Mitigating model biases and constraining North American methane emissions using weak constraint 4D-Var

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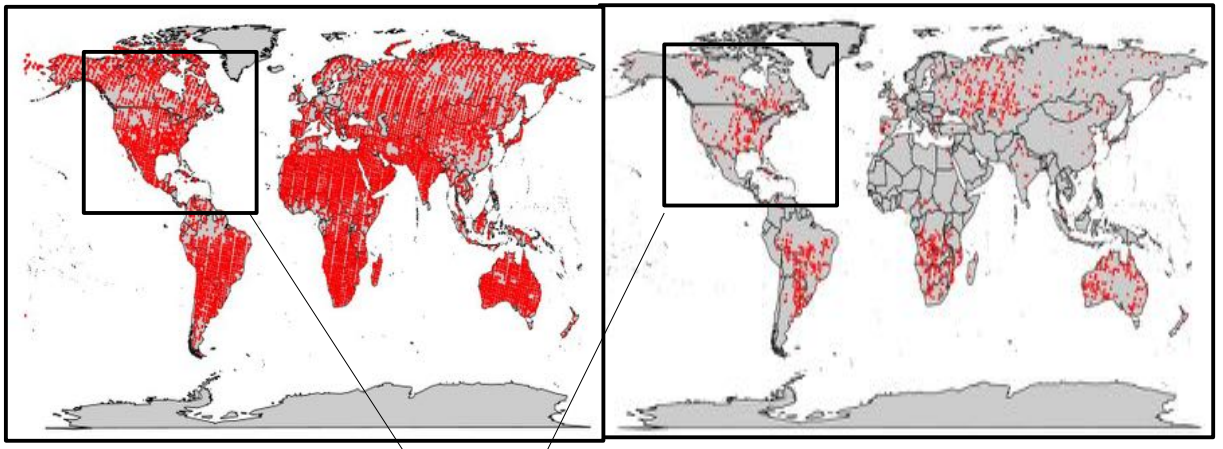
Sensitivity to Biases in North American Boundary Conditions (BCs)

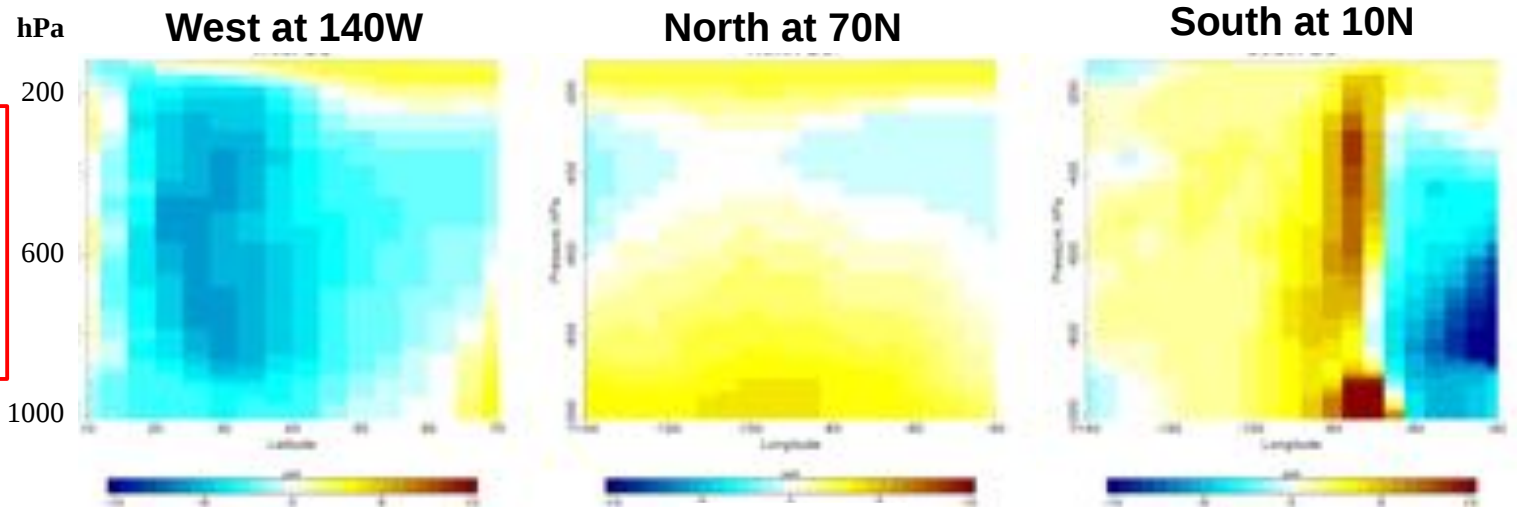
Our previous inversions of Proxy and Full-Physics GOSAT CH4 retrievals using *GEOS-Chem model* produced large differences in the inflow to North America, due in part to differences in observational coverage.

GOSAT UoL Proxy (May 2010)

GOSAT RemoTeC Full-Physics (May 2010)



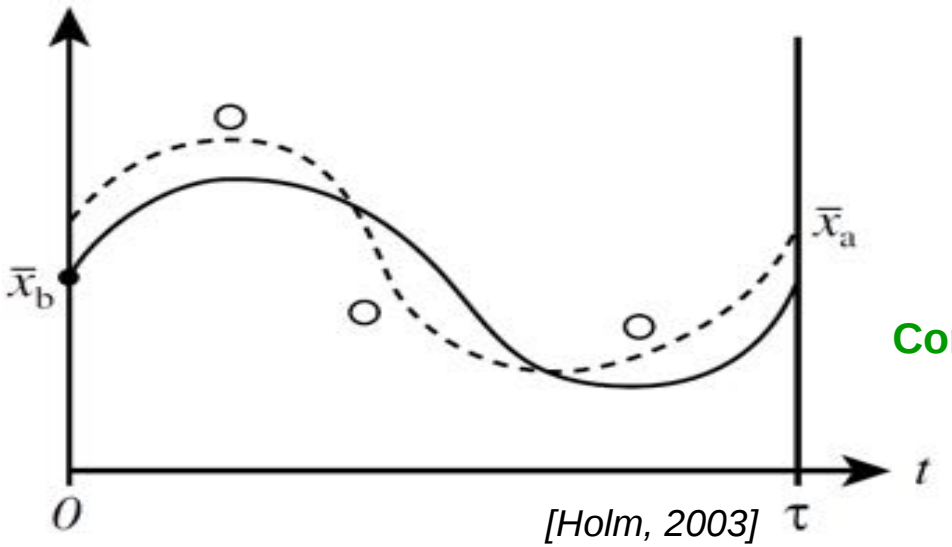
Mean difference between CH4 concentrations at boundaries of North America in May 2010 from inversion of emissions using GOSAT Proxy and Full-Physics retrievals



<u>Objective</u>: can we optimize the state (CH4 concentrations) to mitigate biases in North American BCs?

