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An Inversion Analysis of Recent Variability in Natural CO_2 Fluxes Using GOSAT and In Situ Observations

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1. Introduction

Around one-half of the CO_2 emissions from fossil fuel combustion and deforestation accumulates in the atmosphere, where it contributes to global warming. The rest is taken up by vegetation and the ocean. The precise contribution of the two, and the location and year-to-year variability of the CO_2 sinks are not well understood though.

We conduct a traditional **Bayesian inversion at relatively high resolution** to estimate the global distributions of surface CO_2 fluxes during a recent period. In this top-down approach, fluxes are inferred from atmospheric CO_2 measurements by means of an atmospheric transport model linking the measurements to flux regions upwind, subject also to prior constraints. A focus of this work is the use of data from satellites dedicated to making CO_2 measurements, such as the Greenhouse gases Observing SATellite (GOSAT) launched in 2009 [Yokota et al., 2009]. An advantage of satellites over current ground-based networks is their greater spatial coverage.

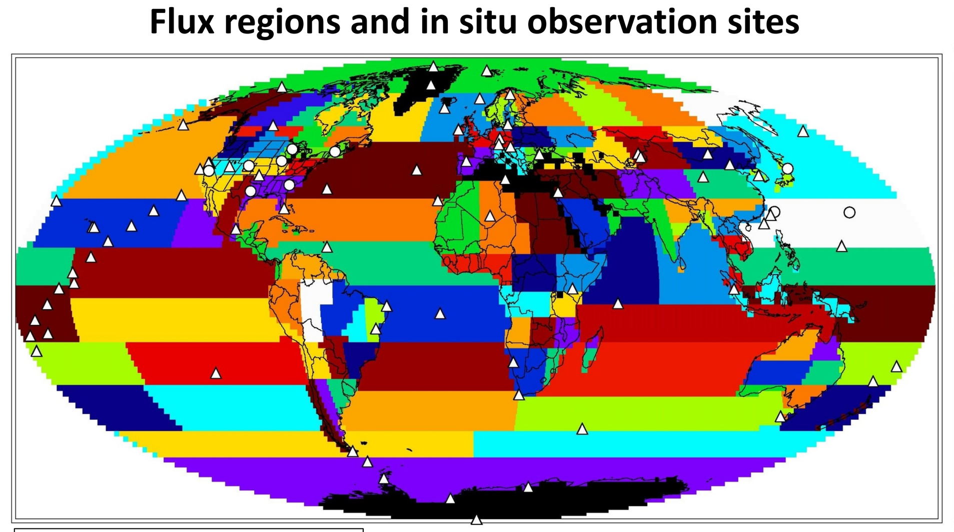
2. Objectives

- Understand recent variability of the global carbon cycle
- Evaluate the bottom-up flux estimates used for the priors
- Compare fluxes and uncertainties inferred using GOSAT vs. in situ observations
- Compare our Bayesian inversion with other approaches, including a variational data assimilation system based on the same transport, to assess the effects of inversion technique on inferred fluxes

3. Methods

- **Observations of CO_2 mixing ratio**
  - In situ
    - Individual flask and afternoon-averaged continuous measurements from NOAA ESRL and JMA
  - GOSAT weighted column-averages
    - ACOS B3.4 retrieval (June 2009 onward); filtered and bias-corrected
- **Prior constraints**
  - Net ecosystem production (NEP) and biomass burning fluxes from CASA-GFED v.3 model, driven by satellite observations and analyzed meteorology.
  - Ocean fluxes from Takahashi et al. [2009]
  - Fossil CO_2 emissions from CDIAC
- **Transport model**
  - **PCTM**, with meteorology from NASA GEOS-5 MERRA reanalysis
  - Grid used: 2° latitude x 2.5° longitude x 56 levels to 0.4 hPa
- **Inversion method**
  - "TransCom"-style **batch Bayesian synthesis inversion**
  - Optimize natural fluxes in **108 regions** (map below) over **8-day intervals**; cf. 22 regions, monthly intervals in TransCom
  - Initial concentrations optimized in the inversion
  - 1.5-year long analysis (Mar 2009-Sep 2010)
- This inversion method gives an exact solution and is relatively simple mathematically, but is very time-consuming at this resolution.
- We are beginning to use a second technique, a **variational data assimilation system also based on PCTM transport** developed by David Baker, for comparison (to be presented later).

