Estimates of European uptake of CO$_2$ inferred from GOSAT X$_{CO_2}$ retrievals: sensitivity to measurement bias inside and outside Europe

L. Feng$^1$, P. I. Palmer$^1$, R. J. Parker$^2$, N. M. Deutscher$^{3,4}$, D. G. Feist$^5$, R. Kivi$^6$, I. Morino$^7$, and R. Sussmann$^8$

$^1$National Centre for Earth Observation, School of GeoSciences, University of Edinburgh, Edinburgh, UK
$^2$National Centre for Earth Observation, Department of Physics and Astronomy, University of Leicester, Leicester, UK
$^3$Institute of Environmental Physics, University of Bremen, Bremen, Germany
$^4$Centre for Atmospheric Chemistry, University of Wollongong, Wollongong, Australia
$^5$Max Planck Institute for Biogeochemistry, Jena, Germany
$^6$FMI-Arctic Research Center, Sodankylä, Finland
$^7$National Institute for Environmental Studies (NIES), Tsukuba, Japan
$^8$Institute of Meteorology and Climate Research – Atmospheric Environmental Research KIT/IMK-IFU, Garmisch-Partenkirchen, Germany

Correspondence to: L. Feng (lfeng@staffmail.ed.ac.uk)

Received: 18 December 2014 – Published in Atmos. Chem. Phys. Discuss.: 21 January 2015
Revised: 10 December 2015 – Accepted: 12 January 2016 – Published: 4 February 2016

Abstract. Estimates of the natural CO$_2$ flux over Europe inferred from in situ measurements of atmospheric CO$_2$ mole fraction have been used previously to check top-down flux estimates inferred from space-borne dry-air CO$_2$ column (X$_{CO_2}$) retrievals. Several recent studies have shown that CO$_2$ fluxes inferred from X$_{CO_2}$ data from the Japanese Greenhouse gases Observing SATellite (GOSAT) and the Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY (SCIAMACHY) have larger seasonal amplitudes and a more negative annual net CO$_2$ balance than those inferred from the in situ data. The cause of this elevated European uptake of CO$_2$ is still unclear, but some recent studies have suggested that this is a genuine scientific phenomenon. Here, we put forward an alternative hypothesis and show that realistic levels of bias in GOSAT data can result in an erroneous estimate of elevated uptake over Europe. We use a global flux inversion system to examine the relationship between measurement biases and estimates of CO$_2$ uptake from Europe. We establish a reference in situ inversion that uses an Ensemble Kalman Filter (EnKF) to assimilate conventional surface mole fraction observations and X$_{CO_2}$ retrievals from the surface-based Total Carbon Column Observing Network (TCCON). We use the same EnKF system to assimilate two independent versions of GOSAT X$_{CO_2}$ data. We find that the GOSAT-inferred European terrestrial biosphere uptake peaks during the summer, similar to the reference inversion, but the net annual flux is 1.40 ± 0.19 GtC a$^{-1}$ compared to a value of 0.58 ± 0.14 GtC a$^{-1}$ for our control inversion that uses only in situ data. To reconcile these two estimates, we perform a series of numerical experiments that assimilate observations with added biases or assimilate synthetic observations for which part or all of the GOSAT X$_{CO_2}$ data are replaced with model data. We find that for our global flux inversions, a large portion (60–90%) of the elevated European uptake inferred from GOSAT data in 2010 is due to retrievals outside the immediate European region, while the remainder can largely be explained by a sub-ppm retrieval bias over Europe. We use a data assimilation approach to estimate monthly GOSAT X$_{CO_2}$ biases from the joint assimilation of in situ observations and GOSAT X$_{CO_2}$ retrievals. The inferred biases represent an estimate of systematic differences between GOSAT X$_{CO_2}$ retrievals and the inversion system at regional or sub-regional scales. We find that a monthly varying bias of up to 0.5 ppm can explain an overestimate of the annual sink of up to 0.20 GtC a$^{-1}$. Our results highlight the sensitivity of CO$_2$ flux estimates to regional observation biases, which have not been fully characterized by the current observation network. Without further dedicated measurements we cannot prove or disprove that European ecosystems are taking up a larger-than-expected amount of CO$_2$. More robust inversion

Published by Copernicus Publications on behalf of the European Geosciences Union.
systems are also needed to infer consistent fluxes from multiple observation types.

