Inverse modeling using TM5 and satellite data

First results from GOSAT

Sourish Basu
Sander Houweling
Maarten Krol

SRON
Netherlands Institute for Space Research

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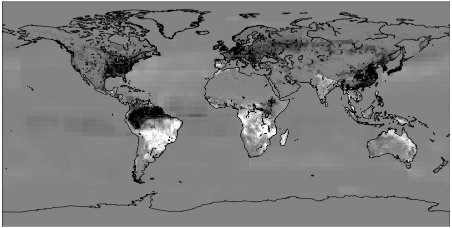
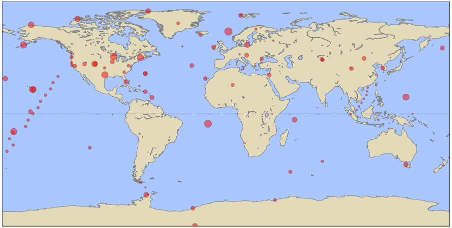
The goal is to derive surface fluxes consistent with a set of measurements under time integration with a transport model (TM5)





Existing network of surface flasks (NOAA, CSIRO, ...)

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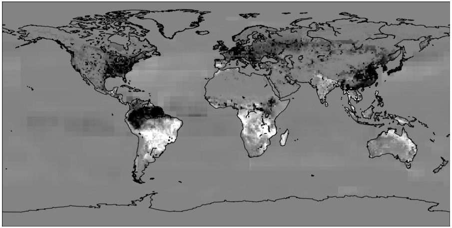

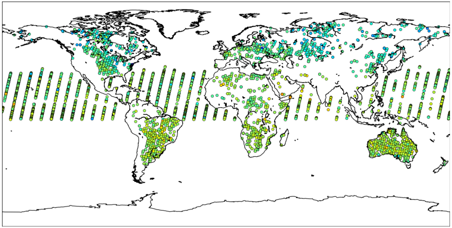

Existing network of surface flasks (NOAA, CSIRO, ...)

New "network" of total column observations from satellites is spatially denser and more extended

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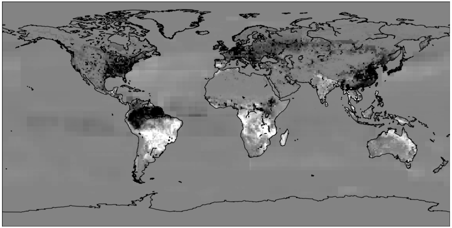
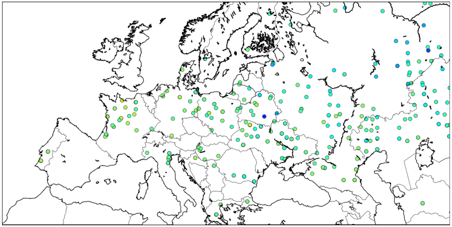
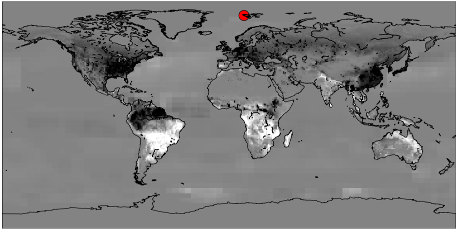
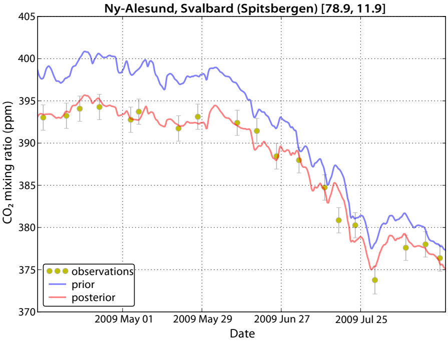




Existing network of surface flasks (NOAA, CSIRO, ...)

