

Supplementary text for “Global CO₂ fluxes estimated from GOSAT retrievals of total column CO₂”

Sourish Basu^{1,2}, Sandrine Guerlet¹, André Butz³, Sander Houweling^{1,2}, Otto Hasekamp¹, Ilse Aben¹, Paul Krummel⁴, Paul Steele⁴, Ray Langenfelds⁴, Margaret Torn⁵, Sebastien Biraud⁵, Britton Stephens⁶, Arlyn Andrews⁷, and Douglas Worthy⁸

¹*SRON Netherlands Institute for Space Research, Utrecht, The Netherlands*

²*Institute for Marine & Atmospheric Research, Utrecht University, Utrecht, The Netherlands*

³*IMK-ASF, Karlsruhe Institute of Technology, Karlsruhe, Germany*

⁴*Commonwealth Scientific and Industrial Research Organisation, Victoria, Australia*

⁵*Lawrence Berkeley National Laboratory, California, USA*

⁶*National Center for Atmospheric Research, Colorado, USA*

⁷*National Oceanic and Atmospheric Administration, Colorado, USA*

⁸*Environment Canada, Toronto, Canada*

S1 Robustness of estimated fluxes

There are many sources of error in the 4DVAR inversion system, of which only two – namely, error in the specification of prior fluxes, and error in simulating observations at sub-grid spatial scales – are explicitly incorporated in the data assimilation system. Our final flux estimates and the associated error bounds reflect the uncertainties introduced by these two error sources. There are other, more systematic errors, however, that are not accounted for by the system. The most critical of them are systematic errors in atmospheric tracer transport, of which there could be many sources, such as finite spatiotemporal resolution, incorrect vertical transport, systematic errors in the driving meteorological fields, and incorrect interhemispheric exchange rates. In this work, we have investigated the impact of some of these errors by running several sensitivity tests, described below.

S1.1 Effect of vertical model resolution

For all the inversions presented in the main text, we have used the TM5 transport model with 25 vertical layers. The meteorological fields driving the model, from the ECMWF ERA Interim dataset, are however available at the finer resolution of 60 vertical layers. It is therefore possible to simulate atmospheric transport by TM5 over 60 vertical layers. We expect the 60 layer model to better simulate the vertical CO₂ profile, to which GOSAT X_{CO₂} is sensitive. Therefore, at least for inversions assimilating GOSAT data, the 60 layer model should yield flux estimates closer to the “truth” than the coarser, 25 layer model. To test the impact of changing the vertical resolution of the transport model on the optimized fluxes, we assimilated the same data sets (surface layer and GOSAT) in inversions using TM5 with 25 and 60 vertical layers.

Yearly aggregated fluxes from both the 25 layer and the 60 layer inversions are presented for a few large regions in figure S1. As we can see, changing the vertical resolution from the coarse 25 layers to the maximum possible 60 layers does not change the optimized fluxes significantly, implying that TM5 with 25 vertical layers is as good as TM5 at the full vertical resolution for ingesting both surface and satellite data. It should be noted that we performed this test using inversions based on an earlier version of the RemoTeC X_{CO₂} product for both vertical resolutions. Since the result of the test was that the vertical model resolution makes only negligible differences to the optimized flux, we did not perform 60-layer inversions with the RemoTeC X_{CO₂} data used for the results presented in the main text.

