Inverse modelling of North American methane emissions using GOSAT Proxy and Full-physics retrievals

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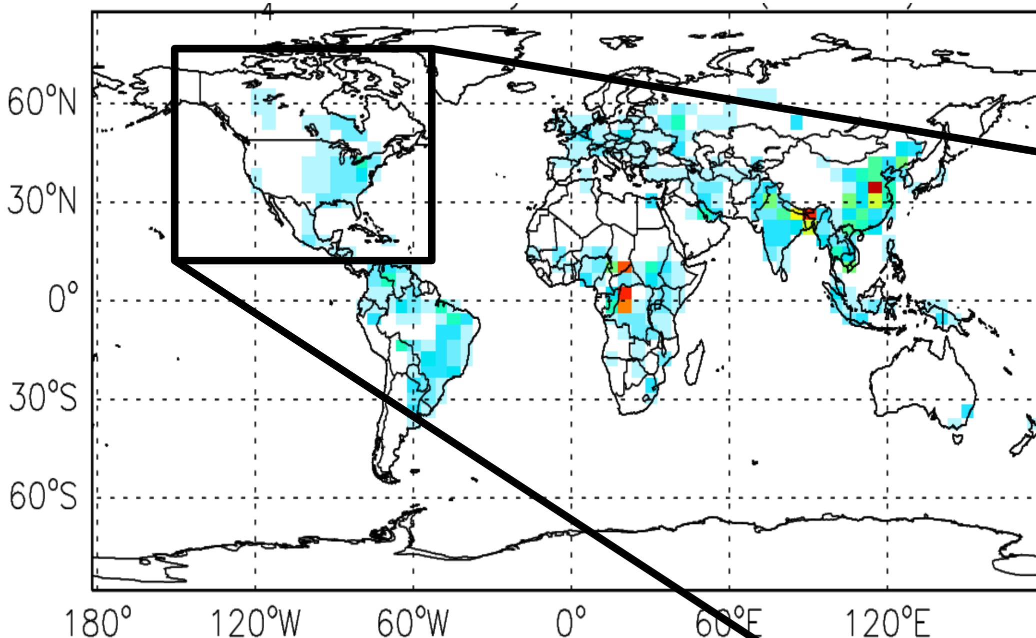
Objectives

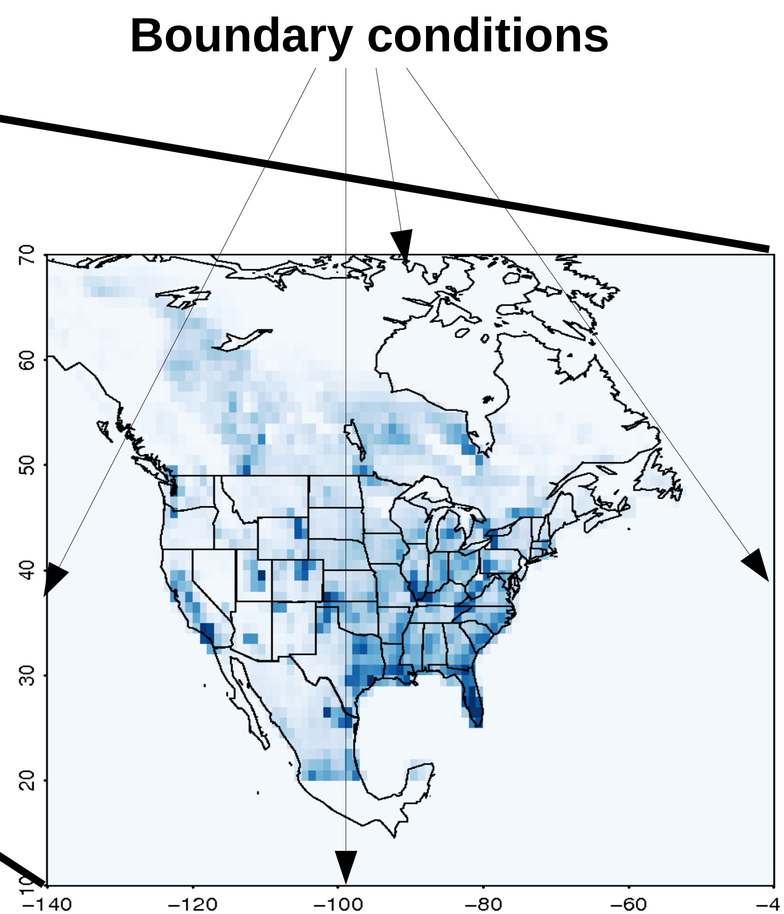
- Evaluate capability of GOSAT Proxy and Full-Physics retrievals to constrain North American fluxes
- Compare performance and results of different inversion approaches:
  - GEOS-Chem model + GOSAT satellite retrievals
  - STILT model + surface flask measurements
- Establish framework for inverse modelling of methane emissions at high spatial resolution resolution

From global to regional modelling

GEOS-Chem for global modelling



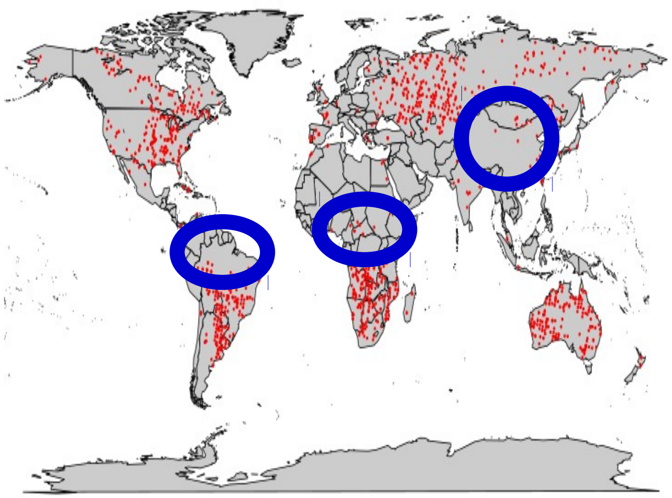
STILT for regional modelling

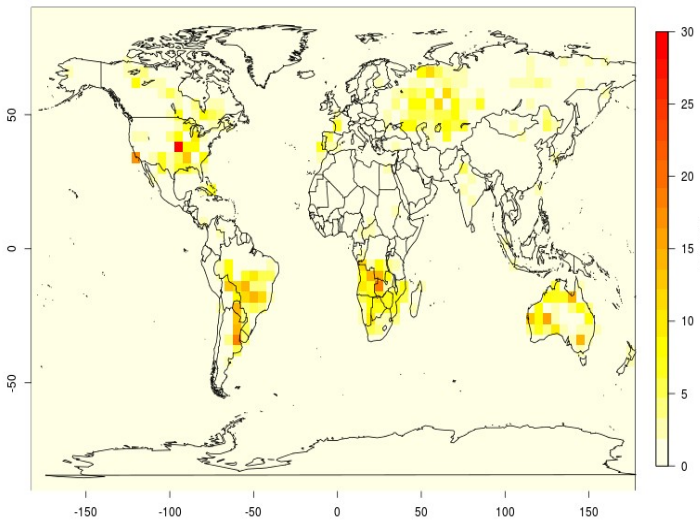


- Global inversion creates optimized 3D field of methane. It is used to generate **boundary conditions** over North America.
- Zooming over North America we consider surface fluxes at higher spatial resolution.
- Global optimization:
  1) 6 months spin up (January 2009 to July 2010) and 1 year monthly inversion
  2) Consider last 2 months of inversion (May-June 2010)

