Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

Atmospheric Chemistry and Physics
Discussions
Open Access

A Global Synthesis Inversion Analysis of Recent Variability in CO_2 Fluxes Using GOSAT and In Situ Observations

James S. Wang,[1,2] S. Randolph Kawa,[2] G. James Collatz,[2] Motoki Sasakawa,[3] Luciana V. Gatti,[4] Toshinobu Machida,[3] Yuping Liu,[5,2] and Michael E. Manyin[5,2]

[1]Universities Space Research Association, Columbia, MD, USA, james.s.wang@nasa.gov

[2]NASA Goddard Space Flight Center, Greenbelt, MD, USA

[3]National Institute for Environmental Studies, Center for Global Environmental Research, Ibaraki, Tsukuba Onogawa, Japan

[4]Instituto de Pesquisas Energéticas e Nucleares (IPEN)–Comissao Nacional de Energia Nuclear (CNEN), Sao Paulo, Brazil

[5]Science Systems and Applications, Inc., Lanham, MD, USA

Abstract

The precise contribution of the two major sinks for anthropogenic CO_2 emissions, terrestrial vegetation and the ocean, and their location and year-to-year variability are not well understood. Top-down estimates of the spatiotemporal variations in emissions and uptake of CO_2 are expected to benefit from the increasing measurement density brought by recent in situ and remote CO_2 observations. We uniquely apply a batch Bayesian synthesis inversion at relatively high resolution to in situ surface observations and bias-corrected GOSAT satellite column CO_2 retrievals to deduce the global distributions of natural CO_2 fluxes during 2009-2010. Our objectives include evaluating bottom-up prior flux estimates, assessing the value added by the satellite data, and examining the impacts of inversion technique and assumptions on posterior fluxes and uncertainties. The GOSAT inversion is generally better constrained than the in situ inversion, with smaller posterior regional flux uncertainties and correlations, because of greater spatial coverage, except over North America and high-latitude ocean. Complementarity of the in situ and GOSAT data enhances uncertainty reductions in a joint inversion; however, spatial and temporal gaps in sampling still limit the ability to accurately resolve fluxes down to the sub-continental scale. The GOSAT inversion produces a shift in the global CO_2 sink from the tropics to the north and south relative to the prior, and an increased source in the tropics of ~2 Pg C y^{-1} relative to the in situ inversion, similar to what is seen in studies using other inversion approaches. This result may be driven by sampling and residual retrieval biases in the GOSAT data, as suggested by significant discrepancies between posterior CO_2 distributions and surface in situ and HIPPO mission aircraft data. While the shift in the global sink appears to be a robust feature of the inversions, the partitioning of the sink between land and ocean in the inversions using either in situ or GOSAT data is found to be sensitive to prior uncertainties because of

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

negative correlations in the flux errors. The GOSAT inversion indicates significantly less CO_2 uptake in summer of 2010 than in 2009 across northern regions, consistent with the impact of observed severe heat waves and drought. However, observations from an in situ network in Siberia imply that the GOSAT inversion exaggerates the 2010-2009 difference in uptake in that region, while the prior CASA-GFED model of net ecosystem production and fire emissions reasonably estimates that quantity. The prior, in situ posterior, and GOSAT posterior all indicate greater uptake over North America in spring to early summer of 2010 than in 2009, consistent with wetter conditions. The GOSAT inversion does not show the expected impact on fluxes of a 2010 drought in the Amazon; evaluation of posterior mole fractions against local aircraft profiles suggests that time-varying GOSAT coverage can bias estimation of flux interannual variability in this region.

1. Introduction

About one-half of the global CO_2 emissions from fossil fuel combustion and deforestation accumulates in the atmosphere (Le Quéré et al., 2015), where it contributes to global climate change. The rest is taken up by vegetation and the ocean. The precise contribution of the two sinks, their location and year-to-year variability, and the environmental controls on the variability are, however, not well understood. Top-down methods involving atmospheric inverse modeling have been used extensively to quantify natural CO_2 fluxes (e.g. Enting and Mansbridge, 1989; Ciais et al., 2010). An advantage of this approach over bottom-up methods such as forest inventories (Pan et al., 2011; Hayes et al., 2012) or direct flux measurements (Baldocchi et al., 2001; Chevallier et al., 2012) is that measurements of atmospheric CO_2 mole fractions generally contain the influence of fluxes over a spatial scale substantially larger than that of individual forest plots or flux measurements, so that errors from extrapolating measurements to climatically relevant scales (e.g. ecosystem, sub-continental, or global) are mitigated. However, the accuracy of top-down methods is limited by sparse data coverage, uncertainties in atmospheric transport modeling, and mixing of signals from different flux types such as anthropogenic and natural.

With the advent of retrievals of atmospheric CO_2 mole fraction from satellites, including the Japanese Greenhouse gases Observing SATellite (GOSAT) (Yokota et al., 2009) and the NASA Orbiting Carbon Observatory-2 (OCO-2) (Crisp, 2015), data coverage has improved greatly. Making measurements since 2009, GOSAT is the first satellite in orbit designed specifically to measure column mixing ratios of CO_2 (as well as methane) with substantial sensitivity to the lower troposphere, close to surface fluxes. A number of modeling groups have conducted CO_2 flux inversions using synthetic GOSAT data (Liu et al., 2014) and actual data

(Takagi et al., 2011; Maksyutov et al., 2013; Basu et al., 2013; Saeki et al., 2013a; Deng et al., 2014; Chevallier et al., 2014; Takagi et al., 2014; Reuter et al., 2014; Houweling et al., 2015; Deng et al., 2016). Unlike in situ measurements, which are calibrated directly for the gas of interest, remote sensing involves challenges in precision and accuracy stemming from the measuring of radiance. The retrievals rely on modeling of radiative transfer involving complicated absorption and scattering by the atmosphere and reflection from the surface (e.g. Connor et al., 2008; O'Dell et al., 2012). Passive measurements that rely on reflected sunlight are more prone to errors than active measurements, as they are affected by not only errors related to meteorological parameters and instrument noise but also systematic errors related to scattering by clouds and aerosols, which can dominate the error budget (Kawa et al., 2010; O'Dell et al., 2012). Furthermore, passive measurements have coverage gaps where there is insufficient sunlight and where there is excessive scattering.

In addition to the model transport examined by a number of inversion intercomparison studies (e.g. Gurney et al., 2002; Baker et al. 2006), the inversion technique and assumptions can contribute to substantial differences in results. For example, Chevallier et al. (2014) found that significant differences in hemispheric and regional flux estimates can stem from differences in Bayesian inversion techniques, transport models, a priori flux estimates, and satellite CO_2 retrievals. Houweling et al. (2015) presented an intercomparison of 8 different inversions using 5 independent GOSAT retrievals, and also found substantial differences in optimized fluxes at the regional level, with modeling differences (priors, transport, inversion technique) contributing approximately as much to the spread in results on land as the different satellite retrievals used.

In this paper, we present inversions of GOSAT and in situ data using a distinct technique, which are compared with results from other studies. All of the previous GOSAT satellite data inversions have used computationally-efficient approaches, such as variational and ensemble Kalman filter data assimilation, to handle the large amounts of data generated by satellites and the relatively large number of flux regions whose estimation is enabled by such data. The computational efficiency of these approaches results from numerical approximations. In this study, we apply a traditional, batch, Bayesian synthesis inversion approach (e.g. Baker et al., 2006) at relatively high spatiotemporal resolution to estimate global, interannually varying CO_2 fluxes from satellite and in situ data. Advantages of this technique include generation of an exact solution along with a full-rank error covariance matrix (e.g. Chatterjee and Michalak, 2013), and an unlimited time window during which fluxes may influence observations, unlike the limits typically imposed in Kalman filter techniques. The major disadvantages of the batch technique are that computational requirements limit the spatiotemporal resolution at which the inversion can be solved and the size of the data set that can be ingested, a large number of transport model runs is required to pre-compute the basis functions (i.e. Jacobian matrix), and the handling of the resulting volume of model output is very time-consuming at relatively high resolution.

We estimate natural terrestrial and oceanic fluxes over the period May 2009 through September 2010. The analysis spans two full boreal summers; longer periods were prohibited by the computational effort. The objectives of this study are: 1) to understand recent variability of the global carbon cycle, 2) to evaluate the bottom-up flux estimates used for the priors, 3) to compare fluxes and uncertainties inferred using in situ observations, GOSAT observations, and the two data sets combined and to assess the value added by the satellite data, and 4) to generate inversion results using a unique Bayesian inversion technique for comparison with other approaches.

Section 2 provides details on the inputs and inversion methods. Section 3 presents prior and posterior model CO_2 mole fractions and their evaluation against independent data sets, fluxes and uncertainties at various spatial and temporal scales, and comparisons with results from inversions conducted by other groups. We discuss the robustness of results, and examine in particular their sensitivity to assumed prior flux uncertainties. We then analyze the possible impacts of several climatic events during the analysis period on CO_2 fluxes. Section 4 contains concluding remarks.

2. Methods

Our method is based on that used in the TransCom 3 (TC3) CO_2 inversion intercomparisons (Gurney et al., 2002; Baker et al. 2006) and that of Butler et al. (2010), the latter representing an advance over the TC3 method in that they accounted for interannual variations in transport and optimized fluxes at a higher spatial resolution. Our method involves further advances over that of Butler et al. (2010), including higher spatial and temporal resolution for the optimized fluxes, and the use of individual flask-air observations and daily averages for continuous observations rather than monthly averages. Inversion theoretical studies and intercomparisons have suggested that coarse resolution for flux optimization can produce biased estimates, i.e. estimates that suffer from aggregation error (Kaminski et al., 2001; Engelen et al., 2002; Gourdji et al., 2012). Although observation networks may not necessarily provide sufficient constraints on fluxes at high resolutions, Gourdji et al. (2012) adopted the approach of estimating fluxes first at fine scales and then aggregating to better-constrained resolutions to minimize aggregation errors. The high spatiotemporal resolution of our inversion relative to other Bayesian synthesis inversions would be expected to reduce aggregation errors. Similarly, use of higher temporal resolution observations allows our inversion to more precisely capture variability due to transport and thus more accurately estimate fluxes. Details on our inversion methodology are provided in the sub-sections below.

2.1. A priori fluxes and uncertainties

Prior estimates for net ecosystem production (NEP = photosynthesis − respiration) and fire emissions (wildfires, biomass burning, and biofuel burning) come from the Carnegie-Ames-Stanford-Approach (CASA) biogeochemical model coupled to version 3 of the Global Fire Emissions Database (GFED3) (Randerson et al., 1996; van der Werf et al., 2006; 2010). CASA-GFED is driven with data on fraction of absorbed photosynthetically active radiation (FPAR) derived from the AVHRR satellite series (Pinzon et al, 2014; Los et al., 2000), burned area from MODIS (Giglio et al, 2010), and meteorology (precipitation, temperature, and solar radiation) from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al., 2011). CASA-GFED fluxes are generated at 0.5° x 0.5° resolution. For use in the atmospheric transport model, monthly fluxes are downscaled to 3-hourly values using solar radiation and temperature (Olsen and Randerson, 2004) along with MODIS 8-day satellite fire detections (Giglio et al., 2006). In general, the biosphere is close to neutral in the CASA-GFED simulation, i.e. there is no long-term net sink although there can be interannual variations in the balance between uptake and release. In the version of CASA used here, a sink of ~100 Tg C y^{-1} is induced by crop harvest in the U.S. Midwest that is prescribed based on National Agriculture Statistics Service data on crop area and harvest. Although respiration of the harvested products is neglected, the underestimate of emissions that is implied is geographically dispersed and in principle correctable by the inversion.

For air-sea CO_2 exchange, monthly, climatological, measurement-based fluxes are taken from Takahashi et al. (2009) for the reference year 2000 on a 4° x 5° lat/lon grid. In contrast to the CASA-GFED flux being close to neutral on a global basis, the prior ocean flux forms a net sink of 1.4 Pg C y^{-1}. For fossil CO_2, 1° x 1°, monthly- and interannually-varying emissions are taken from the Carbon Dioxide Information Analysis Center (CDIAC) inventory (Andres et al., 2012). This includes CO_2 from cement production but not international shipping and aviation emissions. Oxidation of reduced carbon-containing gases from fossil fuels in the atmosphere (~5% of the emissions; Nassar et al., 2010) is neglected, and the entire amount of the emissions is released as CO_2 at the surface. Similarly, CO_2 from oxidation of biogenic and biomass burning gases is neglected. The total amount of CO_2 chemical production from fossil and biospheric gases is estimated to be ~1 Pg C y^{-1} (for year 2006; Nassar et al., 2010).

A priori flux uncertainties are derived from those assumed in the TC3 studies (Table 1), rescaled to our smaller regions and shorter periods with the same approach as Feng et al. (2009). A priori spatial and temporal error correlations are neglected in our standard inversions. The neglect of a priori spatial error correlations is justified by the size of our flux optimization regions, with dimensions on the order of one thousand to several thousand km, likely greater than the error correlation lengths for our 2° × 2.5° grid-level fluxes. For example, Chevallier et al. (2012) estimated a correlation e-folding length of ~500 km for a grid size close to ours of 300 km × 300 km based on comparison of a terrestrial ecosystem model with global flux tower data.

2.2. Observations and uncertainties

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

For constraining fluxes at relatively high temporal resolution, observations are chosen that consist of discrete whole-air samples collected in glass flasks approximately weekly and continuous in situ tall tower measurements of CO_2 mole fraction from the NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network (Dlugokencky et al., 2013; Andrews et al., 2009) supplemented with continuous ground-based measurements at 3 sites in East Asia from the Japan Meteorological Agency (JMA) network (http://ds.data.jma.go.jp/gmd/wdcgg/cgi-bin/wdcgg/catalogue.cgi, accessed 14 Mar 2013; Tsutsumi et al., 2006). Both data sets are calibrated to the WMO-X2007 scale. In the present study, these data sets are referred to collectively as "in situ" observations. The 87 sites (Fig. 1a) are chosen based on data availability for the analysis period, Mar 2009-Sep 2010. Individual flask-air observations are used in the inversions, and for the continuous measurements, afternoon averages are used (between 1200 and 1700 local standard time), avoiding the difficulty of simulating the effects of shallow nighttime boundary layers. For the towers, data from the highest level only is used. We apply minimal filtering of the data. For the NOAA data sets, we exclude only the data with "rejection" flags, retaining data with "selection" flags (NOAA uses statistical filters and other information such as wind direction to flag data that are likely valid but do not meet certain criteria such as being representative of well-mixed, background conditions), since the relatively high-resolution transport model used here (Sect. 2.3) captures much of the variability in the observations beyond background levels. Furthermore, observations strongly influenced by local fluxes are typically assigned larger uncertainties by our scheme (described below), and therefore have less weight in the inversion. For the JMA data, we omit only the hourly data with flag = 0, meaning the number of samples is below a certain level, the standard deviation is high, and there is a large discrepancy with one or both adjacent hourly values. Although some of the observation sites used in our inversion are located close to each other, there is never any exact overlap in grid box (altitude and/or longitude-latitude) or in time. Thus, all of those sites are kept for the inversions, with observations at each site and day treated as independent (i.e. neglecting error correlations).

We estimate the uncertainties for the flask-air observations as the root sum square (RSS) of two uncertainty components: the standard deviation of the observations within a particular hour (up to two pairs of duplicate samples) and a simple estimate of the model transport/representation error. For the first uncertainty component, we assign a value of 0.3 ppm if there is only one sample, and apply a minimum value of 0.01 ppm. The transport/representation error estimation is similar to that of the NOAA CarbonTracker (CT) CO_2 data assimilation system (prior to the CT 2015 version) (Peters et al., 2007; http://carbontracker.noaa.gov), whereby a fixed "model-data mismatch" is assigned based on the type of site, e.g. marine, coastal, continental, or polluted, ranging from 0.4 ppm to 4 ppm. For the continuous measurements, we take the RSS of two uncertainty components: the afternoon root mean square (RMS) of the uncertainties of the 30-second or hourly average observations reported by the data providers (divided by the square root of the number of observations, N), and the standard error of all the 30-second/hourly mole fractions within an afternoon period. This represents an attempt to account for instrument error as well as transport/representation error. In addition, based on initial inversion results, we enlarged all in situ total observation uncertainties by a factor of 2 to lower the normalized chi-squared (χ^2) value closer to 1 (the final value of which is shown in Table 2).

GOSAT measures reflected sunlight in a sun-synchronous orbit with a 3-day repeat cycle and a 10.5 km diameter footprint when in nadir mode (Yokota et al., 2009). The spacing between soundings is ~250 km along-track and ~160 km or ~260 km cross-track (for 5-point/3-

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

point sampling before/after Aug 2010). We use the ACOS B3.4 retrieval of column-average CO_2 dry air mole fraction (XCO_2), with data from June 2009 onward (O'Dell et al., 2012; Osterman et al., 2013). Filtered and bias-corrected land nadir, including high (H) gain and medium (M) gain, and ocean glint data are provided. Three truth metrics were used together to correct biases (separately for H gain, M gain, and ocean glint) (Osterman et al., 2013; Lindqvist et al., 2015; Kulawik et al., 2016): 1) an ensemble of transport model simulations optimized against in situ observations, 2) coincident ground-based column observations from the Total Carbon Column Observing Network (TCCON), which are calibrated to aircraft in situ profiles linked to the WMO scale (Wunch et al., 2011), and 3) the assumption that CO_2 mole fraction ought to exhibit little spatiotemporal variability in the Southern Hemisphere mid-latitudes other than a seasonal cycle and long-term trend. For our inversions, we use the average of GOSAT observations falling within a given 2° latitude × 2.5° longitude transport model column in a given hour. Figure 1b shows the frequency of the ACOS GOSAT observations across the model grid.

The values assumed for the GOSAT uncertainties are based in part on the retrieval uncertainties provided with the ACOS data set. Following guidance from the data providers, these are inflated by a factor of 2 over land and 1.25 over ocean for more realistic estimates of the uncertainties (C. O'Dell, pers. comm., 2013); Kulawik et al. (2016) recommended an overall scale factor of 1.9 for the similar ACOS B3.5 data set. In the case of multiple observations within a model grid, we estimate the overall uncertainty as the RMS of the uncertainties of the individual observations, divided by the square root of N. Error correlations between observations in different model grids and at different hours are neglected.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

Inversions are conducted using different combinations of data, including the in situ data ("in situ-only"), the GOSAT data ("GOSAT-only"), and both ("in situ + GOSAT").

We use several additional data sets for independent evaluation of the inversion results. Aircraft measurements from the HIAPER Pole-to-Pole Observations (HIPPO) campaign consist of vertical profiles of climate-relevant gases and aerosols from the surface to as high as the lower stratosphere, spanning a wide range of latitudes mostly over the Pacific region (Wofsy et al., 2011). Five missions were conducted during different seasons in 2009-2011, with two of the missions overlapping with our analysis period. We use the "best available" CO_2 values derived from multiple measurement systems from the merged 10-second data product (Wofsy et al., 2012). Another data set, the 'Amazonica' aircraft measurements over the Amazon basin, is useful for evaluating inversion performance over tropical land. These measurements consist of profiles of several gases including CO_2 determined from flask samples from just above the forest canopy to 4.4 km altitude over 4 sites across the Brazilian Amazon starting in 2010, taken approximately biweekly (Gatti et al., 2014, 2016). Finally, the Japan-Russia Siberian Tall Tower Inland Observation Network (JR-STATION) of towers provides continuous in situ measurements of CO_2 and CH_4 over different ecosystem types across Siberia beginning in 2002 (Sasakawa et al., 2010; Sasakawa et al., 2013). The JR-STATION data have been used in combination with other in situ observations in CO_2 flux inversions (Saeki et al., 2013b; Kim et al., 2017).