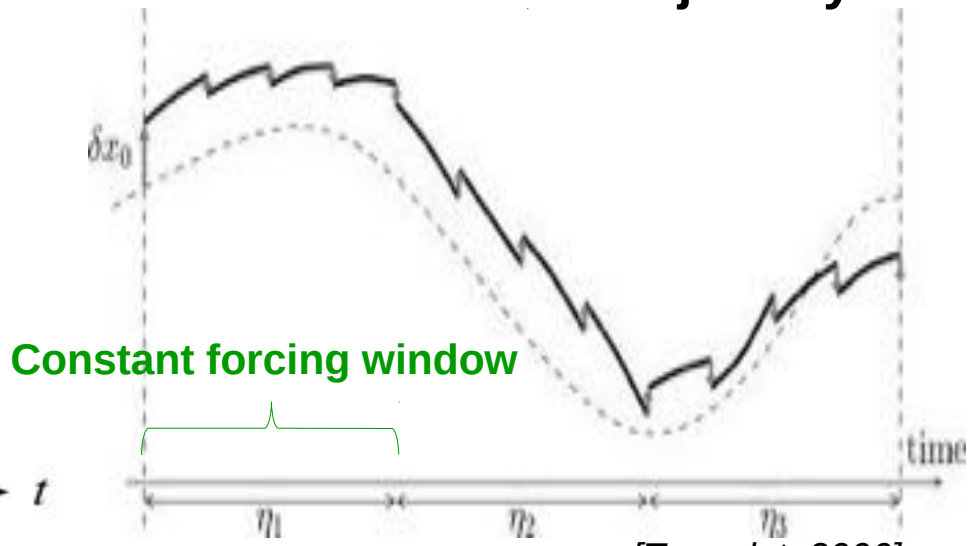
Weak Constraint 4D-Var

Strong constraint trajectory



[Holm, 2003]

Weak constraint trajectory



[Tremolet, 2006]

In weak constraint 4D-Var we account for errors in the forward model by adding corrections (forcing terms) to the modeled state, i.e., CH_4 concentrations (**x**), at each step:

$$\boldsymbol{x}_{n+1} = M(\boldsymbol{x}_n, \boldsymbol{p}) + \boldsymbol{u}_n$$

$$J(p,u) = \underbrace{\sum_{t=t_0}^{t_N} \frac{1}{2}(\boldsymbol{y}_t - H(\boldsymbol{x}_t))^T \boldsymbol{S}_o^{-1}(\boldsymbol{y}_t - H(\boldsymbol{x}_t))}_{\text{Observations contribution}} + \underbrace{\frac{1}{2}(\boldsymbol{p} - \boldsymbol{p}_a)^T \boldsymbol{S}_a^{-1}(\boldsymbol{p} - \boldsymbol{p}_a)}_{\text{A priori contribution}} + \underbrace{\sum_{t=t_0}^{t_N} (\boldsymbol{u}_t)^T \boldsymbol{Q}^{-1}(\boldsymbol{u}_t)}_{\text{Forcing contribution}}$$

OSSEs to Assess State Optimization

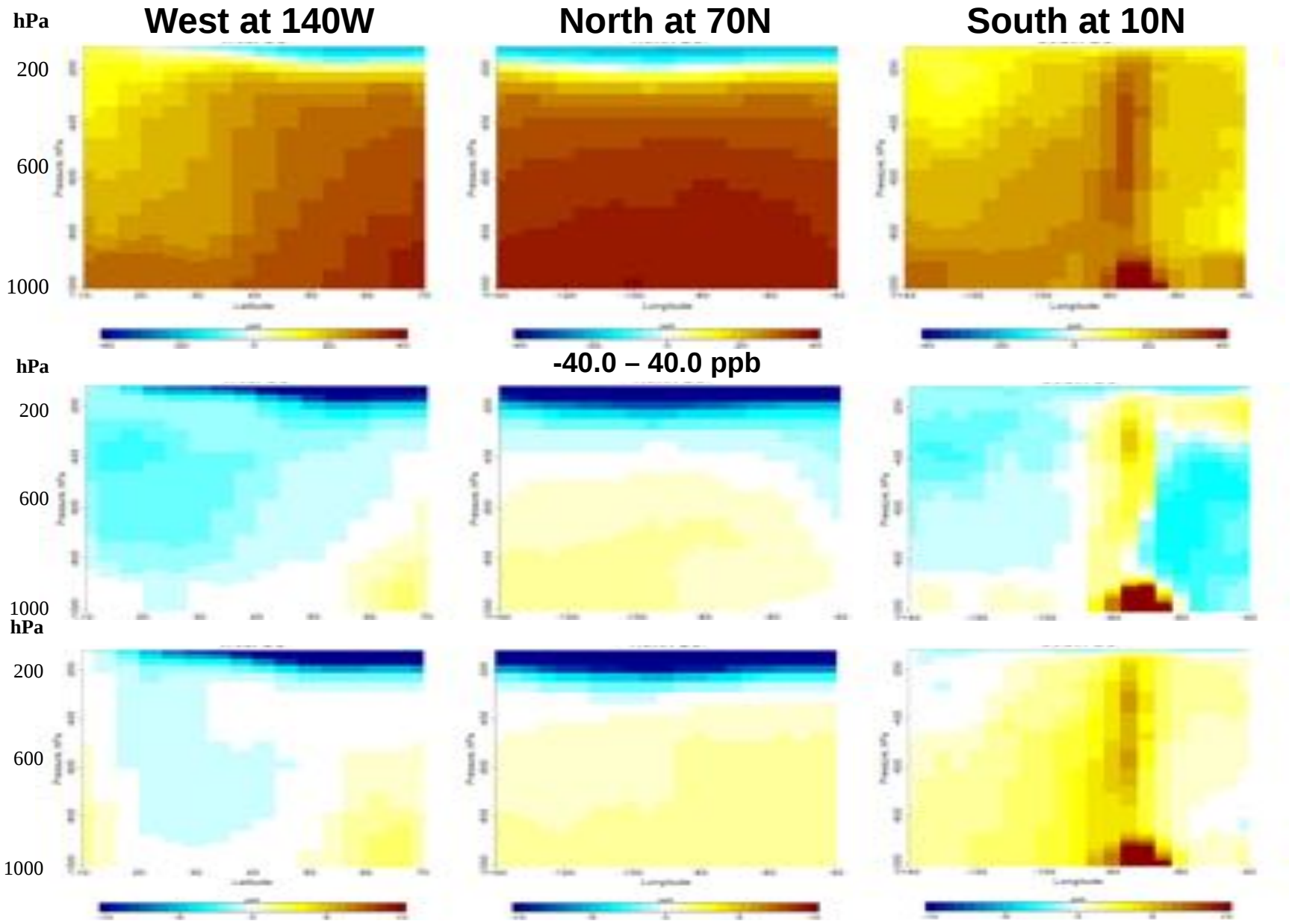
Observing system simulation experiment (OSSE) setup