1 Introduction

Observed atmospheric variations of carbon dioxide (CO$_2$) are due to atmospheric transport and surface flux processes. Using prior knowledge of the spatial and temporal distribution of these fluxes and atmospheric transport it is possible to infer (or invert for) the a posteriori estimate of surface fluxes from atmospheric concentration data. The geographical scarcity of such observations precludes robust flux estimates for some regions due to large uncertainties associated with meteorology and a priori fluxes. Arguably, our knowledge of top-down estimates of regional CO$_2$ fluxes, particularly at tropical and high northern latitudes, has not significantly improved for over a decade (Gurney et al., 2002; Peylin et al., 2013), reflecting the difficulty of maintaining a surface measurement programme over vulnerable and inhospitable ecosystems. Atmospheric transport model errors compound errors introduced by poor observation coverage, resulting in significant differences between flux estimates on spatial scales < O(10 000 km) (e.g. Law et al., 2003; Yuen et al., 2005; Stephens et al., 2007).

The Greenhouse gases Observing SATellite (GOSAT), a space-borne mission launched in a sun-synchronous orbit in early 2009, was purposefully designed to measure CO$_2$ columns using short-wave IR wavelengths. Validation of current X$_{CO_2}$ column retrievals using co-located upward-looking FTS measurements of the Total Carbon Column Observing Network (TCCON) (Wunch et al., 2011) shows a standard deviation of 1.6–2.0 ppm (e.g., Parker et al., 2013). Their global biases are typically smaller than 0.5 ppm (Oschchepkov et al., 2013). The disadvantage of using the TCCON is that sites are mainly at northern extra-tropical latitudes with little or no coverage where our knowledge of the carbon cycle is weakest. Many surface flux estimation algorithms are particularly sensitive to systematic errors so that sub-ppm biases can still significantly change the patterns of regional flux estimates (Chevallier et al., 2010). This is further complicated by the seasonal coverage of GOSAT data at high latitudes during winter months when solar zenith angles are too large to retrieve reliable values for X$_{CO_2}$ (Liu et al., 2014).

Several independent studies have shown that regional flux distributions inferred from GOSAT X$_{CO_2}$ retrievals are significantly different from those inferred from in situ data (Basu et al., 2013; Deng et al., 2014; Chevallier et al., 2014). In particular, these studies report a larger-than-expected annual net emission over tropical continents and a larger-than-expected net annual uptake over Europe. While the GOSAT inversions suffer from larger observation errors, atmospheric transport errors and issues from the seasonal coverage of higher latitudes, the in situ inversions are also unreliable over many regions due to poor coverage and atmospheric transport errors. Inter-comparisons revealed significant inconsistency in regional flux estimates inferred from in situ observations by using different inversion systems, over many regions important for global carbon cycle, including Europe (Peylin et al., 2013). Consequently, there is an ongoing debate about whether a recent study that shows a large European uptake of CO$_2$ (Reuter et al., 2014) reflects a real phenomenon or is an artefact due to deficiencies both in the observations and in the inverse modelling.

We report the results from a small set of experiments that show systematic bias can introduce a large difference between European fluxes inferred from GOSAT and those inferred from in situ data by using a global flux inversion approach. In the next section we provide an overview of the inverse model framework used to interpret data from the in situ observation network (including both the conventional surface observation network and the relatively new TCCON network), and from the space-based GOSAT X$_{CO_2}$ data. In Sect. 3, we present results from two groups of global inversion experiments that characterize the role of systematic bias in regional flux estimates. Further experiments for quasi-regional flux inversions are presented in Appendix A. In Sect. 4, we use a modified version of the inverse model framework to estimate monthly biases by jointly assimilating all data. We conclude the paper in Sect. 5.