2.3. Atmospheric transport model and model sampling

We use the Parameterized Chemistry and Transport Model (PCTM) (Kawa et al., 2004), with meteorology from the NASA Global Modeling and Assimilation Office (GMAO) MERRA reanalysis (Rienecker et al., 2011). For this analysis, PCTM was run at a resolution of 2° latitude × 2.5° longitude and 56 hybrid terrain-following levels up to 0.4 hPa. A "pressure fixer" scheme has been implemented to ensure tracer mass conservation, the lack of which can be a significant problem with assimilated winds (Kawa et al., 2004). This version of PCTM was among the transport models that participated in TransCom intercomparisons (Gurney et al., 2005; Law et al., 2008).

Offshore prior terrestrial biospheric and fossil fluxes are redistributed to the nearest onshore grid cells in the model grid to counteract diffusion caused by our regridding the original fluxes to the coarser 2° x 2.5° resolution, as recommended in the TC3 protocol (Gurney et al., 2000).

The model is initialized with a concentration field appropriate for March 22, 2009 from a multi-year PCTM run with prior fluxes. The initial conditions are optimized in the inversions, as described in Sect. 2.4.

PCTM is sampled at grid cells containing in situ observation sites or GOSAT soundings, at the hours corresponding to the observations. To mimic the sampling protocol for coastal flask sites, which favors clean, onshore wind conditions, the model is sampled at the neighboring offshore grid cell if the cell containing the site is considered land according to a land/ocean mask. For in situ sites in general, the appropriate vertical level as well as horizontal location is selected. Specifically, the model CO_2 profile is interpolated to the level corresponding on average to the altitude above sea level of the observation site. This procedure is relevant primarily for mountain sites and tall towers as well as aircraft samples; the lowest model level was used for most other sites.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

Model columns are weighted using ACOS column averaging kernels applied to deviations of model CO_2 profiles from ACOS a priori profiles (Connor et al., 2008).

Time series of model and observed mole fractions at selected flask and continuous sites spanning a range of latitudes, longitudes, elevations, and proximity to major fluxes are shown for the prior and for the in situ-only inversion in Fig. 2. The prior model as well as the in situ inversion captures much of the observed synoptic-scale variability. This suggests that the PCTM transport is reasonably accurate, consistent with the findings of Parazoo et al. (2008) and Law et al. (2008).

2.4. Inversion approach

The batch, Bayesian synthesis inversion approach optimizes in a single step the agreement between model and observed CO_2 mole fractions and between a priori and a posteriori flux estimates in a least-squares manner (e.g. Enting et al., 1995). As in the paper by Baker et al. (2006), the cost function minimized in this approach can be expressed as

$$J = (\mathbf{c}_{\text{obs}} - \mathbf{c}_{\text{fwd}} - \mathbf{Hx})^T \mathbf{R}^{-1} (\mathbf{c}_{\text{obs}} - \mathbf{c}_{\text{fwd}} - \mathbf{Hx}) + (\mathbf{x}_0 - \mathbf{x})^T \mathbf{P}_0^{-1} (\mathbf{x}_0 - \mathbf{x}), \quad (1)$$

where $\mathbf{c}_{\text{obs}} - \mathbf{c}_{\text{fwd}}$ are mismatches between the observations and the mole fractions produced by the prior fluxes, $\mathbf{H}$ is the Jacobian matrix relating model mole fractions at the observation locations to regional flux adjustments $\mathbf{x}$, $\mathbf{R}$ is the covariance matrix for the errors in $\mathbf{c}_{\text{obs}} - \mathbf{c}_{\text{fwd}}$, $\mathbf{x}_0$ is an a priori estimate of the flux adjustments, and $\mathbf{P}_0$ is the covariance matrix for the errors in $\mathbf{x}_0$. The solution for the a posteriori flux adjustments, $\hat{\mathbf{x}}$, is

$$\hat{\mathbf{x}} = (\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H} + \mathbf{P}_0^{-1})^{-1}(\mathbf{H}^T\mathbf{R}^{-1}(\mathbf{c}_{\mathrm{obs}} - \mathbf{c}_{\mathrm{fwd}}) + \mathbf{P}_0^{-1}\mathbf{x}_0), \quad (2)$$

and the a posteriori error covariance matrix is given by

$$\mathbf{P} = (\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H} + \mathbf{P}_0^{-1})^{-1}. \quad (3)$$

This study focuses on the variability of natural fluxes (terrestrial NEP and ocean), and thus considers adjustments to those fluxes only, assuming the prior estimates for the fossil and fire fluxes are correct. This is commonly done in CO_2 inversion studies (e.g. Gurney et al., 2002; Peters et al., 2007; Basu et al., 2013), with the rationale that the anthropogenic emissions are relatively well known, at least at the coarse spatial scales of most global inversions. In our inversion, flux adjustments are solved for at a resolution of 8 days and for each of 108 regions that are modified from the 144 regions of Feng et al. (2009) (Fig. 1a), which are in turn subdivided from the TC3 regions. (The choice of an 8-day flux interval is based on data considerations, e.g. the quasi-weekly frequency of the flask measurements and reasonable sampling by GOSAT.) This is a significantly higher resolution than the monthly intervals and 22/47 regions in the previous batch inversions of TC3/Butler et al. (2010). One of our regions consists of low-flux land areas (e.g. Greenland, Antarctica) as well as small offshore areas that contain non-zero terrestrial biospheric fluxes but do not fit into any of the TC3-based land regions, similar to what was done by Feng et al. (2009). We also created a region that includes areas with non-zero oceanic fluxes that do not fit into any of the TC3-based ocean regions according to our gridding scheme.

Grid-scale spatial patterns are imposed in our flux adjustments based on the natural fluxes, similar to TC3 and Butler et al. (2010), except that we use patterns specific to our prior NEP or air-sea flux averaged over each particular 8-day period, rather than annual mean net primary productivity (NPP) patterns over land and spatially constant patterns over the ocean. To ensure net changes in flux are possible across each region, absolute values are used for the flux patterns. Prior values of 0 are specified for all flux adjustments.

The initial conditions (i.c.) are also optimized at the same time as the fluxes via two parameters: a scale factor to the i.c. tracer (described below) that allows for overall adjustment of spatial gradients, and a globally uniform offset. A priori uncertainties of 0.01 for the scale factor and 30 ppm for the offset are prescribed. Inversion results from March 22 through April 30, 2009 are discarded to avoid the influence of any inaccuracies in the initial conditions. (Our tests showed that inferred fluxes after the first two months are insensitive to the treatment of i.c.) Although the GOSAT data set begins in June 2009, the observations can provide some constraint on earlier fluxes.

For generating the prior mole fractions, $\mathbf{c}_{\mathrm{fwd}}$, and constructing the Jacobian matrix, $\mathbf{H}$, transport model runs were performed for each of the prior flux types and an i.c. tracer, as well as a run with a flux pulse (normalized to 1 Pg C y^{-1}) for each of the 108 regions and 71 8-day periods. (The last period in 2009 is shortened to 5 days to fit cleanly within the year.) The i.c. tracer is initialized as described in Sect. 2.3 and transported without emissions or removals for the duration of the analysis period. Each flux pulse is transported for up to 13 months, after which the atmosphere is well mixed (within a range of 0.01 ppm). This procedure generated a massive amount of 3-D model output, ~30 terabytes (compressed). All of the model output was then sampled at the observation locations and times.

A singular value decomposition (SVD) approach is used to obtain a stable inversion solution (Rayner et al., 1999). Use of the SVD technique is especially helpful in the case of the inversions using GOSAT data, since the Jacobian matrix is too large to be successfully inverted on our system (with a single CPU).

3. Results

3.1. General evaluation of inversions, including short-term flux variability

Posterior model mole fractions are closer to the assimilated observations than are the prior mole fractions for the in situ-only, GOSAT-only, and in situ + GOSAT inversions, as desired, as suggested by Fig. 2 and indicated by the means and standard deviations of the model-observation differences over all observations shown in Fig. 3 (a, d, e, and f). Comparison of posterior mole fractions with the data set not used (Fig. 3b, c), on the other hand, gives mean differences not as close to 0 as in the comparison with the assimilated data, and standard deviations that are larger than for the prior; this reflects the fact that the in situ and GOSAT data sets are not necessarily consistent with each other and have independent random errors. The improved agreement between model and assimilated observations is reflected also in the chi-squared (cost function) values before and after the inversions shown in Table 2. The expected value of chi-squared (normalized) for a satisfactory inversion is 1, which signifies that the tightness of the fit of the results to the observations and to the a priori parameter estimates is comparable to the level of uncertainty assumed for the observations and the a priori estimates. The posterior chi-squared values for all of the inversions are closer to 1 than the prior values.

In addition to cross-evaluating the in situ-only and GOSAT-only inversions, we evaluate both inversions against the independent, well-calibrated Amazon aircraft data set, which samples an under-observed region with large, variable fluxes. Vertical profiles of the model and the aircraft data (Fig. S1 in the supplementary material) show that the prior mole fractions often exhibit a bias relative to the aircraft observations, especially in a boundary layer-like structure below ~2 km altitude, with the sign of the average bias varying from season to season. The in situ inversion often exhibits worse agreement with the observations than the prior does (with a root mean square error (RMSE) that is more than 1 ppm larger in 27 of 60 cases above 2 km, and in 27 cases below 2 km). The GOSAT inversion not only exhibits smaller discrepancies with the observations than the in situ inversion does in general (29 of 60 cases above 2 km and 28 cases below 2 km, while the reverse is true in only 11 cases above 2 km and 25 cases below 2 km), but it also is more often better than the prior than worse above 2 km (16 vs. 13 cases). In contrast, the in situ inversion is more often worse than the prior than better (e.g. 27 vs. 12 cases above 2 km). Overall statistics, computed separately for lower and higher altitudes, are shown in Fig. 4. The model-observation histograms indicate that agreement with the aircraft observations is again better for the GOSAT inversion than the in situ inversion, with smaller or comparable mean differences and standard deviations. There is a near complete lack of in situ sites in the inversion that are sensitive to Amazon fluxes (as suggested by Fig. 1a), contrasting with the availability of some GOSAT data over the region (Fig. 1b), meaning that regional flux adjustments in the in situ inversion are driven, often erroneously, by correlations with fluxes outside of the region (as will be discussed in depth below in Sect. 3.3). The GOSAT inversion agrees with the aircraft observations better than the prior does above 2 km, implying that incorporating GOSAT data in the inversion results in better performance than no data. However, the posterior model-observation differences have greater variance than the prior below 2 km. A possible explanation for this is that the use of GOSAT observations in an inversion introduces more random error in the model mole fractions, which would not be expected to be correlated with the aircraft measurement error. GOSAT errors presumably affect higher altitudes in the model less, since the mole fractions there are influenced by fluxes across a broader area than at lower altitudes and thus errors are averaged out to a greater extent.

Example time series of 8-day mean prior and posterior NEP and ocean fluxes for the in situ-only and GOSAT-only inversions are shown in Fig. 5. Since the posterior fluxes in our inversion regions tend to have large fractional uncertainties, especially for the in situ-only inversion, we focus in this paper on results aggregated to larger regions. To facilitate comparison with other studies, results are aggregated to TC3 land and ocean regions, accounting for error correlations. The posterior time series exhibit larger fluctuations than the prior time series, especially for the in situ inversion over land. The fluctuations would presumably be smaller if we excluded flagged, outlier in situ observations or used a smoothed data product such as GLOBALVIEW-CO_2 (2009), which has been used in many inversions including those of TC3 and some of those in the Houweling et al. (2015) intercomparison. In addition, some of the fluctuations likely represent actual variability in the fluxes, while other fluctuations are probably noise. In fact, the calculated numbers of degrees of freedom for signal and noise (as defined by Rodgers, 2000) are 3525 and 4186 for the in situ inversion (summing up approximately to the number of inversion parameters, 7674) and 4925 and 2947 for the GOSAT inversion. This indicates that ~45% of the in situ inversion solution is based on actual information from the measurements, given the assumed prior and observation uncertainties, while ~65% of the GOSAT inversion solution is constrained by the measurements. The in situ data set is sparser than GOSAT, especially over land, and thus contains greater spatial sampling bias, so that many of the flux regions are under-determined and may exhibit so-called dipole behavior associated with negative error correlations (discussed further below).

Results for the in situ + GOSAT inversion (not shown in Fig. 5) lie mostly in between the in situ-only and GOSAT-only results. The fluxes generally lie closer to those of the GOSAT-only inversion for regions with a relatively low density of in situ measurements, including tropical and southern land regions, while they lie closer to those of the in situ-only inversion for regions with a relatively high density of in situ measurements, including northern land and many ocean regions.

To average out noise in the posterior fluxes and to better observe the major features in the results, we show monthly average fluxes in Fig. 6. There is a similar onset of seasonal CO_2 drawdown in the GOSAT-only inversion and the CASA-GFED prior in Boreal North America, Temperate North America, and Boreal Asia, whereas the in situ-only inversion is noisier, similar to what was noted above. The GOSAT inversion suggests an overall shift in the global CO_2 sink from tropical and southern land to northern land regions relative to the prior and the in situ inversion, similar to what has been found in previous GOSAT inversions (e.g. Houweling et al., 2015; discussed further below). There are some unusual features in the GOSAT inversion. For example, there is a negative flux in January in some northern regions, with the 1σ range lying entirely below zero for Boreal Asia and Europe; this CO_2 uptake does not seem plausible in the middle of winter for these regions. Also, there are large positive fluxes during winter through spring in Northern Africa, which deviate from the prior beyond any overlap in the 1σ ranges for two months and whose 1σ ranges stay above zero for six months, summing up to a source of 1.9 Pg C over the period December through May, not including fires. The fluxes are larger than those of any sustained period of positive fluxes in any region in either the prior or the in situ inversion. The anomalous features suggest that the GOSAT inversion is affected by uncorrected retrieval biases that vary by season and region (as has been shown by Lindqvist et al. (2015) and Kulawik et al. (2016)) and/or sampling biases, including a lack of observations at high latitudes during winter, which limit the ability to accurately resolve inferred fluxes down to the scale of TransCom regions.

A comparison of the monthly mean fluxes with those from another inversion system, NOAA's CarbonTracker version 2013B (CT2013B), is displayed in Fig. 7. CT2013B is an ensemble Kalman smoother data assimilation system with a window length of five weeks that uses multiple in situ observation networks and prior models to optimize weekly fluxes (Peters et al., 2007; https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2013B/CT2013B_doc.php, accessed 4 October 2016). Similar to the present study, CT2013B uses CASA-GFED3 fluxes from van der Werf et al. (2010) as one of the land NEP priors, though with different FPAR and meteorological driver data. (CASA-GFED2 is the other land prior in its ensemble of priors.) In addition, CT2013B uses the seawater pCO_2 distribution from the Takahashi et al. (2009) climatology to compute fluxes for one of its ocean priors; the other ocean prior is based on results from an atmosphere-ocean inversion. CT2013B uses 93 observation time series while 87 are used here, although the former include measurements by multiple labs at the same site and flask and continuous measurements at the same site (where duplicate observations are de-weighted by inflating the model-data mismatch error by the square root of N). A notable difference is that CT2013B solves for uniform flux scale factors over entire ecosystem types within each TC3 region, with the ecosystem types not necessarily being contiguous. Results from our in situ-only inversion are shown alongside those of CT2013B in Fig. 7 aggregated over

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

large regions. The two sets of posterior flux time series are similar overall, with overlapping 2σ ranges at all times except in the Northern Oceans region. One distinctive feature is that the posterior fluxes stay closer to the priors for CT2013B. A likely explanation is the tighter prior uncertainties in CT2013B, the magnitudes of which are on average 40% of ours for land regions and 30% of ours for ocean regions. For its ocean prior based on an atmosphere-ocean inversion, CT2013B assumes uncertainties consistent with the formal *posterior* uncertainties from the inversion, which are relatively small because of the large number of ocean observations used in the inversion; uniform fractional uncertainties are assumed for the other ocean prior and the land priors. Another feature is the larger month-to-month fluctuations in our results. A number of factors could contribute to smaller fluctuations in the CT2013B results. One of them is the tighter prior uncertainties used. Another factor is the use of prior estimates that represent a smoothing over three assimilation time steps, which attenuates variations in the forecast of the flux parameters in time. And another is that to dampen spurious noise due to the approximation of the covariance matrix by a limited ensemble, CT2013B applies localization for observation sites outside of the marine boundary layer, in which flux parameters that have a non-significant relationship with a particular observation are excluded. We further evaluate our inversions in the following sections.

3.2. Longer-term budgets and observation biases

Longer-timescale budgets can be assessed in Fig. 8, which displays 12-month mean fluxes (Jun 2009-May 2010) over large, aggregated regions, with fires now included, for our inversions and the CT2013B inversion. Results for individual TC3 regions are shown in Table 1. The global total flux (including fossil emissions) is substantially more positive for the GOSAT-

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

only inversion relative to the in situ-only inversion, 6.5 ± 0.2 Pg C y^{-1} vs. 4.1 ± 0.5 Pg C y^{-1}, while that for the in situ + GOSAT inversion lies in between at 5.7 ± 0.2 Pg C y^{-1}. Such a large difference in the atmospheric CO_2 growth rate implied by the two distinct data sets is plausible even if there are no trends in uncorrected biases between the data sets, given their sampling of different regions of the atmosphere and the relatively short 12-month time frame over which the growth occurs. In fact, for a different 12-month period within our analysis, Sep 2009-Aug 2010, the total fluxes for the GOSAT-only and in situ-only inversions are much closer to each other– 5.53 Pg C y^{-1} and 5.47 Pg C y^{-1}. Houweling et al. (2015) also found a larger total flux in the GOSAT-only inversions relative to the in situ during Jun 2009-May 2010 averaged across 8 models, , ~4.8 Pg C y^{-1} vs. ~4.6 Pg C y^{-1}, though the difference may not be statistically significant.

As was noted earlier in this section, the GOSAT-only inversion exhibits a shift in the global CO_2 sink from tropical and southern land to northern land relative to the prior and the in situ-only inversion (Fig. 8). The differences are within the 1σ uncertainty ranges. The shift includes an increase in the source in N. Africa (0.2/1.5/2.0 Pg C y^{-1} for prior/in situ-only/GOSAT-only), Temperate S. America (0.4/0.4/1.1 Pg C y^{-1}), and Australia (0.0/-0.2/0.6 Pg C y^{-1}), and an increase in the sink in Europe (-0.1/0.6/-1.5 Pg C y^{-1}) and Temperate N. America (-0.3/-0.6/-1.5 Pg C y^{-1}) (Table 1). As for the ocean, the GOSAT inversion also exhibits a larger source in the tropics relative to the prior and the in situ inversion (outside of the 1σ ranges; Fig. 8). However, the GOSAT inversion now exhibits a smaller sink over northern ocean relative to the in situ inversion, and a larger sink over southern ocean relative to both the prior and the in situ inversion (at or outside of the 1σ ranges). The TC3 regions contributing the most to these differences include Tropical Indian (0.1/0.0/0.7 Pg C y^{-1} for prior/in situ-only/GOSAT-only), N.