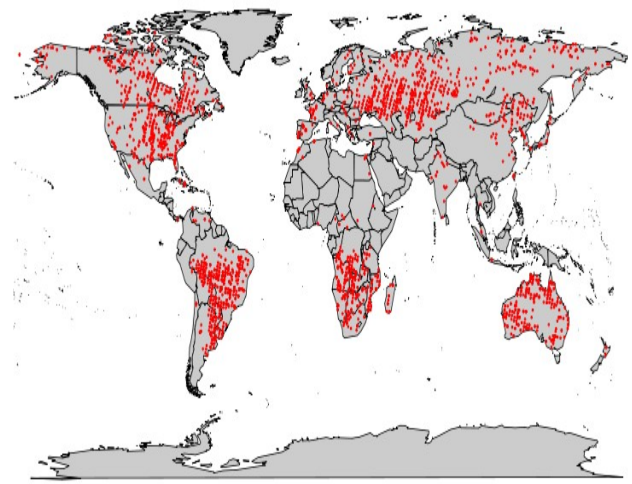
GOSAT coverage

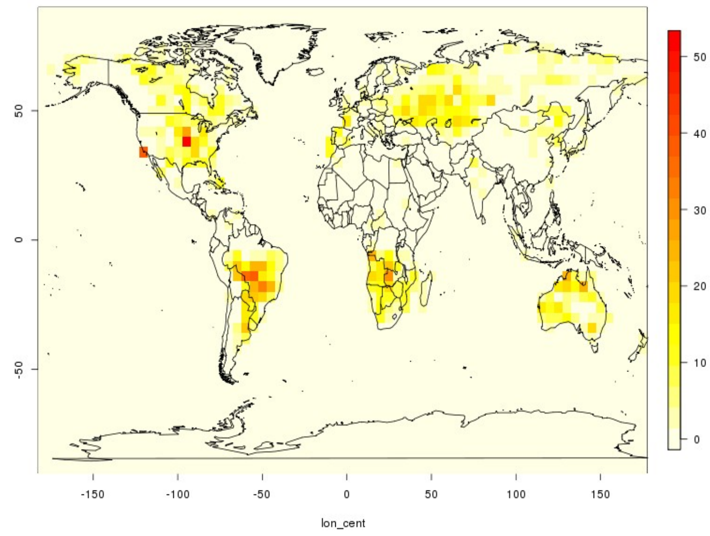
GOSAT Full-Physics
May 2010



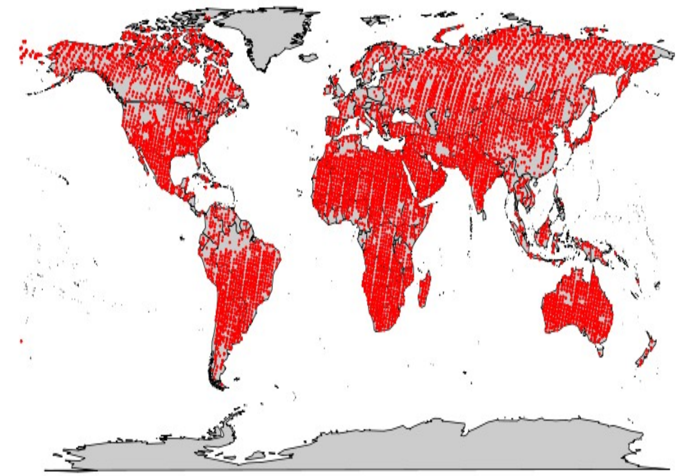


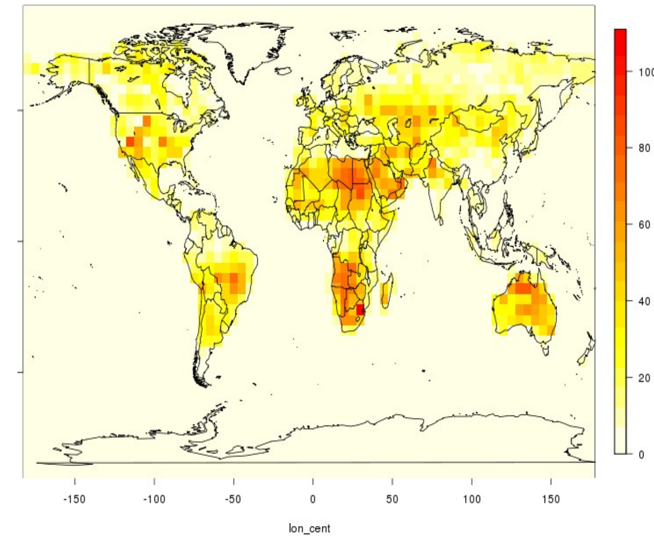
GOSAT Full-Physics
May-June 2010





GOSAT Proxy
May 2010



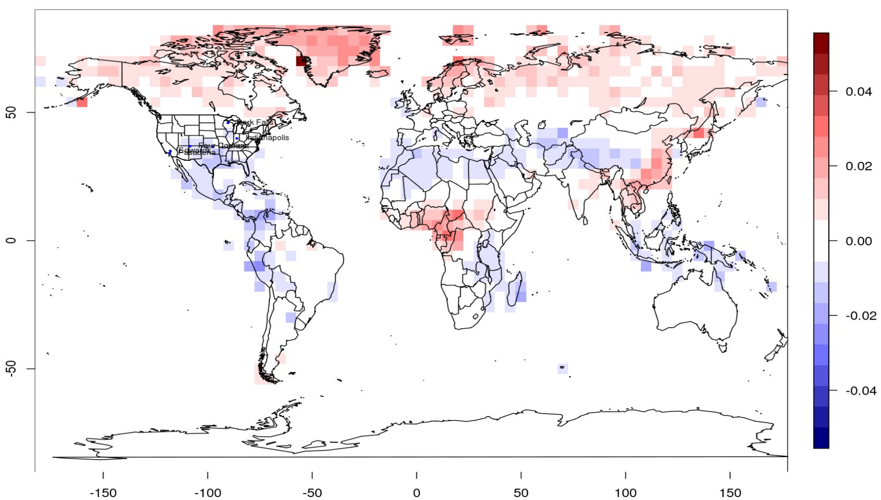


Types of measurements

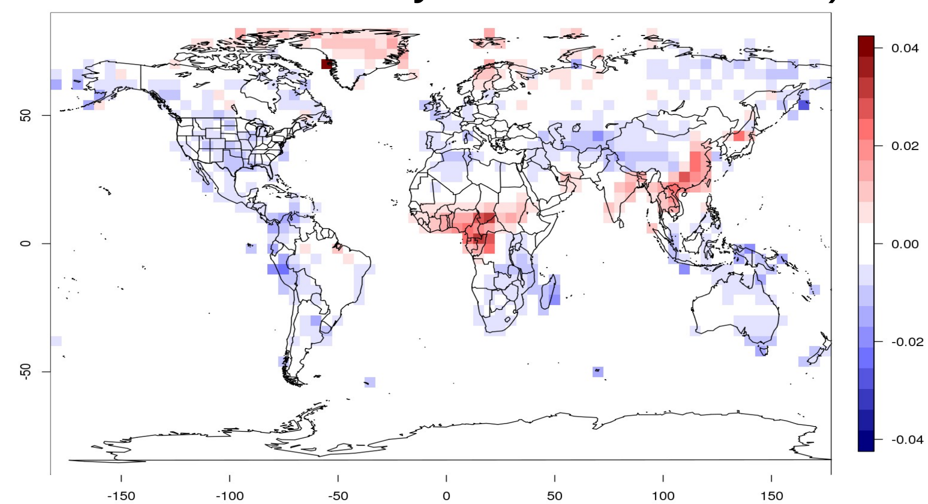
- **UoL v5.1 proxy retrievals (PROXY):**
  1) Use optimized CO_2 fields from global GEOS-Chem inversion constrained by ACOS-GOSAT CO_2 data as proxy for methane
  2) Remove retrievals over Greenland
- **SRON RemoTeC v2.1 full physics retrievals (FP):**
  1) Use retrievals only over land
  2) Filter retrievals with M-gain (over highly reflected surfaces)
- **FP with temporal grouping:**
  1) Use 2 months observation time window to constrain monthly emissions

Mean xCH4 difference:
GEOS-Chem – GOSAT (PROXY)

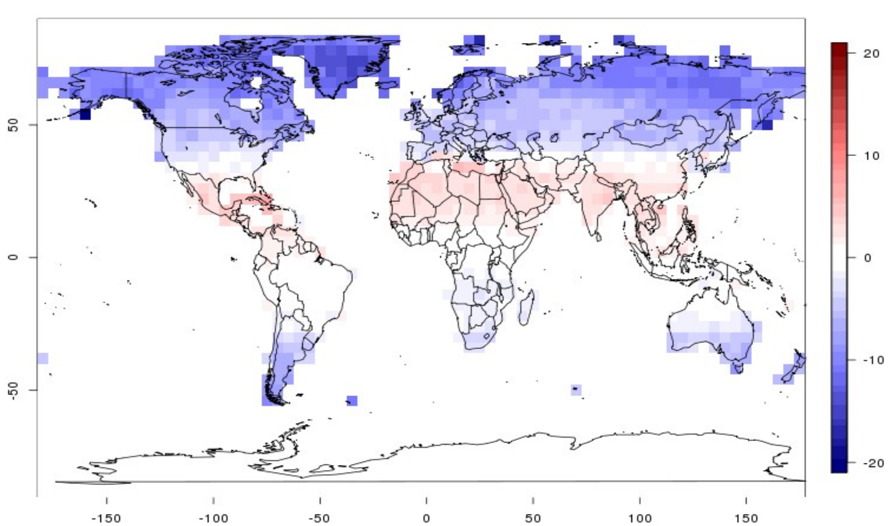
Stratospheric CH4 from GEOS-Chem



Stratospheric CH4 from retrieval a priori profile (stratosphere is from TOMCAT model constrained by ACE-FTS satellite)

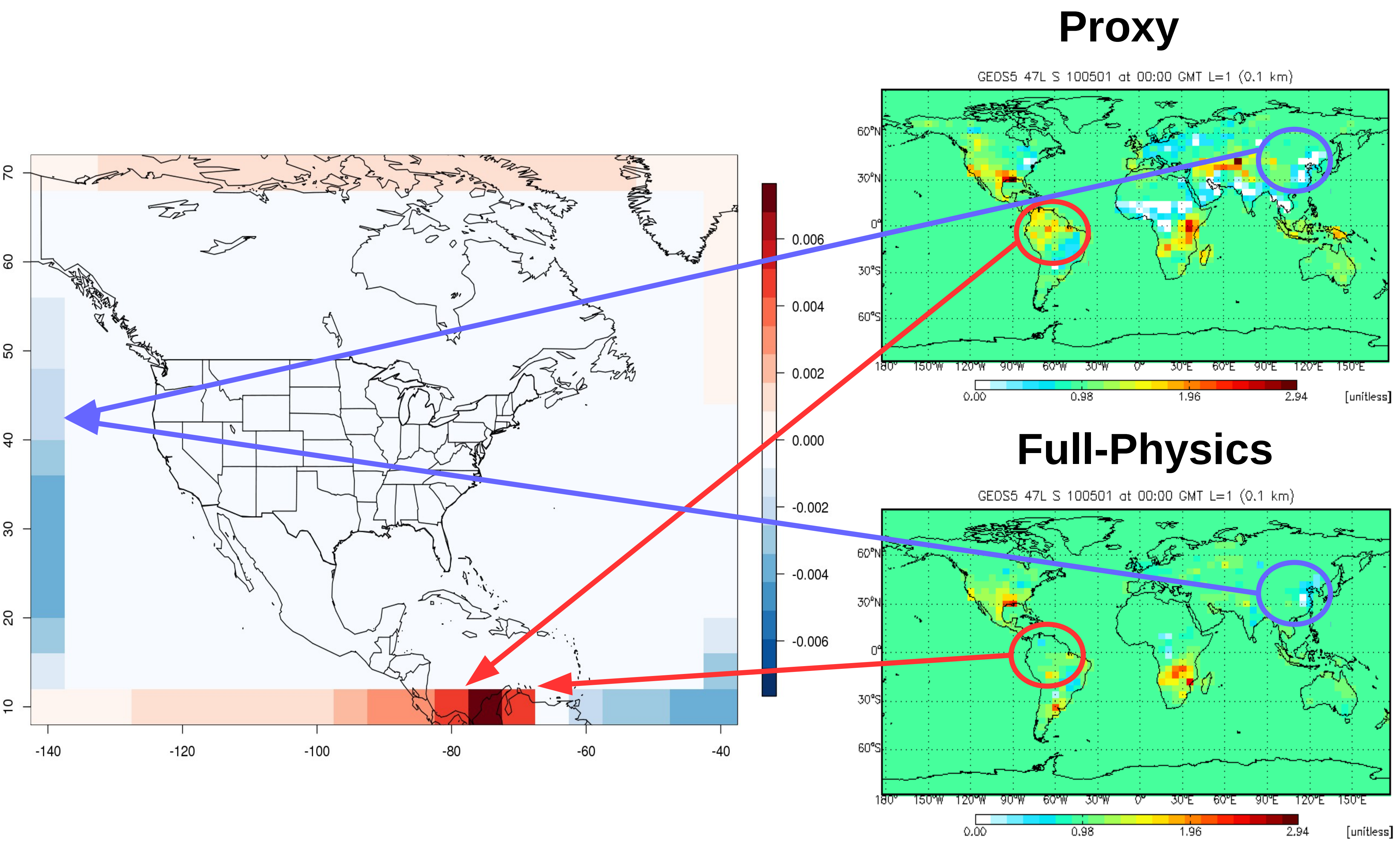


Modelled xCH4 difference: TOMCAT stratosphere case – GEOS-Chem stratosphere case



- Latitudinal bias in GEOS-Chem stratosphere
- GEOS-Chem stratospheric CH4:
  1) High in polar regions
  2) Low in tropics

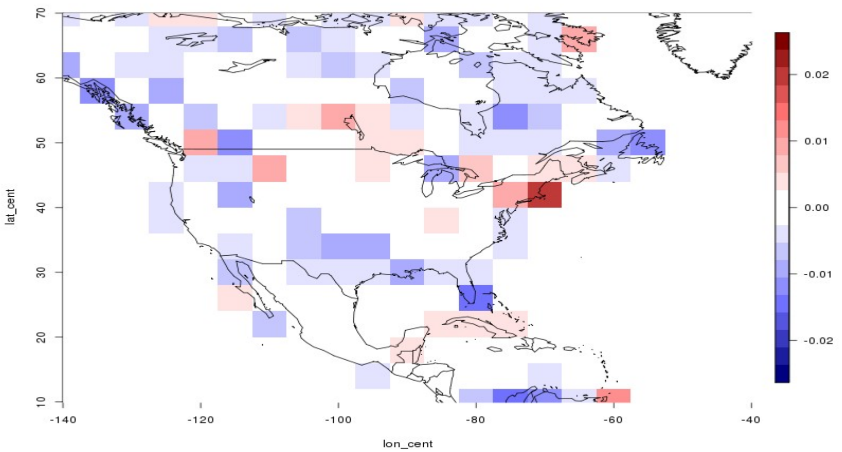
Difference between PROXY and FP BC



GEOS-Chem global inversion results:

From global to regional biases in May 2010

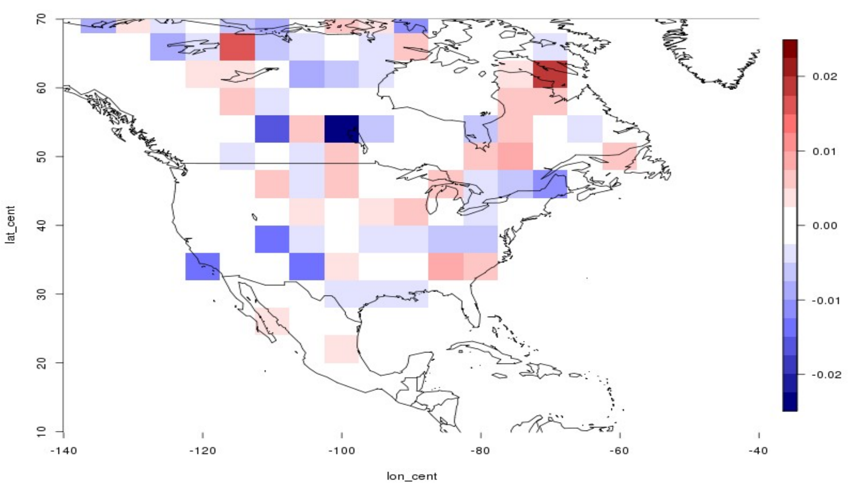
Proxy



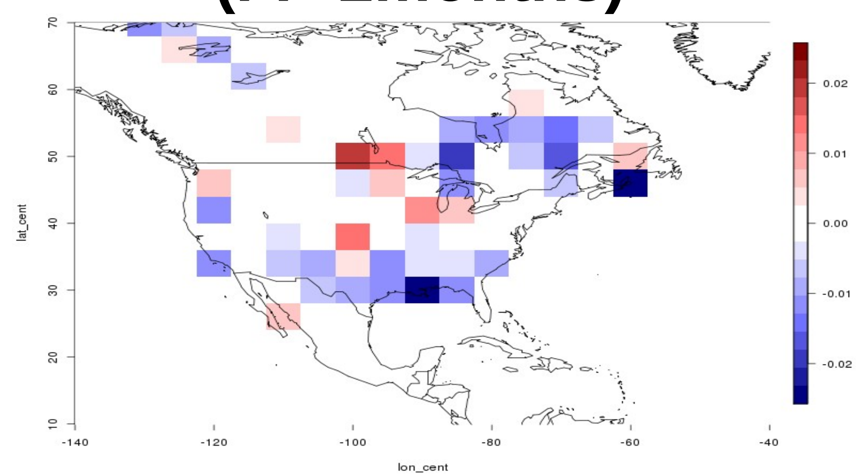
Correlation:

1) with North American hourly surface flask measurements: 0.22 – 0.26;
2) global weekly NOAA surface flask measurements – 0.85-0.9;
3) Validation is underway.

Full-Physics (FP)



Full-Physics 2 month window (FP-2months)



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From global to regional biases

A posteriori statistics GEOS-Chem vs.GOSAT

MAY 2010

	Global bias [ppb]	NA bias [ppb]	Global std [ppb]	NA std [ppb]	Global cor	NA cor
PROXY	-0.69	-2.43	10.6	11.9	0.87	0.65
FP	-4.1	-6.12	12	11.65	0.85	0.69
FP-2m	-1.8	-3.53	11	11.25	0.84	0.71

JUNE 2010

	Global bias [ppb]	NA bias [ppb]	Global std [ppb]	NA std [ppb]	Global cor	NA cor
PROXY	-0.36	-0.23	10.4	11.8	0.86	0.65
FP	-2.7	-1.26	10.7	10.25	0.81	0.77
FP-2m	-1.4	0.57	10.7	10.15	0.8	0.77

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Inversions constrain global and regional CH4 burden quiet well in June

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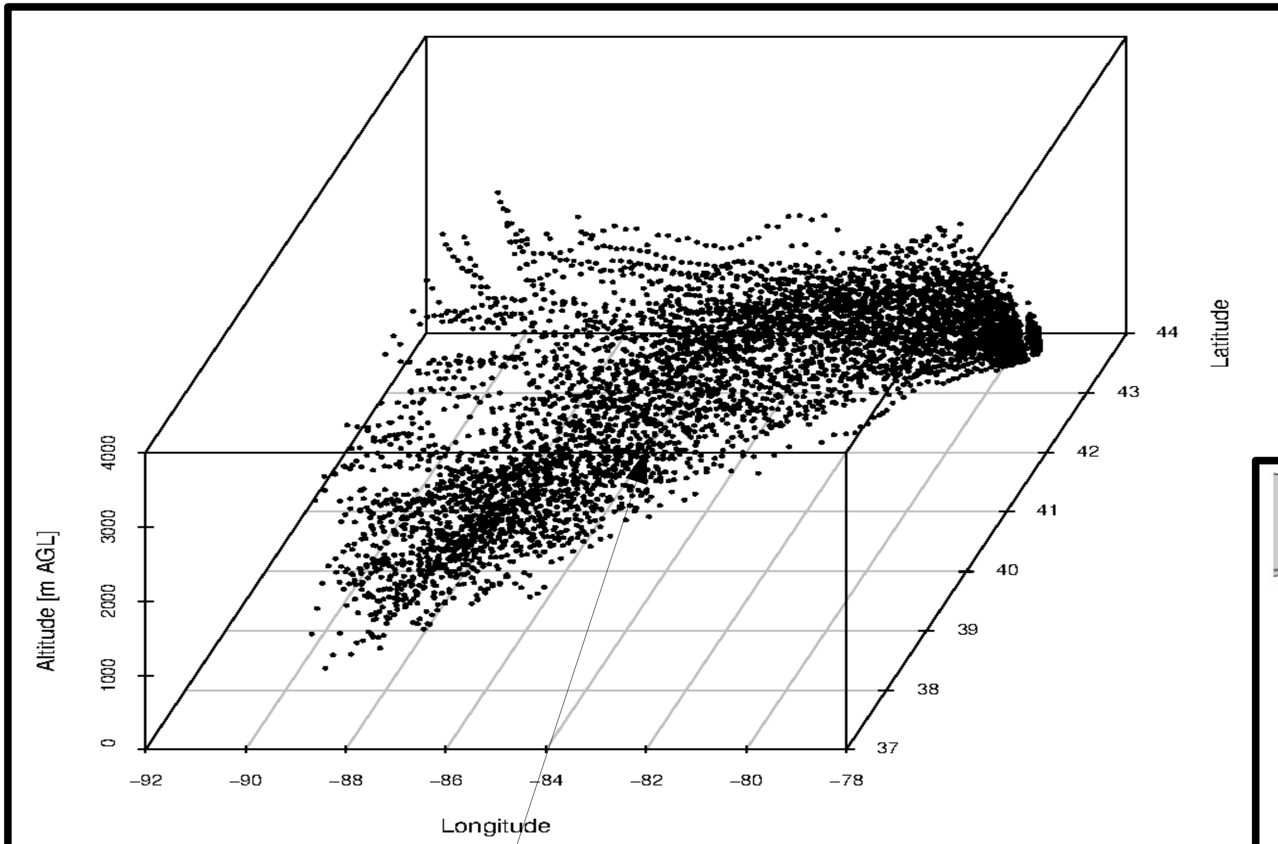
Assume uniform regional NA bias → Bias in CH4 atmospheric burden → Bias in emissions

	NA bias	Bias in total CH4 burden over NA	Bias in surface emissions	Fractional bias in May 2010 emissions
PROXY	-2.43 ppb	0.14%	0.9 Tg	17%
FP	-6.12 ppb	0.35%	2.2 Tg	42%
FP-2m	-3.53 ppb	0.2%	1.3 Tg	24%

GEOS-Chem pseudo inversion corrects for ~1 Tg

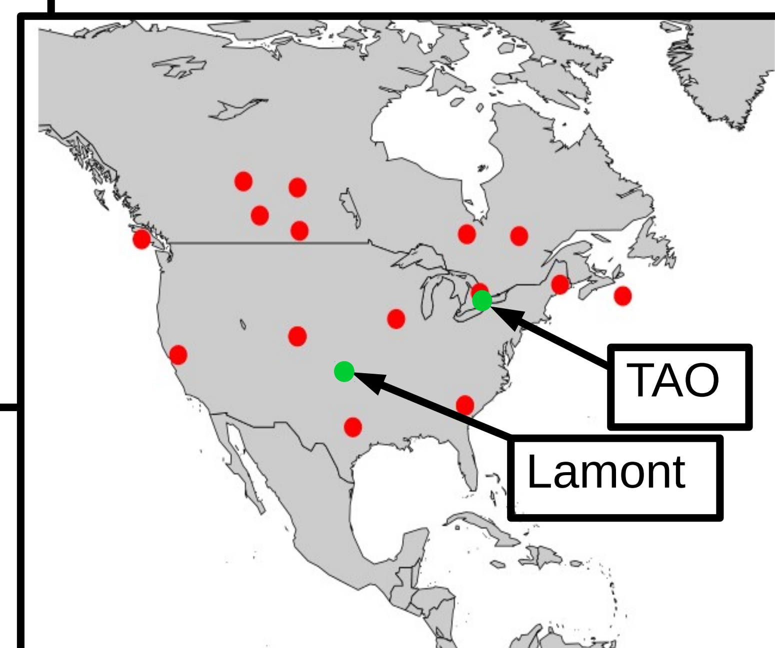
A priori NA emissions in May 2010 – 5.25 Tg

Regional inversion:
Stochastic Time-Inverted Lagrangian Transport
STILT model



$$\frac{d[X]}{dt} = P - [X]f = P - [X]\frac{L}{[X]_0}$$

Use STILT *transport* and OH *chemistry* to model CH4 concentrations at 15 surface stations and 2 FTIR sites



STILT model
Input data and setup

Input fields:

- WRF meteorological fields (30 km resolution) [*temporarily use EDAS*]
- Boundary conditions from GEOS-Chem PROXY optimization
- GEOS-Chem surface fluxes, CH_4 chemical loss rates

Measurements:

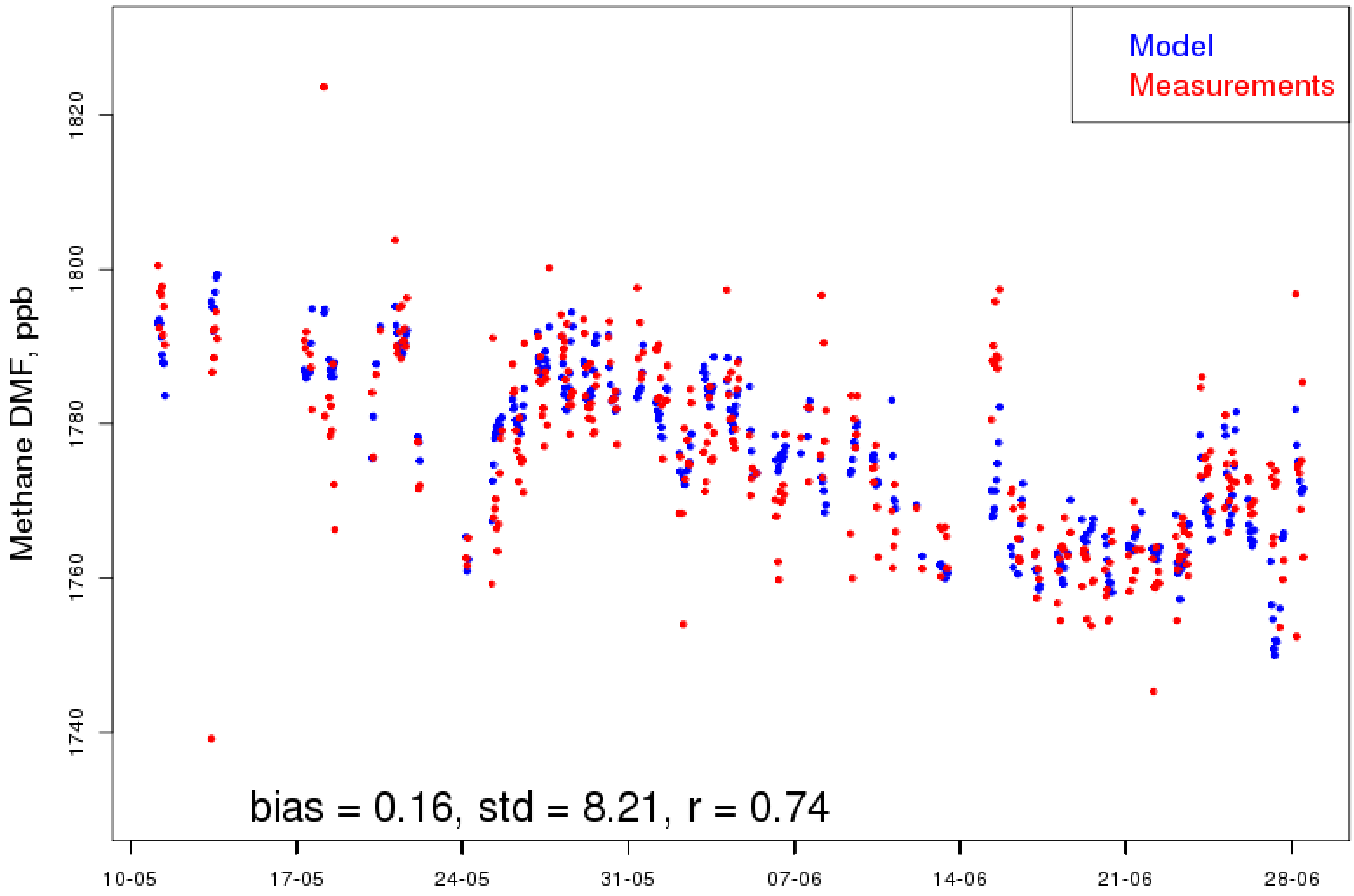
- NOAA and Environment Canada surface flask measurements over North America
- FTIR CH_4 retrievals from Lamont (TCCON site) and TAO (NDACC site)

Setup:

- 10 day backward run for 100 particles
- Modelling period – May-June 2010
- Optimize 1˚ x 1˚ surface emissions using Optimal Estimation

Modelling Lamont xCH4

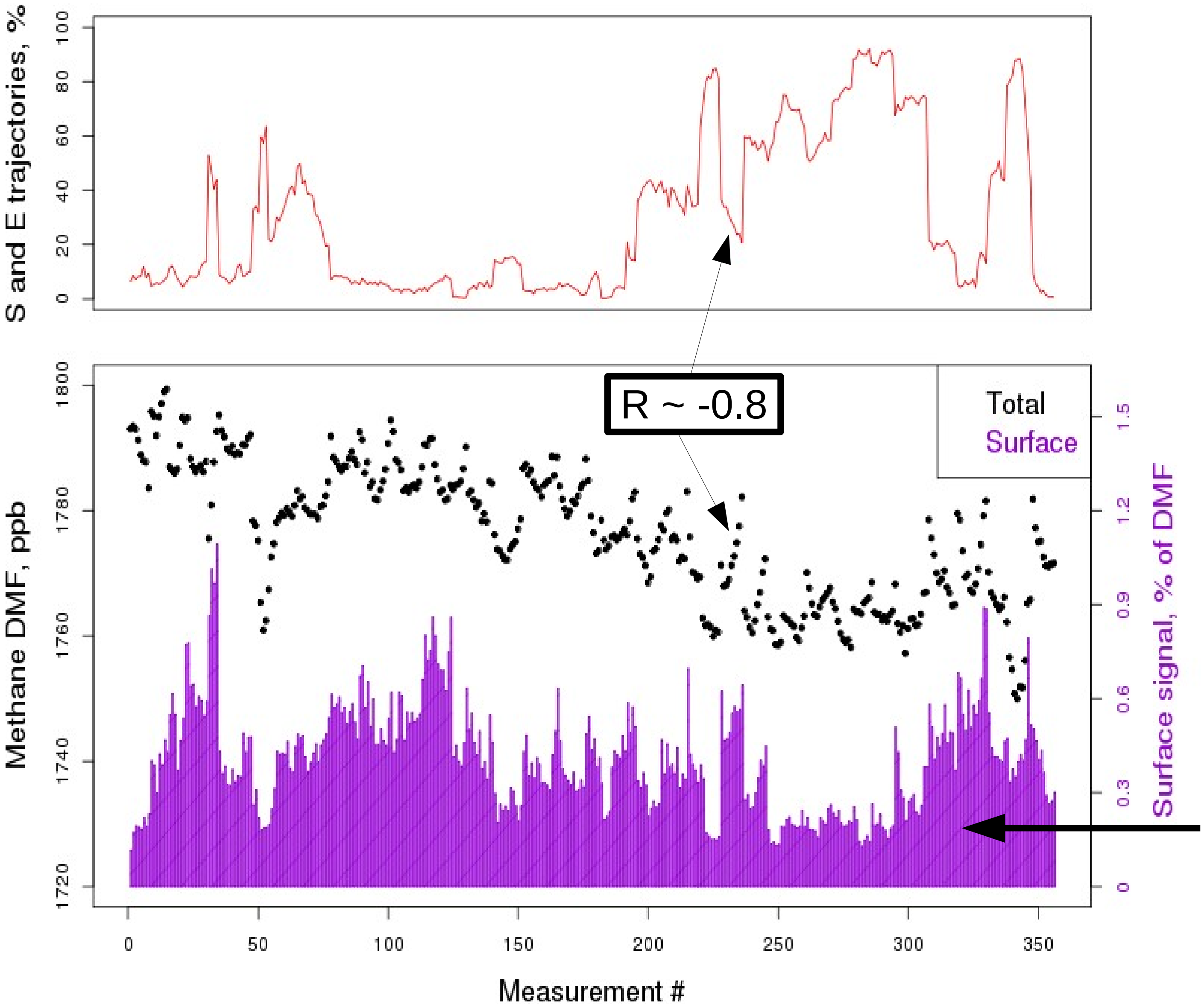
Timeseries of TCCON retrievals versus modelled DMFs



- Model tropospheric CH4 over the range of altitudes using STILT
- Retrieve stratospheric CH4 from GEOS-Chem model
- Interpolate and smooth modelled profiles with TCCON Averaging Kernels

Modelling Lamont xCH4

Interpreting TCCON measurements



Top figure:

- Fraction of trajectories arriving up to 6 km above Lamont location from Southern and Eastern Boundary

Bottom figure:

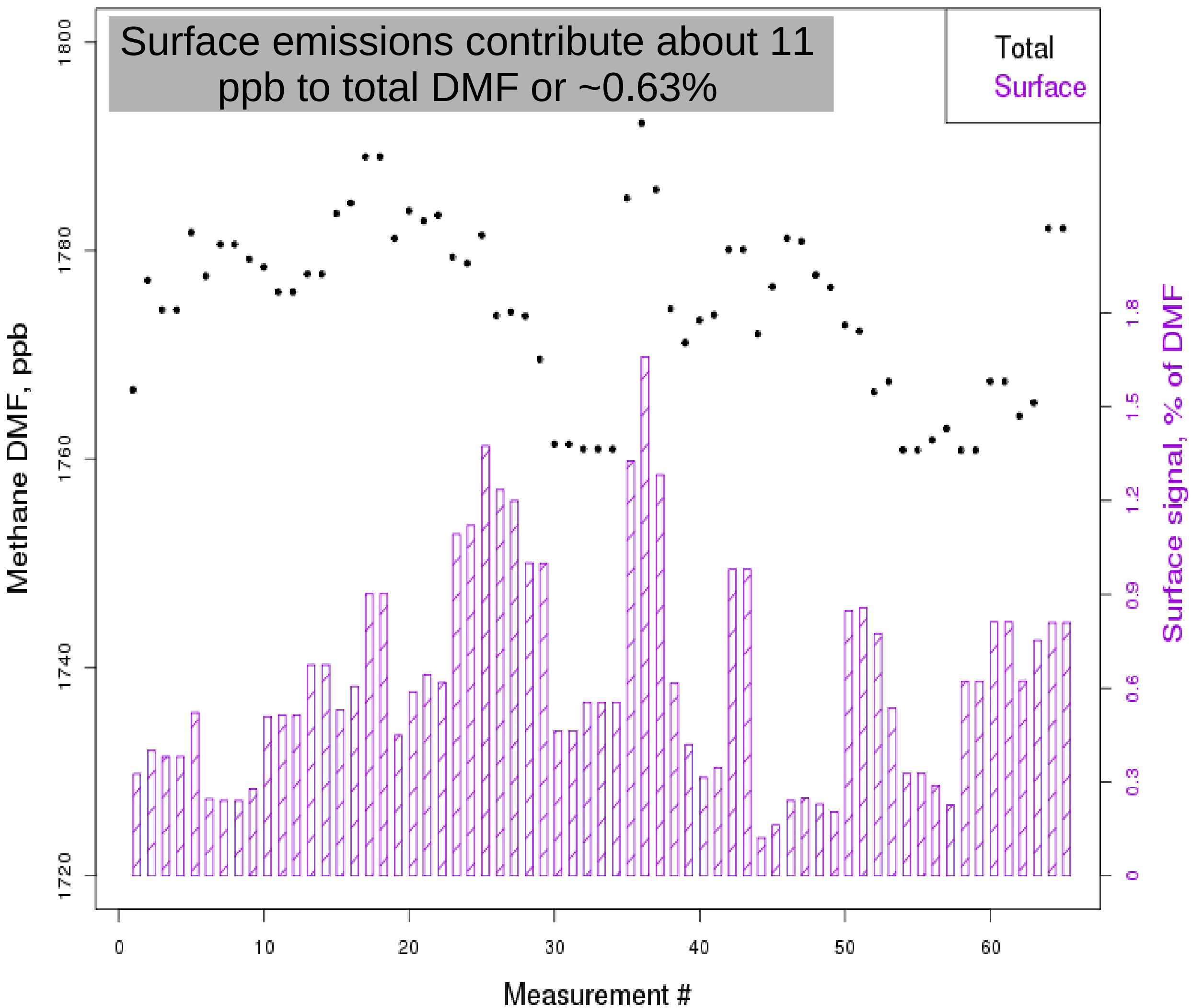
- Modelled Lamont DMFs (black) and fraction of DMF due to local surface emissions (purple).