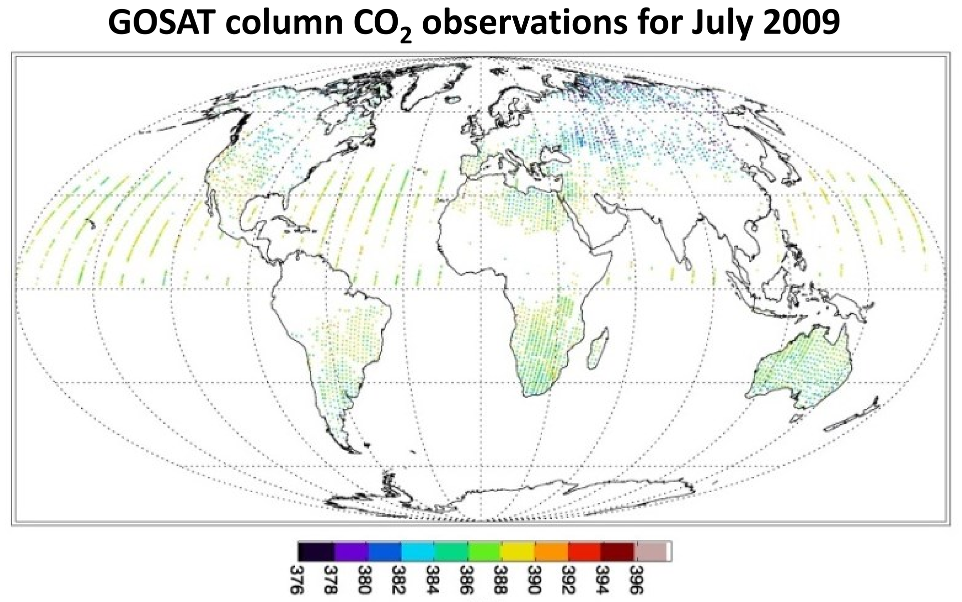
Flux regions and in situ observation sites



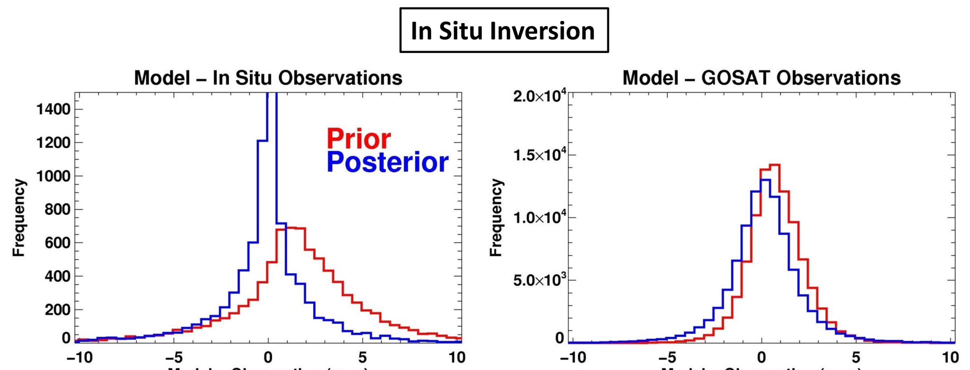
Triangles = flask obs
Circles = continuous obs

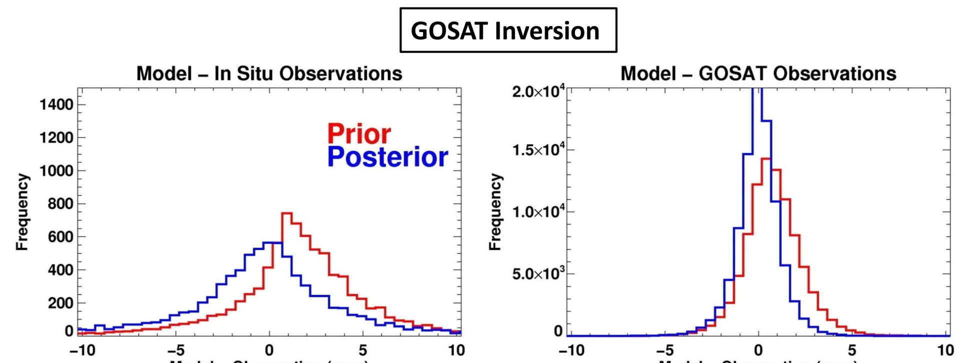
Flux regions modified from L. Feng et al. [2009]