Pacific (-0.9/-0.5 Pg C y^{-1} for in situ-only/GOSAT-only), N. Atlantic (-0.8/-0.5 Pg C y^{-1} for in situ-only/GOSAT-only), and Southern Ocean (-0.2/-0.4/-0.9 Pg C y^{-1} for prior/in situ-only/GOSAT-only) (Table 1).

The GOSAT results appear to contradict global carbon cycle studies that favor a weaker terrestrial net source in the tropics compensated by a weaker northern extratropical sink (e.g. Stephens et al., 2007; Schimel et al., 2015). However, the shift may be due at least in part to GOSAT retrieval and sampling biases. An evaluation of posterior mole fractions in the GOSAT-only inversion against surface in situ observations indicates that the GOSAT inversion may be biased low during much of the analysis period over Europe and Temperate N. America, especially in winter (when there is little direct constraint at high latitudes by GOSAT observations), and biased somewhat high over N. Africa, especially in spring. However, the dearth of in situ sites over N. Africa, with only one in the middle of the region (Assekrem, Algeria) and a few around the edges (e.g. Izaña, Canary Islands and Mt. Kenya, Kenya), precludes a definitive evaluation over that region. Globally, the GOSAT inversion tends to underestimate mole fractions at high latitudes of the Northern Hemisphere, often by more than 1σ, as shown by latitudinal profiles averaged over all surface sites by season (Fig. 9), suggesting an overestimated northern sink. The same is true of the high latitudes of the Southern Hemisphere. The GOSAT inversion overestimates mole fractions in parts of the tropics, sometimes by more than 1σ (Fig. 9), suggesting an overestimated tropical source. Uncorrected retrieval biases may be especially prevalent in the tropics, where there are very few TCCON stations available as input to the GOSAT bias correction formulas; only 1 TCCON station, Darwin, Australia, was operating in the tropics during 2009-2010, and only 2 more stations, Reunion Island and Ascension Island, became operational during the rest of the ACOS B3.4

retrieval period. In contrast, the posterior mole fractions for the in situ-only inversion generally agree well with the surface observations (Fig. 9; also seen in the individual site time series in Fig. 2), which is expected given that these are the observations that are used in the optimization. The prior mole fractions are generally too high, which is consistent with the fact that the CASA-GFED biosphere is near neutral while the actual terrestrial biosphere is thought to generally be a net CO_2 sink.

Evaluation of the inversions against latitudinal profiles constructed from HIPPO aircraft measurements, which provide additional sampling over the Pacific, indicates an overestimate by the GOSAT inversion relative to HIPPO in parts of the tropics at lower altitudes (Fig. 10a, d), similar to what was seen in the comparison with surface observations. And the GOSAT inversion exhibits an underestimate relative to HIPPO in the southern extratropics in the lower to middle levels of the troposphere (Fig. 10a, b, d, e), especially for Mission 2 (Oct-Nov 2009). Again, the lack of GOSAT ocean observations at southern high latitudes points to sampling bias as the cause of the underestimate. In the northern extratropics, the comparison of the inversions with HIPPO has different features from the comparison with surface data: the GOSAT inversion generally exhibits higher mean mixing ratios than HIPPO in the lower troposphere, especially for Mission 2, and the in situ inversion gives higher mixing ratios at some latitudes in the northern extratropics and lower mixing ratios at others for Mission 2. In one particular latitude range, 55-67°N, both inversions give much higher mixing ratios than HIPPO, by up to 67 ppm in the case of the in situ inversion and 30 ppm for the GOSAT inversion. This could reflect inaccuracy in posterior fluxes due to the inversions' being under-constrained over the high-latitude North Pacific and Alaska, with few observations during this season in the case of GOSAT and a tendency for the sparse in situ network to produce noisy inversion results, as was discussed above. However, given that the prior model also gives substantially higher mixing ratios than HIPPO at these latitudes (by up to 11 ppm), the discrepancy could be due in part to transport error.

In the upper troposphere to lower stratosphere, the GOSAT inversion more often than not exhibits better agreement with the HIPPO observations than the in situ inversion does for both Mission 2 and 3 (Fig. 10c, f). A likely explanation is that the GOSAT data provide constraints throughout the atmospheric column, whereas the in situ measurements constrain only surface CO_2. Figure 10 shows that the high-altitude mole fractions from the in situ inversion are consistently close to those of the prior, suggesting that the lack of high-altitude constraints prevents major adjustments in mole fractions at these levels, unlike in the GOSAT inversion. Although GOSAT biases may affect these altitudes as well, it appears to be the case that the data still provide better constraints than no observations above the surface at all. Furthermore, an air parcel at higher altitudes, especially in the upper troposphere or above, generally consists of a mixture of air originating from a broad area near the surface (e.g. Orbe et al., 2013), and thus the effects of different regional biases in posterior fluxes may cancel out at those altitudes.

The conclusion that GOSAT biases may contribute to the shift in the land sink is also supported by Houweling et al. (2015). That study reported a shift in the GOSAT-only inversions relative to the in situ inversions consisting of an increase in the sink in northern extratropical land of 1.0 Pg C y^{-1} averaged across models and an increase in the source in tropical land of 1.2 Pg C y^{-1} during June 2009-May 2010; in comparison, our inversions produce an increase in the northern land sink of 0.4 Pg C y^{-1} and an increase in the tropical land source of 1.2 Pg C y^{-1} (Fig. 8). Houweling et al. (2015) found an especially large and systematic shift in flux of ~0.8 Pg C y^{-1} between N. Africa and Europe, but then provided evidence that the associated latitudinal

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

gradient in CO_2 mole fractions may be inconsistent with that based on surface and HIPPO aircraft in situ observations. They also suggested that the shift in annual flux between the two regions may be a consequence of sampling bias, with a lack of GOSAT observations at high latitudes during winter. Chevallier et al. (2014) also found a large source in N. Africa of ~1 Pg C y^{-1} in their ensemble of GOSAT inversions and considered the magnitude of that unrealistic, given that emissions from fires in that region likely amount to < 0.7 Pg C y^{-1}. (Note that our N. Africa source is even larger than that of Chevallier et al. (2014).) An observing system simulation experiment by Liu et al. (2014) found that GOSAT seasonal and diurnal sampling biases alone could result in an overestimated annual sink in northern high-latitude land regions.

Again, the results for the in situ + GOSAT inversion lie mostly in between those for the in situ-only and GOSAT-only inversions, with the in situ + GOSAT fluxes lying closer to the GOSAT-only ones for the tropical/southern land regions and land as a whole (Table 1 and Fig. 8), suggesting the dominance of the GOSAT constraint in these regions. The posterior uncertainties for the GOSAT inversion (Table 1) are as small as or smaller than those for the in situ inversion, except in Boreal and Temperate N. America, N. Pacific, Northern Ocean, and Southern Ocean. This reflects the fact that GOSAT generally provides better spatial coverage, except over N. America, where the in situ network provides good coverage, and over and near high-latitude ocean areas, where there is decent in situ coverage and poor GOSAT coverage. Uncertainty reductions in the in situ inversion range from 15% to 93% for land regions and 15% to 56% for ocean regions (Table 1). In the GOSAT inversion, the uncertainty reductions range from 43% to 89% for land and 19% to 56% for ocean. And in the inversion with combined in situ and GOSAT data, the uncertainty reductions are larger than or equal to those in either the in situ-only or the GOSAT-only inversion, ranging from 61% to 96% for land and 40% to 67% for ocean.

3.3. Flux error correlations and land-ocean partitioning

Here we elaborate on the subject of posterior error correlations, which indicate the degree to which fluxes are estimated independently of one another. Negative correlations can be manifested in dipole behavior, in which unusually large flux adjustments of opposite signs occur in neighboring regions/time intervals. These are shown in Fig. 11 aggregated to TC3 regions and the 12-month period from June 2009 to May 2010. The full-rank error covariance matrix generated by the exact Bayesian inversion method (from which the correlation coefficients are derived) is a unique product of this study, particularly as applied to satellite data. There are a larger number of sizable correlations between land regions in the in situ inversion than in the GOSAT inversion (in the top left quadrants of the plots). One specific feature is negative correlations among the four TC3 regions in South America and Africa in the in situ inversion, whereas in the GOSAT inversion there are negative correlations within South America and within Africa but not between the two continents. In contrast, the GOSAT inversion exhibits larger anti-correlations over the ocean regions. For example, there are substantial negative correlations between Southern Ocean and each of the other southern regions—S. Pacific, S. Atlantic, and S. Indian. This is consistent with the almost complete lack of GOSAT observations at the latitudes of the Southern Ocean region and the southern edges of the neighboring ocean regions (Fig. 1b). Interestingly, there is not a sizable correlation between N. Africa and Europe in the GOSAT inversion (in either seasonal or 12-month means), which runs counter to what might be expected from the shift in flux discussed above; rather, each of these regions is correlated with a number of other regions. We do find a fairly large correlation of -0.62 between the northern extratropics in aggregate (land + ocean) and the tropics for the 12-month period though. Correlations for the in situ + GOSAT inversion (not shown) generally lie in between those of the in situ-only and GOSAT-only inversions. Even with the incorporation of both sets of observations, there are substantial correlations of as much as -0.6 between regions within a continent, reinforcing our earlier conclusion that sampling gaps limit the ability of the observations to constrain fluxes down to the scale of most TC3 regions.

The in situ-only and CT2013B posterior global totals are nearly the same, but the land-ocean split is different, with our inversion exhibiting a larger sink over ocean than over land (with non-overlapping 2σ ranges) while in CT2013B the land and ocean fluxes are similar, with the ocean flux changing little from the prior (Fig. 8). A likely explanation for the difference is the very tight prior constraints on ocean fluxes of CT2013B that were discussed above, which force the flux adjustments to take place mostly on land. The GOSAT inversion also exhibits a relatively large ocean sink of -3.1 ± 0.5 Pg C y^{-1}; for comparison, the CT2013B estimate is -2.4 ± 0.4 Pg C y^{-1}, our in situ-only estimate is -4.0 ± 0.8 Pg C y^{-1}, and the estimate of the Global Carbon Project (GCP) is -2.5 ± 0.5 Pg C y^{-1} for 2009-2010 (Le Quéré et al., 2013; Le Quéré et al., 2015). The GCP estimate is a synthesis that combines indirect observation-based estimates for the mean over the 1990s with interannual variability from a set of ocean models and accounts for additional observation-based estimates in the uncertainty. The difference between our inversion estimates and the GCP estimate is actually even larger than suggested by those numbers, given that a background river to ocean flux of ~0.5 Pg C y^{-1} should be subtracted from our ocean flux to make it comparable to the GCP ocean sink, which refers to net uptake of *anthropogenic* CO_2 (Le Quéré et al., 2015). Similarly, in comparing our results with those of

Houweling et al. (2015), we find that the global budgets are comparable for all three inversions—in situ-only, GOSAT-only, and in situ + GOSAT—as was mentioned above, but the land-ocean split is different. Our posterior ocean flux is -4.0 ± 0.8 Pg C y^{-1}, -3.1 ± 0.5 Pg C y^{-1}, and -3.9 ± 0.3 Pg C y^{-1} for the three inversions, while it is -1.6 ± 0.5 Pg C y^{-1}, -1.2 ± 0.6 Pg C y^{-1}, and -1.5 ± 0.8 Pg C y^{-1} in the results of Houweling et al. (2015; pers. comm., 2016) (averaged over different weighted averages of the models).

There is a strong negative correlation globally between posterior flux errors for land and ocean of -0.84 and -0.89 in the in situ-only and the GOSAT-only inversion, respectively. Basu et al. (2013) also reported a large negative correlation between land and ocean fluxes of -0.97 in their in situ + GOSAT inversion during September 2009-August 2010. The anti-correlations imply that the observations cannot adequately distinguish between adjustments in the global land and ocean sinks. Thus, land-ocean error correlation may be a fundamental challenge that global CO_2 flux inversions are faced with, at least given the sampling characteristics of the in situ and GOSAT data sets used here. Without tight prior constraints on ocean fluxes, those fluxes are subject to large, and potentially unrealistic, adjustments (i.e. dipole behavior).

To assess the effect of prior constraints on the inversion, we conducted a test with reduced prior uncertainties, for both land and ocean fluxes, so that they are similar on average to those of CT. Results for an in situ-only inversion and a GOSAT-only inversion are shown in Table 1 and Fig. 12. For the in situ-only inversion, the posterior ocean flux is now much smaller in magnitude, -2.8 ± 0.3 Pg C y^{-1}. The posterior ocean flux for the GOSAT inversion does not change as much, decreasing in magnitude from the original -3.1 ± 0.5 Pg C y^{-1} to -2.9 ± 0.2 Pg C y^{-1}. The ocean flux 1σ ranges for both inversions now overlap with that of CT; accounting for the riverine flux, the 1σ range for the in situ inversion overlaps with that of GCP, while the 1σ

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

range for the GOSAT inversion is still just outside of that of GCP. The inversions with tighter priors generally exhibit better agreement with independent observations, e.g. lower-altitude HIPPO observations (Fig. 13), and surface observations in the case of the GOSAT inversion (Fig. 14), indicating that the effects of sampling and retrieval biases are reduced with tighter prior uncertainties. The better agreement also lends support to the smaller ocean sink estimates. (At high altitudes, keeping posterior mole fractions closer to the prior mole fractions results in worse agreement with HIPPO in many places, especially for the GOSAT inversion.) However, the tighter priors do not completely eliminate the discrepancies between the inversions and the independent observations, suggesting that tight priors may not completely counteract the effects of observational biases.

Basu et al. (2013) saw a similar underestimate of mole fractions during parts of the year in the southern extratropics in their GOSAT inversion relative to surface observations and overestimate of the seasonal cycle, though with some differences in the shape of the seasonal cycle from our study (including a later descent toward and recovery from the annual minimum in austral summer and a larger peak in late winter-early spring). They, however, used the SRON-KIT RemoTeC GOSAT retrieval with a known issue over the ocean, and concluded that adding global land and ocean observation bias correction terms to their inversion was needed to make the land-ocean flux split more realistic and to improve the seasonal cycle of CO_2 in the southern extratropics. In contrast, studies have found no noticeable bias in the ACOS B3.5 ocean glint XCO_2 retrievals relative to TCCON (Kulawik et al., 2016) and a mean bias of only -0.06 ppm relative to HIPPO (Frankenberg et al., 2016); the B3.4 version we use is on average ~0.2 ppm lower than B3.5 in 2010 (Deng et al., 2016). So although a small overall negative bias in the bias-corrected ACOS B3.4 ocean data cannot be ruled out, we conclude that the land-ocean flux split in inversions using either in situ or GOSAT data is strongly influenced by error correlations and dependent on the prior uncertainties assumed.

The shift in the global terrestrial sink from the tropics/south to the north when comparing the GOSAT-only inversion with the in situ-only inversion and the prior is still seen when prior uncertainties are decreased, as is a substantially larger global total budget in the GOSAT inversion relative to the in situ (Fig. 12). The uncertainty reductions in the test inversions are smaller than those in the baseline inversions (Table 1), as is expected from the smaller starting values of the uncertainties. In summary, the magnitude of the ocean sink and the partitioning of the global sink between land and ocean are sensitive to the prior uncertainties, but other inferred features of the carbon budget are robust with respect to prior uncertainties.

Given that there is uncertainty in the land-ocean flux partitioning at sub-global scales as well (e.g. as indicated by moderate negative correlations between northern land and northern oceans, tropical land and tropical oceans, etc.), we consider results for combined land and ocean regions in Figs. 8 and 12. They indicate that there is a shift in the global sink from the tropics to the north and the south in the GOSAT inversion relative to the prior, and an increased source in the tropics of ~2 Pg C y^{-1} in the GOSAT inversion relative to the in situ inversion. These features are seen in the inversions with tighter priors as well as in the baseline inversions. Note that the increased source over southern land and increased sink over southern ocean in the GOSAT inversion relative to the in situ inversion that were discussed earlier cancel each other out approximately, suggesting a compensation of errors.

3.4. Impacts of climatic conditions on 2009-2010 fluxes

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

We now analyze the impacts of several climatic events during the analysis period on CO_2 fluxes as indicated by the inversion results. We focus on 1) unusually hot and dry conditions at Northern Hemisphere higher latitudes in summer of 2010, 2) wetter conditions over parts of North America in spring and early summer of 2010 relative to 2009, and 3) record drought in the Amazon in 2010.

Guerlet et al. (2013), who examined GOSAT data and performed a flux inversion using a variational assimilation system, found that there was less net terrestrial CO_2 uptake in summer of 2010 than in 2009 at northern high latitudes, consistent with known severe heat waves, drought, and high fire emissions, especially across Eurasia, centered around western Russia, and to a lesser extent in North America.

Motivated by that study, we examined our inversion results for 2009 and 2010, focusing on the GOSAT inversion. As can be seen in the global maps of natural plus biomass burning fluxes in June-July-August (JJA) in Fig. 15, the GOSAT inversion does appear to exhibit a decreased CO_2 uptake over Eurasia, including the area around western Russia (enclosed in a box in the figure), in 2010. A decreased sink can also be seen in parts of North America. A decreased sink over western Russia can also be seen in the CASA-GFED prior, though of a smaller magnitude. In contrast, there is actually an increased sink in that region in the in situ inversion. In fact, none of the sites used are in or immediately downwind of that region (Fig. 1a). Total NEP and fire fluxes over northern TC3 regions are shown in Fig. 16. There is less CO_2 uptake in JJA 2010 than in 2009 in all the regions except Temperate Asia in the GOSAT-only inversion. The differences exceed the 1σ ranges for 3 of the 5 regions, even exceeding the 3σ ranges for Europe, which includes western Russia. Also shown is the in situ + GOSAT inversion, which exhibits a similar pattern of 2010-2009 differences. These inversion results are thus consistent with the earlier GOSAT study. In contrast, the 2010-2009 differences in the prior are small and, for some regions, of the opposite sign as that in the inversions (Fig. 16).

Measurements from the JR-STATION tower network are suitably located for evaluating the inferred flux interannual variability over Eurasia. Time series are shown in Fig. 17 for observations, the prior model, and the GOSAT-only inversion at 6 sites with complete summertime data in 2009-2010. (As with the continuous measurements used in the in situ inversion, afternoon data are selected to avoid difficulties associated with nighttime boundary layers.) Posterior mole fractions are noisier in the wintertime, likely a result of the lack of GOSAT observations during that season at these high latitudes. Focusing on 2010-2009 differences, the observations suggest a shallower drawdown in 2010 than in 2009 at most of the sites, which is generally captured by both the prior and the GOSAT posterior. It appears though that the GOSAT inversion exaggerates the 2010-2009 difference at some of the sites, overestimating especially the drawdown in 2009. For a more quantitative analysis, we calculate the average 2010-2009 difference in mole fractions over June-July-August for each site (Table 3). The GOSAT-only inversion overestimates the 2010-2009 difference at 5 of the 6 sites. The in situ + GOSAT inversion exhibits less of an overestimate overall than the GOSAT-only inversion, with 3 of the 6 sites being substantially overestimated. The prior exhibits the best agreement with the observations overall.

The earlier study by Guerlet et al. (2013) assumed that the differences between 2010 and 2009 posterior biospheric fluxes are relatively insensitive to biases in the GOSAT data, since at least some of those errors may be similar between the two years. However, our evaluation of the inversions using JR-STATION data suggests that retrieval biases can vary significantly from year to year. Kulawik et al. (2016) estimated a year-to-year variability in GOSAT biases relative to TCCON of 0.3 ppm averaged over the stations. Another study has raised a separate but related issue of inversion results potentially being sensitive to the spatiotemporal distribution of observations in different data sets (e.g. different GOSAT retrievals) (H. Takagi, pers. comm., 2015); by extension, comparison of fluxes from two time periods can be affected by changes in the distribution of observations over time within a particular data set. But in JJA 2009 and 2010, there are similar numbers of ACOS GOSAT observations overall in the northern land region, so differences in data coverage are probably not a factor in this particular case study.