- Sample model at locations and times of Proxy retrievals to produce pseudo-observations
- Run a series of OSSEs with the forward model artificially biased relative to the truth in terms of the emissions and model transport

Optimization period	February 1, 2010 – May 31, 2010
Model resolution	GEOS-Chem: global 4 x 5 degrees
Biased a priori	70% of a priori emissions
Biased initial conditions:	Initial condition is generated by running with CONVECTION TURNED OFF EVERYWHERE and 70% of a priori emissions from July 1, 2009, to February 1, 2010.
Biased transport during optimization period	Two experiments: 1. Convection is turned on (perfect transport) 2. Convection is off everywhere (biased transport)
Inversions:	Two experiments: 1. Weak constraint **(WC)** state optimization 2. Strong constraint **(SC)** monthly flux optimization
Truth	CH4 state from inversion of monthly CH4 fluxes using real GOSAT Proxy retrievals from July 1, 2009 to Dec. 31, 2010

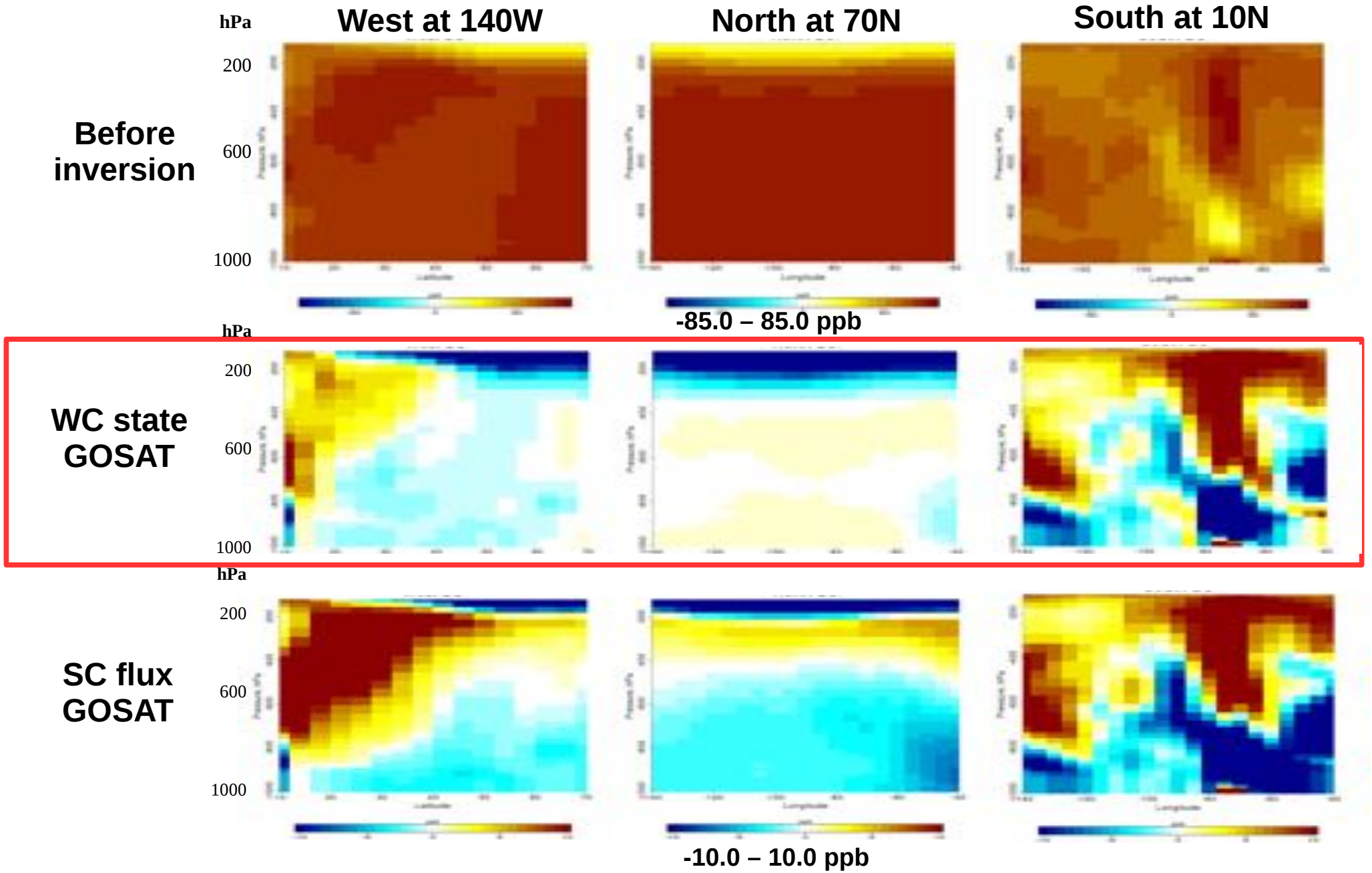
OSSE: mean difference between “true” and optimized BCs in May 2010

