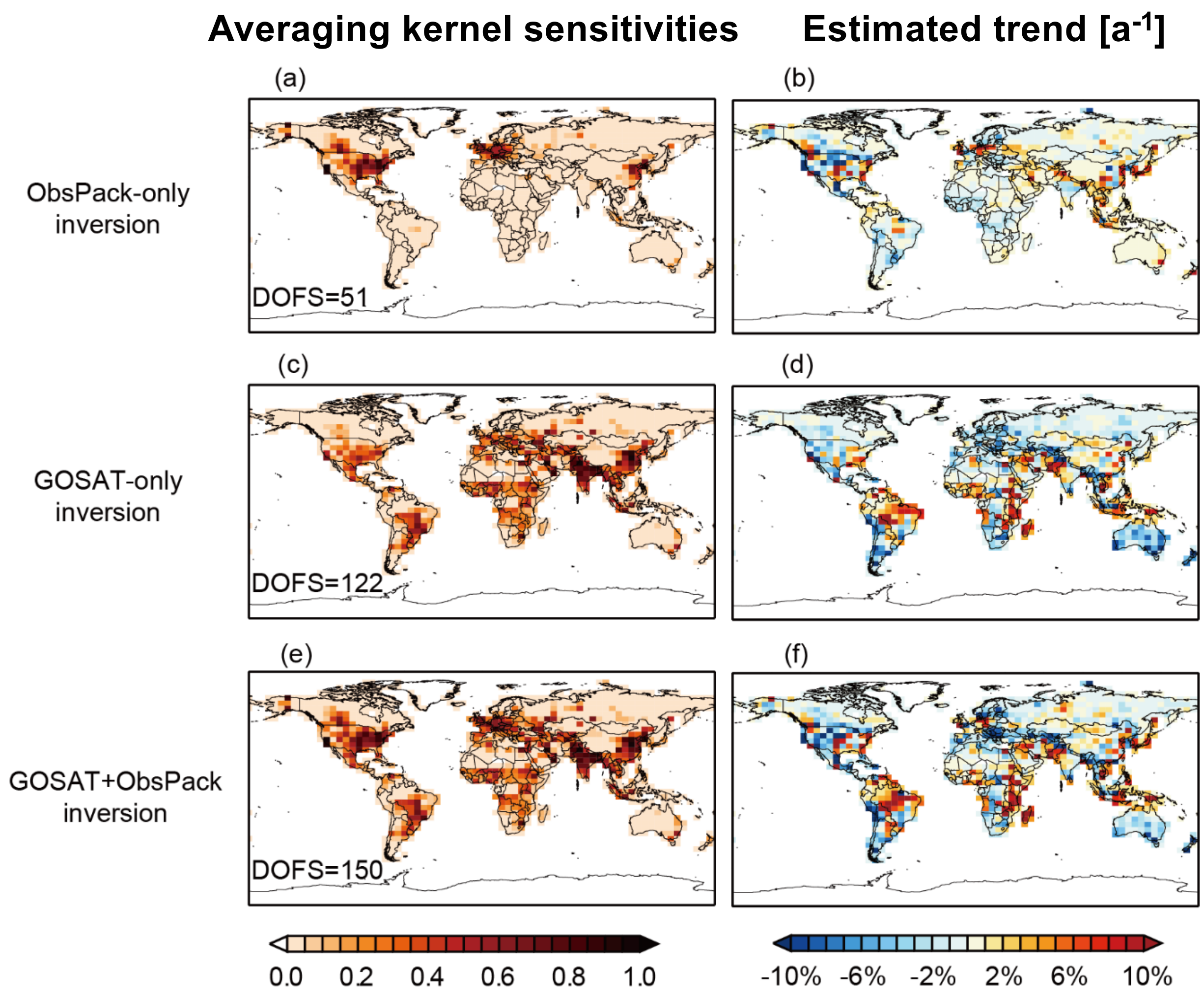


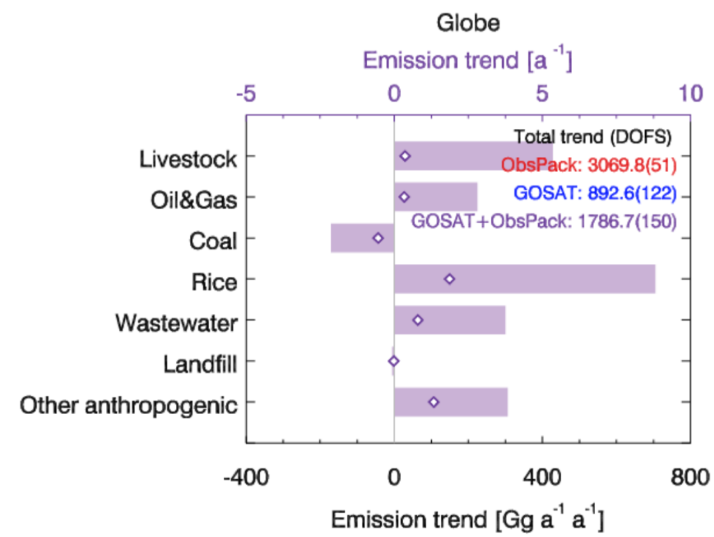
- Prior US emissions are too low, from oil/gas.
- Prior Chinese emissions are too high, from coal.
- Prior Canadian emissions are too low, from oil/gas.

Note: prior oil, gas, and coal emissions match the UN report.