Our evaluation using JR-STATION data also indicates that the prior may be a reasonable estimate of the 2010-2009 difference in growing season fluxes, at least over Siberia, despite possible shortcomings in the simulation of drought impacts on NEP and of the overall magnitude of fire emissions by CASA-GFED3. The latest version of GFED (version 4s), which includes small fires, tends to generate higher emissions than GFED3 (van der Werf et al., 2017).

Over large parts of North America, conditions were wetter in spring and early summer of 2010 than in 2009, especially in the western half of the U.S. and adjacent parts of Mexico and Canada, as suggested by North American drought maps for June 2010 vs. June 2009 (e.g. https://www.drought.gov/nadm/content/map/2010/06) and shallow groundwater status maps for the U.S. based on GRACE (Gravity Recovery and Climate Experiment) satellite data for May-June (Houborg et al., 2012; http://droughtcenter.unl.edu/NASA/GRACE/). Consistent with the wetter conditions in 2010 are a larger CO_2 sink over North America (Boreal + Temperate) in May-June 2010 relative to 2009 in our priors (-5.0 ± 3.9 Pg C y^{-1} vs. -3.4 ± 3.9 Pg C y^{-1}), in situ-only posteriors (-5.0 ± 0.4 Pg C y^{-1} vs. -3.8 ± 0.5 Pg C y^{-1}), and GOSAT-only posteriors (-5.8 ± 0.4 Pg C y^{-1} vs. -3.3 ± 1.8 Pg C y^{-1}). We consider the in situ inversion result to be reliable here, given the large uncertainty reduction for North America and small error correlations with other regions (not shown). The 2010 and 2009 fluxes differ such that their 1σ ranges do not overlap for the in situ and the GOSAT posteriors. Despite the increased sink in June 2010 over North America, the 2010 summer exhibits a decreased sink relative to 2009 when integrated through JJA (Fig. 16).

The Amazon basin experienced a record drought in 2010, which led to decreased vegetation greenness and a net carbon loss to the atmosphere (Xu et al., 2011; Gatti et al., 2014). Dry conditions in the north and center of the basin in the first three months were caused by the El Niño of late 2009-early 2010, and an enhanced and prolonged dry season in the southern areas of the basin was connected to an Atlantic sea surface temperature anomaly during the second half of the year (Gatti et al., 2014). According to our prior estimate, fire emissions minus NEP represented a near-zero net flux of -0.1 ± 2.1 Pg C y^{-1} in Jul-Sep 2010 (a period that includes peak drought conditions and fire counts of that year) and a sink of -1.9 ± 2.1 Pg C y^{-1} in Jul-Sep 2009 in the TC3 Tropical America region. (The fire emissions amounted to 2.0 Pg C y^{-1} and 0.2 Pg C y^{-1} in Jul-Sep 2010 and 2009, respectively, while NEP was 2.1 Pg C y^{-1} in both periods.) However, our GOSAT inversion suggests the reverse, -0.9 ± 0.6 Pg C y^{-1} vs. -0.4 ± 0.3 Pg C y^{-1} for Jul-Sep 2010 and 2009, respectively. (We do not report the analogous results for the in situ inversion, since the uncertainties are large in this undersampled region.) The prior estimate seems more consistent with the expected impact of drought on fluxes than the inversion estimate does. The inversion is hampered in the region by the relatively small number of GOSAT soundings that are retrieved and pass the quality filters, especially during the burning season (with substantial light scattering by aerosols) and the rainy season (with extensive cloud cover). The dearth of observations results in relatively large posterior uncertainties and/or sizable flux error correlations. Furthermore, there is differing data coverage, with 2010 having fewer observations than 2009 in the TC3 Tropical America region during the height of the fire season (85 and 20 in Aug and Sep 2010 vs. 101 and 33 in 2009) and more observations than 2009 in July (150 vs. 85). The differing data coverage itself could affect the flux estimates differently in 2009 and 2010. The Amazonica data set does not enable an evaluation of the flux estimates for both 2009 and 2010, since the data set begins in 2010. However, comparison of the prior and GOSAT model mole fractions in 2010 with the Amazonica data shows that biases for both can vary substantially over time, e.g. in July vs. Aug-Sep (Fig. S1). This raises the possibility that neither the prior nor the GOSAT inversion correctly estimates the interannual flux difference in this region and also supports the idea that inversion bias can vary with data coverage.

4. Discussion and conclusions

We have presented global, high-resolution, batch Bayesian CO_2 inversions using GOSAT and in situ observations and compared them with flux estimates using Kalman filter and variational approaches that involve various approximations. The exact inversion method provides full posterior error covariances, which allows us to quantitatively evaluate the degree to which regional fluxes are constrained independently of one another.

The GOSAT inversion is generally better constrained than the in situ inversion, with smaller posterior regional flux uncertainties and correlations, except in places like North America and high-latitude ocean where the in situ observation networks used provide relatively good coverage. Note that our in situ inversion did not make use of all the surface monitoring sites that operated during the analysis period, omitting for example a number of sites operated exclusively by agencies in Canada, Australia, and Europe

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

(http://ds.data.jma.go.jp/gmd/wdcgg/cgi-bin/wdcgg/catalogue.cgi), and that the surface networks have been enhanced with additional sites since then. Furthermore, the in situ data sets that we used for evaluation of the inversions, including JR-STATION and Amazonica, could also be used as input in the inversions. And yet other aircraft data sets and column measurements such as from TCCON could be added. The use of GOSAT data in combination with in situ data provides even greater flux uncertainty reductions than the use of either data set alone, indicative of complementary constraints in the two datasets. Nevertheless, gaps in GOSAT sampling, including a lack of observations at high latitudes during winter over land and year-round over the ocean, and spatially, seasonally, and interannually varying coverage over tropical land, limit the ability to accurately resolve fluxes down to the scale of TransCom sub-continental regions.

Our GOSAT inversion suggests a shift in the global terrestrial CO_2 sink from the tropics and south to the north, relative to the prior and the in situ inversion; for combined land and ocean fluxes, the GOSAT inversion produces a shift in the global sink from the tropics to the north and the south relative to the prior, and an increased source in the tropics of ~2 Pg C y^{-1} relative to the in situ inversion. Similar shifts are seen in studies using other inversion approaches, such as the inversion intercomparison of Houweling et al. (2015). This result may be driven at least in part by sampling and uncorrected retrieval biases in the ACOS GOSAT data set, as suggested by sizable discrepancies between posterior mole fractions in the GOSAT-only inversion and surface in situ and lower-tropospheric HIPPO aircraft observations. While the shift in the global sink appears to be a robust feature of the inversions, the partitioning of the sink between land and ocean in the inversions using either in situ or GOSAT data is found to be sensitive to prior uncertainties because of negative correlations in the flux errors for the two domains. The loose prior uncertainties assumed in our baseline inversions may explain the larger ocean sink estimates compared to other studies, including CT2013B and the Houweling et al. (2015) intercomparison. A rationale for specifying loose prior uncertainties is that this allows the results to be driven more by the observations than by the prior estimates. However, in light of increasing confidence in estimates of the global ocean sink (e.g. from GCP), it may be more appropriate to start with a reliable set of ocean fluxes and apply tighter prior uncertainties similar to those from our sensitivity test. In any case, more weight should be given to combined land and ocean fluxes across latitudinal bands than to separate land and ocean flux estimates for the current observational configurations. Gaps in coverage at higher latitudes, especially in winter, as well as limited sampling over tropical land are a fundamental limitation of passive satellite measurements (including OCO-2) and imply an important future role for active satellites such as NASA's proposed Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission (Kawa et al., 2010; ASCENDS Ad Hoc Science Definition Team, 2015). Additional in situ and TCCON measurements in the tropics, especially in Africa, would also be valuable for validating satellite retrievals and flux inversions using satellite data.

The GOSAT inversion indicates significantly less CO_2 uptake in summer of 2010 than in 2009 in the north, consistent with a previous GOSAT analysis and likely reflecting severe heat waves and drought especially across Eurasia. However, observations from the JR-STATION in situ network suggest that the GOSAT inversion (and to a lesser extent, the in situ + GOSAT inversion) exaggerates the 2010-2009 difference in uptake in Siberia, while the CASA-GFED prior reasonably estimates that quantity. Thus, it may not be accurate to assume that year-to-year posterior flux differences are insensitive to satellite retrieval biases, as was done in the other study. The prior, in situ posterior, and GOSAT posterior all indicate greater CO_2 uptake over North America in spring to early summer of 2010 than in 2009, consistent with wetter conditions over large parts of the continent. Decreased net uptake in July-September of 2010 relative to 2009 in our prior appears to be consistent with record drought in the Amazon in 2010, while the GOSAT inversion shows the reverse. However, time-varying biases in both the prior model and the GOSAT inversion relative to Amazon aircraft profiles raise the possibility that neither one correctly estimates the interannual flux difference in this region and also support the idea that inversion bias can vary with data coverage. Overall, the results do demonstrate that climatic conditions can drive significant year-to-year variability in natural carbon fluxes on regional scales.

This study has successfully applied the batch inversion method to satellite data at relatively high resolution to generate a solution useful for comparison with other techniques. However, for inversions over longer periods, using larger volumes of data such as from OCO-2, or at higher flux resolution, more computationally efficient methods are essential.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgments

This work has been supported by the NASA Atmospheric CO_2 Observations from Space program element and the NASA Carbon Monitoring System Program. The NASA Goddard High-End Computing Program has provided access to and assistance with supercomputing resources at the NASA Center for Climate Simulation. The ACOS GOSAT data were produced by the ACOS/OCO-2 project at the Jet Propulsion Laboratory, California Institute of Technology

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

using spectra acquired by the GOSAT Project. We thank Chris O'Dell for providing the ACOS data to us, John Miller and Manuel Gloor for their partnership in producing the Amazonica data (with support from NERC, FAPESP, ERC, NASA, CNPQ, NOAA, IPEN, and U. of Leeds for the Amazon Greenhouse measurement program led by L. Gatti), NOAA ESRL GMD CCGG for making their flask and continuous tower data publicly available, JMA (including Yukio Fukuyama and Atsushi Takizawa) for making their in situ data publicly available on the WDCGG website and providing assistance, and Steven Wofsy for making HIPPO data available. CT2013B results are provided by NOAA ESRL, Boulder, Colorado, USA from the website at http://carbontracker.noaa.gov. Many thanks go to Martha Butler for providing inversion code and documentation. We also thank Zhengxin Zhu for contributing to data processing, Liang Feng and Paul Palmer for their inversion region map, David Baker for advice on inversions, Sander Houweling for providing results from his intercomparison paper and for helpful discussion, Lesley Ott for help with using ACOS data files and for discussions, Chris O'Dell, Ed Dlugokencky, and especially Arlyn Andrews for comments on the manuscript, and Sourish Basu and Brad Weir for discussions.

References

Andres, R. J., Boden, T. A., and Marland, G.: Monthly Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A., doi:10.3334/CDIAC/ffe.MonthlyMass.2012, 2012.

Andrews, A. E., Kofler, J., Bakwin, P. S., Zhao, C., and Tans, P.: Carbon Dioxide and Carbon Monoxide Dry Air Mole Fractions from the NOAA ESRL Tall Tower Network, 1992-2009, Version: 2011-08-31, Path: ftp://ftp.cmdl.noaa.gov/ccg/towers/, 2009.

ASCENDS Ad Hoc Science Definition Team: Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission Science Mission Definition Study (draft), https://cce.nasa.gov/ascends_2015/ASCENDS_FinalDraft_4_27_15.pdf, 2015.

Baker, D. F., Law, R. M., Gurney, K. R., Rayner, P., Peylin, P. and co-authors: TransCom 3 inversion intercomparison: Impact of transport model errors on the interannual variability of regional CO_2 fluxes, 1988–2003, Global Biogeochem. Cycles, 20, GB1002, doi:10.1029/2004GB002439, 2006.

Baldocchi, D., et al.: FLUXNET: A new tool to study the temporal and spatial variability of ecosystem–scale carbon dioxide, water vapor, and energy flux densities, Bull. Am. Meteorol. Soc., 82, 2415–2434, 2001.

Basu, S., Guerlet, S., Butz, A., Houweling, S., Hasekamp, O., Aben, I., Krummel, P., Steele, P., Langenfelds, R., Torn, M., Biraud, S., Stephens, B., Andrews, A., and Worthy, D.: Global CO_2 fluxes estimated from GOSAT retrievals of total column CO_2, Atmos. Chem. Phys., 13, 8695–8717, doi:10.5194/acp-13-8695-2013, 2013.

Butler, M. P., Davis, K. J., Denning, A. S., and Kawa, S. R.: Using continental observations in global atmospheric inversions of CO_2: North American carbon sources and sinks, Tellus, 62B, 550–572, doi:10.1111/j.1600-0889.2010.00501.x, 2010.

Chatterjee, A. and Michalak, A. M.: Technical Note: Comparison of ensemble Kalman filter and variational approaches for CO_2 data assimilation, Atmos. Chem. Phys., 13, 11643–11660, doi:10.5194/acp-13-11643-2013, 2013.

Chevallier, F., et al.: What eddy-covariance measurements tell us about prior land flux errors in CO_2-flux inversion schemes, Global Biogeochem. Cycles, 26, GB1021, doi:10.1029/2010GB003974, 2012.

Chevallier, F., Palmer, P. I., Feng, L., Boesch, H., O'Dell, C. W., and Bousquet, P.: Toward robust and consistent regional CO_2 flux estimates from in situ and spaceborne measurements of atmospheric CO_2, Geophys. Res. Lett., 41, 1065–1070, doi:10.1002/2013GL058772, 2013.

Ciais, P., Rayner, P., Chevallier, F., Bousquet, P., Logan, M., Peylin, P., and Ramonet, M.: Atmospheric inversions for estimating CO_2 fluxes: methods and perspectives, Climatic Change, 103:69–92, DOI 10.1007/s10584-010-9909-3, 2010.

Connor, B. J., Bösch, H., Toon, G., Sen, B., Miller, C., and Crisp, D.: Orbiting Carbon Observatory: Inverse method and prospective error analysis, J. Geophys. Res., 113, A05305, doi:10.1029/2006JD008336, 2008.

Crisp, D.: Measuring atmospheric carbon dioxide from space with the Orbiting Carbon Observatory-2 (OCO-2), Proc. SPIE 9607, Earth Observing Systems XX, 960702, doi:10.1117/12.2187291, 2015.

Deng, F., Jones, D. B. A., Henze, D. K., Bousserez, N., Bowman, K. W., Fisher, J. B., Nassar, R., O'Dell, C., Wunch, D., Wennberg, P. O., Kort, E. A., Wofsy, S. C., Blumenstock, T., Deutscher, N. M., Griffith, D. W. T., Hase, F., Heikkinen, P., Sherlock, V., Strong, K., Sussmann, R., and Warneke, T.: Inferring regional sources and sinks of atmospheric CO_2 from GOSAT XCO_2 data, Atmos. Chem. Phys., 14, 3703–3727, doi:10.5194/acp-14-3703-2014, 2014.

Deng, F., Jones, D. B. A., O'Dell, C. W., Nassar, R., and Parazoo, N. C.: Combining GOSAT XCO_2 observations over land and ocean to improve regional CO_2 flux estimates, J. Geophys. Res. Atmos., 121, 1896–1913, doi:10.1002/2015JD024157, 2016.

Dlugokencky, E. J., Lang, P. M., Masarie, K. A., Crotwell, A. M., and Crotwell, M. J.: Atmospheric Carbon Dioxide Dry Air Mole Fractions from the NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network, 1968-2012, Version: 2013-08-28, available at: ftp://aftp.cmdl.noaa.gov/data/trace_gases/co2/flask/surface/ (last access: 18 February 2014), 2013.

Engelen, R. J., Denning, A. S., and Gurney, K. R.: On error estimation in atmospheric CO_2 inversions, J. Geophys. Res., 107, 4635, doi:10.1029/2002JD002195, 2002.

Enting, I. G. and Mansbridge, J. V.: Seasonal sources and sinks of atmospheric CO_2: Direct inversion of filtered data, Tellus, 41B, 111-126, 1989.

Enting, I. G., Trudinger, C. M., and Francey, R. J.: A synthesis inversion of the concentration and $\delta^{13}C$ of atmospheric CO_2, Tellus, 47B, 35–52, 1995.

Feng, L., Palmer, P. I., Boesch, H., and Dance, S.: Estimating surface CO_2 fluxes from space-borne CO_2 dry air mole fraction observations using an ensemble Kalman Filter, Atmos. Chem. Phys., 9, 2619–2633, doi:10.5194/acp-9-2619-2009, 2009.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

Atmospheric Chemistry and Physics Discussions
Open Access

Frankenberg, C., Kulawik, S. S., Wofsy, S., Chevallier, F., Daube, B., Kort, E. A., O'Dell, C., Olsen, E. T., and Osterman, G.: Using airborne HIAPER Pole-to-Pole Observations (HIPPO) to evaluate model and remote sensing estimates of atmospheric carbon dioxide, Atmos. Chem. Phys., 16, doi:10.5194/acp-2015-961, 2016.

Gatti, L. V., Gloor, M., Miller, J. B., Doughty, C. E., Malhi, Y., Domingues, L. G., Basso, L. S., Martinewski, A., Correia, C. S. C., Borges, V. F., Freitas, S., Braz, R., Anderson, L. O., Rocha, H., Grace, J., Phillips, O., and Lloyd, J.: Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements, Nature, 506, 76-80, doi:10.1038/nature12957, 2014.

Gatti , L., Gloor, E., and Miller, J.: Greenhouse gas profile measurements (CO, CO_2, CH_4) above the forest canopy at four sites for the Amazonica project. NCAS British Atmospheric Data Centre, accessed 5 Dec 2016. http://catalogue.ceda.ac.uk/uuid/7201536a8b7a1a96de584e9b746acee3, 2016.

Giglio, L., Csiszar, I., and Justice, C. O.: Global distribution and seasonality of active fires as observed with the Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) sensors, J. Geophys. Res., 111, G02016, doi:10.1029/2005JG000142, 2006.

Giglio, L., Randerson, J. T., van der Werf, G. R., Kasibhatla, P. S., Collatz, G. J., Morton, D. C., and DeFries, R. S.: Assessing variability and long-term trends in burned area by merging multiple satellite fire products, Biogeosciences, 7, 1171–1186, doi:10.5194/bg-7-1171-2010, 2010.

GLOBALVIEW-CO_2: Cooperative Atmospheric Data Integration Project-Carbon Dioxide, CD-ROM, NOAA-ESRL, Boulder, Colo. [Also available on Internet via anonymous FTP to ftp.cmdl.noaa.gov,Path:ccg/co2/ GLOBALVIEW], 2009.

Gourdji, S. M., Mueller, K. L., Yadav, V., Huntzinger, D. N., Andrews, A. E., Trudeau, M., Petron, G., Nehrkorn, T., Eluszkiewicz, J., Henderson, J., Wen, D., Lin, J., Fischer, M., Sweeney, C., and Michalak, A. M.: North American CO_2 exchange: intercomparison of modeled estimates with results from a fine-scale atmospheric inversion, Biogeosciences, 9, 457–475, 2012.