Perfect model transport during optimization period



OSSE: mean difference between "true" and optimized BC in May 2010

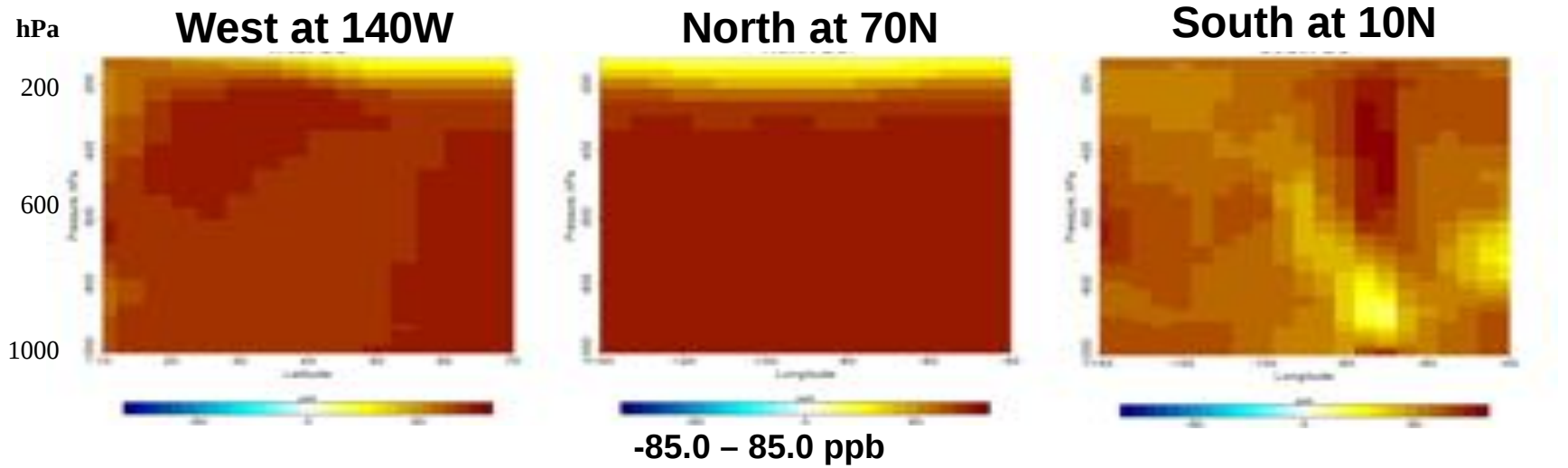
Convection is off during optimization period



OSSE: mean difference between “true” and optimized BC in May 2010

Convection is off during optimization period

Before inversion



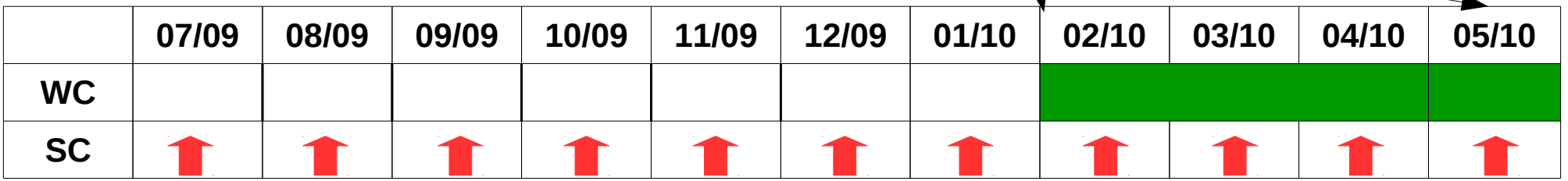
A priori and a posteriori bias, [ppb]

	Western Boundary			Northern Boundary			Southern Boundary		
	Lower trop	Upper trop	Total	Lower trop	Upper trop	Total	Lower trop	Upper trop	Total
A priori	71.1	64.7	68.1	77.4	61.0	69.5	57.9	60.0	58.9
WC (State)	-0.2	-0.8	-0.4	0.0	-5.5	-2.6	-3.0	3.9	0.3
SC (Source)	1.0	5.8	3.3	-3.0	-2.4	-2.7	-4.8	6.1	0.4

Inversions of real GOSAT Proxy retrievals

Inversions Setup

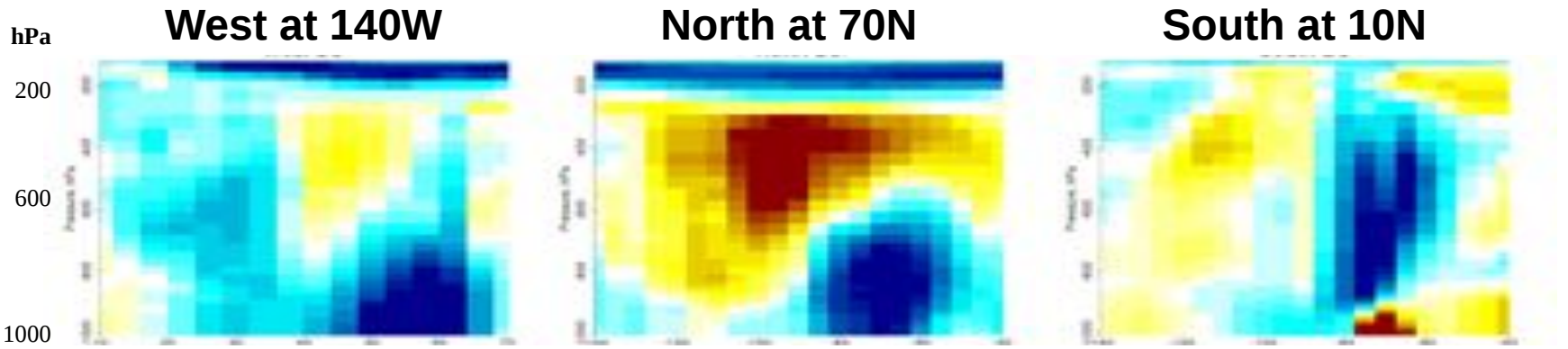
- **Observations:** GOSAT UoL v5.1 Proxy retrievals
- **Model:** GEOS-Chem global 4 x 5 degrees
- **Two inversions:**
  - Strong constraint (SC) in which we optimize the monthly fluxes from July 1, 2009 to May 31, 2010
  - Weak constraint (WC) in which we optimize the state from Feb. 1, 2010 to May 31, 2010
- Both inversions have the same a priori emissions and initial conditions on Feb. 1
- **Objective:** obtain optimized Boundary Condition over North America in May 2010



Global inversion with GOSAT Proxy retrievals

Mean difference between optimized BC in May 2010

Weak constraint – Strong constraint



A posteriori statistics in May 2010

Strong constraint

	Bias, ppb	Scatter, ppb	Correlation	Slope	R^2
NOAA surface flask	7.5	25.2	0.91	0.96	0.83
TCCON	11.1	13.8	0.83	0.82	0.7

