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A 5-year record of surface CO_2 fluxes inferred from ACOS B3.5 GOSAT X_{CO2} retrievals using a variational data assimilation method

Introduction

New measurements of column-integrated atmospheric CO_2 concentration have become available in the past few years with more complete spatio-temporal coverage than have been available from the traditional *in situ* network -- potentially allowing greater detail in the surface sources/sinks of CO_2 to be estimated.

In particular, CO_2 mixing ratios measured from solar radiation reflected from the surface in the near-infrared (1.6 and 2.0 μm bands) allow sensitivity to the full atmospheric column, including the lower troposphere where surface CO_2 fluxes have their largest impact. The TANSO instrument aboard the Japanese Greenhouse Gases Observing Satellite (GOSAT) has been measuring the full-column dry air mixing ratio of CO_2 ("X_{CO2}") since its launch in early 2009. Recently a 5+ year span of this data (April 2009 – June 2014) has been re-processed using consistent calibration and retrieval schemes by NASA's Atmospheric CO_2 Observations from Space (ACOS) group at JPL and CSU, using its latest b3.5 retrieval approach.

Here, we use an atmospheric inversion approach to infer the surface sources and sinks of carbon that caused the observed patterns in X_{CO2}. A variety of different models of land biospheric, air-sea, and fossil fuel emission fluxes are run forward through the PCTM atmospheric transport model, added in various combinations to form *a priori* estimates of global CO_2 mixing ratios, and then compared to the globally-distributed X_{CO2} fields retrieved from GOSAT. Inversions are performed using several of these prior estimates – comparing the resulting CO_2 fluxes then allows the dependence of the final CO_2 flux estimate on the assumed *a priori* fluxes to be assessed. The sensitivity of the resulting GOSAT-informed fluxes to the tightness of the assumed flux prior and to the type of GOSAT data used was investigated.

GOSAT X_{CO2} Data

ACOS b3.5 GOSAT X_{CO2} retrievals for Apr 2009 to June 2014 from Chris O'Dell's "lite" Level 2 product were used, with the following scenes being screened out, in addition to those (e.g. cloudy scenes) removed in forming this product:

- All those south of 60° S and north of 75°N
- All those with a retrieved X_{CO2} uncertainty of ≥ 1.5 ppm
- All those with high "warn levels" of 17-19

Number of scenes passing the screening criteria:

~444,000	land, high-gain (non-desert areas)
~87,000	land, medium-gain (desert areas)
~420,000	ocean glint

In addition, the GOSAT data in the ACOS b3.5 build were bias-corrected beforehand using the following formulas:

Land, H-gain:

$$X_{CO2} = X_{CO2\_Raw} - 0.155*(dp\_cld + 2.70) + 10.6*(alb\_3p-0.204) + 0.0146*(co2\_grad\_del - 35.0) + 12.8*(aod\_du -0.0100)-0.35 \text{ ppm}$$