New "network" of total column observations from satellites is spatially denser and more extended





- Adjust fluxes to better fit modeled concentrations with observations
- Minimize a “cost function”

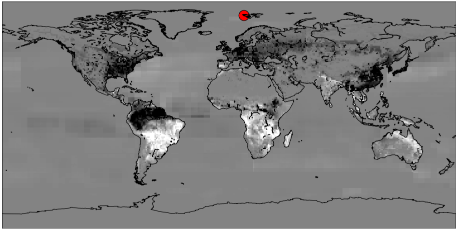
$$J(\vec{x}) = J_{\text{prior}} + J_{\text{stations}} + J_{\text{satellite}}$$

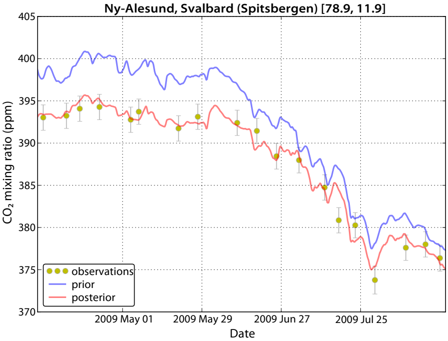
where $\vec{x}$ contains emissions

- The adjoint model effectively evaluates the gradient

$$\frac{\partial J}{\partial \vec{x}}$$

to help minimization routines





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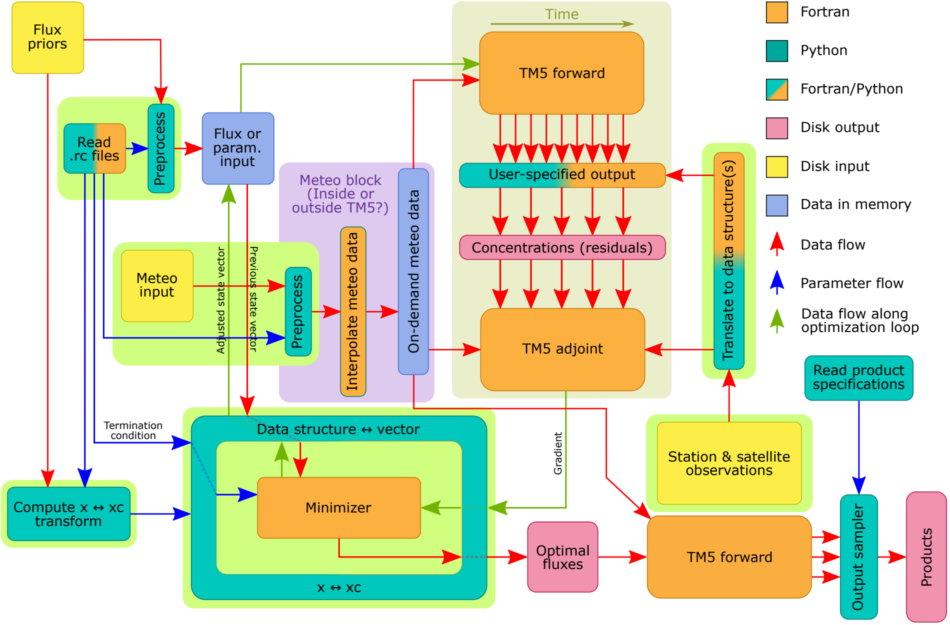

Flux priors
Read .rc files
Preprocess
Flux or param. input
Meteo block (Inside or outside TM5?)
Meteo input
Adjusted state vector
Previous state vector
Preprocess
Interpolate meteo data
On-demand meteo data
Time
TM5 forward
User-specified output
Concentrations (residuals)
TM5 adjoint
Translate to data structure(s)
Fortran
Python
Fortran/Python
Disk output
Disk input
Data in memory
Data flow
Parameter flow
Data flow along optimization loop
Read product specifications
Termination condition
Data structure ↔ vector
Minimizer
x ↔ xc
Compute x ↔ xc transform
Gradient
Station & satellite observations
Optimal fluxes
TM5 forward
Output sampler
Products

Satellite/TCCON input file

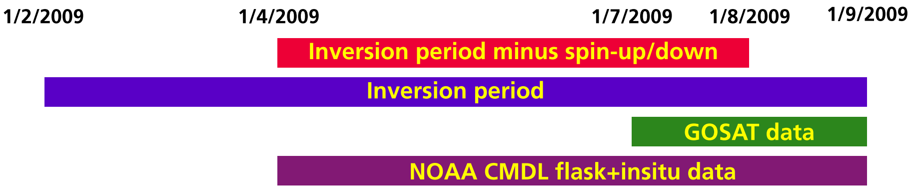
```
variables:
        float avg_kernel(n_obs, n_levels) ;
        ...
        short cdate(n_obs, n_time) ;
        float overpass_loc(n_obs, n_coor) ;
```