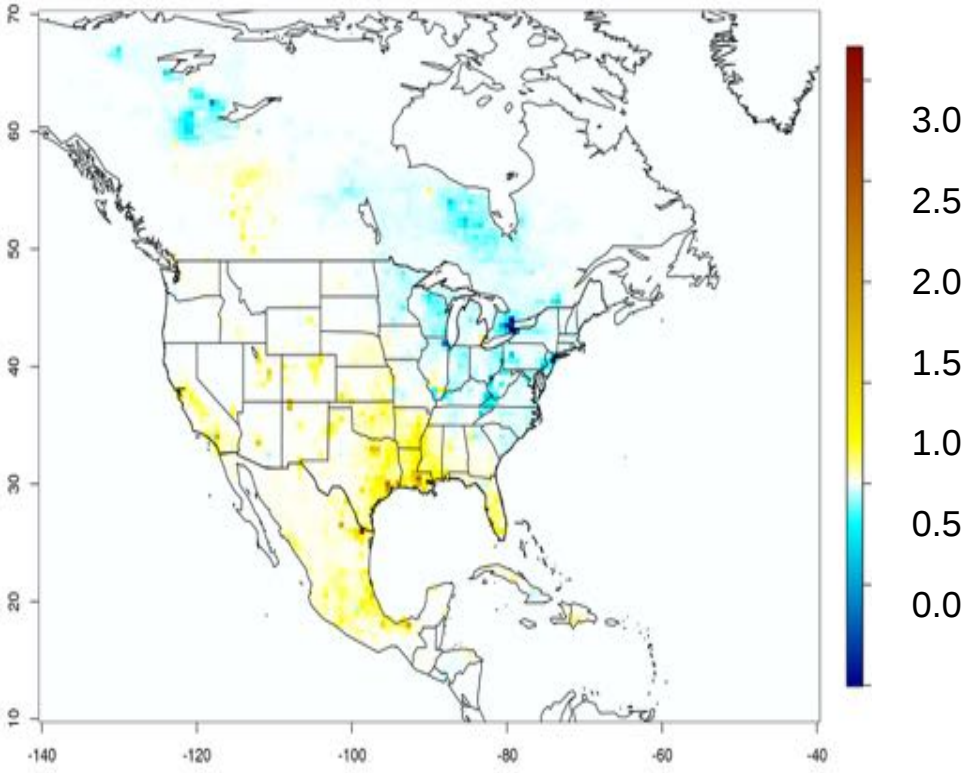
Weak constraint

	Bias, ppb	Scatter, ppb	Correlation	Slope	R^2
NOAA surface flask	9.2	26.2	0.91	1.02	0.82
TCCON	8.7	10.7	0.91	0.86	0.82

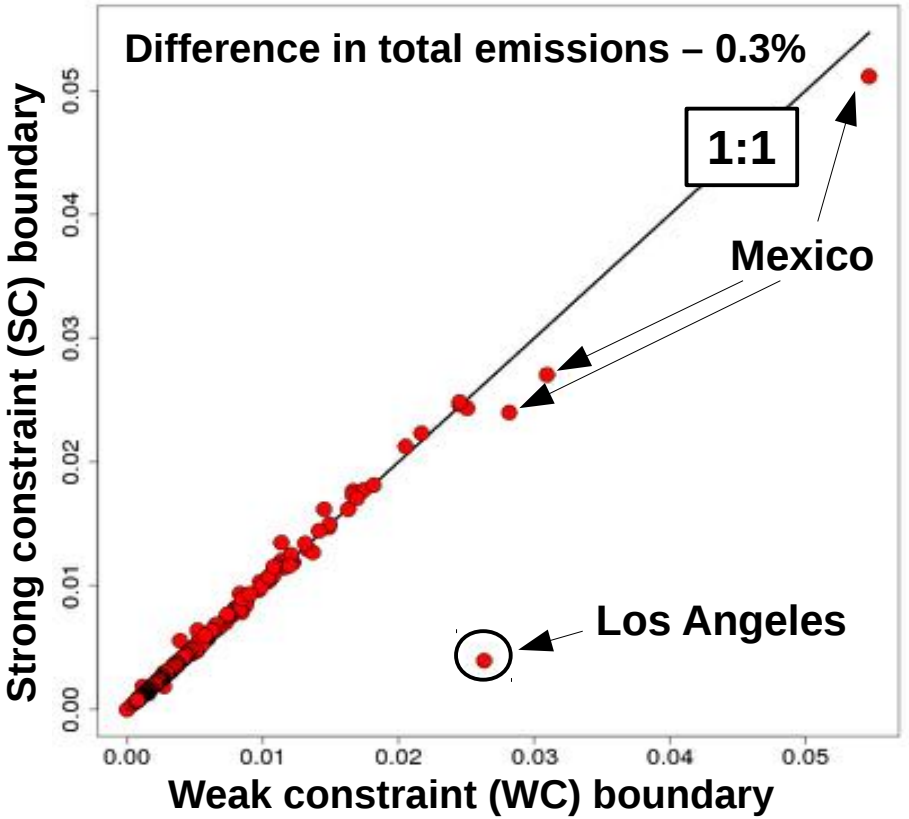
Nested inversion of North American methane emissions in May 2010

Period	April 22, 2010 – May 31, 2010
Model	Nested GEOS-Chem, 0.5x0.67 degrees resolution
Optimization	Strong constraint 4D-Var flux optimization
Observation	GOSAT UoL v5.1 Proxy retrievals
Boundary and initial conditions	1. From global Strong constraint (SC) inversion 2. From global Weak constraint (WC) inversion