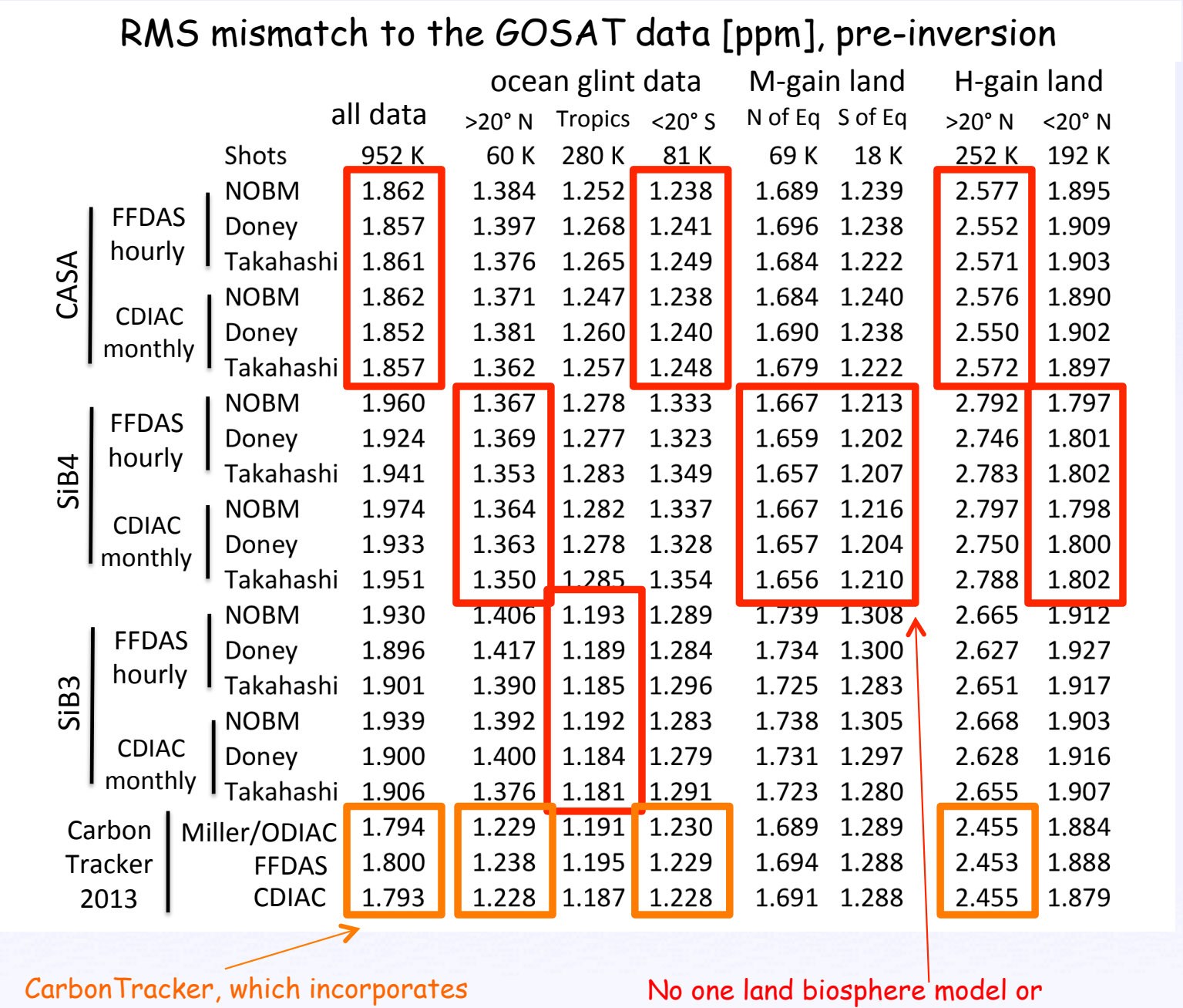
Land, M-gain:

$$X_{CO2} = X_{CO2\_Raw} + 0.200*(dp + 1.20) + 4.60*(alb\_3\ 0.400) + 0.0150*(co2\_grad\_del - 20.0) + 8.00*(aod\_du - 0.0100) +0.10 \text{ ppm}$$

Ocean glint:

$$X_{CO2} = X_{CO2\_Raw} - 52.0*(s32 - 0.610) +0.450*(b1\_offset + 1.00) + 1.30*(aod\_height\_ic - 0.240) - 1.90 \text{ ppm}$$

Each GOSAT retrieval was considered to be independent in the inversion, with a measurement uncertainty assumed to be 1.6 times the *a posteriori* X_{CO2} uncertainty provided by the retrieval. The uncertainty of outliers in the prior model-data mismatch greater than 3σ was increased to bring the prior misfit to 3σ.