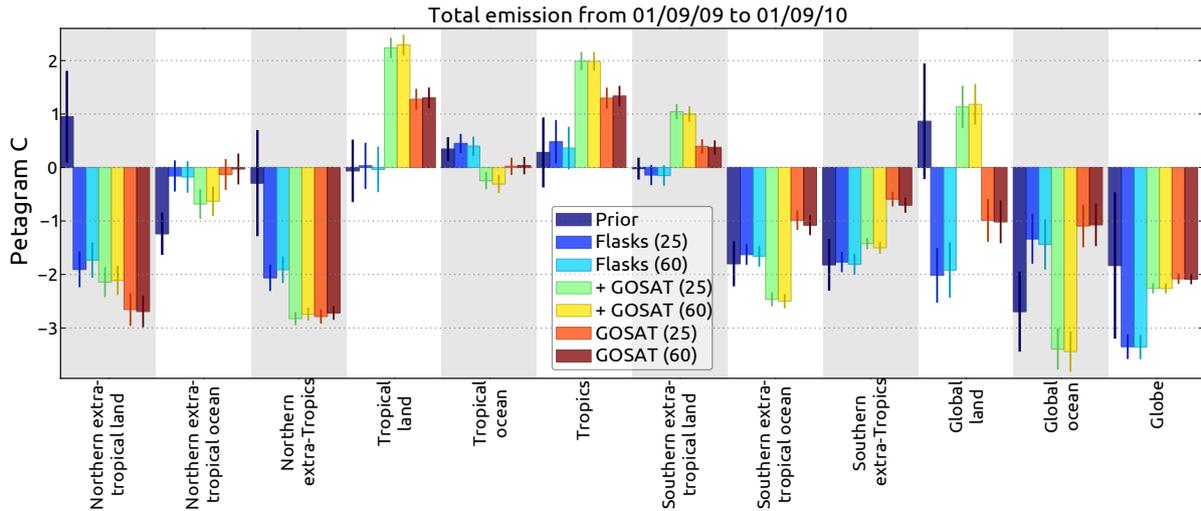


FIGURE S1: Aggregated fluxes between Sep 1, 2009 and Sep 1, 2010, partitioned over larger regions such as different continents and latitude bands. The emission figures do not include fossil fuel emission. Error bars denote 1σ errors. Each data source (surface data, GOSAT data) has been assimilated by running the TM5 transport model at two different vertical resolutions, 25 and 60 layers, which are indicated in the legend in parentheses.

S1.2 Effect of horizontal model resolution

For all the inversions presented in the main text, we ran our transport model globally on a $6^\circ \times 4^\circ$ grid. The second sensitivity test involves changing the lateral model resolution to $3^\circ \times 2^\circ$. Changing the horizontal resolution changes the resolution of synoptic weather patterns, the time scales for horizontal diffusion and vertical convection and thereby the interhemispheric transport time, and the representability of local fluctuations in the CO_2 concentration. It would not be unreasonable, therefore, to expect very different optimized fluxes (compared to the $6^\circ \times 4^\circ$ transport model) given the same set of assimilated observations. In practice, however, the effect of running our inversions at a different lateral resolution did not turn out to be large, as seen in figure S2. Over some regions such as the northern extra-tropics, changing the horizontal resolution changed the estimate of optimized fluxes, although at the level of the posterior error estimates the changes were not significant. Over other regions such as the tropics, refining the lateral model resolution did not change the flux estimates.

S1.3 Changing the driving meteorological data

The third sensitivity test involved changing the assimilated meteorological dataset driving the TM5 transport model. Using ECMWF operational forecasts instead of Era Interim reanalyzed meteorological data was equivalent to using a different realization of atmospheric transport, and we would in general have expected estimated fluxes to differ, especially if one of the meteorological datasets were significantly different from the “truth”. However, the effect of changing the driving meteo did not prove to be large, as seen in figure S3. Over all regions, the estimated fluxes from the two realizations of transport were within 1σ of each other.

S1.4 Changing the assumed prior flux correlation structure

There is some degree of arbitrariness in the choice of the prior correlation structure, which can be problematic since the posterior fluxes depend heavily on the choice of prior correlations. However, the sensitivity to the prior correlations depends on what aspects of the posterior fluxes one wants to present. For example, if one only presents annual and seasonal aggregated fluxes over continental length scales – as we have done – then assuming shorter spatiotemporal correlations than we have done do not significantly alter those aggregates. There will certainly be differences, but as long as those differences are smaller