GOSAT column CO_2 observations for July 2009



4. Comparison of model and observed CO_2 concentrations





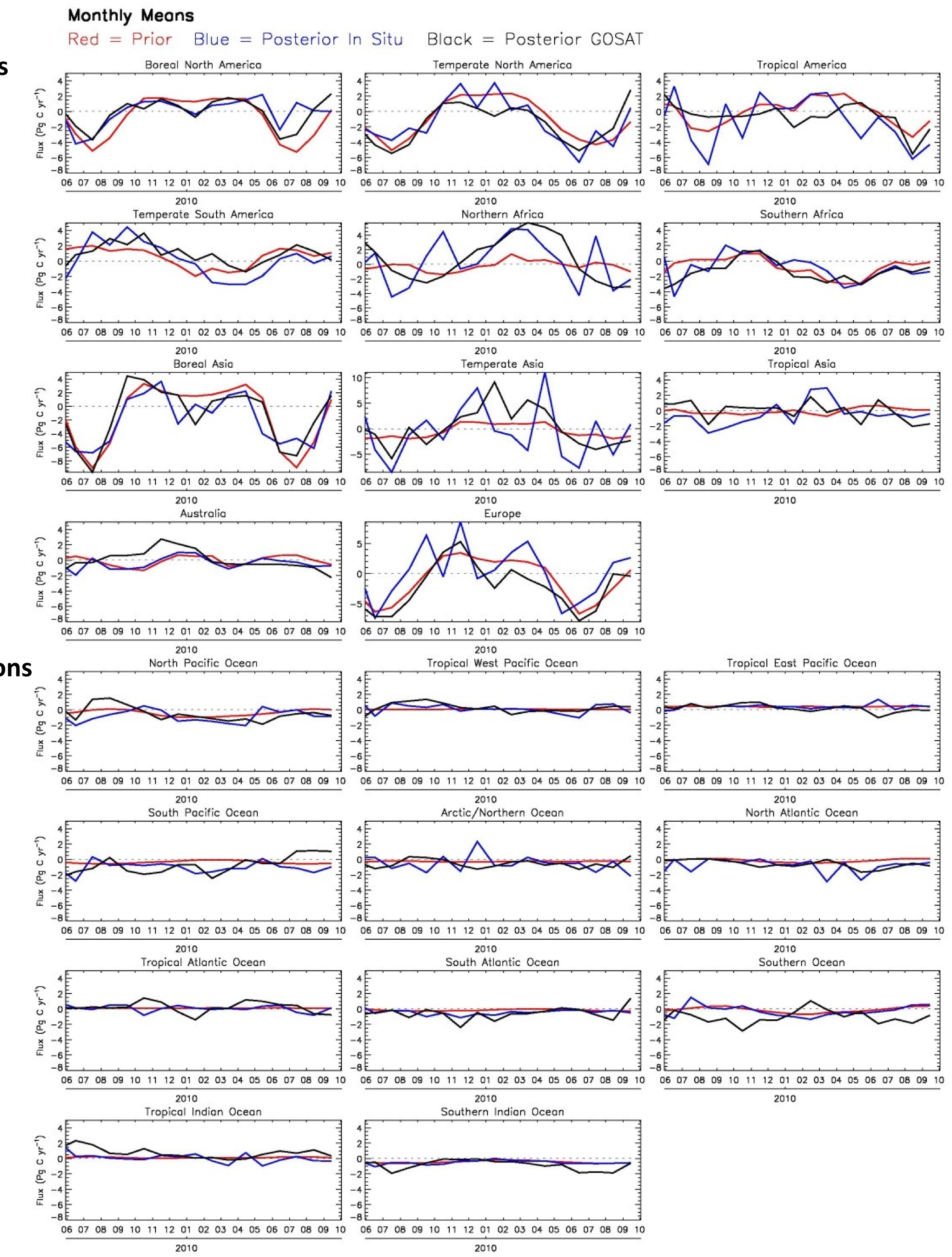
- Agreement between model and observations improves through the inversion optimization (posterior vs. prior), as expected.
- Agreement of model with observations not used in the inversion also improves overall (i.e. in situ inversion vs. GOSAT observations, GOSAT inversion vs. in situ observations).