RMS mismatch to the GOSAT data [ppm], pre-inversion

			all data	ocean glint data			M-gain land		H-gain land	
				>20° N	Tropics	<20° S	N of Eq	S of Eq	>20° N	<20° N
		Shots	952 K	60 K	280 K	81 K	69 K	18 K	252 K	192 K
CASA	FFDAS hourly	NOBM	1.862	1.384	1.252	1.238	1.689	1.239	2.577	1.895
		Doney	1.857	1.397	1.268	1.241	1.696	1.238	2.552	1.909
		Takahashi	1.861	1.376	1.265	1.249	1.684	1.222	2.571	1.903
	CDIAC monthly	NOBM	1.862	1.371	1.247	1.238	1.684	1.240	2.576	1.890
		Doney	1.852	1.381	1.260	1.240	1.690	1.238	2.550	1.902
		Takahashi	1.857	1.362	1.257	1.248	1.679	1.222	2.572	1.897
SiB4	FFDAS hourly	NOBM	1.960	1.367	1.278	1.333	1.667	1.213	2.792	1.797
		Doney	1.924	1.369	1.277	1.323	1.659	1.202	2.746	1.801
		Takahashi	1.941	1.353	1.283	1.349	1.657	1.207	2.783	1.802
	CDIAC monthly	NOBM	1.974	1.364	1.282	1.337	1.667	1.216	2.797	1.798
		Doney	1.933	1.363	1.278	1.328	1.657	1.204	2.750	1.800
		Takahashi	1.951	1.350	1.285	1.354	1.656	1.210	2.788	1.802
SiB3	FFDAS hourly	NOBM	1.930	1.406	1.193	1.289	1.739	1.308	2.665	1.912
		Doney	1.896	1.417	1.189	1.284	1.734	1.300	2.627	1.927
		Takahashi	1.901	1.390	1.185	1.296	1.725	1.283	2.651	1.917
	CDIAC monthly	NOBM	1.939	1.392	1.192	1.283	1.738	1.305	2.668	1.903
		Doney	1.900	1.400	1.184	1.279	1.731	1.297	2.628	1.916
		Takahashi	1.906	1.376	1.181	1.291	1.723	1.280	2.655	1.907
Carbon Tracker 2013		Miller/ODIAC	1.794	1.229	1.191	1.230	1.689	1.289	2.455	1.884
		FFDAS	1.800	1.238	1.195	1.229	1.694	1.288	2.453	1.888
		CDIAC	1.793	1.228	1.187	1.228	1.691	1.288	2.455	1.879

CarbonTracker, which incorporates information from *in situ* CO_2 measurements, fits the GOSAT data better overall than the free-running flux models, but not for all GOSAT data types

No one land biosphere model or combination of prior fluxes is obviously better than another at fitting the GOSAT data: which model is best depends on the type of GOSAT data.

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Method

The following CO_2 tracers were run forward through the off-line PCTM atmospheric tracer transport model (Kawa, et al., 2004). The fluxes from most models ended in 2012; climatologies were created from the years available for use in 2013-2014:

1. Diurnally-varying net ecosystem exchange (NEE) and respiration from the following land ecosystem models:
   - CASA-GFED (from Jim Collatz, NASA/GSFC) – wild-fires and biofuels included as explicit tracers
   - SiB4 (from Kathy Haynes, Colorado State)
   - SiB3 (from Ian Baker, Colorado State)
2. Monthly-varying air-sea CO_2 fluxes from the following:
   - The NOBM ocean model (from Watson Gregg, NASA/GSFC)
   - The Takahashi, et al (2009) pCO_2 and CO_2 flux product
   - An anthropogenic run of the Doney ocean model (Scott Doney & Ivan Lima, Woods Hole Oceanographic Inst.)
3. Fossil fuel burning emissions from the following models:
   - CDIAC monthly-varying product (Andres *et al.* 2013)
   - FFDAS monthly-varying product (Asefi-Najafabady)
   - FFDAS product with diurnal, day-of-week, and monthly variability (Asefi-Najafabady et al., 2014)
4. The *a posteriori* estimate of total flux (land biosphere + ocean + fossil fuel + wild fires) from CarbonTracker-2013 (http://carbontracker.noaa.gov). Through the end of 2012, the CT fluxes have been optimized against surface *in situ* CO_2 measurements.