Satellite/TCCON output file

```
group: glb6x4 {
  variables:
        int input_positions(n_obs) ;
        ...
        short model_loc(n_unique_obs, n_coor) ;
        double profiles(n_unique_obs, n_lev) ;
        short time_windows(n_tsteps, n_tint) ;
  } // group glb6x4
```

Satellite/TCCON adjoint forcing

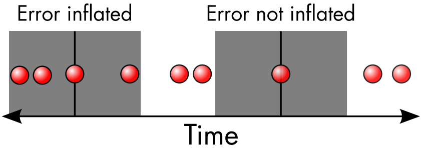
```
group: glb6x4 {
  variables:
        short input_index(n_obs) ;
        ...
        short time_windows(n_tsteps, n_tint) ;
        double departures(n_unique_obs, n_lev) ;
        short unique_model_loc(n_unique_obs, n_coor) ;
  } // group glb6x4
```

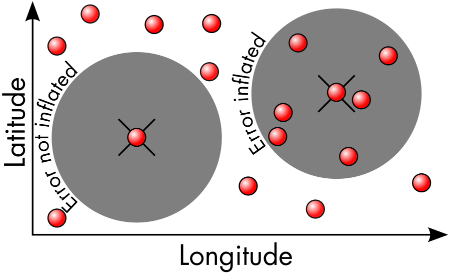


- Starting CO_2 field (not optimized) from CarbonTracker 2010
- GOSAT L2 data from SRON, no bias correction
- Surface station data from NOAA network, includes flask and in-situ measurements
- Surface data averaged over 3 hours for each station, only daytime observations

- GOSAT data not averaged spatio-temporally
- Number of observations $\neq$ number of independent constraints
- Observation errors inflated to account for spatiotemporal correlation

Time window = 3 hours each side
Space window = 500 km (radius)





If observations X_i with errors σ_i fall within the space-time window around observation X_0 with error σ_0, then

$$\sigma_0^{\text{inflated}} = \sigma_0 \times \frac{\sum_i \sigma_i}{\left[\sum_i \sigma_i^2\right]^{1/2}}$$

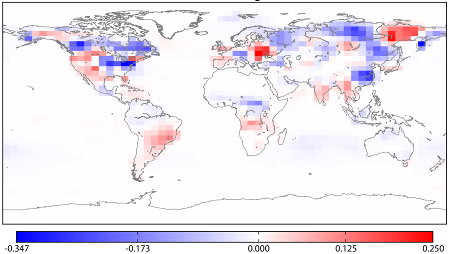
- Prior fluxes from CarbonTracker 2010
- Diurnal cycle (non-optimized) added to monthly mean flux

Prior errors

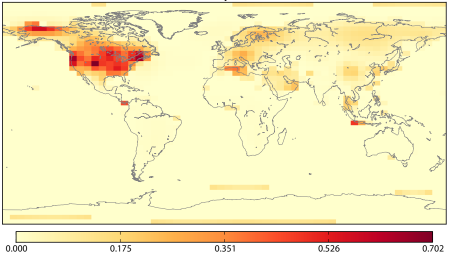
Category	Error (%)	Temporal correlation (months)	Spatial correlation (km)
Terrestrial biosphere	250	3	1000
Oceanic	250	6	1000
Fossil fuel	50	3	5000
Biomass burning	50	1	500

Using NOAA stations

Posterior emission (kg/sec/km^2)

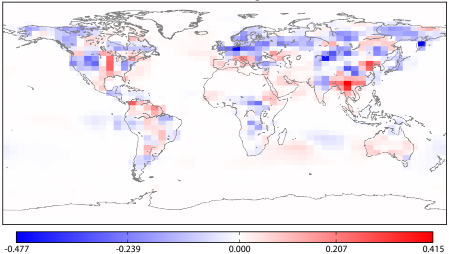


Uncertainty reduction

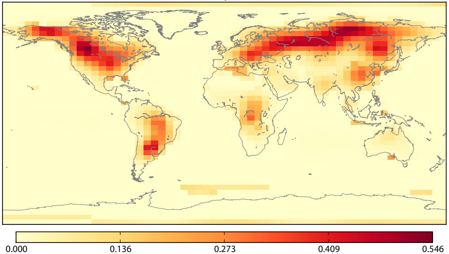


Using GOSAT

Posterior emission (kg/sec/km^2)