80% of variability in total columns is explained by the direction from which BC are advected

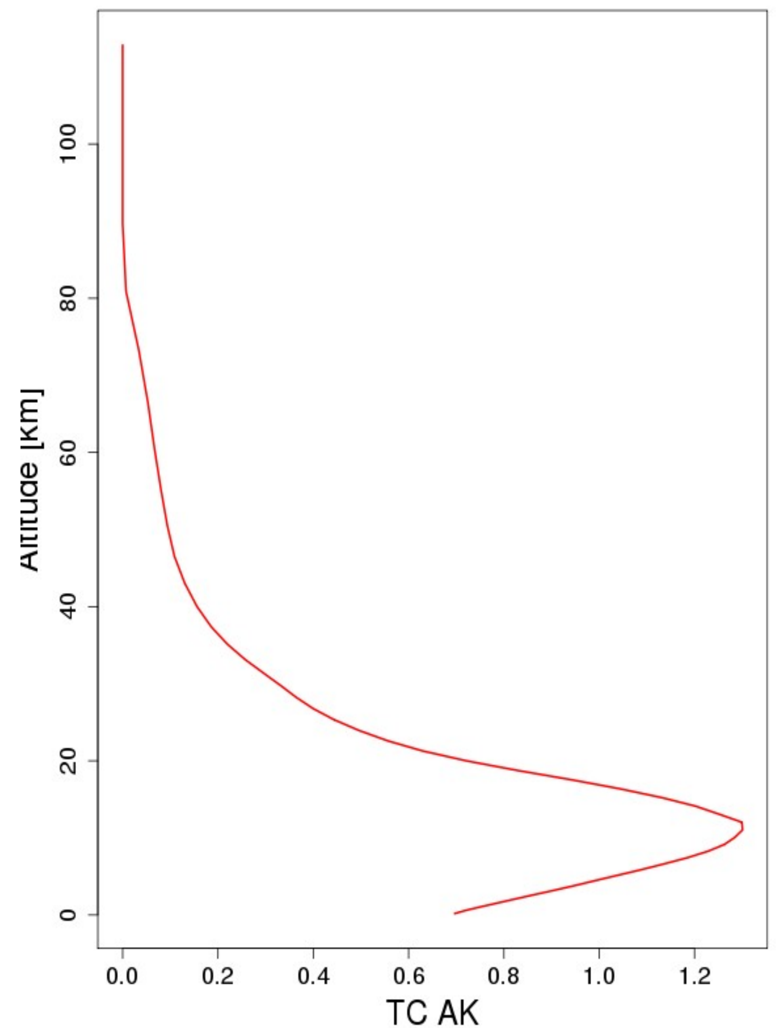
Mean surface signal in Lamont CH4 DMFs is about 7 ppb (~0.4% of total DMF)

Modelling TAO xCH4

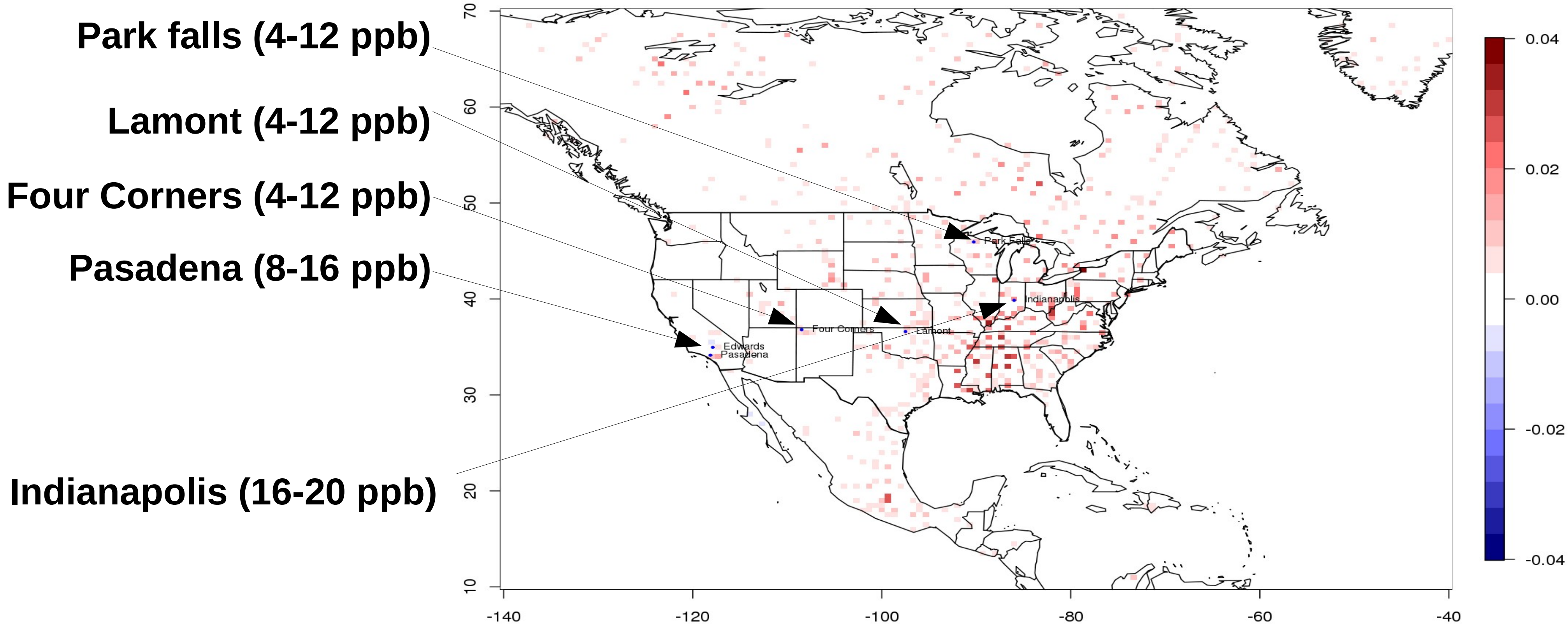
Modelled Lamont DMFs (black) and fraction of DMF due to local surface emissions (purple)



TAO mean total column averaging kernel



Signal of North American emissions in GOSAT retrievals in May 2010



Maximum difference between GEOS-Chem CH4 columns for the runs with ***a priori emissions*** and ***without any emissions from North America***

CH4 DMFs are samples at GOSAT measurement locations and smoothed with GOSAT AK

Signal of North American emissions in GOSAT retrievals in May 2010

Below 1% of total column

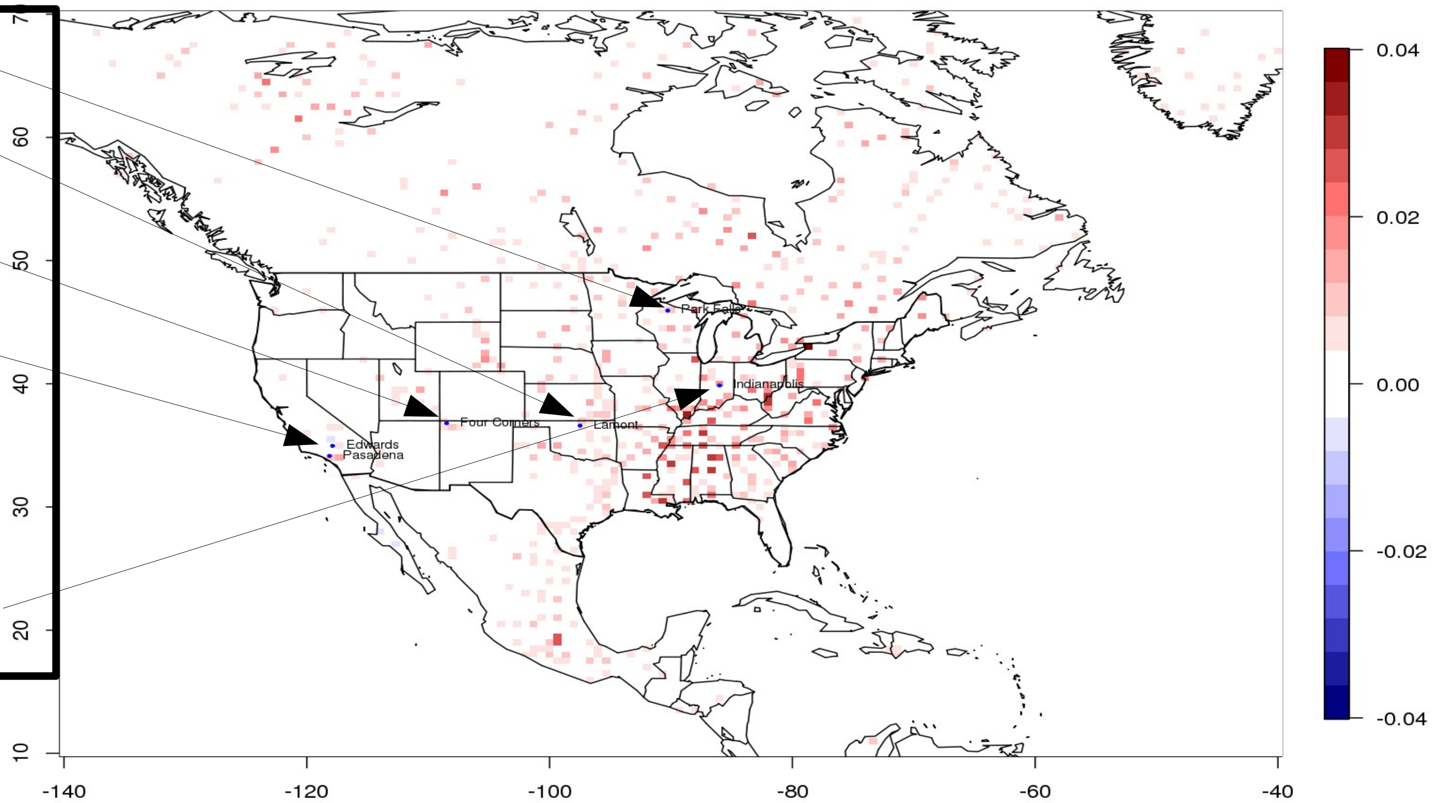
Park falls (4-12 ppb)

Lamont (4-12 ppb)

Four Corners (4-12 ppb)

Pasadena (8-16 ppb)

Indianapolis (16-20 ppb)