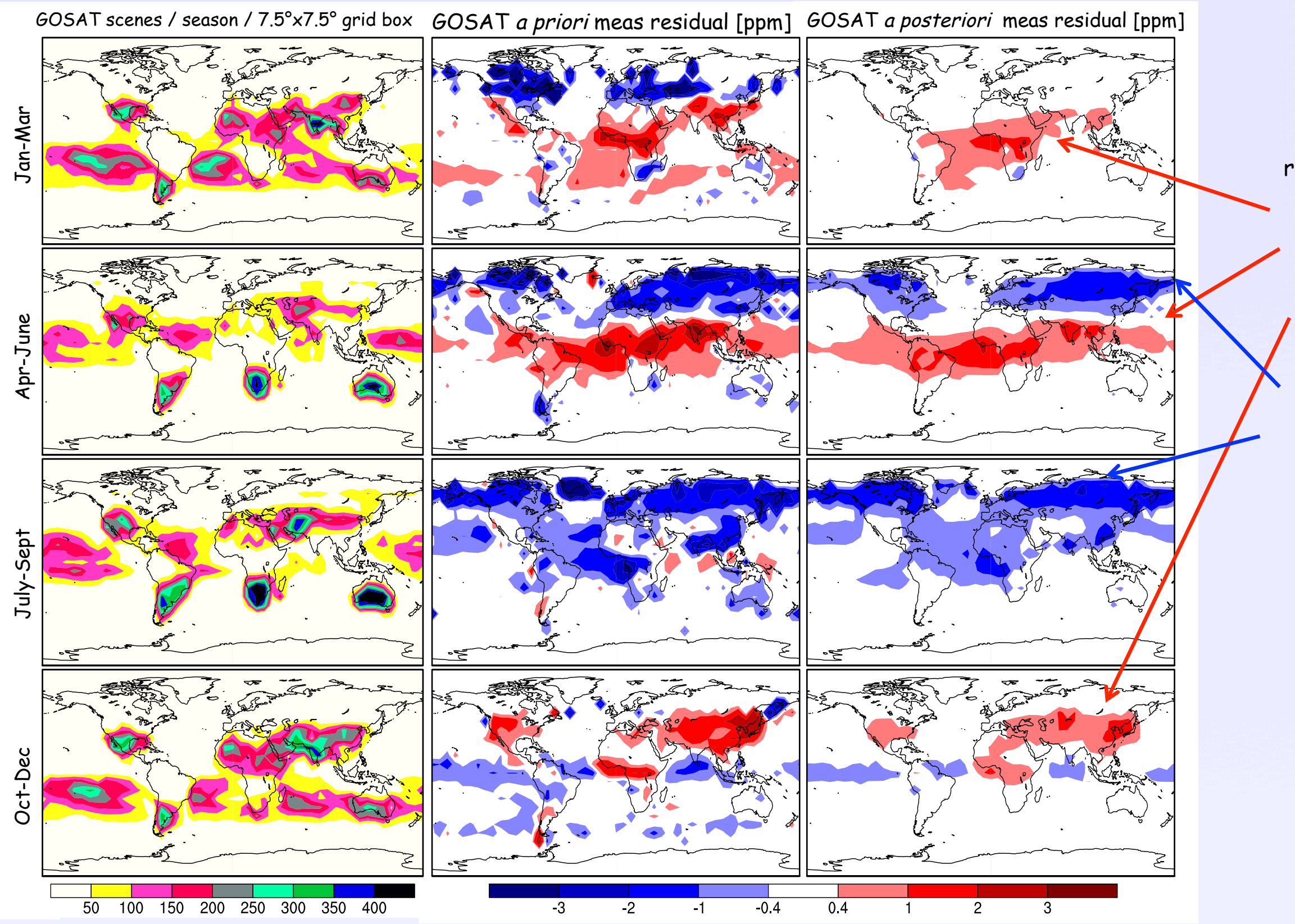
Different a priori estimates of global time-varying 3-D CO_2 concentration have been created for 2009-2014 by adding together a tracer from each of categories 1-3 (land bio, ocean, and fossil). Because the land biosphere models above are close to being flux-neutral across any given year (i.e., do not include realistic land uptake), a multiple of respiration for each model, along with a global constant offset, has been estimated for each combination to match the observed growth rate at Mauna Loa across 2009-2014. Similarly, alternative versions of the CarbonTracker fluxes have been created by replacing its own fossil emissions with either CDIAC or FFDAS; a correction using a multiple of the CASA land biospherc fluxes has been solved for in those cases.

The various model fluxes have been interpolated to the 2.0° x 2.5° (lat/lon) resolution of the MERRA meteorological drivers for these forward PCTM runs. The resulting CO_2 concentrations are sampled using the vertical averaging kernel and prior CO_2 profile used in the ACOS GOSAT retrievals, then compared to the bias-corrected retrievals, to obtain model-data mismatches. RMS error statistics for these mismatches are given below.