[Scarpelli et al., 2020]

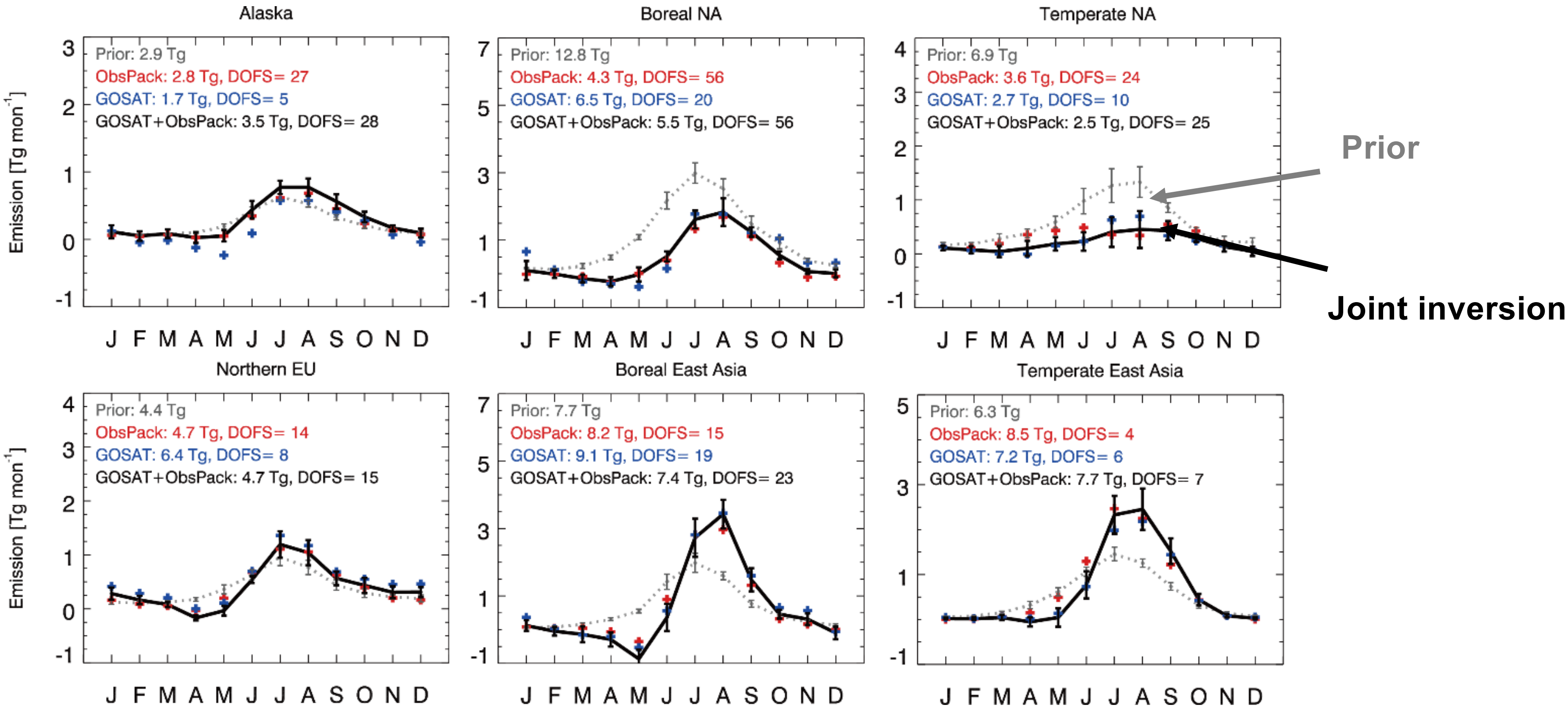
Anthropogenic emission trends in 2010-2017





- Increases of anthropogenic methane emissions by 1.8 Tg a^{-1}, driven by agricultural emissions in the tropics. (from the joint inversion)

Posterior correction to wetland emissions



Prior wetland emissions from the WetCHARTs inventory. [Bloom et al., 2017]

- ObsPack is more powerful than GOSAT in North America to constrain wetland emissions. (Complementarity!)
- Both show that prior is too high in NA, correction to late-spring low and summer peak. (Consistency!)

Global methane budget in 2010-2017

	Prior	ObsPack	GOSAT	GOSAT+ObsPack
Total sources [Tg a^{-1}]	**533**	**520**	**504**	**539**
Anthropogenic	344	359	333	361
Wetland emission	161	131	140	145
Fire emissions	14	15	16	16
Seep, termites	14	15	15	16
Total sinks [Tg a^{-1}]	**540**	**499**	**478**	**515**
OH oxidation	468	426	406	442
Other loss	73	73	72	73
Mean imbalance [Tg a^{-1}]	**-7**	**21**	**26**	**24**
Methane chemical lifetime [a]	**10.6**	**11.9**	**12.5**	**11.5**

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 inversion reproduce the mean methane budget imbalance, though sources and sinks are different.
- GOSAT+ObsPack provides the most consistent budget with literatures.

Take home message

- GOSAT and ObsPack are complementary in the inversion, with GOSAT dominating the global patterns, but ObsPack being more important for northern mid-latitudes.

- GOSAT+ObsPack joint inversion finds:
  - underestimation of oil/gas emissions in US and Canada
  - overestimation of coal mining emissions in China
  - Wetland emissions in North America are over estimated
  - oil/gas emissions are increasing in US
  - Global anthropogenic methane emissions are increasing by 1.8 Tg a^{-2}

- Methane emissions and loss are 539 and 515 Tg a^{-1} in 2010-2017.