Guerlet, S., Basu, S., Butz, A., Krol, M., Hahne, P., Houweling, S., Hasekamp, O. P., and Aben, I.: Reduced carbon uptake during the 2010 Northern Hemisphere summer from GOSAT, Geophys. Res. Lett., 40, 2378–2383, doi:10.1002/grl.50402, 2013.

Gurney, K., Law, R., Rayner, P., and Denning, A. S.: TransCom 3 Experimental Protocol, Department of Atmospheric Science, Colorado State University, USA, Paper 707 (Available at http://transcom.colostate.edu/TransCom_3/transcom_3.html), 2000.

Gurney, K. R., et al.: Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models, Nature, 415, 626–630, 2002.

Gurney, K. R., Chen, Y.-H., Maki, T., Kawa, S. R., Andrews, A., and Zhu, Z.: Sensitivity of atmospheric CO_2 inversions to seasonal and interannual variations in fossil fuel emissions, J. Geophys. Res., 110, D10308, doi:10.1029/2004JD005373, 2005.

Hayes, D. J., Turner, D. P., Stinson, G., McGuire, A. D., Wei, Y., West, T. O., Heath, L. S., deJong, B., McConkey, B. G., Birdsey, R. A., Kurz, W. A., Jacobson, A. R., Huntzinger, D. N., Pan, Y., Post, W. M., and Cook, R. B.: Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions, and a new approach for estimating net ecosystem exchange from inventory-based data, Global Change Biology, doi: 10.1111/j.1365-2486.2011.02627.x, 2012.

Houborg, R., Rodell, M., Li, B., Reichle, R., and Zaitchik, B.: Drought indicators based on model assimilated GRACE terrestrial water storage observations, Wat. Resour. Res, 48, W07525, doi:10.1029/2011WR011291, 2012.

Houweling, S., Baker, D., Basu, S., Boesch, H., Butz, A., Chevallier, F., Deng, F., Dlugokencky, E. J., Feng, L., Ganshin, A., Hasekamp, O., Jones, D., Maksyutov, S., Marshall, J., Oda, T., O'Dell, C. W., Oshchepkov, S., Palmer, P. I., Peylin, P., Poussi, Z., Reum, F., Takagi, H., Yoshida, Y., and Zhuravlev, R.: An intercomparison of inverse models for estimating sources and sinks of CO_2 using GOSAT measurements, J. Geophys. Res. Atmos., 120, 5253–5266, doi:10.1002/2014JD022962, 2015.

Kaminski, T., Rayner, P. J., Heimann, M., and Enting, I. G.: On aggregation errors in atmospheric transport inversions, J. Geophys. Res., 106, 4703–4715, 2001.

Kawa, S. R., Erickson III, D. J., Pawson, S., and Zhu, Z.: Global CO_2 transport simulations using meteorological data from the NASA data assimilation system, J. Geophys. Res., 109, D18312, doi:10.1029/2004JD004554, 2004.

Kawa, S. R., Mao, J., Abshire, J. B., Collatz, G. J., Sun, X., and Weaver, C. J.: Simulation studies for a space-based CO_2 lidar mission, Tellus B, 62, 759-769, doi:10.1111/j.1600-0889.2010.00486.x, 2010.

Kim, J., Kim, H. M., Cho, C.-H., Boo, K.-O., Jacobson, A. R., Sasakawa, M., Machida, T., Arshinov, M., and Fedoseev, N.: Impact of Siberian observations on the optimization of surface CO_2 flux, Atmos. Chem. Phys., 17, doi:10.5194/acp-17-2881-2017, 2017.

Kulawik, S., Wunch, D., O'Dell, C., Frankenberg, C., Reuter, M., Oda, T., Chevallier, F., Sherlock, V., Buchwitz, M., Osterman, G., Miller, C. E., Wennberg, P. O., Griffith, D., Morino, I., Dubey, M. K., Deutscher, N. M., Notholt, J., Hase, F., Warneke, T., Sussmann, R., Robinson, J., Strong, K., Schneider, M., De Mazière, M., Shiomi, K., Feist, D. G., Iraci, L. T., and Wolf, J.: Consistent evaluation of ACOS-GOSAT, BESD-SCIAMACHY, CarbonTracker, and MACC through comparisons to TCCON, Atmos. Meas. Tech., 9, 683–709, doi:10.5194/amt-9-683-2016, 2016.

Law, R. M., et al.: TransCom model simulations of hourly atmospheric CO_2: Experimental overview and diurnal cycle results for 2002, Global Biogeochem. Cycles, 22, GB3009, doi:10.1029/2007GB003050, 2008.

Le Quéré, C., Andres, R. J., Boden, T., Conway, T., Houghton, R. A., House, J. I., Marland, G., Peters, G. P., van der Werf, G. R., Ahlström, A., Andrew, R. M., Bopp, L., Canadell, J. G., Ciais, P., Doney, S. C., Enright, C., Friedlingstein, P., Huntingford, C., Jain, A. K., Jourdain, C., Kato, E., Keeling, R. F., Klein Goldewijk, K., Levis, S., Levy, P., Lomas, M., Poulter, B., Raupach, M. R., Schwinger, J., Sitch, S., Stocker, B. D., Viovy, N., Zaehle, S., and Zeng, N.: The global carbon budget 1959–2011, Earth Syst. Sci. Data, 5, 165–185, doi:10.5194/essd-5-165-2013, 2013.

Le Quéré, C., Moriarty, R., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Friedlingstein, P., Peters, G. P., Andres, R. J., Boden, T. A., Houghton, R. A., House, J. I., Keeling, R. F., Tans, P., Arneth, A., Bakker, D. C. E., Barbero, L., Bopp, L., Chang, J., Chevallier, F., Chini, L. P., Ciais, P., Fader, M., Feely, R. A., Gkritzalis, T., Harris, I., Hauck, J., Ilyina, T., Jain, A. K., Kato, E., Kitidis, V., Klein Goldewijk, K., Koven, C., Landschützer, P., Lauvset, S. K., Lefévre, N., Lenton, A., Lima, I. D., Metzl, N., Millero, F., Munro, D. R., Murata, A., Nabel, J., Nakaoka, S., Nojiri, Y., O'Brien, K., Olsen, A., Ono, T., Pérez, F. F., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Rödenbeck, C., Saito, S., Schuster, U., Schwinger, J., Séférian, R., Steinhoff, T., Stocker, B. D., Sutton, A. J., Takahashi, T.,

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

Atmospheric Chemistry and Physics Discussions

Tilbrook, B., van der Laan-Luijkx, I. T., van der Werf, G. R., van Heuven, S., Vandemark, D., Viovy, N., Wiltshire, A., Zaehle, S., and Zeng, N.: Global Carbon Budget 2015. Earth System Science Data, 7:349-396. doi:10.5194/essd-7-349-2015, 2015.

Lindqvist, H., et al.: Does GOSAT capture the true seasonal cycle of carbon dioxide?, Atmos. Chem. Phys., 15, 13023–13040, doi:10.5194/acp-15-13023-2015, 2015.

Liu, J., Bowman, K. W., Lee, M., Henze, D. K., Bousserez, N., Brix, H., Collatz, G. J., Menemenlis, D., Ott, L., Pawson, S., Jones, D., and Nassar, R.: Carbon monitoring system flux estimation and attribution: Impact of ACOS-GOSAT XCO_2 sampling on the inference of terrestrial biospheric sources and sinks, Tellus B, 66, 22,486, doi:10.3402/tellusb.v66.22486, 2014.

Los, S. O., Collatz, G. J., Sellers, P. J., Malmström, C. M., Pollack, N. H., DeFries, R. S., Bounoua, L., Parris, M. T., Tucker, C. J., and Dazlich, D. A.: A global 9-yr biophysical land surface dataset from NOAA AVHRR data. J. Hydrometeorol., 1, 183–199, 2000.

Maksyutov, S., et al.: Regional CO_2 flux estimates for 2009–2010 based on GOSAT and ground-based CO_2 observations, Atmos. Chem. Phys., 13, 9351–9373, 2013.

Nassar, R., Jones, D. B. A., Suntharalingam, P., Chen, J. M., Andres, R. J., Wecht, K. J., Yantosca, R. M., Kulawik, S. S., Bowman, K. W., Worden, J. R., Machida, T., and Matsueda, H.: Modeling global atmospheric CO_2 with improved emission inventories and CO_2 production from the oxidation of other carbon species, Geosci. Model Dev., 3, 689–716, doi:10.5194/gmd-3-689-2010, 2010.

O'Dell, C. W., et al.: The ACOS CO_2 retrieval algorithm Part 1: Description and validation against synthetic observations, Atmos. Meas. Tech., 5, 99–121, 2012.

Olsen, S. C. and Randerson, J. T.: Differences between surface and column atmospheric CO_2 and implications for carbon cycle research, Journal of Geophysical Research, 109, D02301, doi:10.1029/2003JD003968, 2004.

Orbe, C., Holzer, M., Polvani, L. M., and Waugh, D.: Air-mass origin as a diagnostic of tropospheric transport, J. Geophys. Res. Atmos., 118, 1459–1470, doi:10.1002/jgrd.50133, 2013.

Osterman, G., Eldering, A., Avis, C., O'Dell, C., Martinez, E., Crisp, D., Frankenberg, C., and Frankenberg, B.: ACOS Level 2 Standard Product Data User's Guide, v3.4, Jet Propulsion Laboratory, Pasadena, California, 2013.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S., and Hayes, D.: A Large and Persistent Carbon Sink in the World's Forests, Science, 333, 988-993, doi: 10.1126/science.1201609, 2011.

Parazoo, N. C., Denning, A. S., Kawa, S. R., Corbin, K. D., Lokupitiya, R. S., and Baker, I. T.: Mechanisms for synoptic variations of atmospheric CO_2 in North America, South America and Europe, Atmos. Chem. Phys., 8, 7239-7254, https://doi.org/10.5194/acp-8-7239-2008, 2008.

Peters, W., Jacobson, A. R., Sweeney, C., Andrews, A. E., Conway, T. J., Masarie, K., Miller, J. B., Bruhwiler, L. M. P., Pétron, G., Hirsch, A. I., Worthy, D. E. J., van der Werf, G. R., Randerson, J. T., Wennberg, P. O., Krol, M. C., and Tans, P. P.: An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker, PNAS, 104, 18925-18930, 2007.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

Pinzon, J. E. and Tucker, C. J.: A non-stationary 1981-2012 AVHRR $NDVI_{3g}$ time series, Remote Sensing 6, 6929-6960; doi:10.3390/rs6086929, 2014.

Randerson, J. T., Thompson, M. V., and Malmstrom, C. M.: Substrate limitations for heterotrophs: Implications for models that estimate the seasonal cycle of atmospheric CO_2, Global Biogeochem. Cycles, 10(4), 585–602, doi:10.1029/96GB01981, 1996.

Rayner, P. J., Enting, I. G., Francey, R. J., and Langenfelds, R.: Reconstructing the recent carbon cycle from atmospheric CO_2, $\delta^{13}C$ and O_2/N_2 observations, Tellus B, 51, 213–232, 1999.

Reuter, M., et al.: Satellite-inferred European carbon sink larger than expected, Atmos. Chem. Phys. Discuss., 14, 21,829–21,863, doi:10.5194/acpd-14-21829-2014, 2014.

Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M. G., Schubert, S. D., Takacs, L., Kim, G.-K., Bloom, S., Chen, J., Collins, D., Conaty, A., Da Silva, A., Gu, W., Joiner, J., Koster, R. D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C. R., Reichle, R., Robertson, F. R., Ruddick, A. G., Sienkiewicz, M., and Woollen, J.: MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications, J. Climate, 24, 3624–3648, 2011.

Rodgers, C. D.: Inverse Methods for Atmospheric Sounding: Theory and Practice, World Scientific, Singapore, 2000.

Saeki, T., Maksyutov, S., Saito, M., Valsala, V., Oda, T., Andres, R. J., Belikov, D., Tans, P., Dlugokencky, E., Yoshida, Y., Morino, I., Uchino, O., and Yokota, T.: Inverse modeling of CO_2 fluxes using GOSAT data and multi-year ground-based observations, Sci. Online Lett. Atmos., 9, 45–50, doi:10.2151/sola.2013-011, 2013a.

Saeki, T., Maksyutov, S., Sasakawa, M., Machida, T., Arshinov, M., Tans, P., Conway, T. J., Saito, M., Valsala, V., Oda, T., Andres, R. J., and Belikov, D.: Carbon flux estimation for

Siberia by inverse modeling constrained by aircraft and tower CO_2 measurements, J. Geophys. Res., 118, doi:10.1002/jgrd.50127, 2013b.

Sasakawa, M., Shimoyama, K., Machida, T., Tsuda, N., Suto, H., Arshinov, M., Davydov, D., Fofonov, A., Krasnov, O., Saeki, T., Koyama, Y., and Maksyutov, S.: Continuous measurements of methane from a tower network over Siberia, Tellus B: Chemical and Physical Meteorology, 62:5, 403-416, doi: 10.1111/j.1600-0889.2010.00494.x, 2010.

Sasakawa, M., Machida, T., Tsuda, N., Arshinov, M., Davydov, D., Fofonov, A., and Krasnov, O.: Aircraft and tower measurements of CO_2 concentration in the planetary boundary layer and the lower free troposphere over southern taiga in West Siberia: Long-term records from 2002 to 2011, J. Geophys. Res., doi:10.1002/jgrd.50755, 2013.

Schimel, D., Stephens, B. B., and Fisher, J. B.: Effect of increasing CO_2 on the terrestrial carbon cycle, PNAS, 112, doi/10.1073/pnas.1407302112, 2015.

Stephens, B. B., et al.: Weak northern and strong tropical land carbon uptake from vertical profiles of atmospheric CO_2, Science, 316, 1732–1735, 2007.

Takagi, H., et al.: On the benefit of GOSAT observations to the estimation of regional CO_2 fluxes, Sci. Online Lett. Atmos., 7, 161–164, 2011.

Takagi, H., et al.: Influence of differences in current GOSAT XCO_2 retrievals on surface flux estimation, Geophys. Res. Lett., 41, 2598–2605, doi:10.1002/2013GL059174, 2014.

Takahashi, T., et al.: Climatological mean and decadal change in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans, Deep Sea Res., Part II, 56(8–10), 554–577, 2009.

Tsutsumi, Y., Mori, K., Ikegami, M., Tashiro, T., and Tsuboi, K.: Long-term trends of greenhouse gases in regional and background events observed during 1998-2004 at

Yonagunijima located to the east of the Asian continent, Atmospheric. Environment., 40, 5868-5879, 2006.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Kasibhatla, P. S., and Arellano Jr., A. F.: Interannual variability in global biomass burning emissions from 1997 to 2004, Atmos. Chem. Phys., 6, 3423–3441, doi:10.5194/acp-6-3423-2006, 2006.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.

van der Werf, G. R., Randerson, J. T., Giglio, L., van Leeuwen, T. T., Chen, Y., Rogers, B. M., Mu, M., van Marle, M. J. E., Morton, D. C., Collatz, G. J., Yokelson, R. J., and Kasibhatla, P. S.: Global fire emissions estimates during 1997–2016, Earth Syst. Sci. Data, 9, 697-720, doi:10.5194/essd-9-697-2017, 2017.

Wofsy, S. C., et al.: HIAPER Pole-to-Pole Observations (HIPPO): fine-grained, global-scale measurements of climatically important atmospheric gases and aerosols, Philos. T. R. Soc. A, 369, 2073–2086, doi:10.1098/rsta.2010.0313, 2011.

Wofsy, S. C., et al.: HIPPO Merged 10-second Meteorology, Atmospheric Chemistry, Aerosol Data (R_20121129), Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/hippo_010 (Release 20121129), 2012.

Wunch, D., Wennberg, P. O., Toon, G. C., Connor, B. J., Fisher, B., Osterman, G. B., Frankenberg, C., Mandrake, L., O'Dell, C., Ahonen, P., Biraud, S. C., Castano, R., Cressie, N., Crisp, D., Deutscher, N. M., Eldering, A., Fisher, M. L., Griffith, D. W. T., Gunson, M.,

Atmospheric Chemistry and Physics
Open Access
Discussions

Heikkinen, P., Keppel-Aleks, G., Kyrö, E., Lindenmaier, R., Macatangay, R., Mendonca, J., Messerschmidt, J., Miller, C. E., Morino, I., Notholt, J., Oyafuso, F. A., Rettinger, M., Robinson, J., Roehl, C. M., Salawitch, R. J., Sherlock, V., Strong, K., Sussmann, R., Tanaka, T., Thompson, D. R., Uchino, O., Warneke, T., and Wofsy, S. C.: A method for evaluating bias in global measurements of CO_2 total columns from space, Atmos. Chem. Phys., 11, 12317–12337, doi:10.5194/acp-11-12317-2011, 2011.

Xu, L., Samanta, A., Costa, M. H., Ganguly, S., Nemani, R. R., and Myneni, R. B.: Widespread decline in greenness of Amazonian vegetation due to the 2010 drought, Geophys. Res. Lett., 38, L07402, doi:10.1029/2011GL046824, 2011.

Yokota, T., Yoshida, Y., Eguchi, N., Ota, Y., Tanaka, T., Watanabe, H., and Maksyutov, S.: Global concentrations of CO_2 and CH_4 retrieved from GOSAT: first preliminary results, SOLA, 5, 160–163, doi:10.2151/sola.2009-041, 2009.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

Atmospheric Chemistry and Physics
Discussions
Open Access

Table 1. Inversion Prior and Posterior Fluxes and Uncertainties Aggregated to TransCom 3 Regions, June 2009-May 2010.