The following sub-set of flux model combinations were used as *a priori* fluxes in separate GOSAT inversions, performed using the 4DVar carbon data assimilation system of Baker *et al* (2006). Weekly CO_2 flux corrections were estimated at 7.5°x7.5° resolution (lat/lon) then added to the 2.0°x2.5° prior to obtain the final estimates:

- CASA-GFED NEE+fires+fuel; Takahashi *et al* (2009) ocean, hourly FFDAS fossil
- SiB4 NEE, Doney ocean, hourly FFDAS fossil:
  - Ocean glint, land M- and H-gain data
  - land M- and H-gain (no ocean)
  - Land H-gain, only
- CarbonTracker-2013 *a posteriori* fluxes

In addition to inversions with the prior flux constraint applied at a typical degree of tightness, a parallel set of inversions are performed with the prior flux uncertainty applied at a level 10,000 times looser ("loose prior"). The results of these inversions show where the GOSAT data want to drive the flux result, almost completely un-constrained by the prior fluxes.



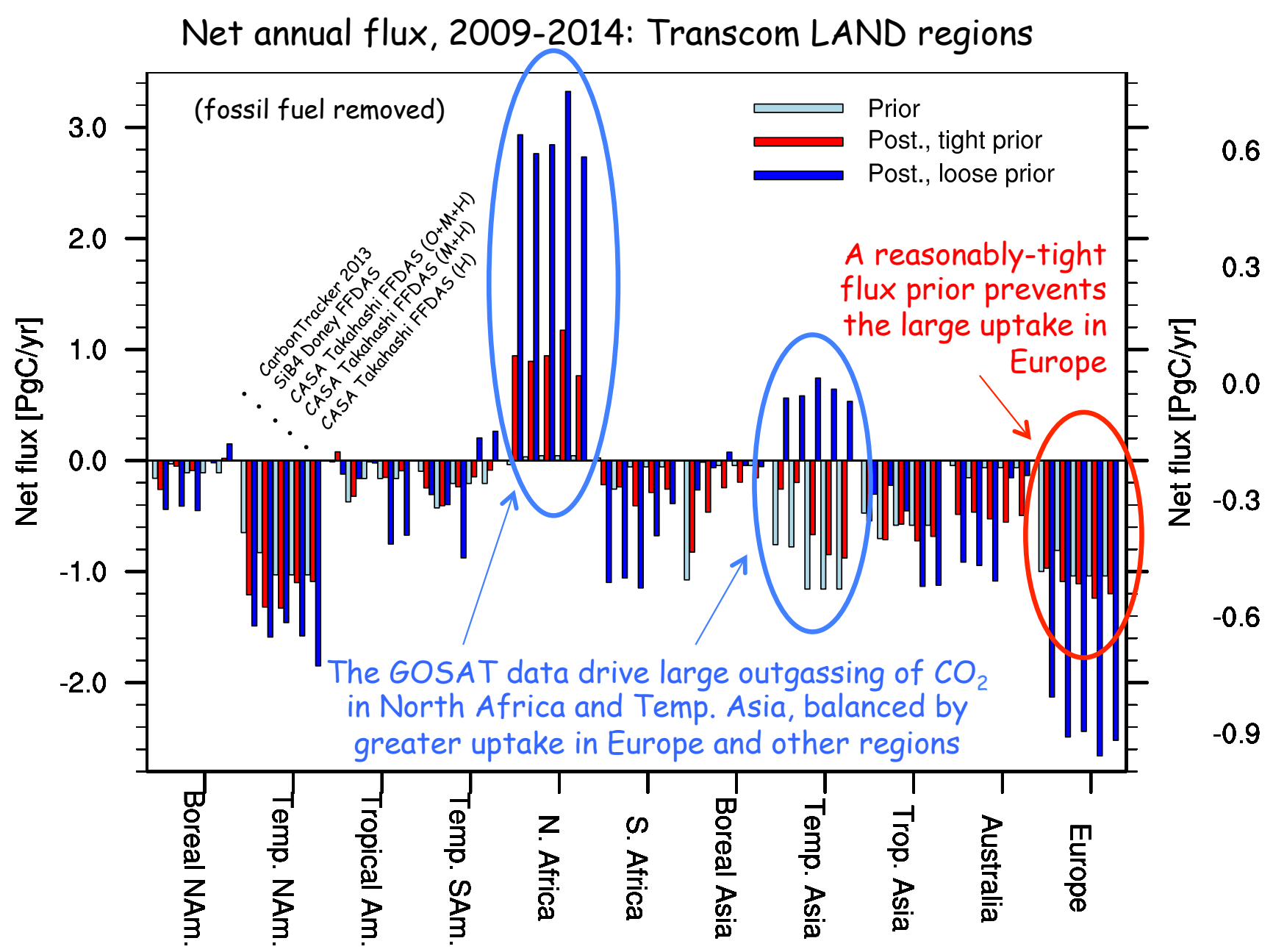
Systematic positive differences between GOSAT retrievals and optimized CO_2 column remain after inverting with typical assumptions for the prior flux uncertainty. When this uncertainty is loosened, more outgassing is obtained in North Africa, with balancing uptake elsewhere to satisfy the global total flux constraint.