Ratio of optimized to a priori emissions in May 2010
WC boundary



Optimized emissions, Tg
SC vs. WC



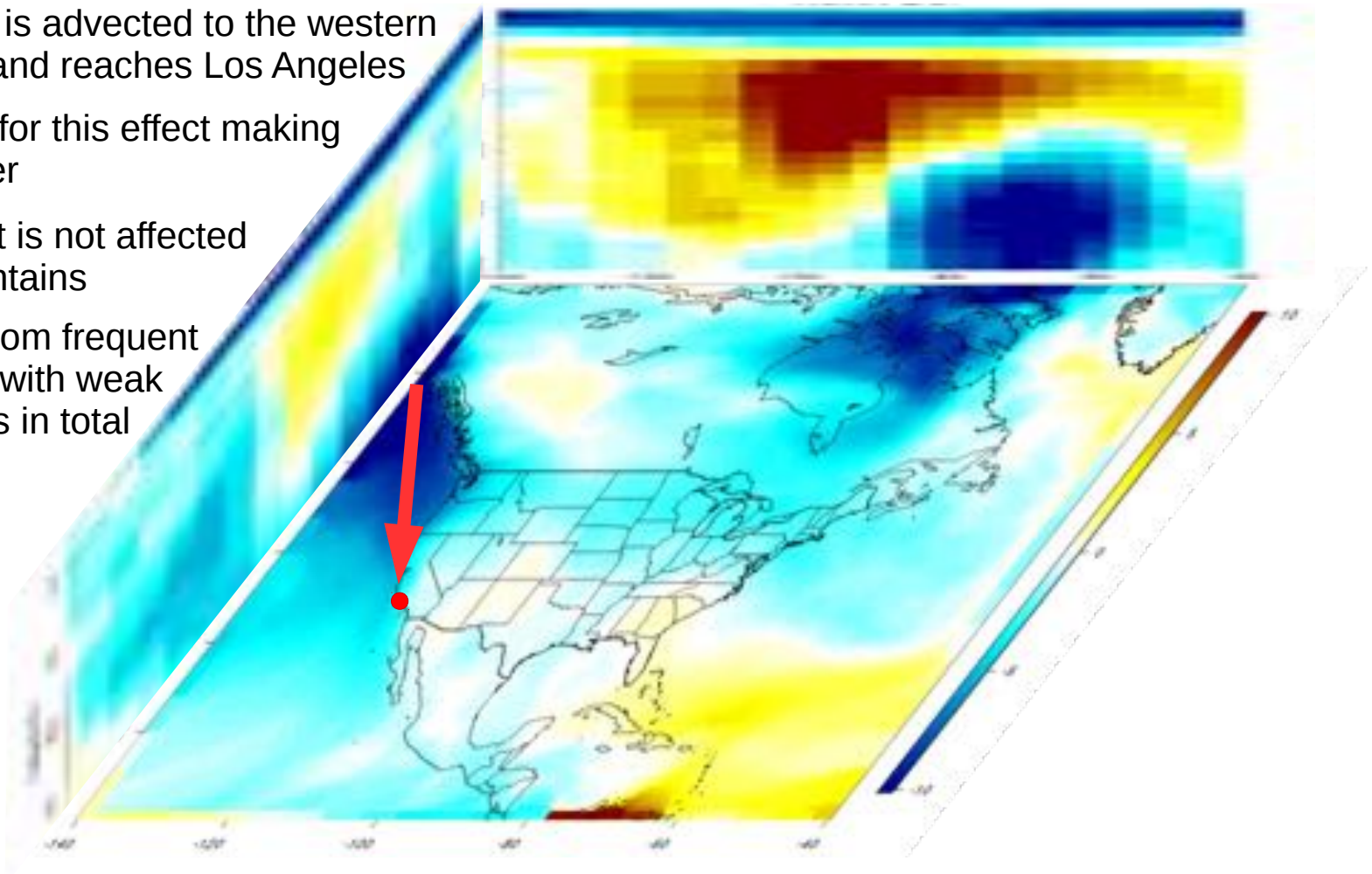
Nested inversion of North American emissions

Why inversions with WC boundary inferred higher Los Angeles emissions?

Mean difference between CH4 fields at the boundary and surface in May 2010 [*before inversion*]

Weak constraint – Strong constraint [+/- 10 ppb]

- Air depleted in methane is advected to the western coast of North America and reaches Los Angeles
- Inversion compensates for this effect making emissions become larger
- The rest of the continent is not affected due to blocking by mountains
- High sensitivity arises from frequent GOSAT sampling of LA with weak signal of local emissions in total column above the city



Conclusions

- Although GOSAT retrievals have limited vertical sensitivity, the OSSEs show that the weak constraint (WC) 4D-Var method is able to mitigate model biases related to transport.

- The WC (state) optimization is in closer agreement with TCCON data, whereas the SC (source) optimization better matches the surface in situ data.

- Regional inversion of Proxy data using boundary conditions from the WC (state) and SC (source) optimization produced consistent total North American emission estimates (differences of 0.3%), but regional difference in emissions (e.g. Los Angeles emissions significantly reduced with SC boundary conditions) due to discrepancies in the boundaries.

  - With better satellite coverage of North America sensitivity of inverted fluxes to biases in BCs may increase due to higher chance to sample biased background air

Can we trust our regional inversion?