5. Fluxes aggregated to "TransCom-3" regions

Only NEP and ocean fluxes are shown in this section (no fossil fuel, biomass burning)

Land regions

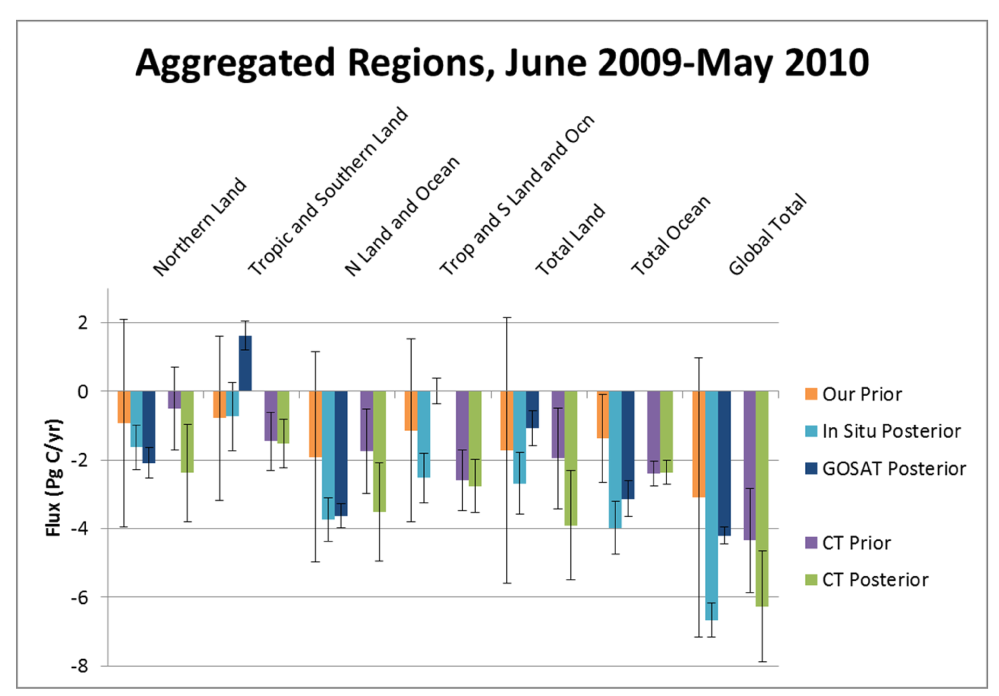
Ocean regions



- GOSAT inversion suggests overall shift in global CO_2 sink from tropics/south to northern regions.
  - Anomalous features in GOSAT inversion (e.g. negative flux in Jan. in some northern regions, and large positive flux winter-spring in N. Africa) may be artifacts of retrieval and sampling biases (e.g. Houweling et al., 2015).
- In situ inversion exhibits large fluctuations → In situ data set sparser than GOSAT, so the inversion is less well constrained.

Annual Summary

Shown for comparison are results from NOAA's **CarbonTracker (CT)**, an ensemble data assimilation system that uses multiple in situ observation networks