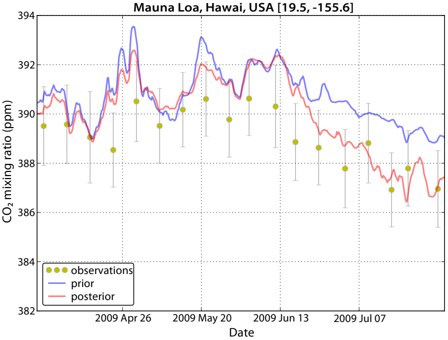


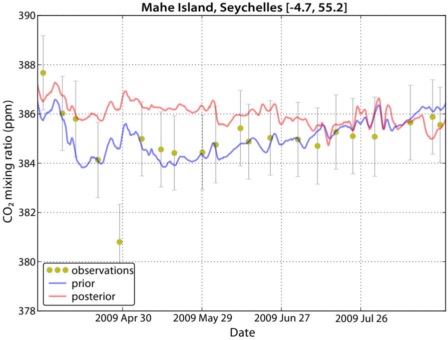
Uncertainty reduction

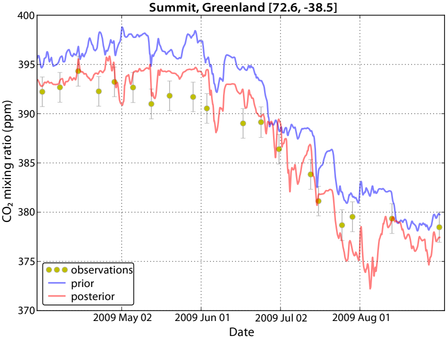


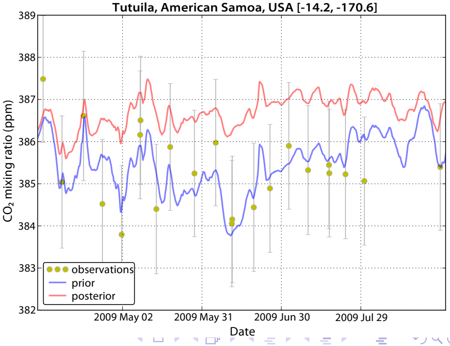
What happens if we invert GOSAT data?

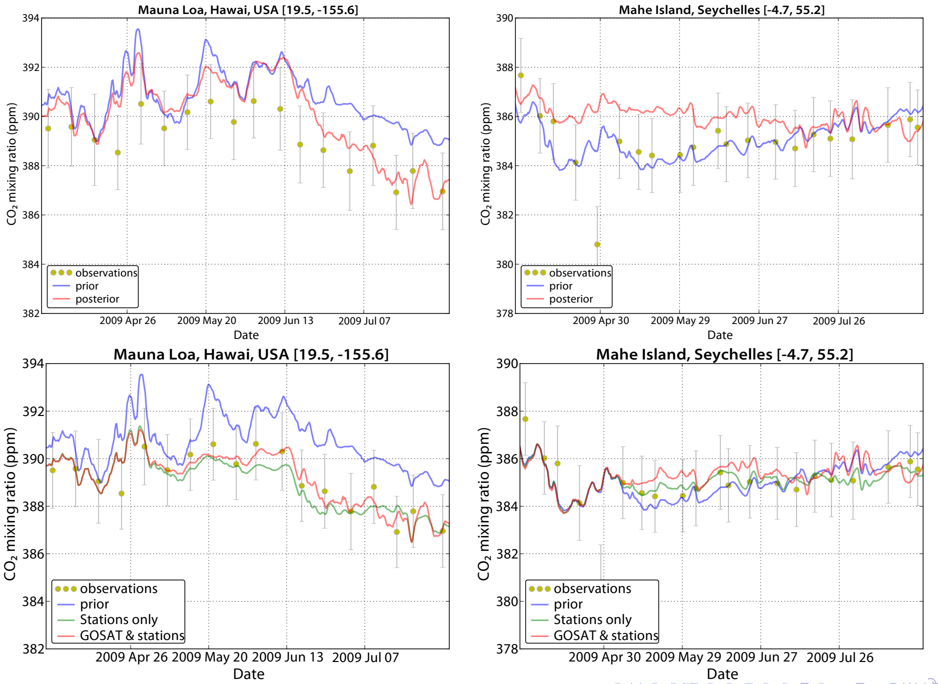
- GOSAT provides constraints between the tropics and over the Southern hemisphere, where stations are sparse
- What about areas where there are stations?
- GOSAT+stations is "worse" than GOSAT-only and stations-only, but not by much
- Fluxes consistent w.r.t. stations produce latitudinal gradient w.r.t. GOSAT