TransCom Region	Prior		Fires	In Situ-Only			GOSAT-Only			In Situ + GOSAT			In Situ-Only, Tighter Prior			GOSAT-Only, Tighter Prior		
	Flux[a]	Unc	Flux	Flux	Unc	U.R. (%)[b]	Flux	Unc	U.R. (%)	Flux	Unc	U.R. (%)	Flux	Unc	U.R. (%)	Flux	Unc	U.R. (%)
Boreal North America	-0.1	0.6	0.1	0.1	0.1	81	0.2	0.3	43	0.1	0.1	87	-0.1	0.1	71	0.0	0.2	27
Temperate North America	-0.3	1.5	0.0	-0.6	0.1	93	-1.5	0.3	82	-0.7	0.1	96	-0.6	0.1	87	-1.2	0.2	71
Tropical America	0.4	1.0	0.1	-0.4	0.7	33	-0.2	0.2	79	-0.3	0.2	82	-0.2	0.3	26	-0.1	0.1	67
Temperate South America	0.4	1.2	0.1	0.4	0.8	31	1.1	0.2	85	1.0	0.2	85	0.3	0.3	27	0.9	0.1	73
Northern Africa	0.2	1.1	0.4	1.5	0.7	38	2.0	0.2	83	1.8	0.2	84	1.1	0.3	28	2.0	0.1	70
Southern Africa	0.0	1.2	0.8	-0.1	0.7	44	-0.6	0.1	89	-0.5	0.1	89	-0.1	0.3	38	-0.6	0.1	80
Boreal Asia	-0.1	1.2	0.1	-1.2	0.4	70	-0.5	0.4	65	-1.2	0.2	87	-1.0	0.2	60	-0.5	0.2	51
Temperate Asia	0.0	1.8	0.1	-0.1	0.7	61	1.4	0.4	79	0.9	0.3	85	-0.5	0.3	53	1.0	0.2	67
Tropical Asia	0.3	0.6	0.4	0.0	0.4	33	0.5	0.3	54	0.7	0.2	61	0.4	0.2	25	0.8	0.1	39
Australia	0.0	0.5	0.1	-0.2	0.4	15	0.6	0.2	71	0.3	0.1	73	-0.2	0.2	12	0.3	0.1	56
Europe	-0.1	1.3	0.0	0.6	0.4	70	-1.5	0.3	75	-0.6	0.2	87	0.3	0.2	61	-1.6	0.2	64
North Pacific Ocean	-0.5	0.3	0.0	-0.9	0.1	51	-0.5	0.2	29	-1.1	0.1	67	-0.8	0.1	29	-0.5	0.1	11
Tropical West Pacific Ocean	0.1	0.3	0.0	0.1	0.2	26	0.3	0.1	51	0.5	0.1	59	0.1	0.1	15	0.3	0.1	24
Tropical East Pacific Ocean	0.4	0.3	0.0	0.4	0.2	25	0.4	0.1	54	0.3	0.1	62	0.4	0.1	13	0.4	0.1	25
South Pacific Ocean	-0.3	0.6	0.0	-1.0	0.4	32	-1.1	0.3	51	-1.8	0.2	60	-0.6	0.2	18	-0.9	0.1	30
Arctic/Northern Ocean	-0.3	0.3	0.0	-0.4	0.1	56	-0.5	0.2	19	-0.1	0.1	62	-0.3	0.1	31	-0.4	0.1	5
North Atlantic Ocean	-0.2	0.2	0.0	-0.8	0.1	35	-0.5	0.1	23	-1.0	0.1	50	-0.5	0.1	12	-0.3	0.1	6
Tropical Atlantic Ocean	0.1	0.3	0.0	0.1	0.2	23	0.3	0.2	42	0.4	0.1	56	0.1	0.1	9	0.2	0.1	14
South Atlantic Ocean	-0.2	0.4	0.0	-0.5	0.3	19	-0.7	0.2	38	-1.0	0.2	49	-0.3	0.1	8	-0.5	0.1	18
Southern Ocean	-0.2	0.6	0.0	-0.4	0.3	48	-0.9	0.4	41	0.2	0.2	62	-0.5	0.1	34	-1.1	0.1	22
Tropical Indian Ocean	0.1	0.4	0.0	0.0	0.3	27	0.7	0.2	56	0.5	0.2	62	0.1	0.1	16	0.4	0.1	32
Southern Indian Ocean	-0.4	0.3	0.0	-0.5	0.2	15	-0.6	0.2	29	-0.6	0.2	40	-0.5	0.1	7	-0.4	0.1	11

[a]Fluxes in table, in Pg C, include fires but not fossil emissions

[b]Uncertainty reduction

Table 2. Normalized Chi-Squared (Cost Function) Values for the Inversions.

Inversion	A Priori	A Posteriori
In situ only	112.4	4.0
GOSAT only	2.2	0.8
In situ + GOSAT	12.2	1.1
In situ only, decreased prior uncertainties	112.4	5.0
GOSAT only, decreased prior uncertainties	2.2	0.8

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

Table 3. Mean 2010-2009 difference in mole fractions over June-July-August at Siberian sites (in ppm).

Site	Observations	Prior	GOSAT-Only Post	In Situ + GOSAT Post	Prior - Obs	(GOSAT-Only) - Obs	(In Situ + GOSAT) - Obs
VGN	5.2	5.3	7.4	6.6	0.1	2.2	1.4
AZV	7.0	6.3	8.1	7.1	-0.7	1.1	0.1
SVV	2.6	4.0	3.4	4.6	1.4	0.8	2.0
IGR	4.9	5.7	5.1	4.6	0.8	0.2	-0.3
KRS	6.6	5.4	3.8	3.2	-1.2	-2.8	-3.4
YAK	2.1	2.5	4.2	2.5	0.4	2.1	0.4

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

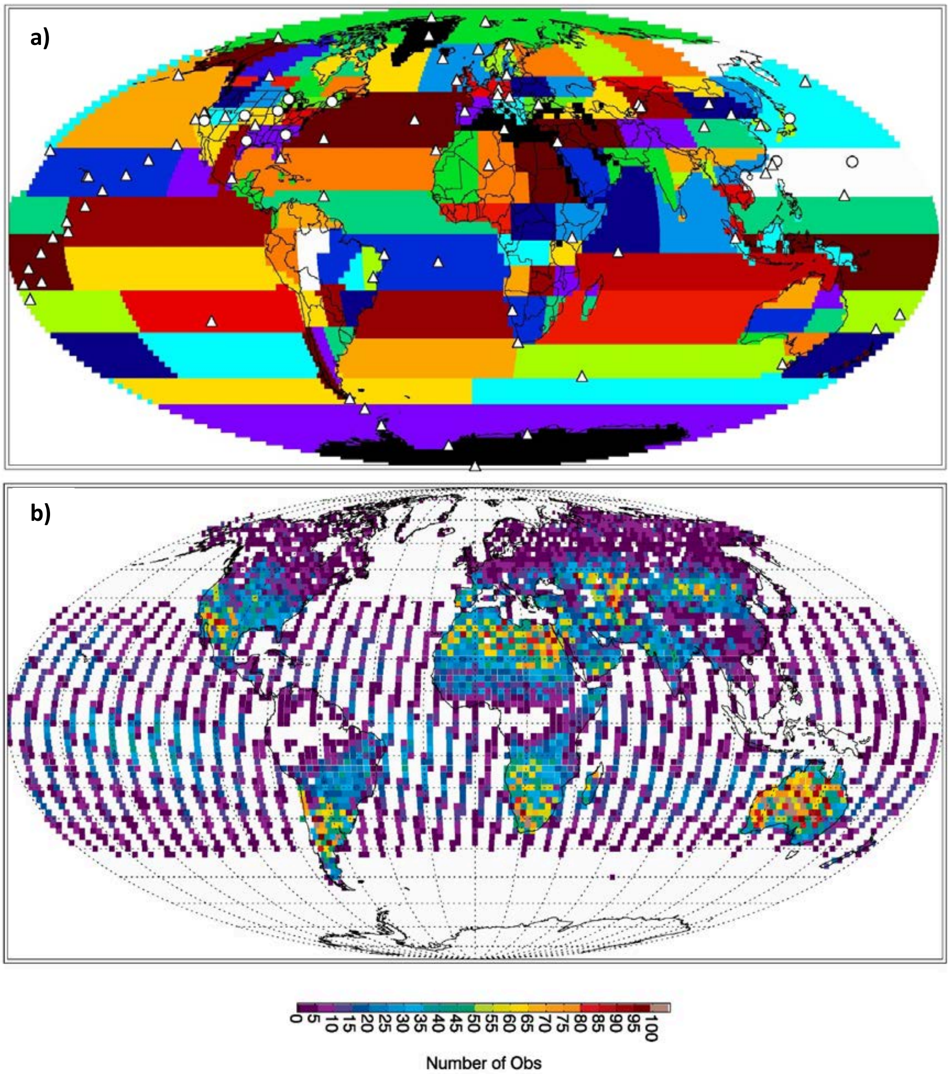
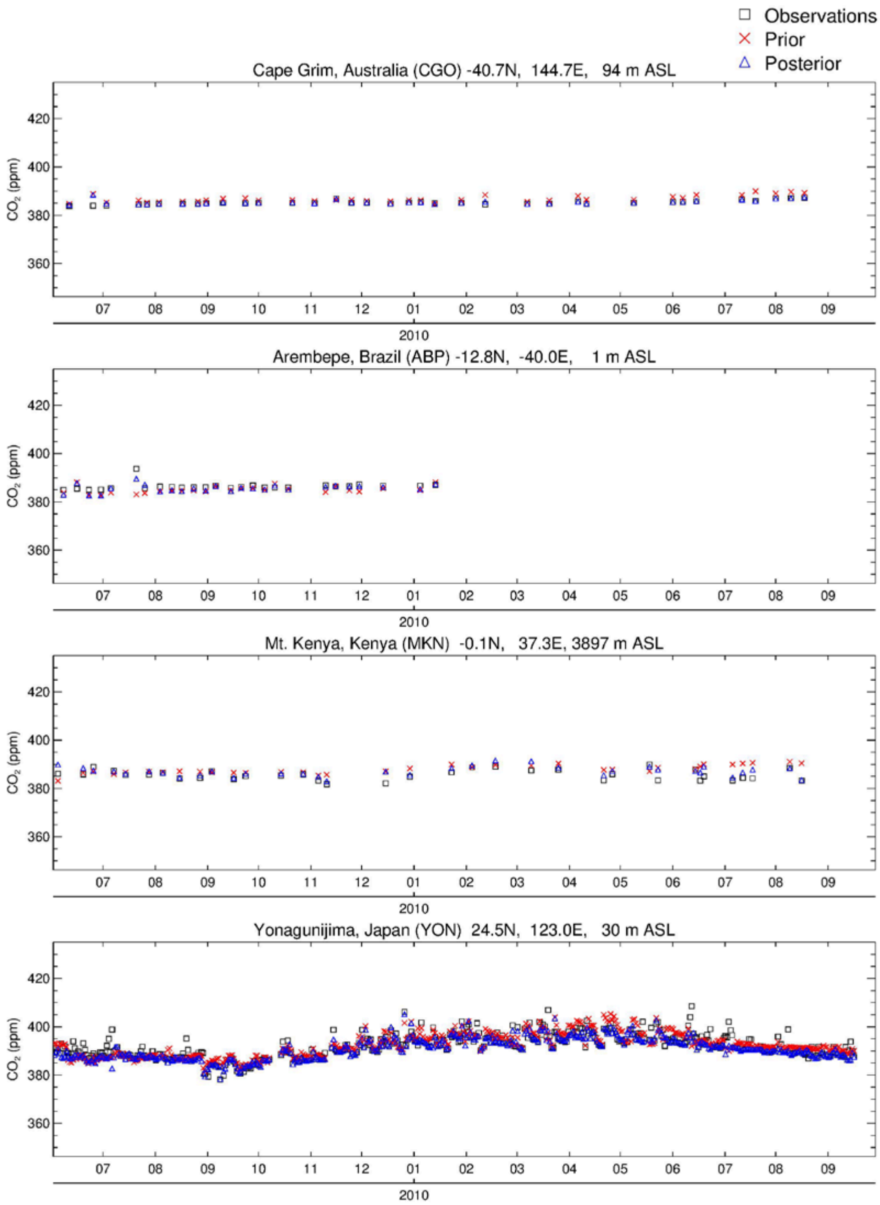


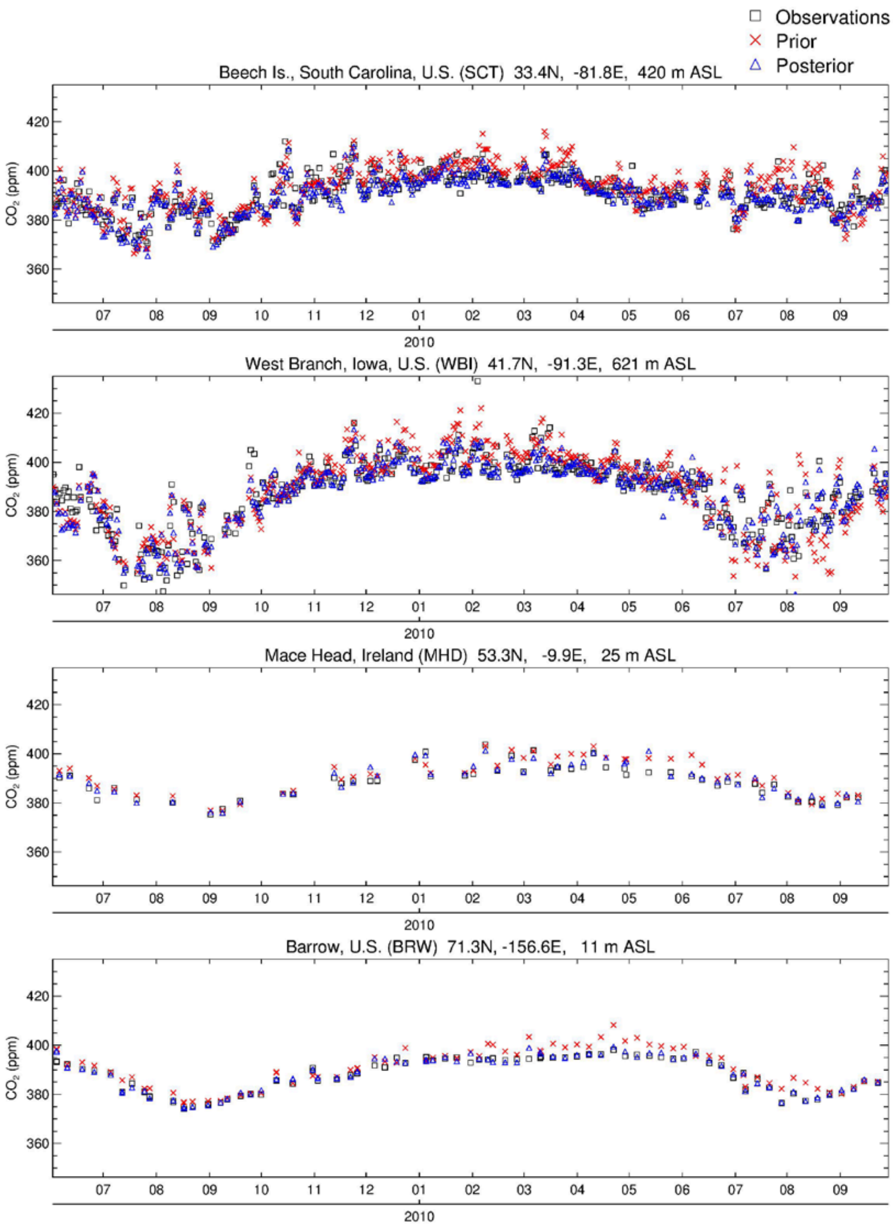
Figure 1. Locations of a) in situ observation sites and b) GOSAT XCO_2 observations used in the inversions. Also shown in a) are the 108 flux regions. Triangles in a) indicate flask sites, circles indicate continuous measurement sites. Observations in b) correspond to the ACOS B3.4 retrieval, are filtered and averaged over each hour and 2° x 2.5° PCTM model grid column, and are shown for June 2009-May 2010.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017



1239

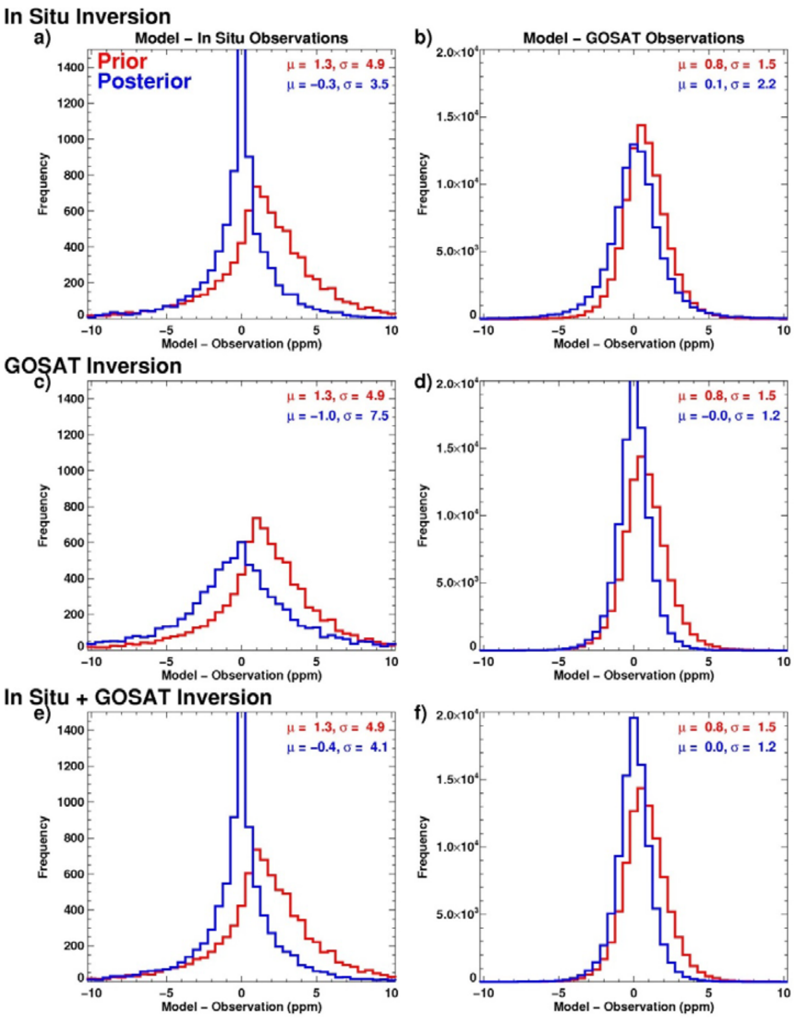
1240 **Figure 2.** Comparison of model and observed time series of CO_2 mole fractions at selected surface sites. Posterior mole fractions are for the in situ-only inversion. Sites are arranged from south to north. Elevations include intake heights on towers where applicable.



1243

1244 **Figure 2.** (continued)

1245



1246

1247 **Figure 3.** Full comparison of model and observations. Model-observation difference histograms
1248 are shown for (a) in situ-only inversion and in situ observations, (b) in situ-only inversion and
1249 GOSAT observations, (c) GOSAT-only inversion and in situ observations, (d) GOSAT-only
1250 inversion and GOSAT observations, (e) in situ + GOSAT inversion and in situ observations, and
1251 (f) in situ + GOSAT inversion and GOSAT observations. Mean differences and standard
1252 deviations are indicated in the panels.