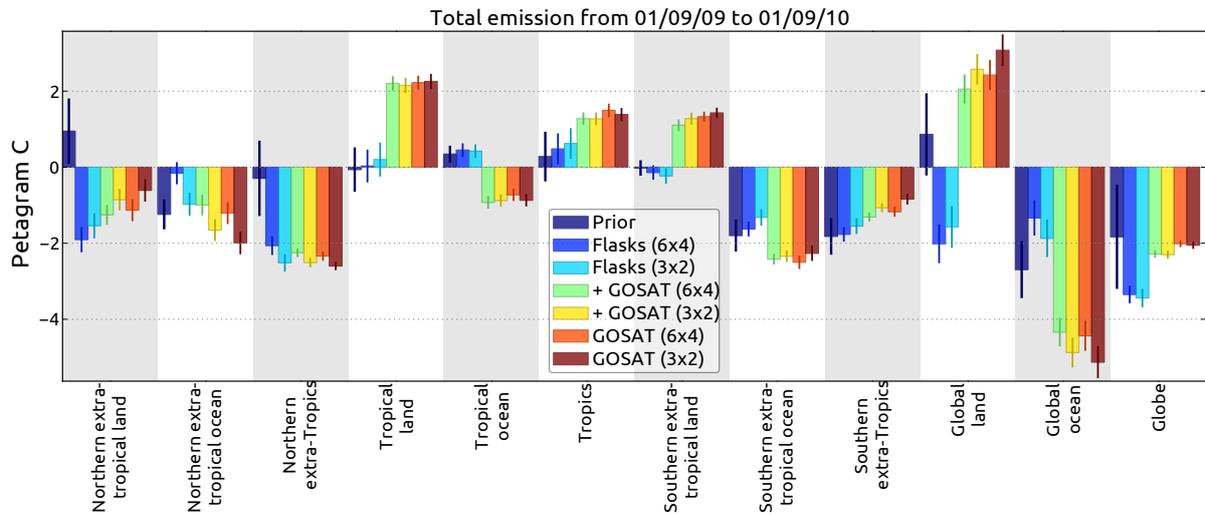


FIGURE S2: Aggregated fluxes over different regions between Sep 1, 2009 and Sep 1, 2010, similar to figure S1. Each data source (surface data, GOSAT data) has been assimilated by running the TM₅ transport model at two different horizontal resolutions, $3^{\circ} \times 2^{\circ}$ and $6^{\circ} \times 4^{\circ}$, which are indicated in the legend in parentheses.

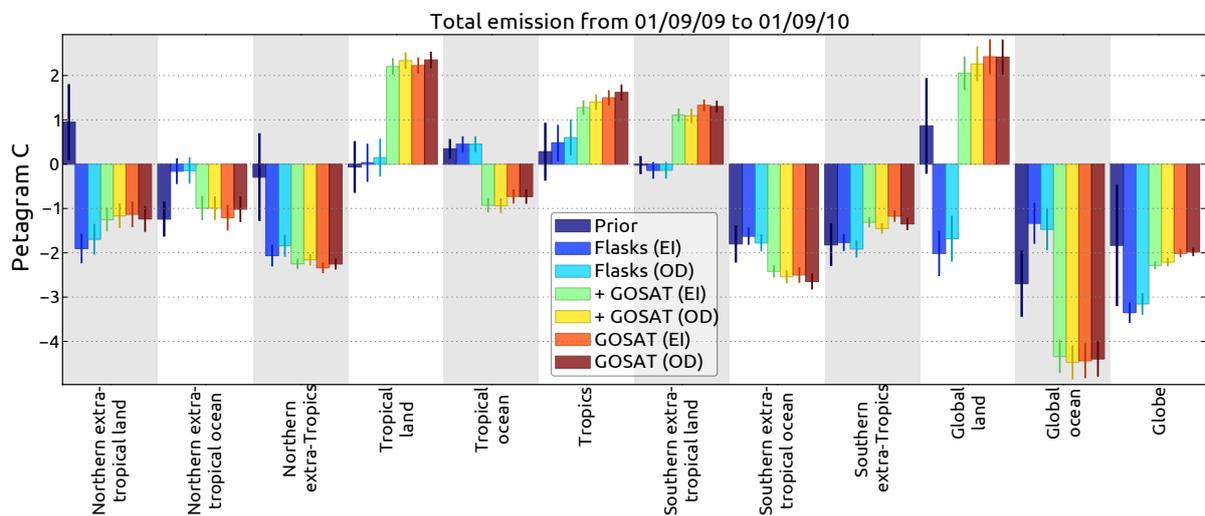


FIGURE S3: Aggregated fluxes over different regions between Sep 1, 2009 and Sep 1, 2010, similar to figure S1. Each data source (surface data, GOSAT data) has been assimilated by running the TM₅ transport model with two different assimilated meteorological data sets, ECMWF Era Interim (“EI” in the legend) and ECMWF operational forecasts (“OD” in the legend).