Mauna Loa, Hawai, USA [19.5, -155.6]
CO_2 mixing ratio (ppm)
394
392
390
388
386
384
382
2009 Apr 26
2009 May 20
2009 Jun 13
2009 Jul 07
Date
observations
prior
posterior


Mahe Island, Seychelles [-4.7, 55.2]
CO_2 mixing ratio (ppm)
390
388
386
384
382
380
378
2009 Apr 30
2009 May 29
2009 Jun 27
2009 Jul 26
Date
observations
prior
posterior


Summit, Greenland [72.6, -38.5]
CO_2 mixing ratio (ppm)
400
395
390
385
380
375
370
2009 May 02
2009 Jun 01
2009 Jul 02
2009 Aug 01
Date
observations
prior
posterior

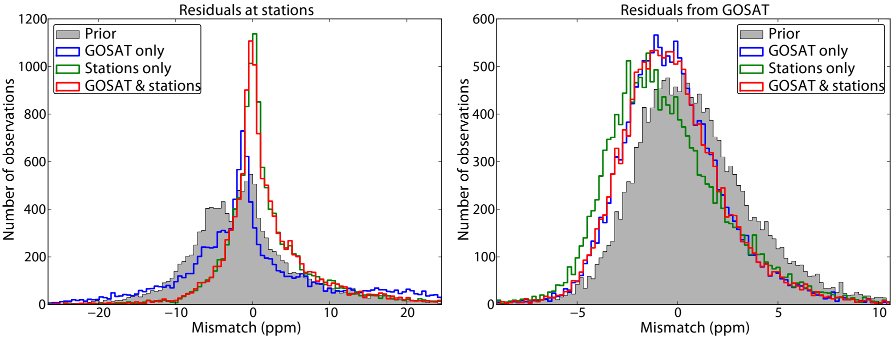

Tutuila, American Samoa, USA [-14.2, -170.6]
CO_2 mixing ratio (ppm)
389
388
387
386
385
384
383
382
2009 May 02
2009 May 31
2009 Jun 30
2009 Jul 29
Date
observations
prior
posterior


Mauna Loa, Hawai, USA [19.5, -155.6]
Mahe Island, Seychelles [-4.7, 55.2]
CO$_2$ mixing ratio (ppm)
Date
394
392
390
388
386
384
382
380
378
2009 Apr 26
2009 May 20
2009 Jun 13
2009 Jul 07
2009 Apr 30
2009 May 29
2009 Jun 27
2009 Jul 26
observations
prior
posterior
Stations only
GOSAT & stations

What happens if we invert GOSAT data?

- GOSAT provides constraints between the tropics and over the Southern hemisphere, where stations are sparse
- Over some stations, GOSAT improves fit. Over other stations – generally in the Southern hemisphere – GOSAT worsens fit.
- Globally, is adding GOSAT data to a stations-only (or station-data to a GOSAT-only) inversion an “improvement”?
- Fluxes consistent w.r.t. stations produce latitudinal gradient w.r.t. GOSAT

Residual = model − observation



Ideally, adding GOSAT to a stations-only inversion, or adding stations to a GOSAT-only inversion, should decrease both station and GOSAT residuals