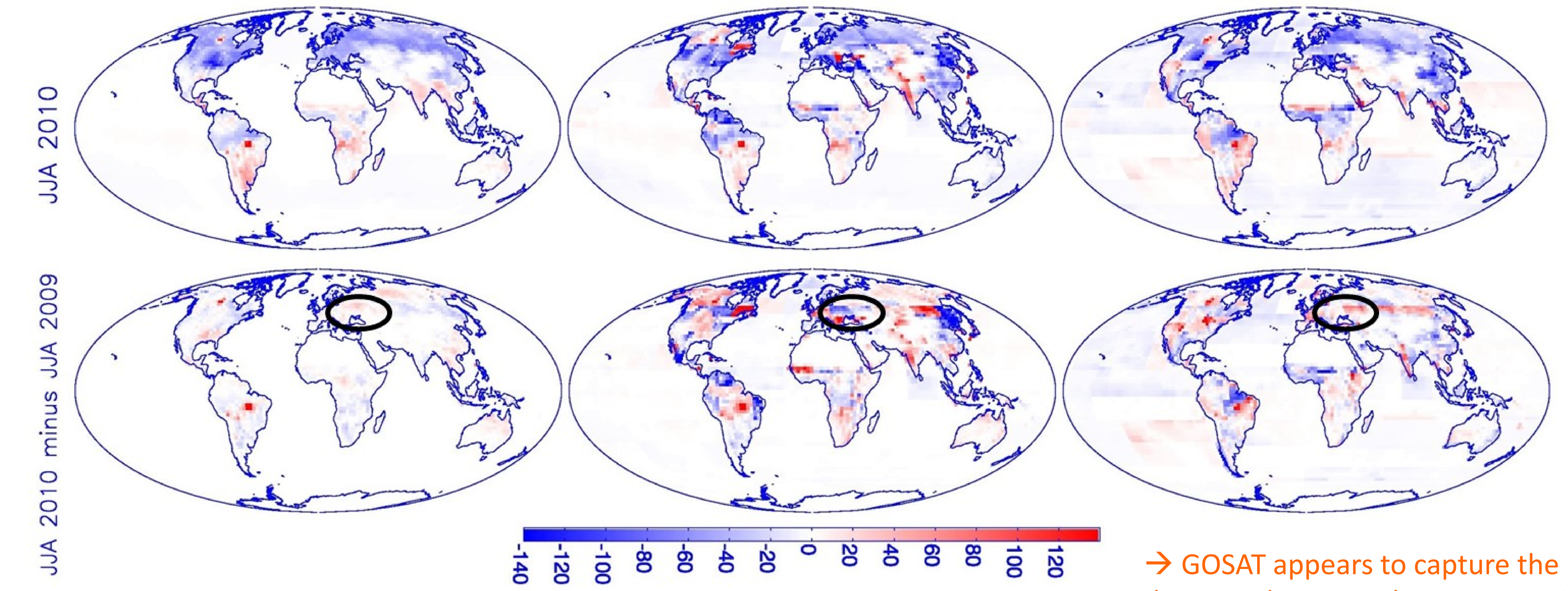


Error bars represent 1σ uncertainties

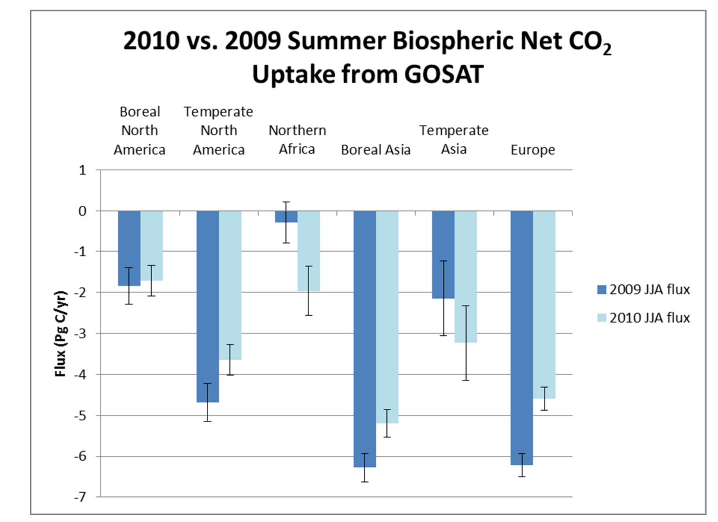
- GOSAT inversion: Shift in the global CO_2 sink from the tropics/south to the north.
- GOSAT posterior fluxes have smaller or comparable uncertainties relative to in situ results → Greater spatial coverage.
- Our in situ and CT's posterior global and regional totals similar, but land-ocean split different.
  - CT places tight prior constraints on ocean fluxes, so most of the flux adjustments take place on land.