2 Description and evaluation of control in situ and GOSAT experiments

We use the GEOS-Chem global chemistry transport model to relate surface fluxes to the observed variations of atmospheric CO$_2$ concentrations (Feng et al., 2009) at a horizontal resolution of 4° × 5°, driven by GEOS-5 meteorological analyses from the Global Modeling and Assimilation Office Global Circulation Model based at NASA Goddard Space Flight Centre. We use an Ensemble Kalman Filter (EnKF) (Feng et al., 2009, 2011) to estimate regional fluxes from in situ or GOSAT observations for 3 years from 2009–2011, but we focus on 2010 to minimize error due to spin-up and edge effects. We estimate monthly fluxes on a spatial distribution that is based on TransCom-3 (Gurney et al., 2002) with each continental region further divided equally into 12 sub-regions and each ocean region further divided equally into six sub-regions. As a result, we estimate fluxes for 199 regions, compared to 144 regions we have used in previous studies (Feng et al., 2009; Chevallier et al., 2014).

In all global inversion experiments we assume the same set of a priori flux inventories, including the following: (1) monthly fossil fuel emissions (Oda and Maksyutov, 2011); (2) weekly biomass burning emissions (GFED v3.0) (van der Werf et al., 2010); (3) monthly oceanic surface CO$_2$ fluxes (Takahashi et al., 2009); and (4) 3-hourly terrestrial biosphere-atmosphere CO$_2$ exchange (Olsen and Ran...
Table 1. The magnitude and uncertainty of the European annual CO₂ biosphere flux (GtC a⁻¹) from 14 global flux inversion experiments. Except INV_ACOS_INS_DBL_ERR and INV_ACOS_DBL_ERR, the aggregated European annual uptake of the a priori fluxes is −0.1 ± 0.52 GtC a⁻¹.

<table>
<thead>
<tr>
<th>Name</th>
<th>Data</th>
<th>Flux (GtC a⁻¹)</th>
<th>Uncertainty (GtC a⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INV_TCCON</td>
<td>In situ Flask and TCCON XCO₂</td>
<td>−0.58</td>
<td>0.14</td>
</tr>
<tr>
<td>INV_ACOS</td>
<td>ACOS XCO₂ retrievals</td>
<td>−1.40</td>
<td>0.19</td>
</tr>
<tr>
<td>INV_UOL</td>
<td>UOL XCO₂ retrievals</td>
<td>−1.4</td>
<td>0.20</td>
</tr>
<tr>
<td>INV_ACOS_MOD_ALL</td>
<td>Model simulation of ACOS XCO₂ by using INV_TCCON posterior fluxes</td>
<td>−0.64</td>
<td>0.19</td>
</tr>
<tr>
<td>INV_ACOS_MOD_NOEU</td>
<td>As INV_ACOS_MOD_ALL but the real ACOS XCO₂ retrievals are assimilated within Europe.</td>
<td>−0.88</td>
<td>0.19</td>
</tr>
<tr>
<td>INV_UOL_MOD_NOEU</td>
<td>As INV_UOL, but outside the Europe, UOL XCO₂ retrievals are replaced with INV_TCCON simulations.</td>
<td>−0.67</td>
<td>0.19</td>
</tr>
<tr>
<td>INV_ACOS_MOD_ONLYEU</td>
<td>As INV_ACOS, but XCO₂ retrievals within EU are replaced by INV_TCCON simulations.</td>
<td>−1.17</td>
<td>0.19</td>
</tr>
<tr>
<td>INV_ACOS_OUT_0.5ppm</td>
<td>As INV_ACOS, but a bias of −0.5 ppm has been added to XCO₂ retrievals outside Europe.</td>
<td>−0.98</td>
<td>0.19</td>
</tr>
<tr>
<td>INV_ACOS_SPR_0.5ppm</td>
<td>As INV_ACOS, but 0.5 ppm bias has been added to the European data in February, March, and April.</td>
<td>−1.30</td>
<td>0.19</td>
</tr>
<tr>
<td>INV_ACOS_SUM_0.5ppm</td>
<td>As INV_ACOS, but 0.5 ppm bias has been added to the European data in June, July, and August.</td>
<td>−1.25</td>
<td>0.19</td>
</tr>
<tr>
<td>INV_ACOS_INS</td>
<td>ACOS XCO₂ retrievals and In situ flask and TCCON data</td>
<td>−0.62</td>
<td>0.13</td>
</tr>
<tr>
<td>INV_UOL_INS</td>
<td>UOL XCO₂ retrievals and in situ flask and TCCON data</td>
<td>−0.67</td>
<td>0.13</td>
</tr>
<tr>
<td>INV_ACOS_DBL_ERR</td>
<td>ACOS XCO₂ retrievals, but the a priori uncertainties have been doubled</td>
<td>−1.61</td>
<td>0.27</td>
</tr>
<tr>
<td>INV_ACOS_INS_DBL_ERR</td>
<td>GOSAT ACOS XCO₂ retrievals and In situ flask and TCCON data but the a priori flux uncertainties have been doubled</td>
<td>−0.67</td>
<td>0.16</td>
</tr>
</tbody>
</table>