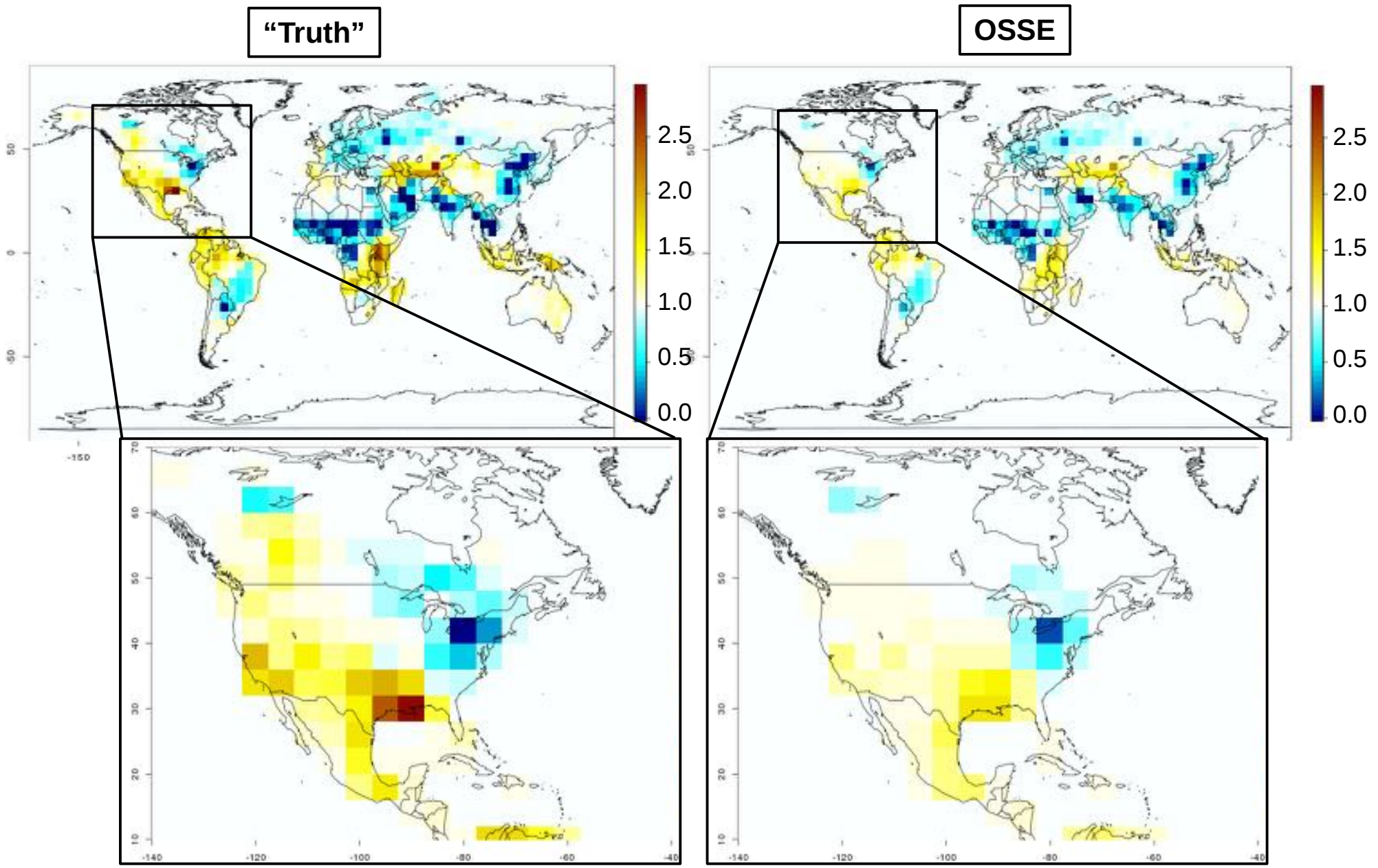
Consider ideal situation

Observing system simulation experiment (OSSE) setup

Optimization period	May 2010
Model resolution	Global 4 x 5 degrees
A priori emissions	Same as “true” inversion
Initial conditions	Same as “true” inversion
Model biases	Perfect model
Data assimilation	Strong constraint 4D-Var flux inversion
Observations	Pseudo GOSAT Proxy total columns sampled from “true” CH4 fields with no noise added and real retrieval uncertainties
“True” inversion	Inversions of global CH4 emissions in May 2010 with real GOSAT Proxy retrievals: • Inferred emissions = “true” emissions • Updated CH4 fields = “true” CH4 fields
Purpose	Obtain the original (“true”) emissions

Ideal OSSE: results

Ratio of optimized to a priori emissions in May 2010



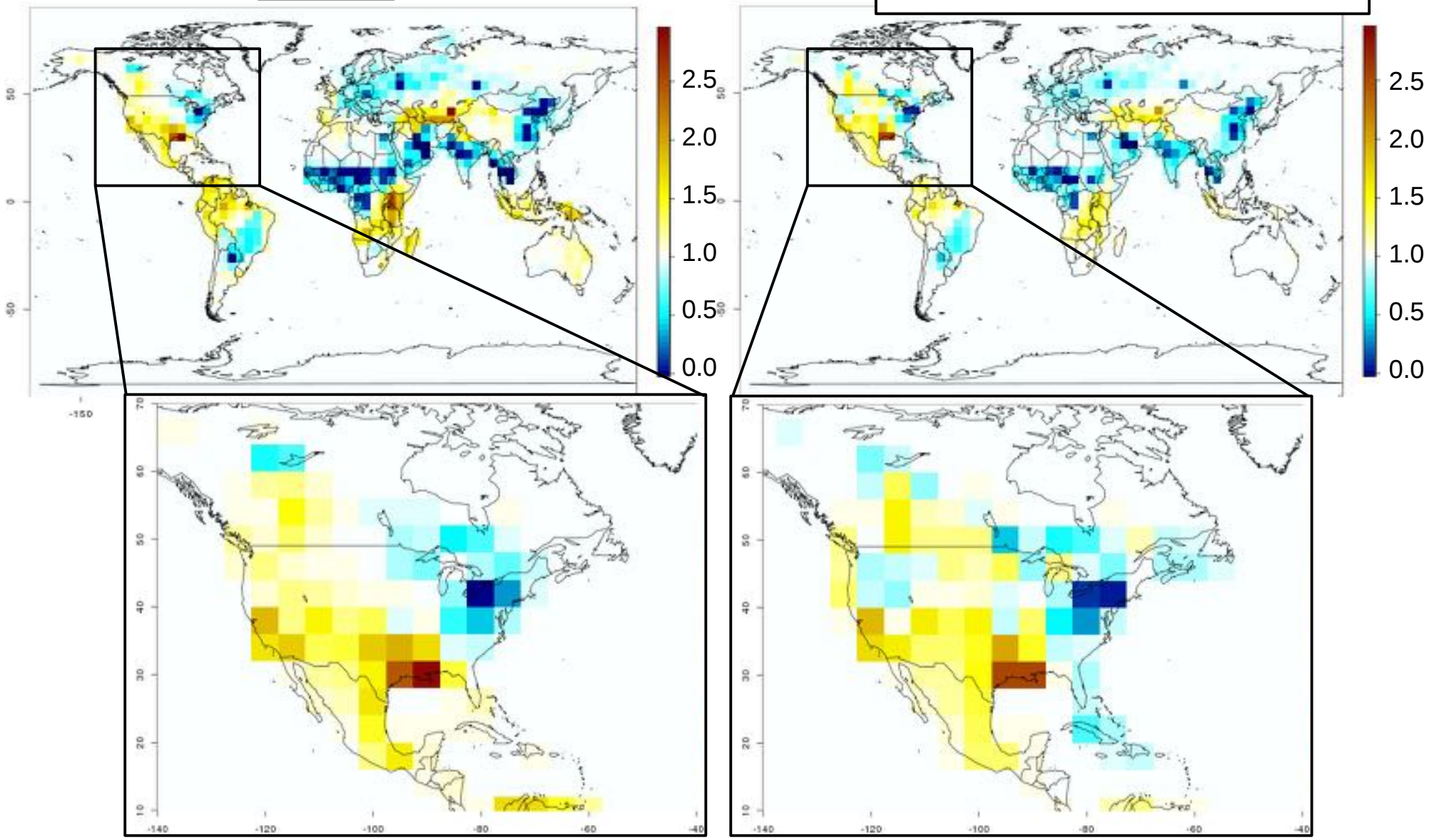
Ideal OSSE: results

Ratio of optimized to a priori emissions in May 2010

"Truth"