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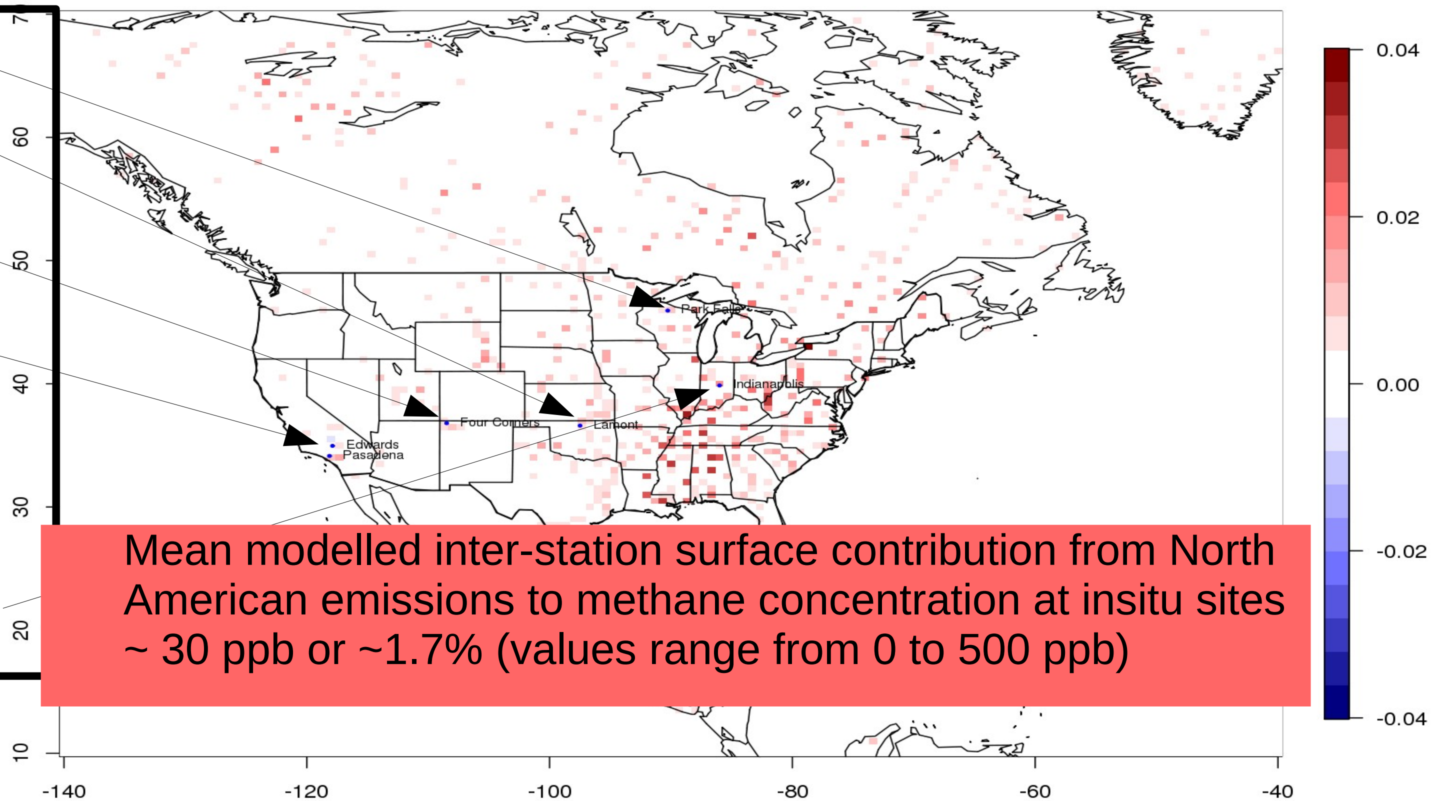
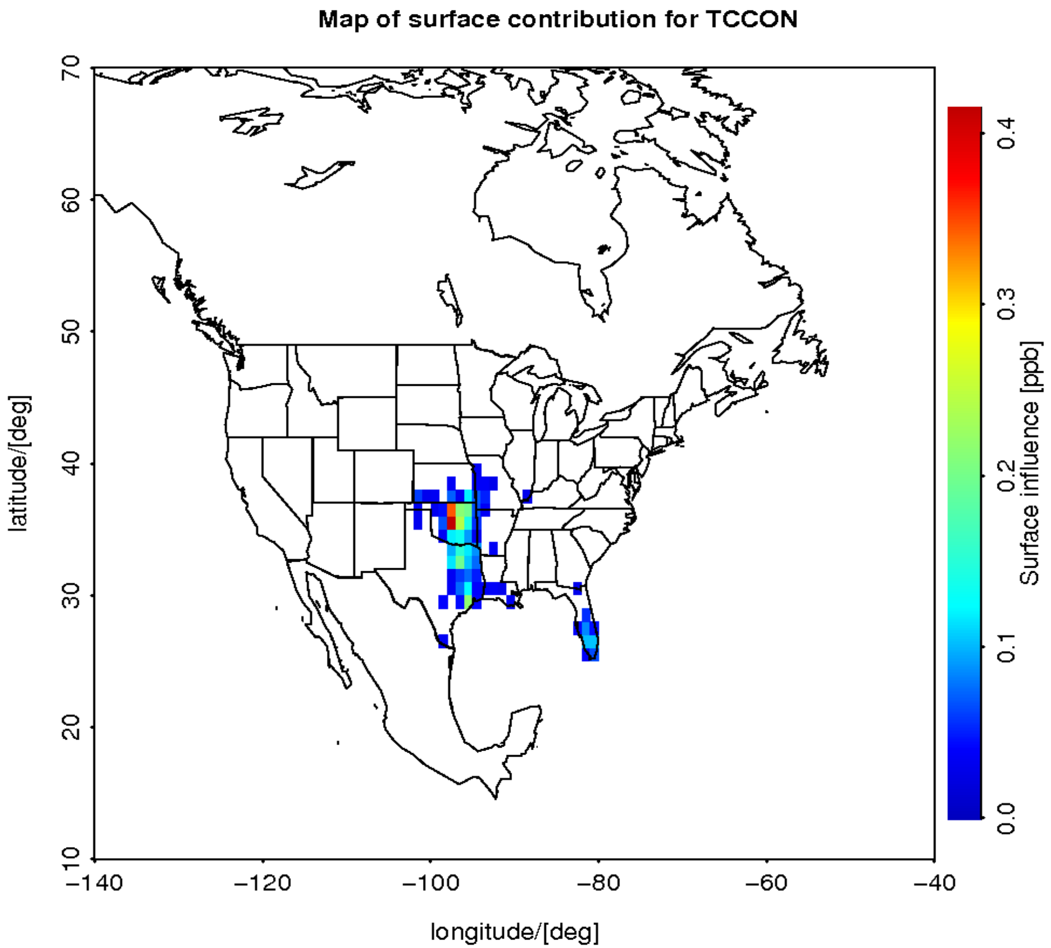


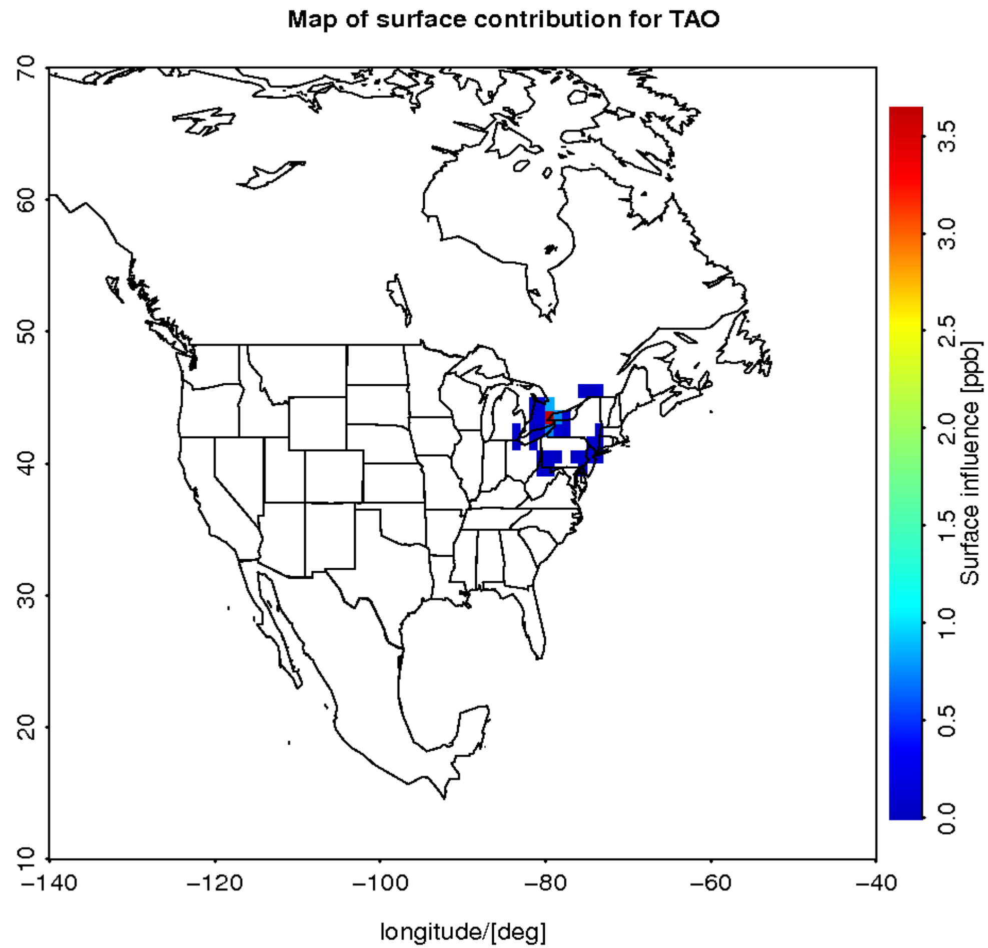
Mean modelled inter-station surface contribution from North American emissions to methane concentration at insitu sites ~ 30 ppb or ~1.7% (values range from 0 to 500 ppb)

Maximum difference between GEOS-Chem CH4 columns for the runs with ***a priori emissions*** and ***without any emissions from North America***

CH4 DMFs are samples at GOSAT measurement locations and smoothed with GOSAT AK

Mean surface signal in Lamont and TAO retrievals in May 2010

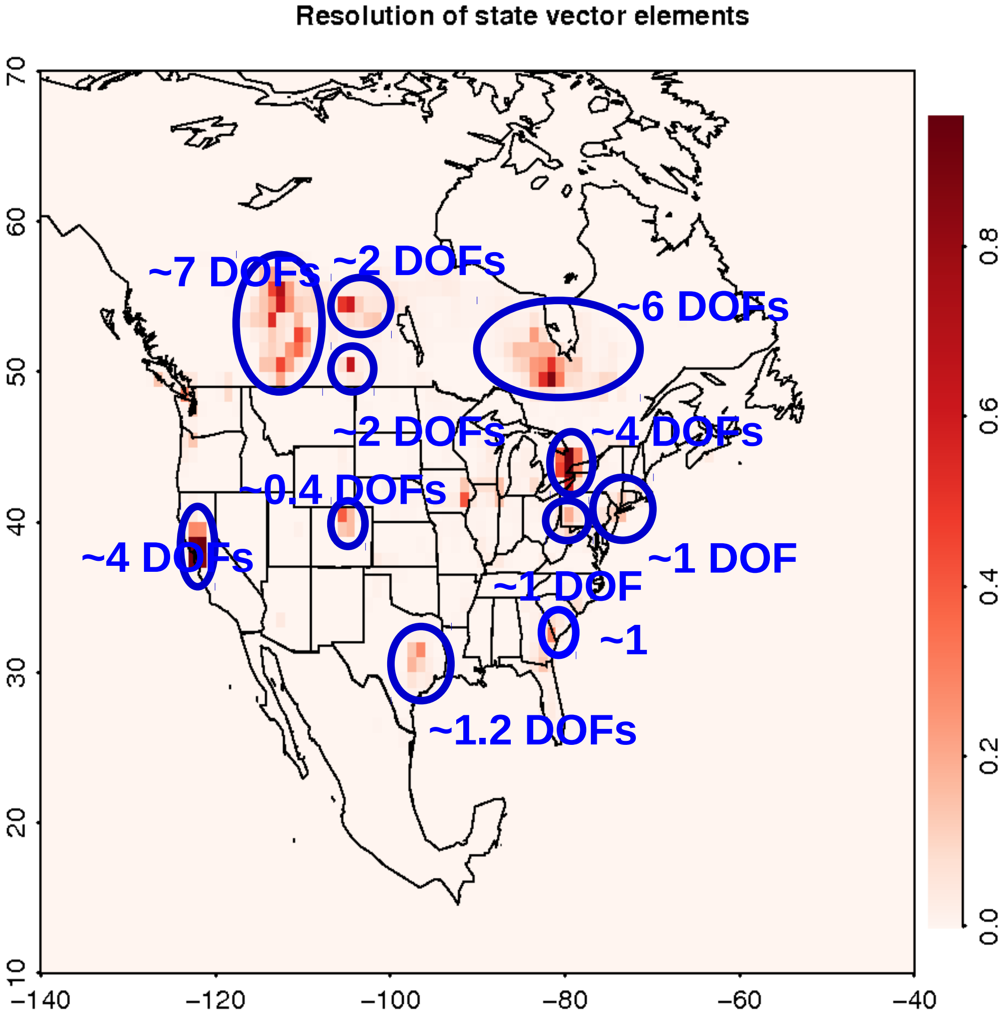




- Surface signal is localized very close to the instrument location
- Surface signal for Lamont is very weak but spread over larger area
- TAO surface signal is stronger and localized mainly at Toronto grid box