Negative differences at high northern latitudes have less impact, due to the fewer scenes assimilated there.

Conclusions / Future Work

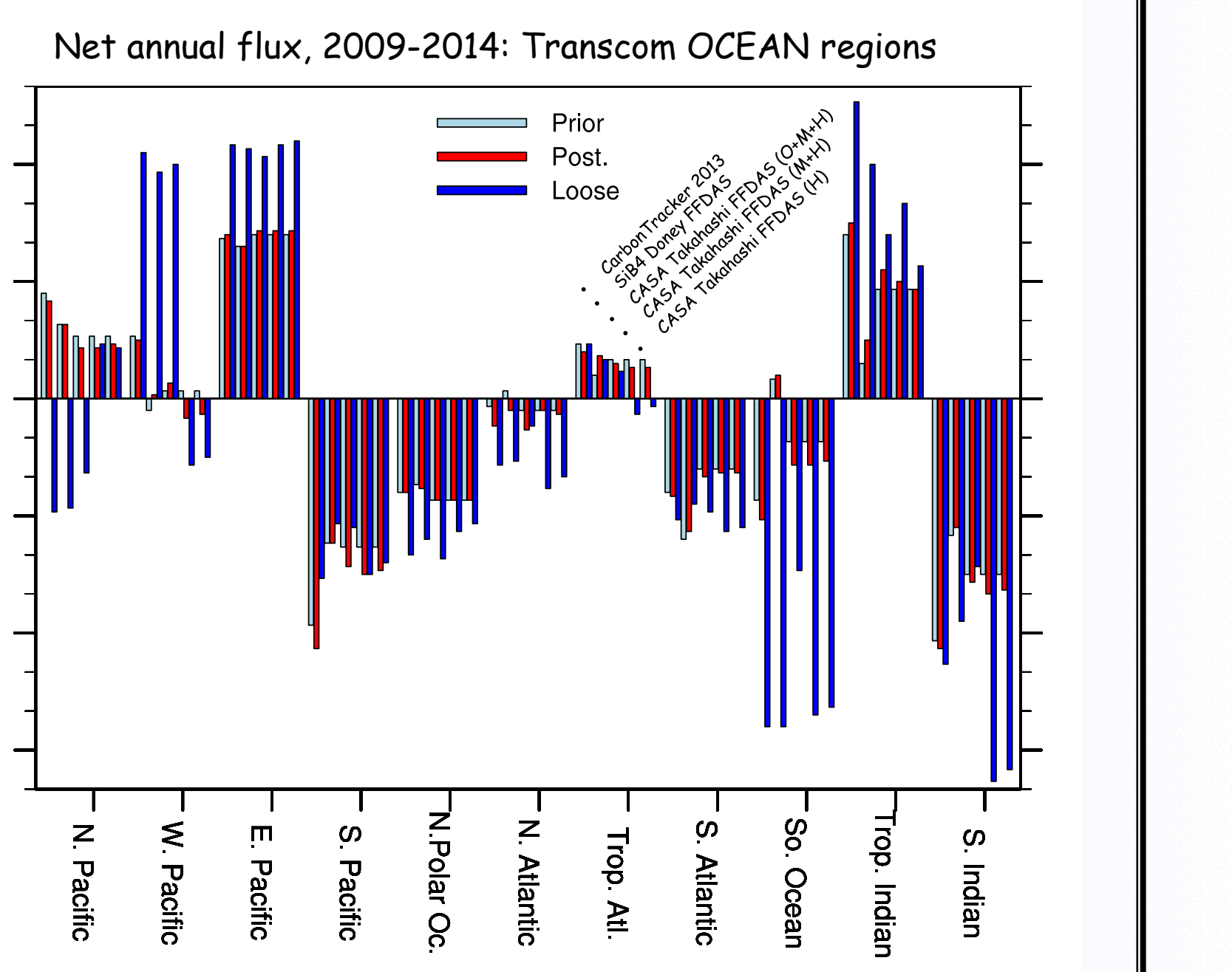
- Surface CO_2 fluxes have been estimated from the 5-year record of ACOS b3.5 GOSAT X_{CO2} retrievals, using a 4DVar assimilation scheme, and starting from several different sets of *a priori* fluxes.
- The impact of the GOSAT ocean glint, M- and H-gain land have been examined.
- A set of loose-prior inversions have been performed to clarify the fluxes most in agreement with the GOSAT data themselves, independent of the flux prior
- The GOSAT data favor strong outgassing of CO_2 from North Africa, with a compensating unrealistic uptake in Europe; these features are likely due to un-corrected biases in the GOSAT retrievals (i.e., the biases remaining after the ACOS bias corrections have been applied are still substantial); if true, a further bias correction should be calculated/applied
- The strongest change to the prior fluxes is also found in North Africa: the GOSAT data favor a seasonal cycle closer to SiB4 than CASA, though this may be unrealistic and therefore not a strong argument that SiB4 is better there
- Inversions done without the GOSAT M- and H-gain land data should be done to assess to what extent the ocean glint data are biased; experiment with keeping only lower warn level data
- The *a posteriori* CO_2 fields given by the GOSAT inversions should be compared to independent data (NOAA aircraft profiles, surface *in situ* data, TCCON columns) to help assess the GOSAT biases