We assume that the a priori uncertainty for each land sub-region is proportional to a combination of the net biospheric emission (70%) at the current month, and its annual variation (30%). We also assume that the a priori errors are correlated with each other with a spatial correlation length of 800 km, and a temporal correlation of 1 month (Chevallier et al., 2014). We then determine the coefficient for the assumed a priori uncertainty by scaling the aggregated annual uncertainty over all 133 land sub-regions to 1.9 GtC a⁻¹. In particular, the resulting annual a priori uncertainty for the European region is about 0.52 GtC a⁻¹, with the monthly uncertainty varying from 2.0 GtC a⁻¹ for the summer months to about 0.8 GtC a⁻¹ for winter months, which is generally larger than the a priori monthly uncertainty used by Deng et al. (2014). Prior uncertainties over oceans are determined under similar assumption but with a longer spatial correlation (1500 km), and a smaller aggregated annual error (0.6 GtC a⁻¹). Our experiments show that doubling the a priori uncertainty increases the European uptake inferred from GOSAT data by about 0.21 GtC a⁻¹ (from 1.40 to 1.61 GtC a⁻¹), compared to a smaller increase of 0.09 GtC a⁻¹ for the in situ inversion (from 0.58 to 0.67 GtC a⁻¹).

Our control inversion experiment (INV_TCCON, Table 1 and Fig. 1) assimilates in situ observations, including the conventional surface observations at 76 sites (Feng et al., 2011) and, in particular, the total column XCO₂ retrievals from all the TCCON sites of the GGG2014 data set (see Wennberg et al., 2014, and https://tccom-wiki.caltech.edu for more details) to improve observation constraints. In some studies, TCCON data were used to evaluate posterior fluxes. However TCCON data have been used to derive bias corrections for GOSAT XCO₂ retrievals (Cogan et al., 2012), and also the nature of total column measurements means that they are sensitive to air mass transported from other regions, which complicate the assessment of European flux estimates.

We use daytime (09:00 to 15:00 local time) mean TCCON retrievals, with the observation errors determined by the standard deviation about their daytime mean. To account for the inter-site biases as well as the model representation errors, we enlarge the TCCON observation errors by 0.5 ppm. Including TCCON observations increases the annual net uptake over Europe in 2010 from 0.49 GtC a⁻¹, as inferred from surface observations only, to 0.58 GtC a⁻¹. The increase is mainly due to a larger summer uptake. TCCON data also reduce the a posteriori uncertainty by about 15% from 0.16 to 0.14 Gt a⁻¹. However considering the limited spatial resolu-
As a performance indicator for our ability to fit fluxes in 2010 using three inversion experiments (e.g., Deng et al., 2014; Chevallier et al., 2014). But the GOSAT inversions have an annual net uptake of about 1.40 \pm 0.19 GtC a\(^{-1}\) compared to the in situ inversion of 0.58 \pm 0.14 GtC a\(^{-1}\). Figure 1 also shows significant differences between their monthly flux estimates in early spring and winter when there is only sparse GOSAT observation coverage, particularly over northern Europe. Both INV_UOL and INV_ACOS have a cumulative total of about 0.51 GtC more uptake than INV_TCCON during February–April of 2010, with a further 0.37 GtC uptake accumulated over the following summer and autumn. This larger uptake is partially cancelled out by larger emissions (0.17–0.08 GtC) at the end of 2010.