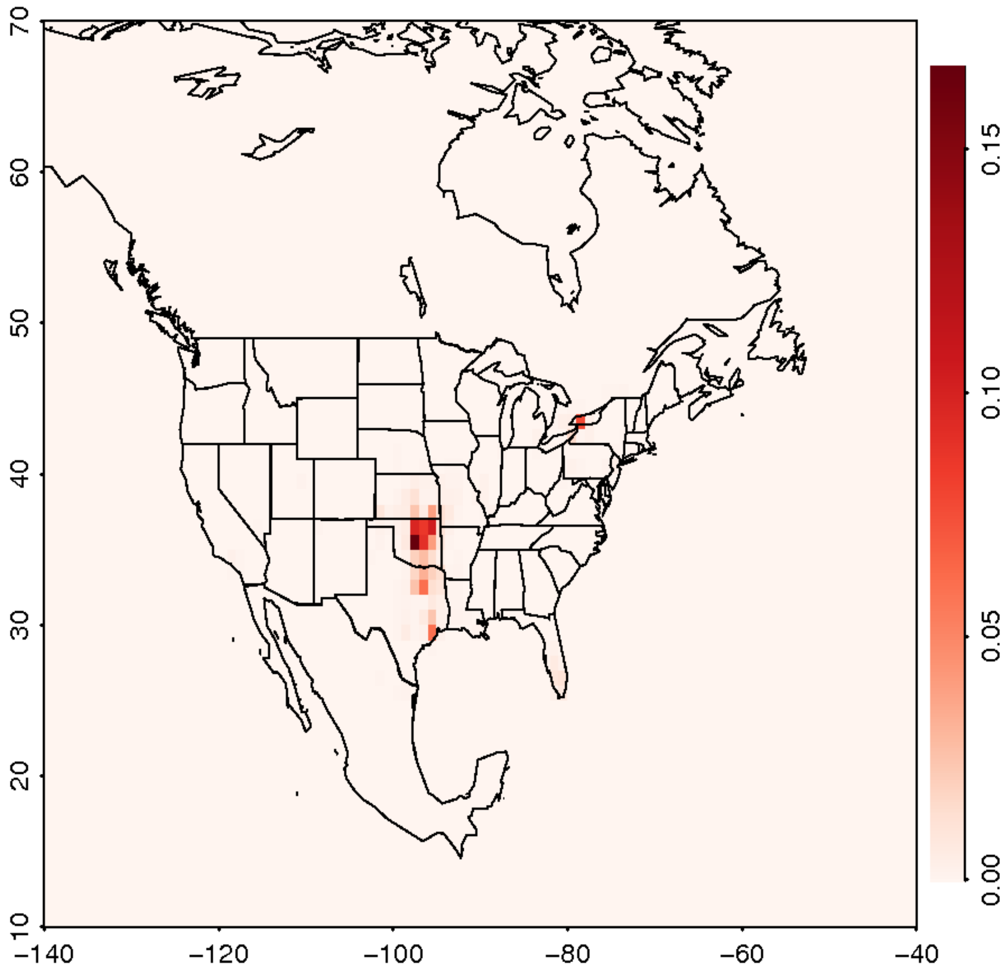
Distribution of information (May 2010)

Insitu measurements only inversion



Total # of DOFs ~38.4

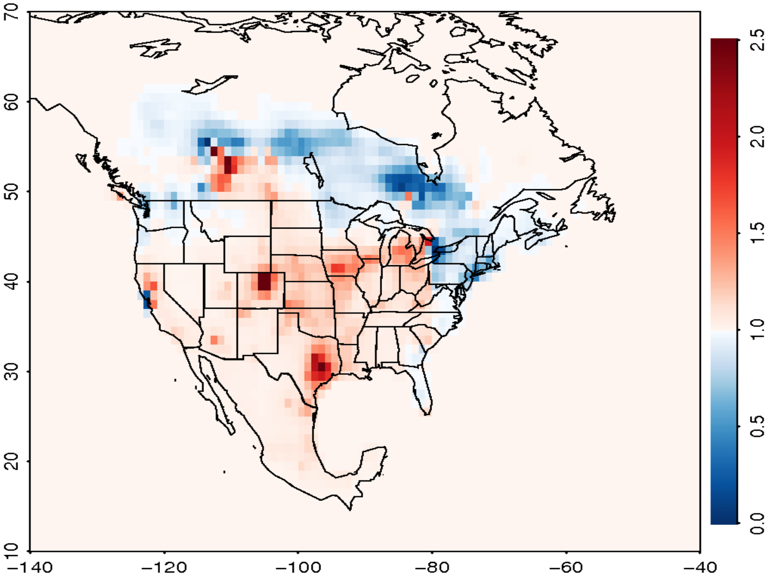
All measurements inversion



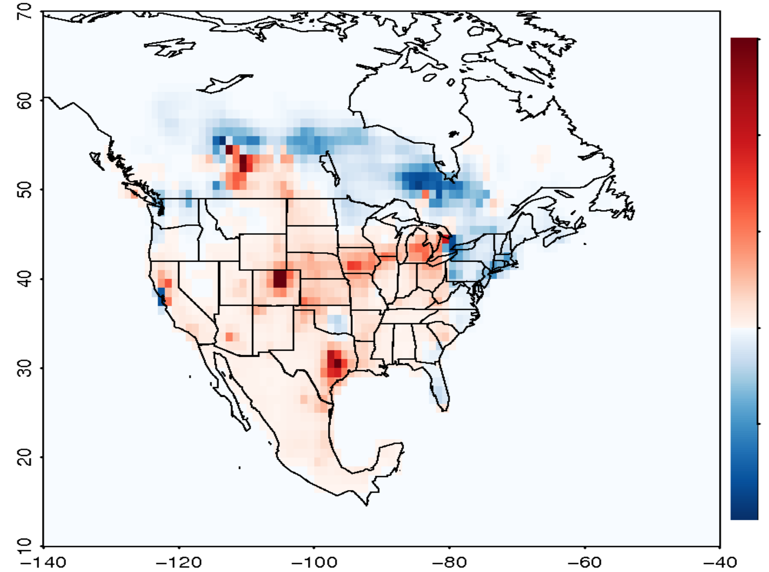
+1.5 DOF

Inversion results: scaling factors

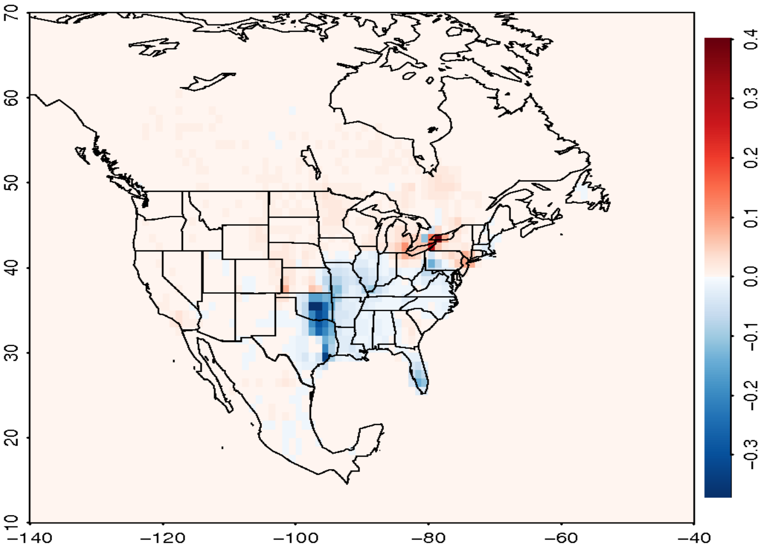
Insitu measurements only inversion



All measurements inversion



Difference: ALL- INSITU

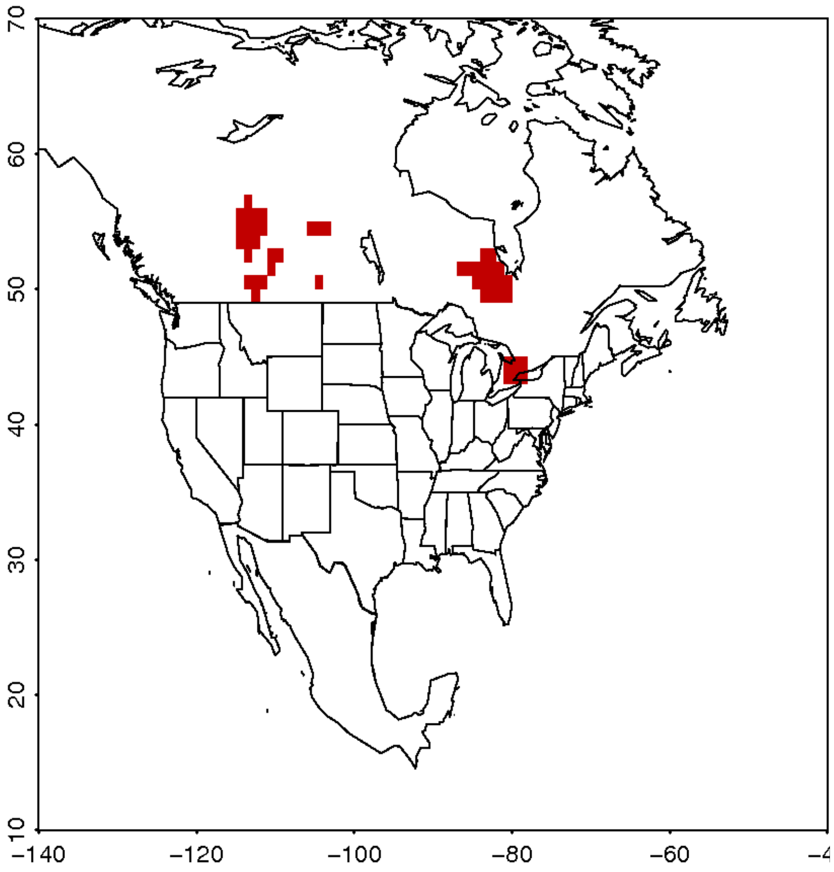


	Bias [ppb]	Std [ppb]	Cor
A priori	6.9	38.6	0.65
A posteriori	-0.7	19.7	0.84

- TAO measurements scale mainly Toronto emissions
- Lamont measurements introduce moderately lower local surface fluxes
- Overall FTIR measurements bring very little additional information in regional flux inversion:
  - Insitu site at Egbert (near Toronto) provides main constraint on Toronto emissions
  - Surface sensitivity of Lamont site is very small