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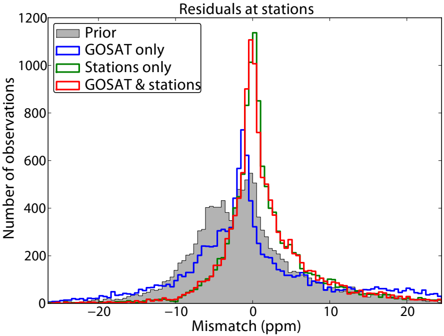
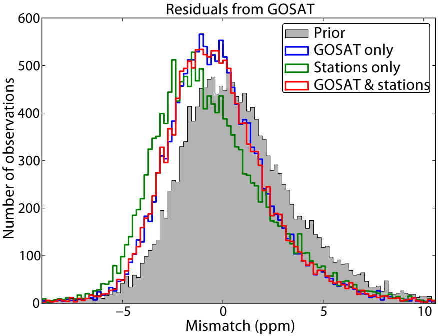
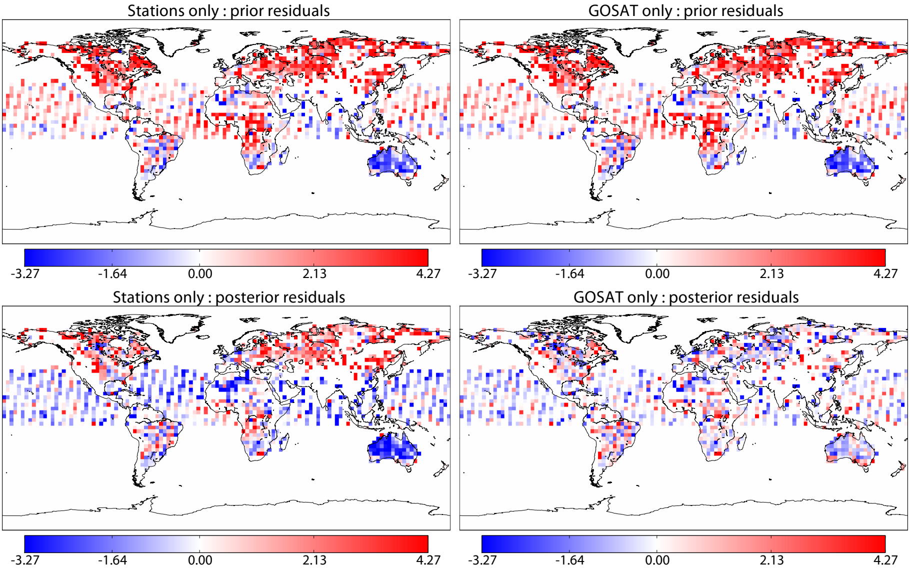
- Over some stations, GOSAT improves fit. Over other stations – generally in the Southern hemisphere – GOSAT worsens fit.
- GOSAT+stations is "worse" than GOSAT-only and stations-only, but not by much
- Who's responsible for the "worsening"?





Stations-only inversion skews GOSAT residuals


Stations only : prior residuals
GOSAT only : prior residuals
-3.27
-1.64
0.00
2.13
4.27
Stations only : posterior residuals
GOSAT only : posterior residuals

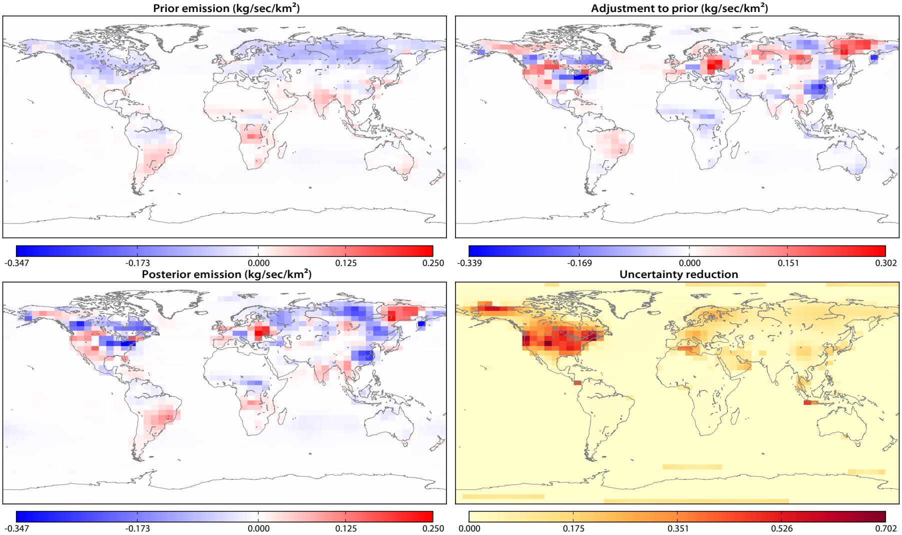
What happens if we invert GOSAT data?