Flux Results

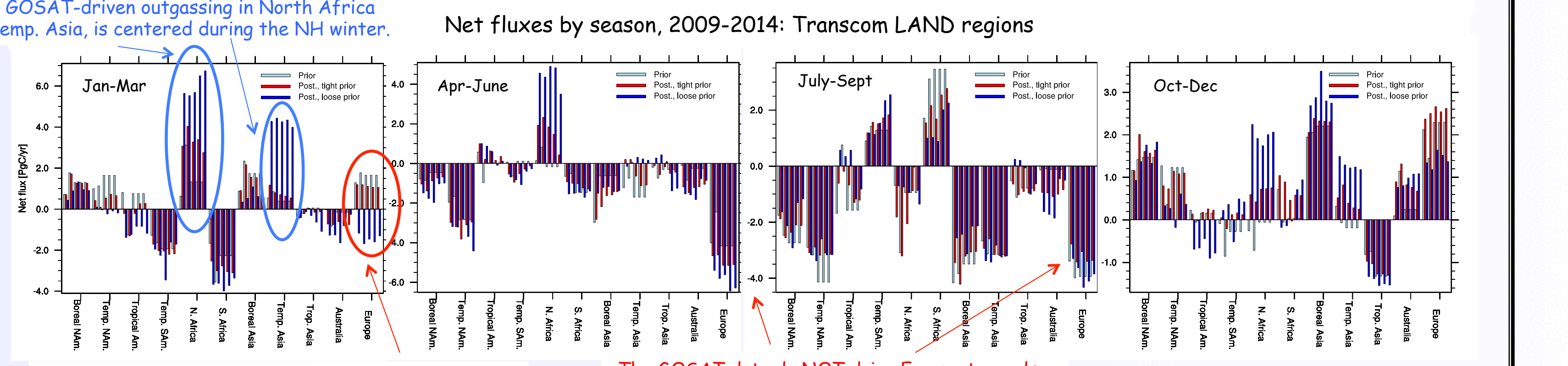


A reasonably-tight flux prior prevents the large uptake in Europe

The GOSAT data drive large outgassing of CO_2 in North Africa and Temp. Asia, balanced by greater uptake in Europe and other regions



The GOSAT-driven outgassing in North Africa and Temp. Asia, is centered during the NH winter.