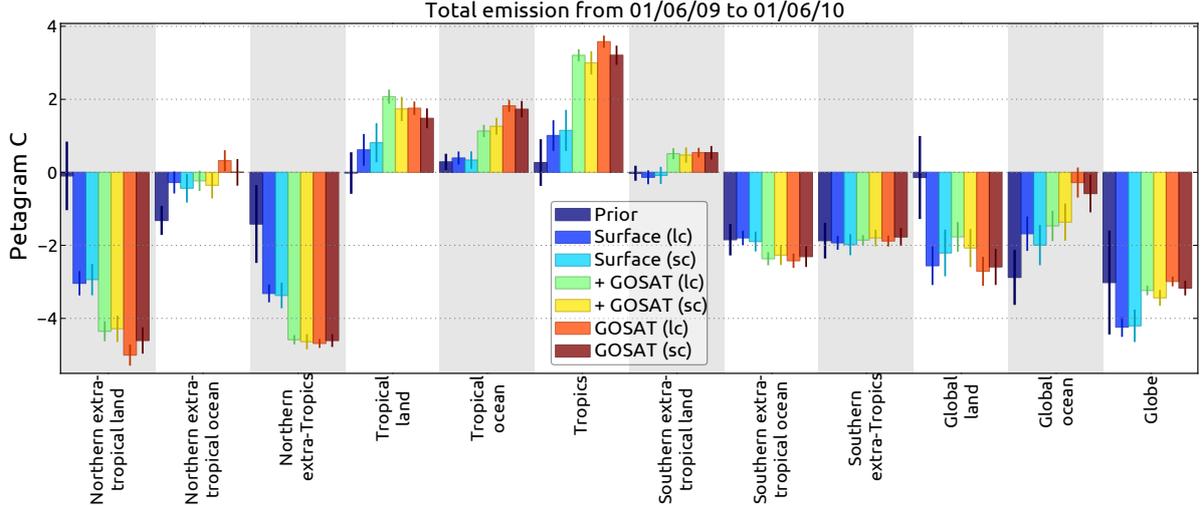


FIGURE S4: The impact of changing the prior spatiotemporal correlations on annual flux aggregates over continental length scales. The “lc” set – for “long correlation” – corresponds to the standard correlation parameters used in the main text, whereas the “sc” set – for “short correlation” – corresponds to shorter spatiotemporal correlation lengths, as tabulated in table S1.

than the error estimates on the posterior fluxes, those differences are not significant. To test whether this was the case, we performed the three inversions (surface only, GOSAT only and joint) with dramatically different correlation times and lengths. The two sets of correlation parameters are tabulated in table S1, while the flux aggregates are presented in figure S4.

TABLE S1: Covariance parameters for different categories, original (lc) and modified (sc). The “lc” values are the same as those in table 1 in the main text.

Class	Category	L (km)	T (months)	ξ
lc	Biosphere flux	500	3	0.84
lc	Oceanic flux	3000	6	0.60
sc	Biosphere flux	200	1	2.213
sc	Oceanic flux	1000	3	1.569

The ξ , i.e., the flux uncertainty per gridbox as a fraction of the absolute flux per category, was chosen for the modified correlation parameters to keep the global total prior flux uncertainty per category the same. Since shorter correlations imply larger cancellations when aggregating, ξ had to be increased to keep the global total uncertainty constant. As can be seen from figure S4, although the aggregated fluxes can be different between the “sc” and the “lc” inversions, in all cases the two numbers are within 1σ of each other. Therefore, we think that our flux estimates – as presented in the main text – are robust to reasonable changes in the correlation parameters. One minor difference between the sensitivity tests presented in § S1.1 – § S1.3 and this one was that the inversion system included, by default, a land-sea bias correction as described in § 4.5 in the main text. Therefore, the inversions “+ GOSAT” in figure S4 denote an inversion where a land-sea bias was optimized (equivalent to “+ GOSAT (BC)” of figure 12 in the main text). The “GOSAT” inversions in figure S4 assimilated GOSAT XCO₂ with this optimal land-sea bias applied. This of course does not change the conclusion of this sensitivity analysis, which is that changing the correlation parameters as described in table S1 does not change the conclusions in our manuscript.