- GOSAT provides constraints between the tropics and over the Southern hemisphere, where stations are sparse
- Over some stations, GOSAT improves fit. Over other stations – generally in the Southern hemisphere – GOSAT worsens fit.
- GOSAT+stations is "worse" than GOSAT-only and stations-only, but not by much
- Fluxes consistent w.r.t. stations produce latitudinal gradient w.r.t. GOSAT

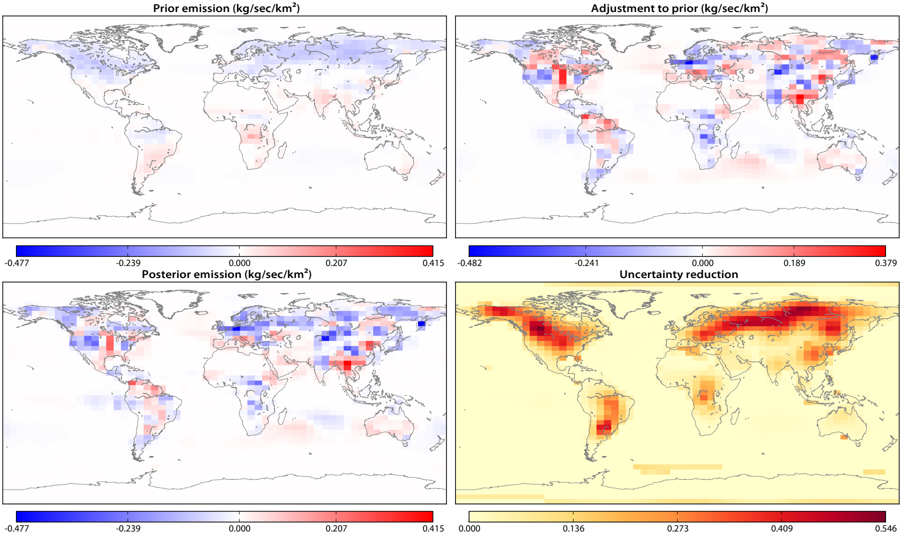
- Evaluate GOSAT and station inversions by an independent set of measurements, such as CONTRAIL
- Do a full year's inversion, and check summer uptake in the northern temperate latitudes
- Interpolate model profile to reduce and quantify representation error
- Generate spatiotemporal correlation map of column errors for GOSAT

- $\chi^2(\text{fit}) < 4$
- Field-of-view that is cloud free > 0.99
- GOSAT zenith angle $< 30°$
- CO_2 degrees of freedom > 1
- Aerosol optical thickness in O_2 A-band < 0.25
- Signal to noise (all bands) > 70
- Solar zenith angle $< 70°$
- Surface elevation variation inside field of view $< 300\,\text{m}$
- Aerosol optical thickness $\times$ aerosol height / aerosol size < 300