6. Effects of 2010 northern droughts detected by GOSAT?

Only natural and biomass burning fluxes are included below



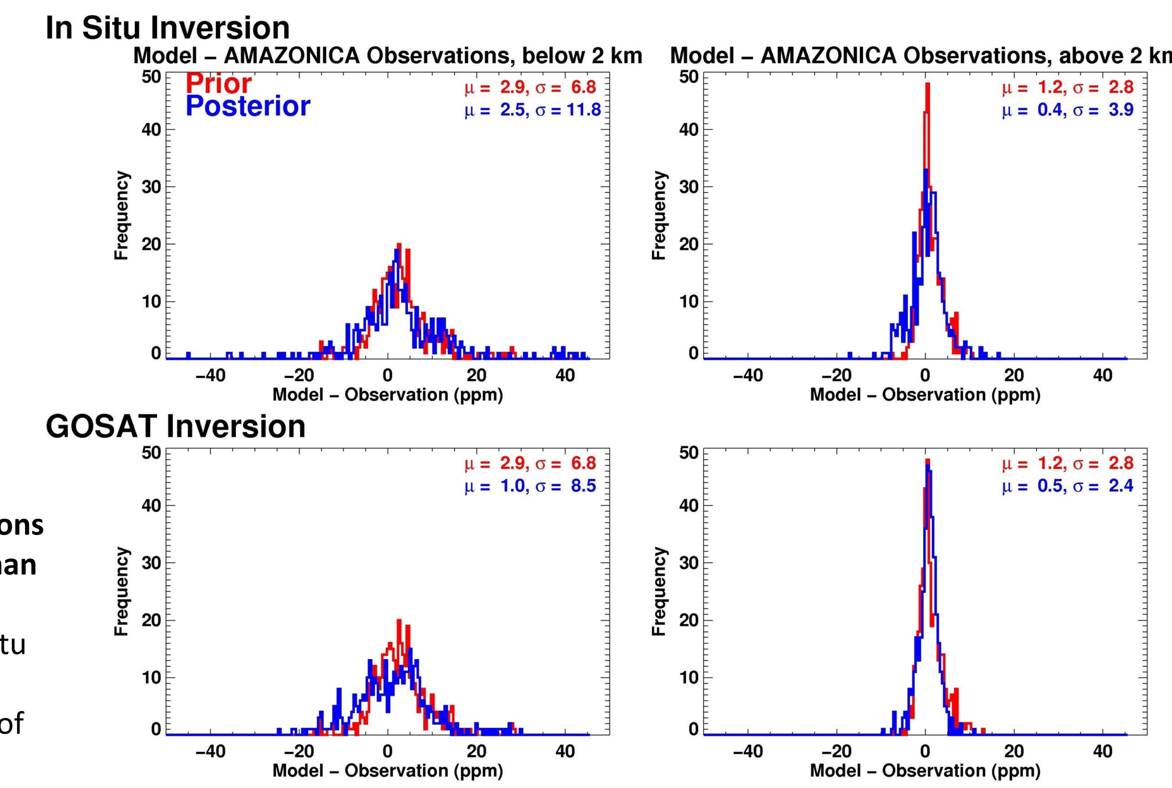
→ GOSAT appears to capture the decreased CO_2 uptake over Eurasia in 2010



- Guerlet et al. [2013]: GOSAT data suggest less CO_2 uptake in summer of 2010 than in 2009 at northern high latitudes, consistent with known severe heat waves and drought.
- Our results appear to support the hypothesis.

7. Comparison of model and Amazon aircraft observations

–The AMAZONICA data set consists of aircraft CO_2 profiles from 0.3 to 4.4 km over 4 sites across the Amazon starting in 2010, taken approx. twice a month [Gatti et al., 2014].
–We used these independent data to help evaluate inversion performance in the tropics.



- **Agreement with aircraft observations is better for the GOSAT inversion than the in situ inversion.**
  - There is a complete lack of in situ sites sensitive to Amazon fluxes, contrasting with the availability of some GOSAT data over region.
- GOSAT inversion agrees with the aircraft observations better than the prior does **above 2 km → Incorporating GOSAT data in inversion is better than no data.**
- However, the model-observation differences have greater variance than prior **below 2 km** → GOSAT isn't sensitive enough to boundary layer concentrations? Few GOSAT observations in immediate region?

8. Conclusions and further work

- The incorporation of observations in the inversions pulls the model closer to observations, even those not used in the inversion, on the whole.
  - The GOSAT inversion improves model agreement with Amazon aircraft observations at higher altitudes, whereas the in situ inversion does no better than the prior model.
- Our GOSAT inversion suggests a shift in the global CO_2 sink from the tropics/south to the north, relative to the prior and the in situ inversion. This is similar to studies using other inversion approaches.
  - May be driven at least in part by biases in the GOSAT data set.
- Results indicate less CO_2 uptake in summer of 2010 relative to 2009 in the north, consistent with another study.
- We are beginning to replicate this analysis using the variational data assimilation system based on PCTM transport to assess the effects of inversion technique on inferred fluxes.

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