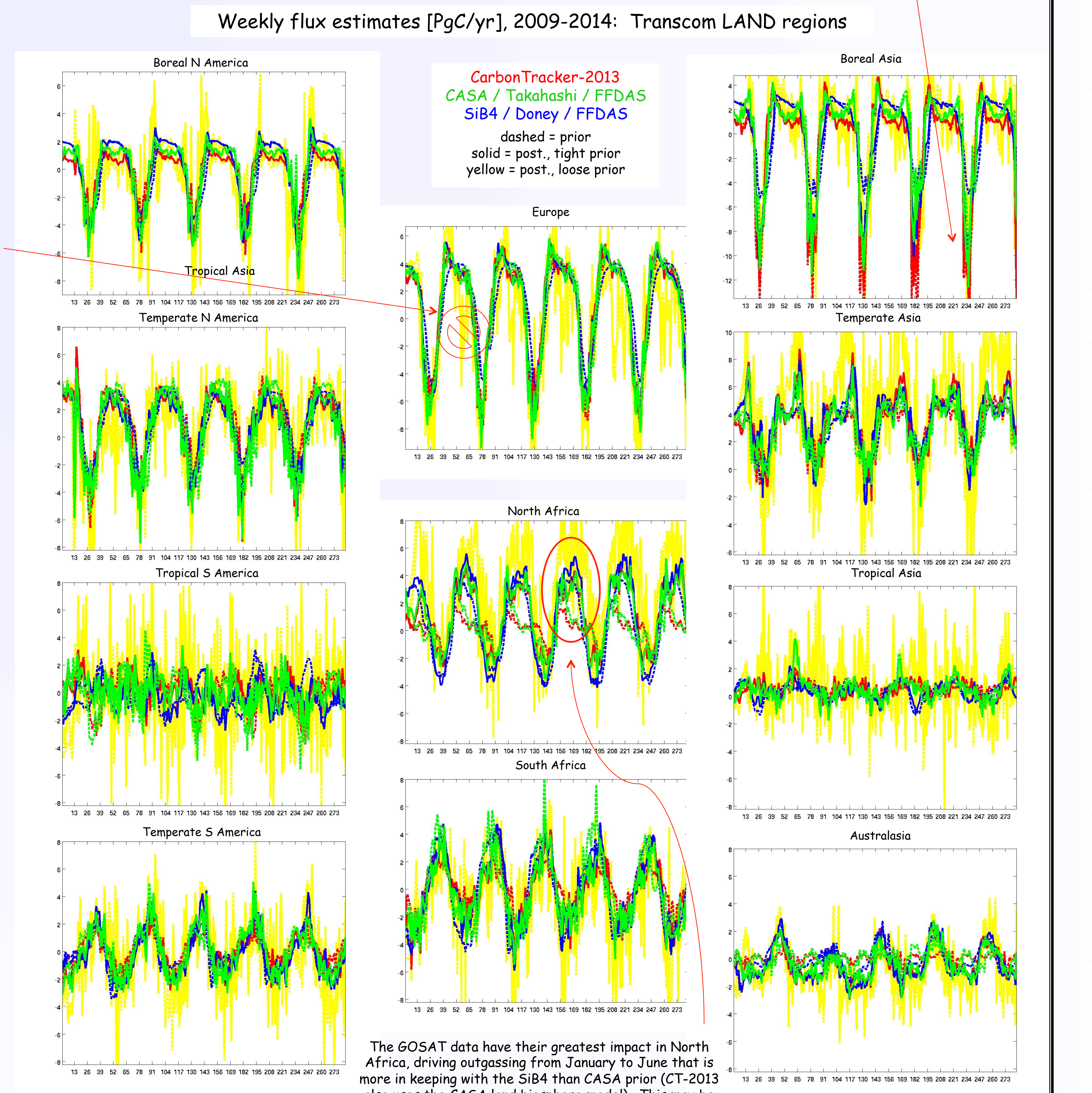


The GOSAT data want to drive Europe towards a large uptake of CO_2 in the NH winter – unphysical !!

The GOSAT data do NOT drive Europe towards a much greater uptake in the NH summer

Stronger uptake in Boreal Asia is obtained; this is more in agreement with the CASA prior than SiB4's..

When the flux prior is loosened to allow the GOSAT data to dictate the fluxes, un-physical net uptake is obtained in Europe during the winter.



The GOSAT data have their greatest impact in North Africa, driving outgassing from January to June that is more in keeping with the SiB4 than CASA prior (CT-2013 also uses the CASA land biosphere model). This may be less a function of SiB4 doing a better job there than the possibility that the GOSAT data suffer local biases.