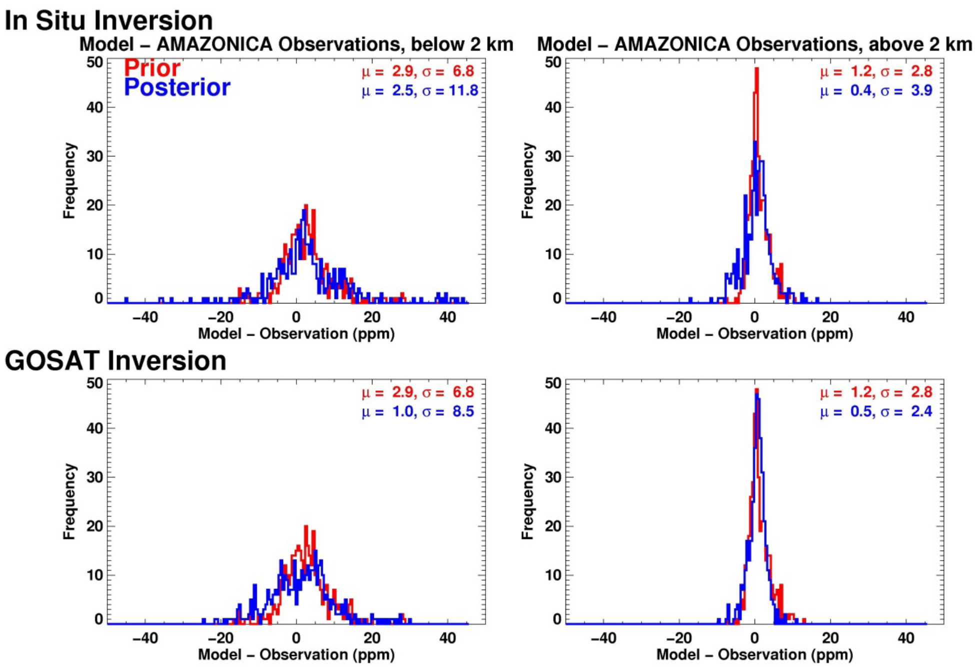


Figure 4. Comparison of model and Amazon aircraft observations (Amazonica project) over the period of overlap, Jan.-Sep. 2010. Top two panels show model-observation difference histograms for the in situ-only inversion and bottom two panels show results for the GOSAT-only inversion. Comparisons are shown separately for model and data below 2 km altitude (left) and above 2 km (right). Mean differences and standard deviations are indicated in the panels.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

Atmospheric Chemistry and Physics
Discussions

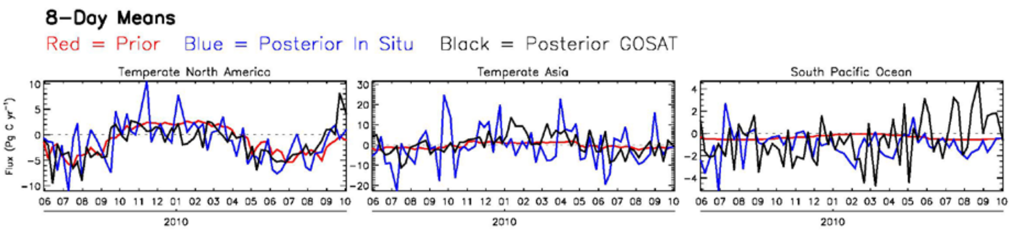


Figure 5. Prior, posterior in situ-only, and posterior GOSAT-only 8-day mean NEP (× -1) and ocean fluxes, aggregated over selected TransCom regions. Note that vertical scales are different in each of the panels.

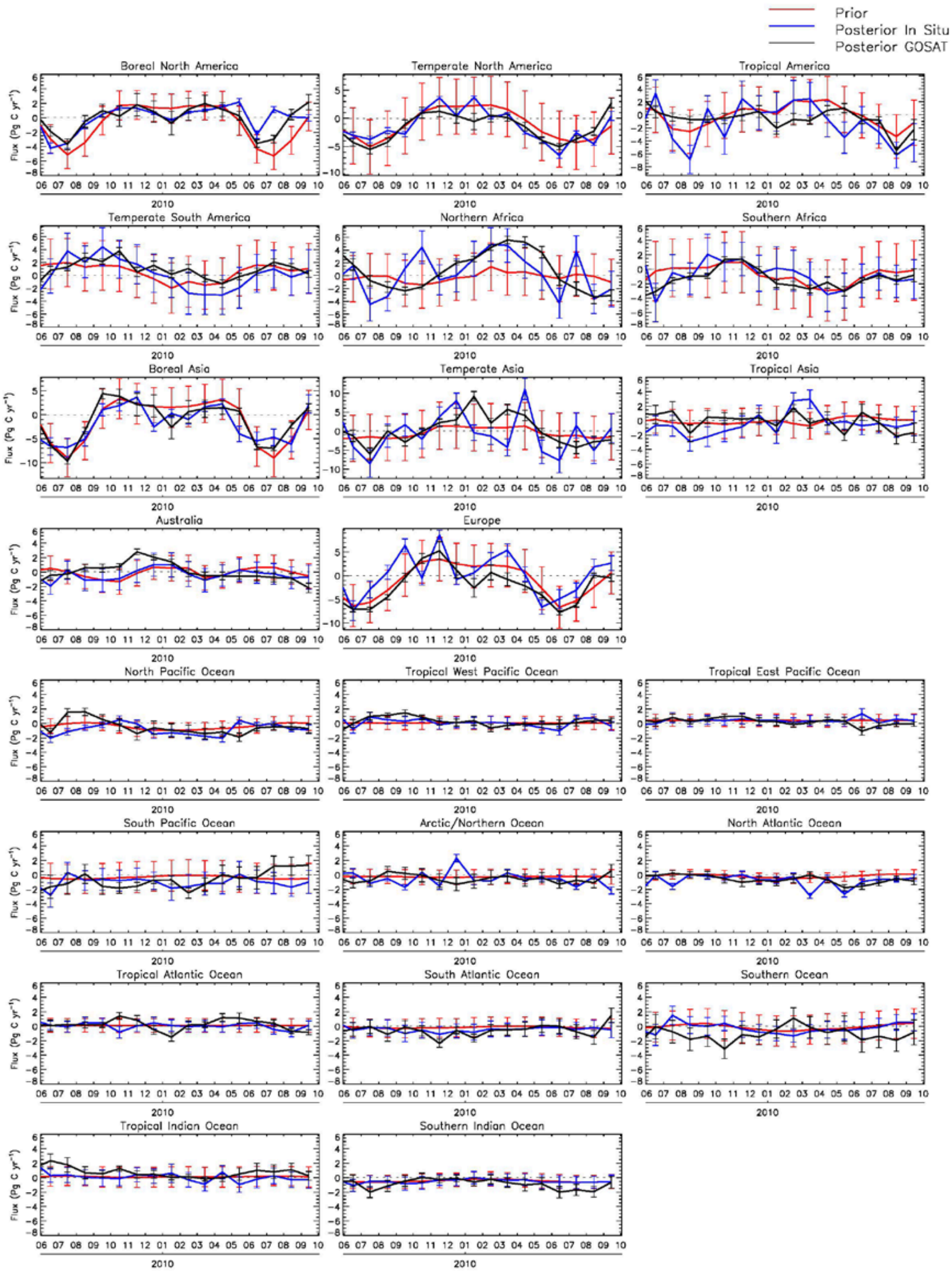
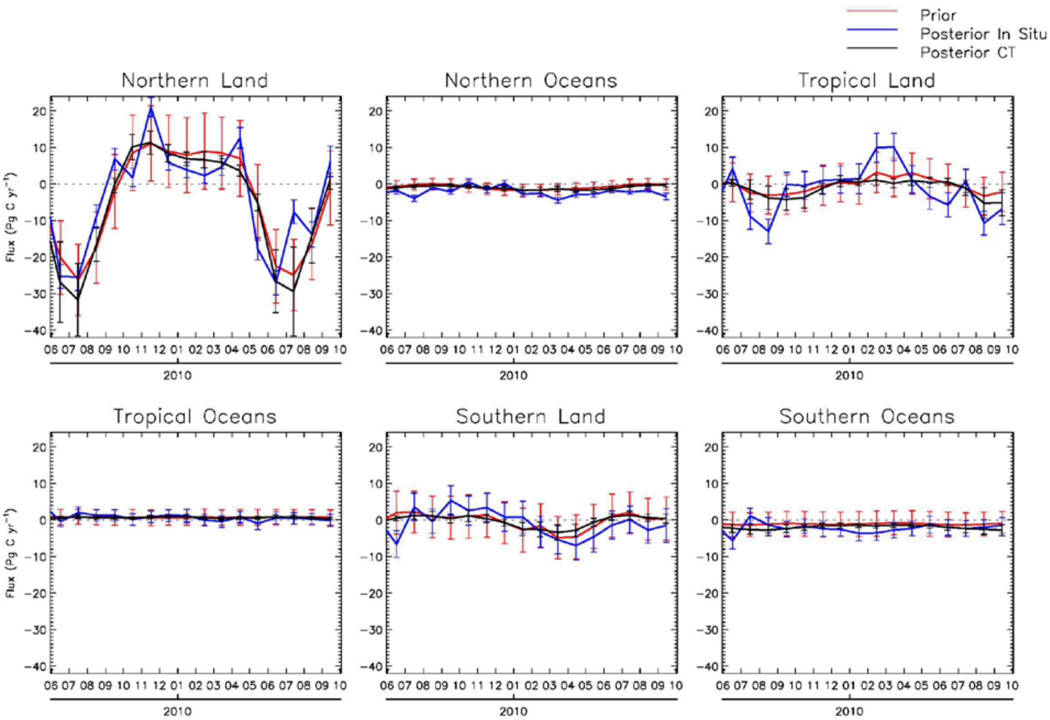


Figure 6. Same as Fig. 5, except showing monthly means of fluxes for all TransCom regions, with error bars that represent 1σ uncertainties.

1268



1269

1270 **Figure 7.** Comparison of our in situ-only inversion monthly mean NEP (× -1) and ocean fluxes,
1271 aggregated over large regions (as defined in TC3), with posterior fluxes from NOAA's
1272 CarbonTracker (CT2013B) data assimilation system. The priors shown are from our analysis;
1273 CT2013B priors are similar. Error bars represent 1σ uncertainties.

1274

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

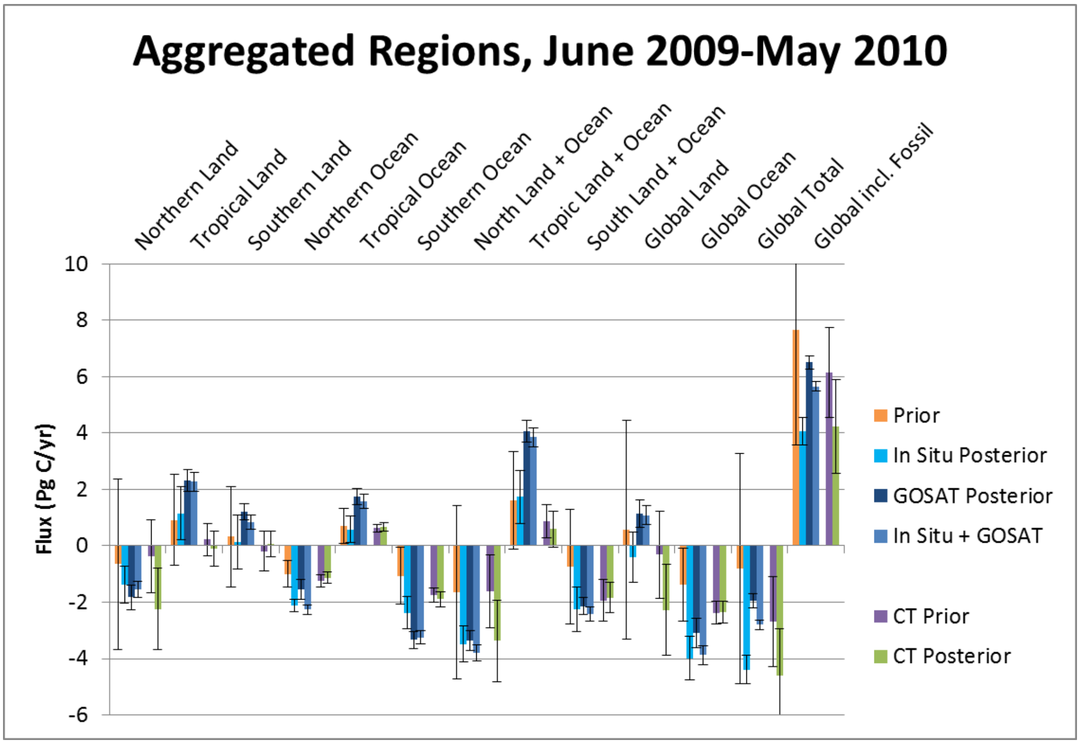
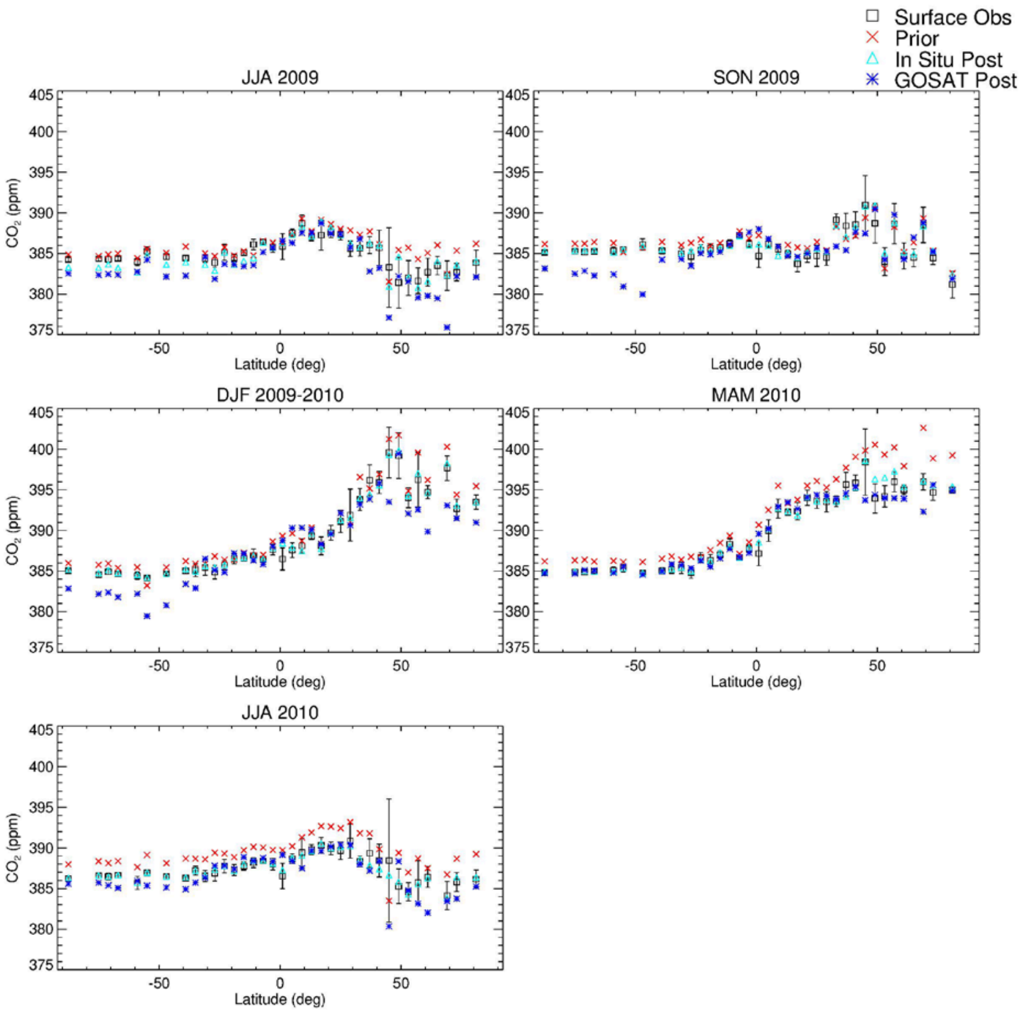


Figure 8. Twelve-month mean NEP (× -1), fire, and ocean fluxes aggregated over large regions. Included are results for the in situ-only, GOSAT-only, and in situ + GOSAT inversions as well as priors. Shown for comparison are priors and posteriors from CT2013B. Error bars represent 1σ uncertainties; for CT2013B, "external" (across a set of priors) as well as "internal" (within a particular inversion) uncertainties are included. In summing monthly CT2013B fluxes over the 12 months, we assumed zero error correlation between months.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

Atmospheric Chemistry and Physics
Open Access
Discussions



1283

1284 **Figure 9.** Latitudinal profiles of seasonal mean CO_2 mole fractions at surface sites for observations, prior, in situ-only posterior, and GOSAT-only posterior. Values are averaged in 4° bins. Error bars account for the spread of the observations within each season and bin as well as the uncertainty of each observation.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

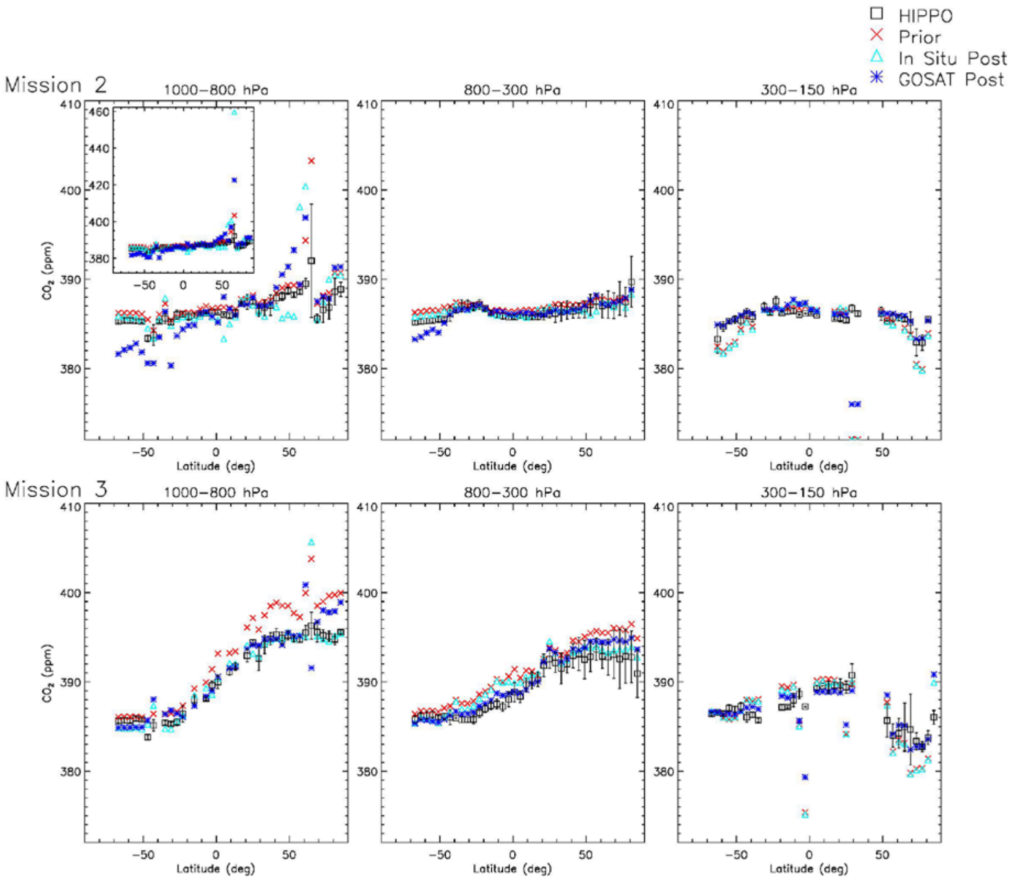


Figure 10. Latitudinal profiles of CO_2 mole fractions for HIPPO observations and co-sampled prior, in situ-only posterior, and GOSAT-only posterior. Mission 2 took place during Oct 31-Nov 22, 2009; Mission 3 took place Mar 24-Apr 16, 2010. Values are averaged in three altitude bins and 4° latitude bins. The inset in the first panel contains an expanded y-axis range that shows two points that do not fit into the default range. Flight segments over the temperate North American continent (east of -130°) are excluded from this comparison in order to focus on the Pacific. Error bars represent the standard deviations of the observations within each bin.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