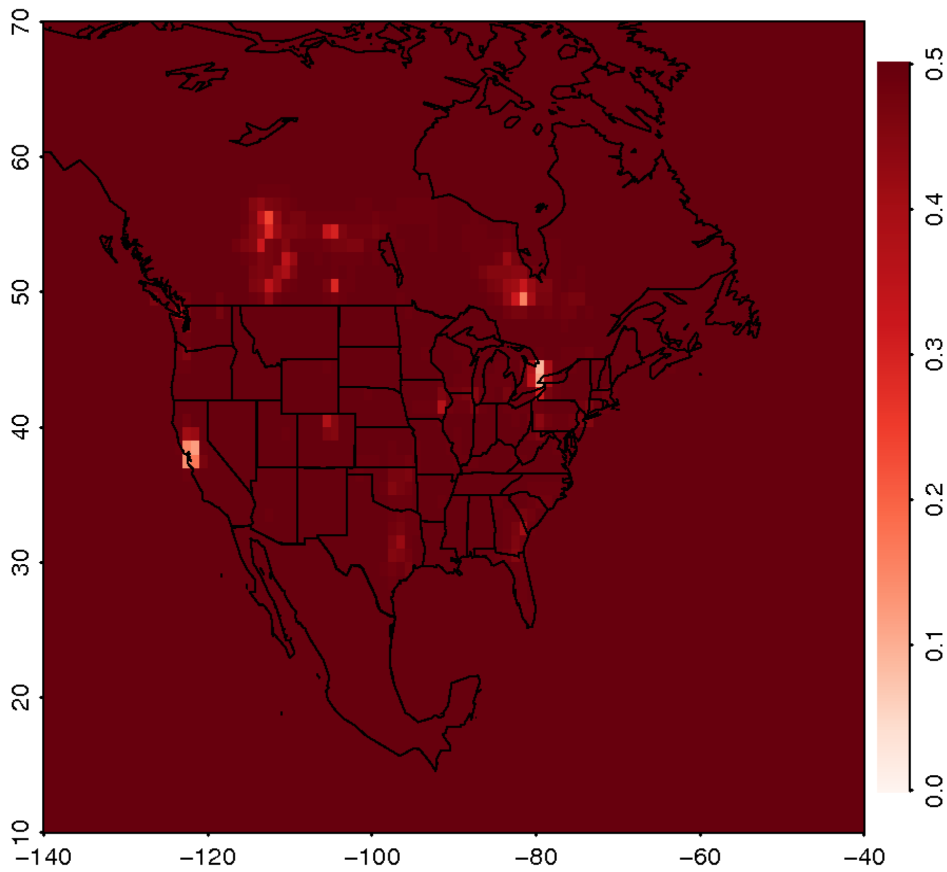
Uncertainty reduction on Canadian emissions in May 2010

Areas of Canada measurements are sensitive to



- Based on analysis of Jacobian matrix
- Outlined areas contain only **14% of total Canadian emissions**

A posteriori uncertainty



- A priori uncertainty on monthly emissions in each grid cell – 50%
- Uncertainty is reduced locally by up to 80 %; total uncertainty reduction is small

Sensitivity to bias in BC (May 2010)

Global inversion: A posteriori statistics GEOS-Chem vs.GOSAT

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Assume uniform regional NA bias ──► Bias in CH4 atmospheric burden ──► Bias in emissions

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Sensitivity to bias in BC

	NA bias	Bias in total CH4 burden over NA	Bias in surface emissions	Fractional bias in May 2010 emissions
PROXY	-2.43 ppb	0.14%	0.9 Tg	17%

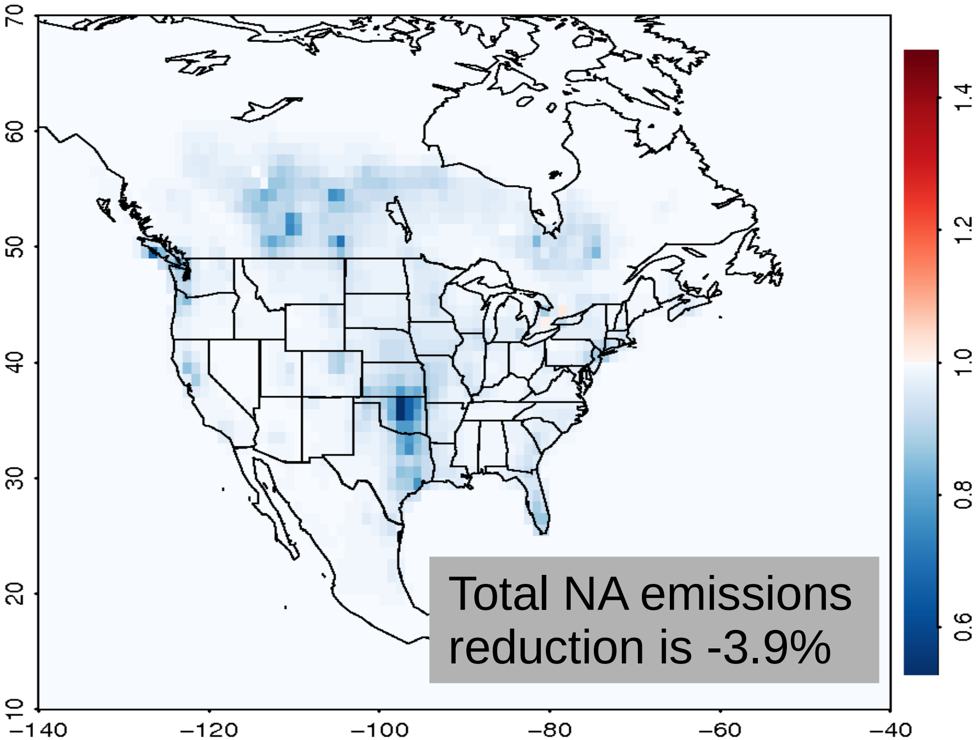
- Assume that the BIAS of 2.4 ppb in CH4 total columns is uniform over the box [-140; -40] East and [10; 70] North – GEOS-Chem nested NA region
- Apply scaling factor of 1.0015 to CH4 atmospheric concentrations over this region to correct for the bias
- Run pseudo inversion to understand how regional inversion reacts on such bias correction:
  1) Using nested GEOS-Chem model
  2) Using STILT model

Pseudo inversion setup

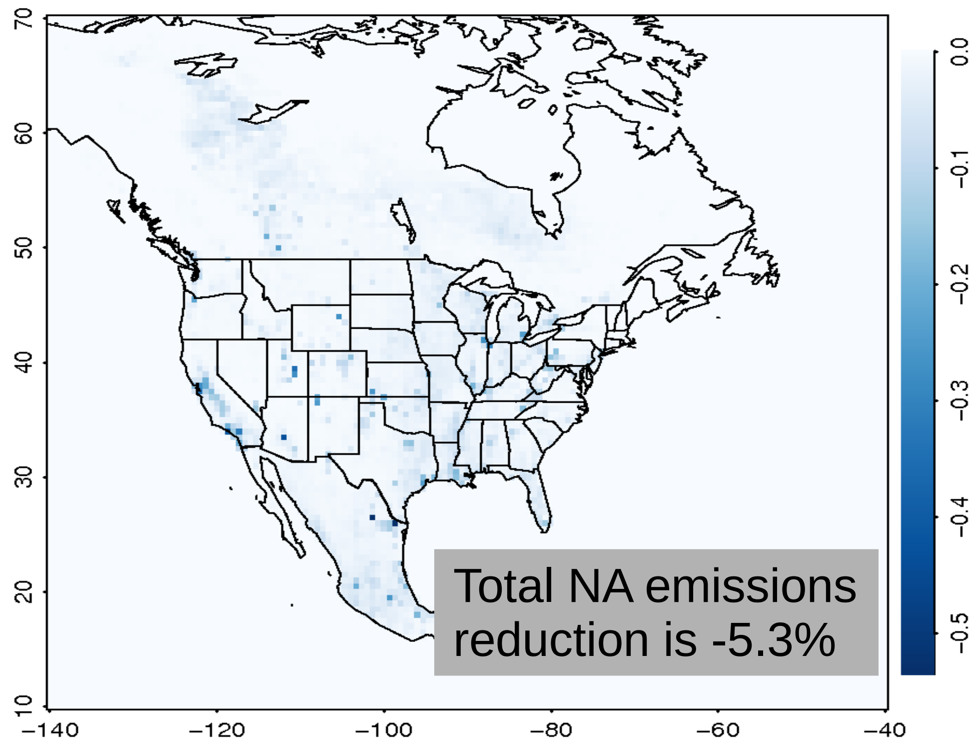
- Sample the model at times and locations of measurements using a priori emissions and Proxy boundary conditions; use model output as pseudo observations
- Introduce bias in BC (and in initial condition for GEOS-Chem)
  1) Uniformly increase BC by a factor of 1.0015 (0.15%)
- Constrain a new state using pseudo observations

Sensitivity to bias in BC

Scaling factors from STILT pseudo inversion



Scaling factors from GEOS-Chem pseudo inversion



- Although for NA we should ideally get reduction of total emissions by about 17% (possible bias in real inversion), local changes in surface fluxes are much larger:
  - Up to **-45%** reduction in STILT inversion (1x1 grid inversion)
  - Up to **-53%** reduction in GEOS-Chem nested GOSAT inversion (0.5x0.67 grid inversion)
- This suggests that emissions have to be estimated at lower spatial resolution even near measurement sites (some local aggregation has to be performed) – limitation on the highest possible resolution

Conclusions

- GOSAT PROXY retrievals constrain global CH_4 budget better than Full-Physics retrievals however still do not correct well for the regional biases which may result in significant biases in emissions.
- FTIR retrievals are weakly sensitive to methane surface emission; area of their sensitivity in localized close to measurement location
- Regional inversion successfully reduces misfit between model and observations and significantly improves correlation
- Canadian emissions: chosen observational network is sensitive to only about 14% of Canadian emissions which means that we cannot constrain well total Canadian emissions. Sensitivity to US emission is even smaller
- Inversion shows that we are able to constrain well some local emission sources (such at Toronto emissions) when emission uncertainty is strongly reduced near measurement site
- Estimated emissions are very sensitive to uncorrected biases in Boundary Conditions which result in large changes in local small area emission – this provides a possible limitation on emissions optimization at high resolution

Acknowledgements

This work was supported by the Canadian Space Agency through its funding of the Canadian FTIR Observing Network (CAFTON).