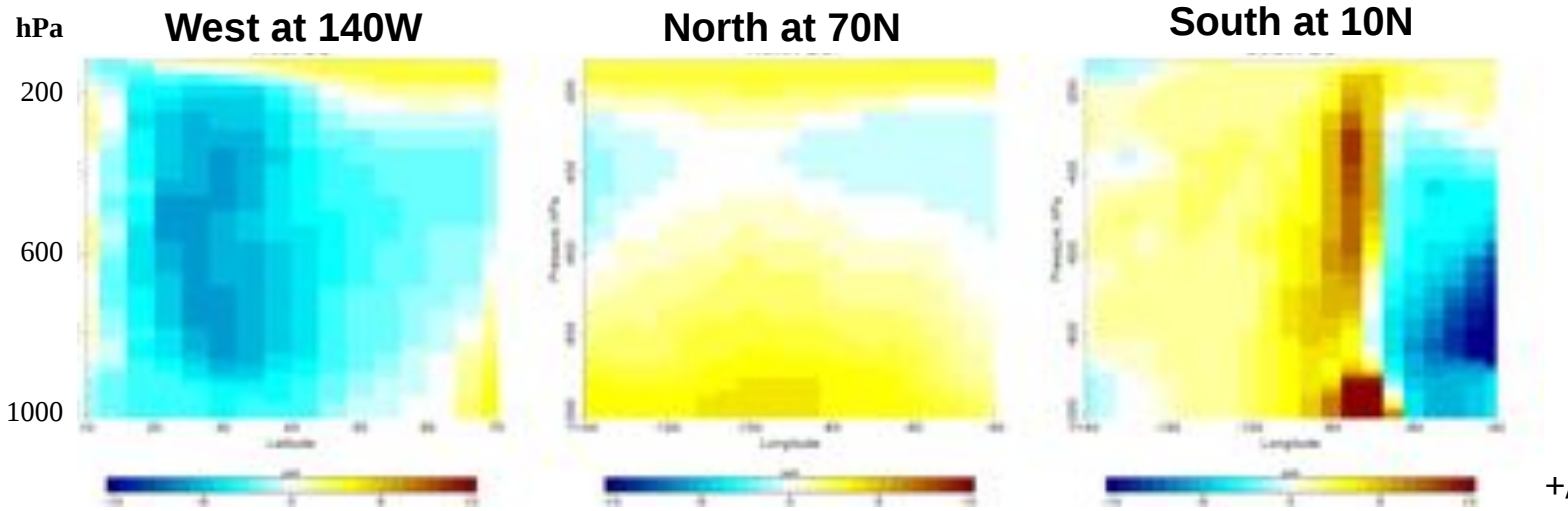
OSSE

Here we also include in situ pseudo observations daily at 1pm at North American surface sites

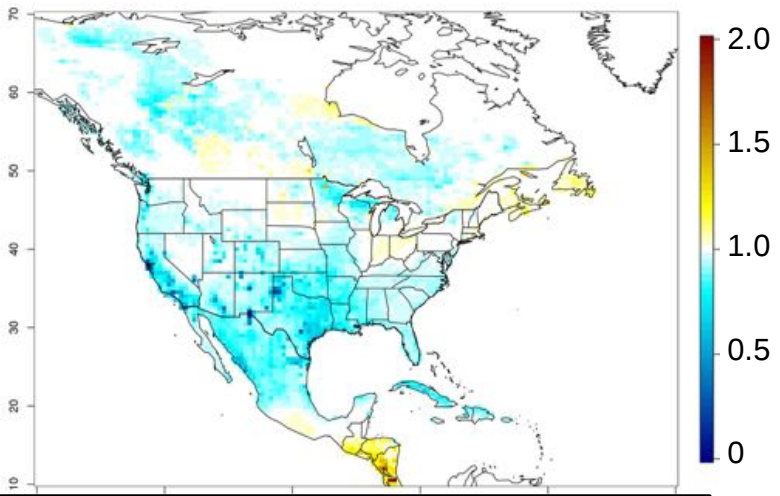


Sensitivity of inferred fluxes to biases in boundary conditions (BC)

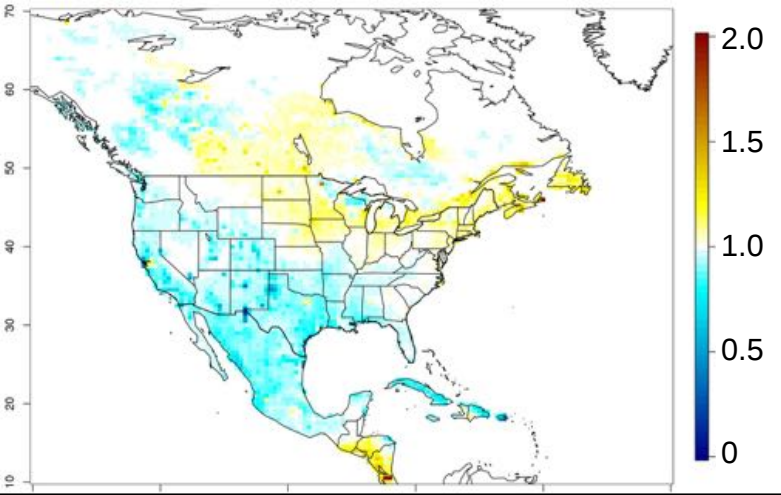
Bias in boundary conditions taken as a difference between optimized methane fields from global PROXY and FP inversions (with a "-" sign).



Pseudo inversion test



Pseudo-obs: hourly total column measurements over every land gridbox



Pseudo-obs: hourly boundary layer column (ground to ~750 hPa) measurements over every land gridbox

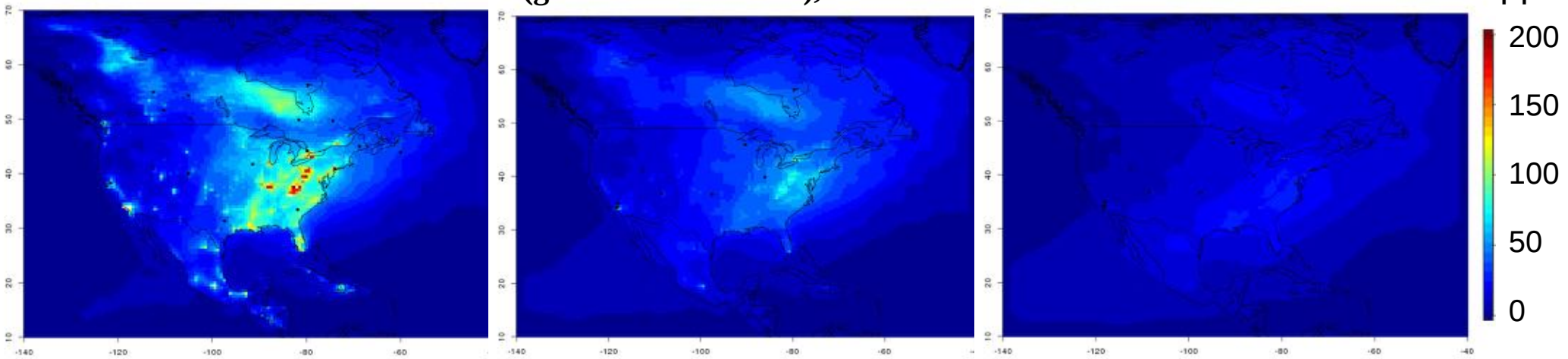
Impact a priori emissions on atmospheric CH_4 in August

SIGNAL OF CH_4 EMISSIONS

In surface measurements

In boundary layer column (ground to ~750 hPa), SZA < 70

In total column, SZA < 70



Propagated BC bias as a fraction of emissions signal, August 2010

At the surface

In total columns