Atmospheric Chemistry and Physics
Open Access
Discussions

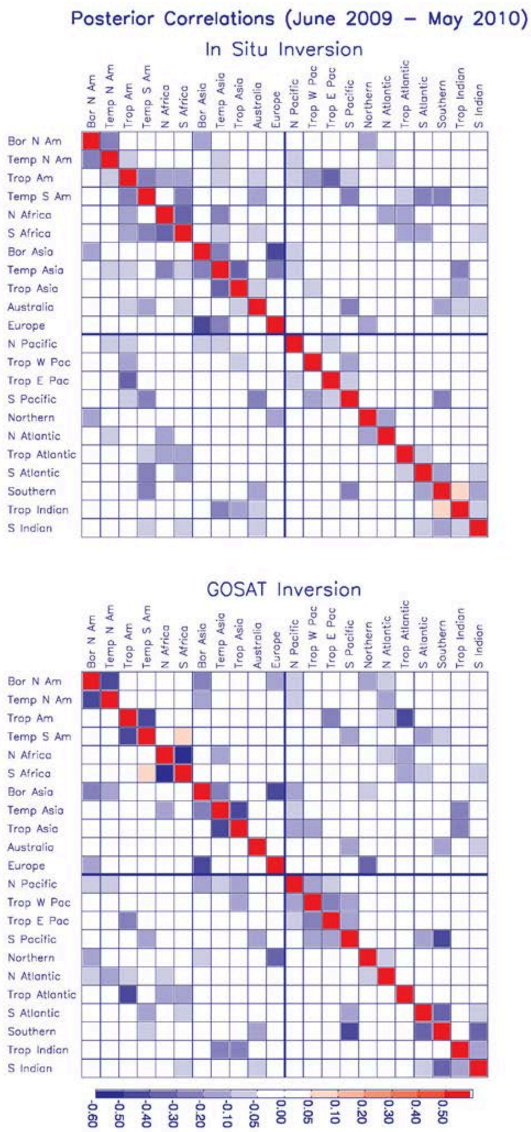


Figure 11. Posterior flux error correlations, aggregated to TC3 regions and a 12-month period, for (a) the in situ-only inversion, and (b) the GOSAT-only inversion. The correlation is equal to the error covariance divided by the product of the corresponding flux uncertainties (σ). Values on the main diagonal are equal to 1.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017

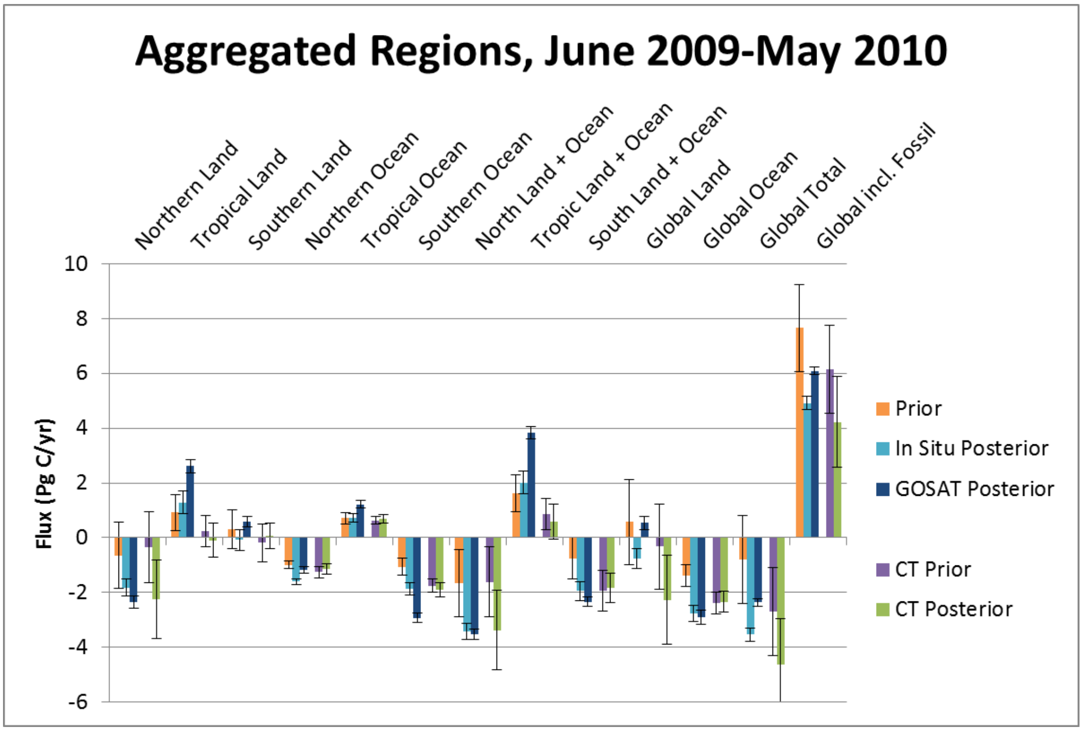
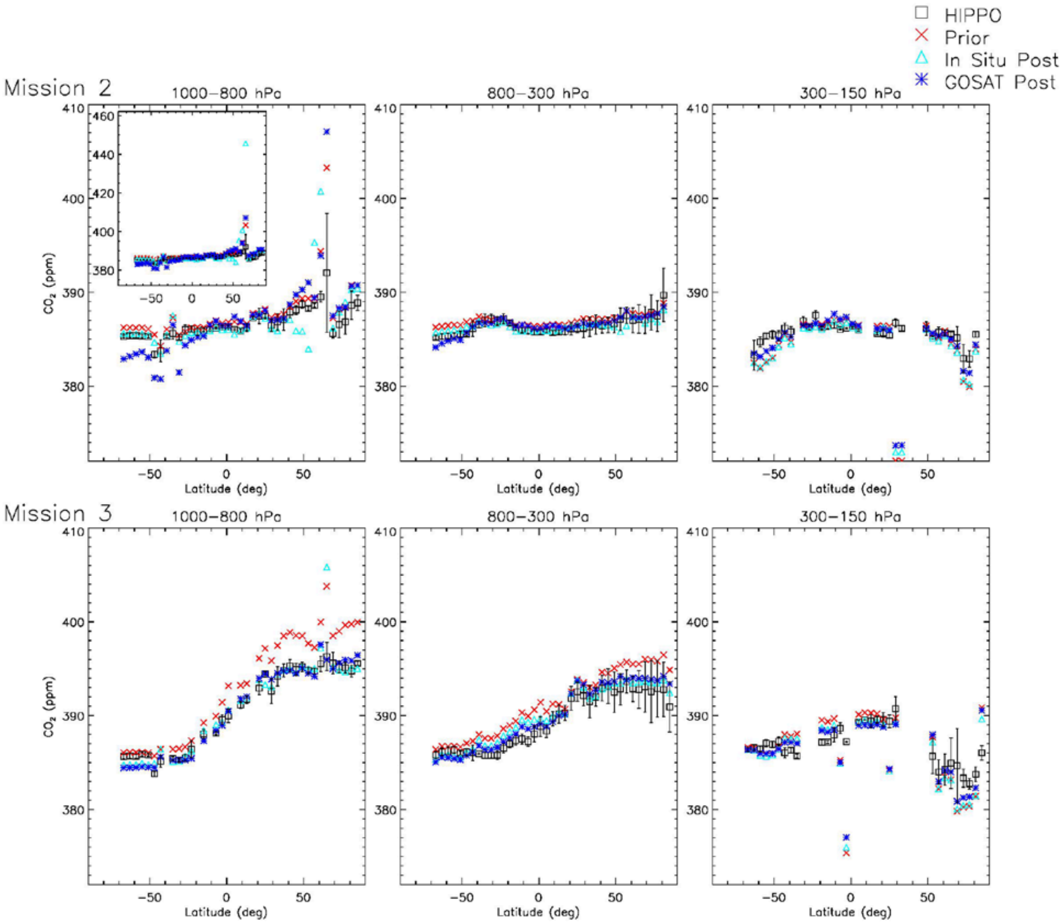


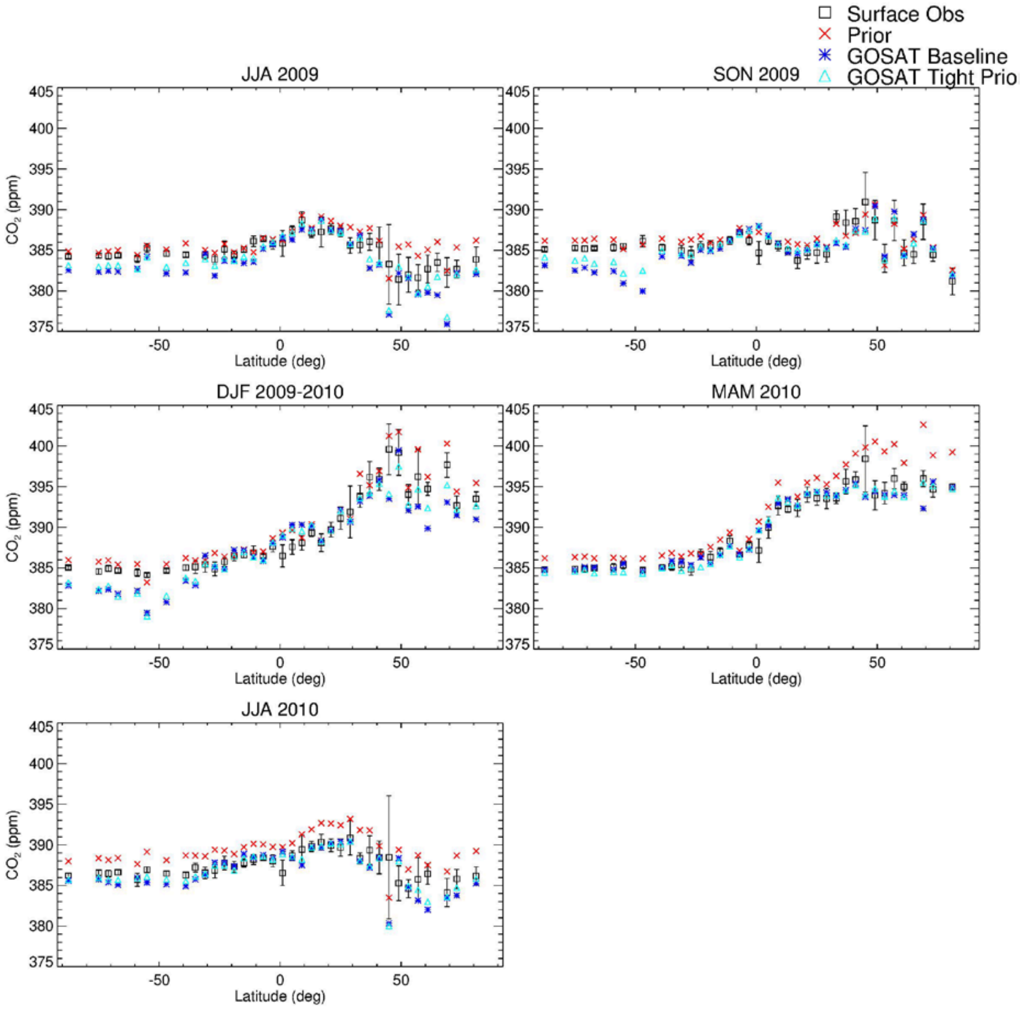
Figure 12. Similar to Fig. 8, except showing results for inversions with tighter prior constraints (with prior uncertainties similar to CarbonTracker's). Included are results for the in situ-only and GOSAT-only inversions. CT2013B results shown in Fig. 8 are repeated here. Error bars represent 1σ uncertainties.



1308

1309 **Figure 13.** Same as Fig. 10 except showing inversions with tighter prior uncertainties.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-960
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 26 October 2017



1310

1311 **Figure 14.** Same as Fig. 9 except showing GOSAT-only inversions with baseline vs. tighter

1312 prior uncertainties.

1313

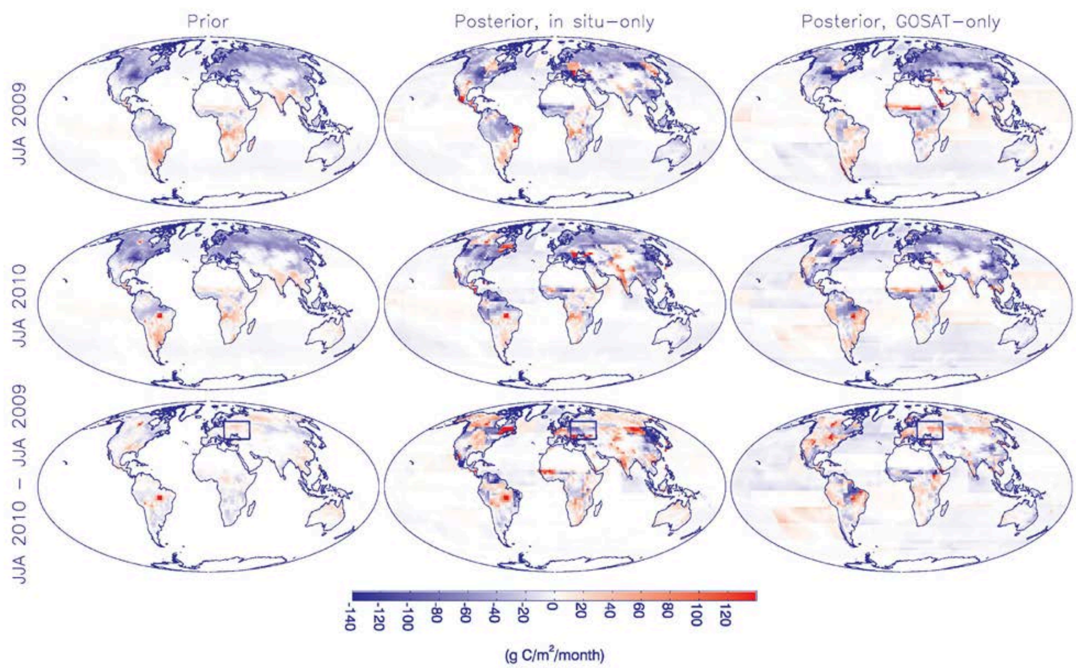


Figure 15. Comparison of spatial distribution of fluxes for June-July-August of 2010 vs. 2009. Included are natural and fire fluxes. Shown are fluxes for 2009 (top), 2010 (middle), and the 2010-2009 difference (bottom), for the priors (left), in situ-only inversion (middle), and GOSAT-only inversion (right). In the bottom row, boxes enclose the region around western Russia where there were intense heat waves, severe drought, and extensive fires. Note that the grid-scale spatial variability shown is not optimized in the inversions, so only patterns at the scale of the 108 flux regions contain information from the observations.

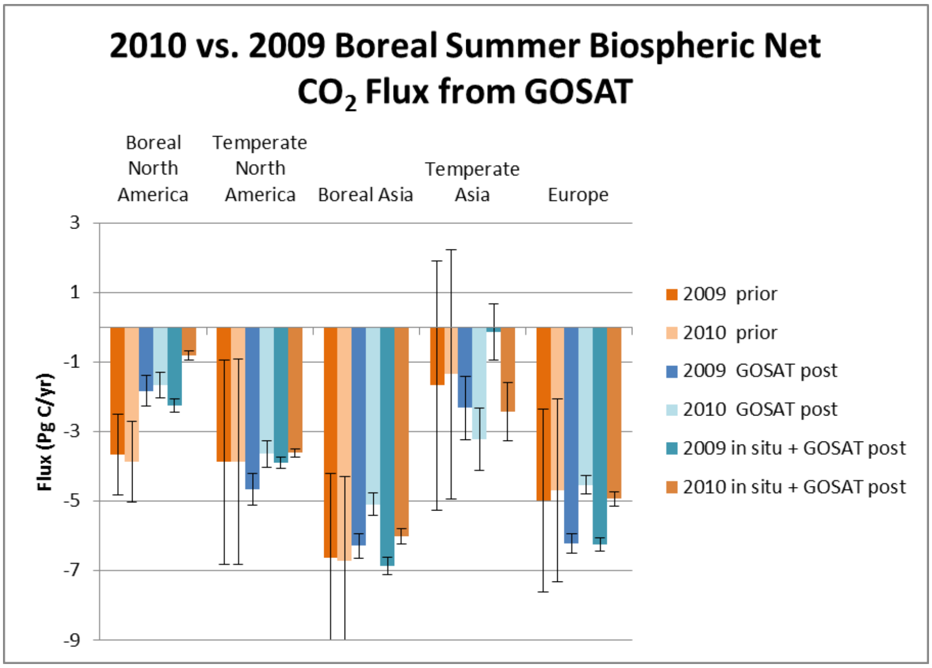


Figure 16. Comparison of prior, GOSAT-only posterior, and in situ + GOSAT posterior fluxes aggregated over northern regions for June-July-August of 2010 vs. 2009. Included are NEP (× -1) and fire fluxes. Error bars represent 1σ uncertainties.

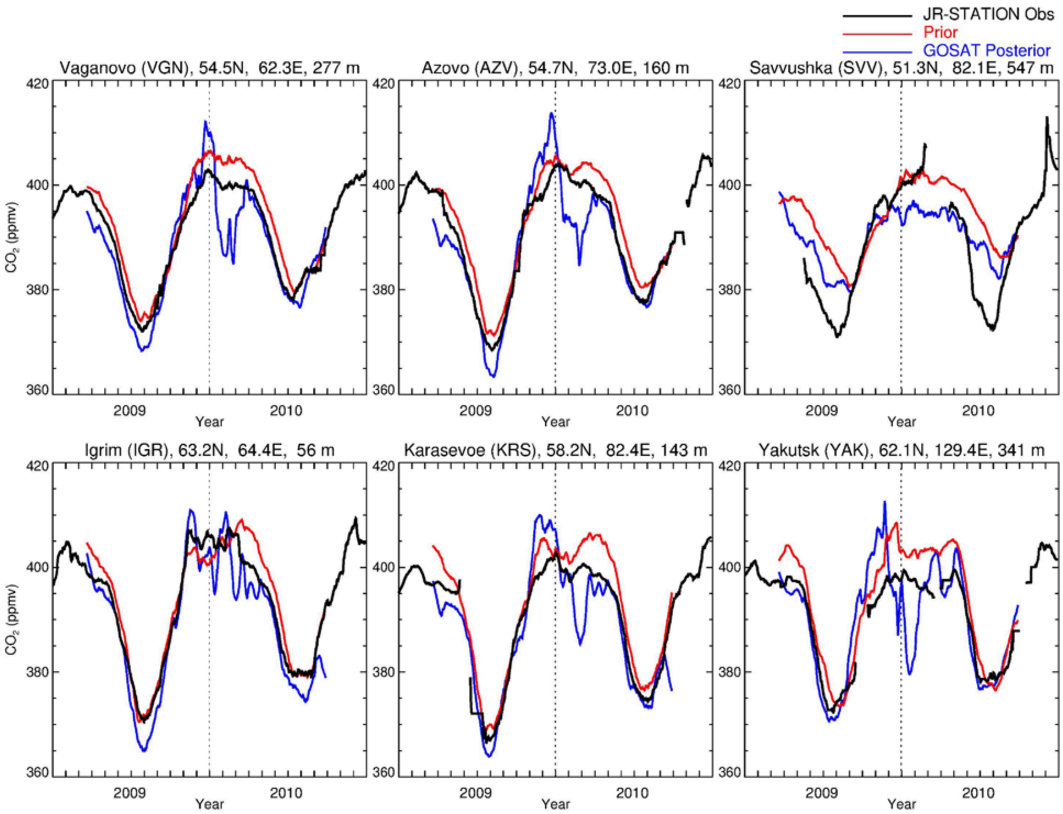


Figure 17. Evaluation of the prior model and GOSAT-only inversion against JR-STATION in situ observations in Siberia. Shown are daily afternoon average (1200-1700 local time) mole fractions from the highest level on each tower, the time series of which are smoothed with a 31-day window. Sites are arranged from west to east, first at lower latitudes and then at higher latitudes, excluding those with data gaps in the summer. Elevations shown include intake heights on towers.