Using NOAA stations

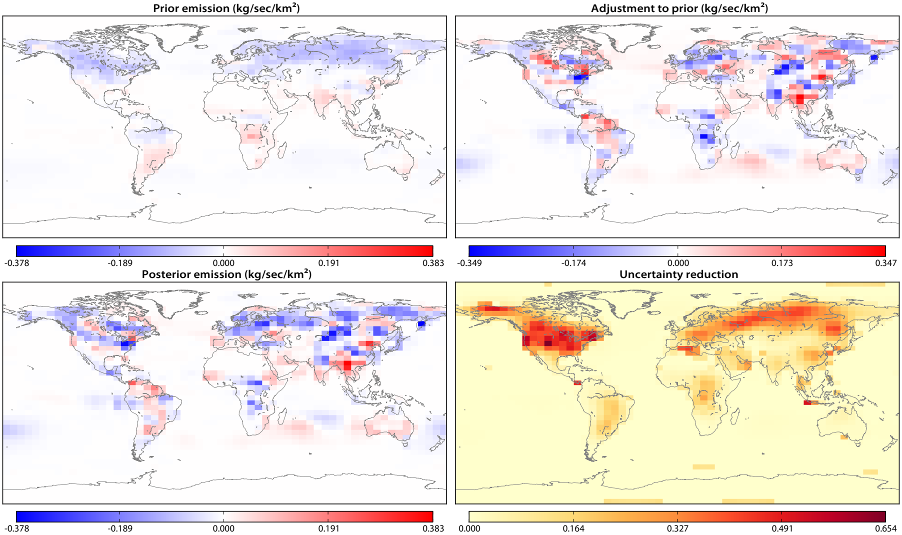


Using GOSAT



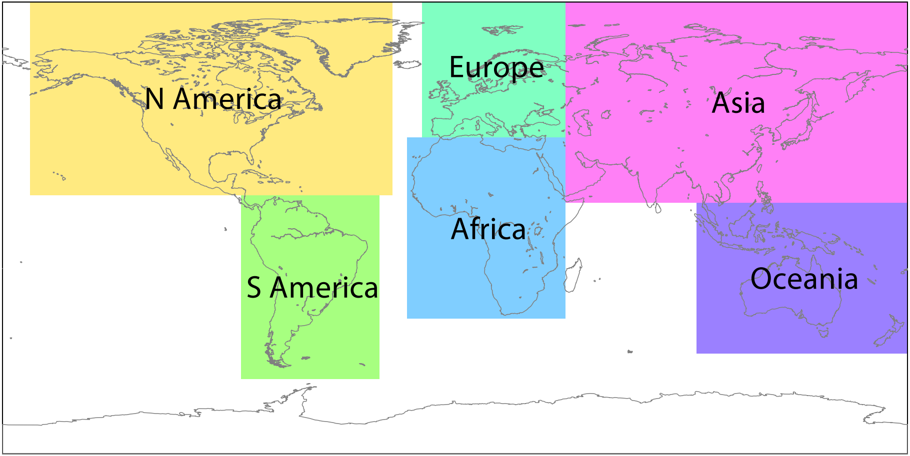
GOSAT inversion has finer structure of fluxes over the low latitudes and SH

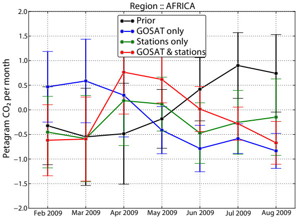
Using GOSAT & NOAA stations

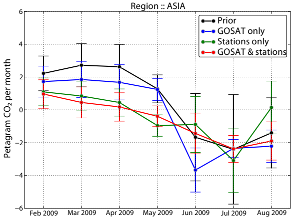


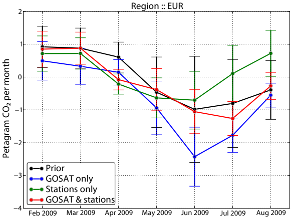
GOSAT+station looks similar to GOSAT

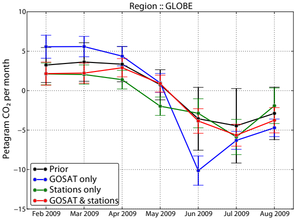
Flux aggregated over rectangular regions (TRANSCOM regions to follow)

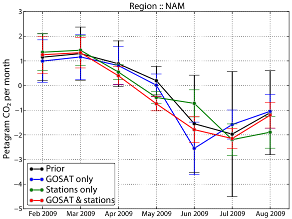


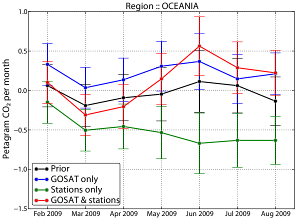

Region :: AFRICA
Petagram CO_2 per month
Prior
GOSAT only
Stations only
GOSAT & stations


Region :: ASIA
Petagram CO_2 per month
Prior
GOSAT only
Stations only
GOSAT & stations


Region :: EUR
Petagram CO_2 per month
Prior
GOSAT only
Stations only
GOSAT & stations


Region :: GLOBE
Petagram CO_2 per month
Prior
GOSAT only
Stations only
GOSAT & stations


Region :: NAM
Petagram CO_2 per month
Prior
GOSAT only
Stations only
GOSAT & stations


Region :: OCEANIA
Petagram CO_2 per month
Prior
GOSAT only
Stations only
GOSAT & stations

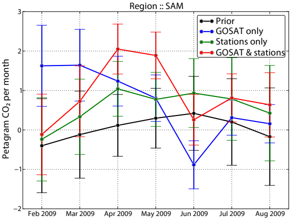

Region :: SAM
Petagram CO_2 per month
Prior
GOSAT only
Stations only
GOSAT & stations

Table of Contents