Figure 2 shows that INV_TCCON a posteriori CO\(_2\) mole fractions agree well with the independent HIAPER Pole-to-Pole Observations (HIPPO-3) aircraft measurements below 5 km over the Pacific Ocean in 2010 (Wofsy et al., 2011), with a small bias of 0.05 ppm, and a sub-ppm standard deviation.

### 3 Results

Figure 1 and Table 1 shows the three inversion experiments, INV_TCCON, INV_ACOS, and INV_UOL, have similar European uptake values in June 2010 (0.69 GtC for INV_TCCON and \(\sim 0.72\) GtC for GOSAT inversions), and are generally consistent with other GOSAT inversion experiments (e.g., Deng et al., 2014; Chevallier et al., 2014).
tematic differences in the inflow into the European domain

INV_TCCON simulation and the hybrid run reveals that sys-

tematically higher than the INV_TCCON simulation, in

particular during spring months, despite the same European

expected, higher than the a posteriori model concentrations

from GOSAT data is incorrect, because unaccounted small

local emissions and/or sinks, and model transport errors can

affect the comparison against aircraft observations.

Figure 3 also presents an additional model simulation

forced by a hybrid flux (denoted by the magenta broken

line) where the INV_TCCON a posteriori fluxes outside Eu-

rope are replaced by the results from INV_ACOS. The re-

sulting CO₂ concentrations from these hybrid fluxes are, as

expected, higher than the a posteriori model concentrations

for INV_ACOS because of the larger European emissions

(i.e., less uptake) inferred by INV_TCCON. But they are also

systematically higher than the INV_TCCON simulation, in

particular during spring months, despite the same European

fluxes being used to force these two simulations. This sugges-
tes an overestimate of CO₂ transported into the European

region by the GOSAT inversions. Further comparison of the

INV_TCCON simulation and the hybrid run reveals that sys-
tematic differences in the inflow into the European domain

can affect the atmospheric X₂CO₂ gradient across this region.

In the INV_TCCON simulation, the mean X₂CO₂ differ-
ence between east (east of 20° E) and west (west of 20° E) Europe is

−0.04 ppm for May 2010, which is increased to 0.16 ppm

in the hybrid run (cf. E–W X₂CO₂ gradient of −0.20 ppm for

GOSAT ACOS data).

To understand the differences between the INV_TCCON

and GOSAT inversions, we conducted two groups of sen-

sitivity tests (Table 1 and Fig. 4). First, we replaced all or part of the GOSAT X₂CO₂ retrievals assimilated in

INV_ACOS with those from a model simulation forced by the a posteriori fluxes from INV_TCCON. In experiment

INV_ACOS_MOD_ALL (Fig. 4), where we replace all GOSAT data with CO₂ concentrations inferred from

INV_TCCON, we reproduce INV_TCCON with small excep-

tions at the beginning of 2010, reflecting the sea-

sonal variation in GOSAT coverage. In a related experi-

ment INV_ACOS_MOD_NOEU for which we only re-

place X₂CO₂ retrievals outside Europe with the model simu-

lation, the differences between the GOSAT and in situ

inversions are significantly reduced, particularly over the

period with limited observation coverage, although the ac-

tual X₂CO₂ retrievals are still assimilated over Europe. The

simulated GOSAT data outside Europe reduces the esti-

mate of European uptake from 1.40 to 0.88 GtC a⁻¹. In

other words, the GOSAT observations outside the Euro-

pean region are responsible for about 60 % (0.52 GtC a⁻¹)
of the total enhanced European sink (0.82 GtC a⁻¹) with

the remainder (0.30 GtC a⁻¹) due to observations taken di-

rectly over Europe. The large contribution from GOSAT

retrievals outside Europe has also been confirmed by the

high uptake (1.17 GtC a⁻¹) in a counterpart experi-

ment INV_ACOS_MODONLYEU where only GOSAT

retrievals within Europe are replaced by the model simu-

lations. We show in Appendix B that theoretically the dif-

ference between INV_ACOS and INV_ACOS_MOD_ALL

is equal to the sum of the individual uptake increases in

the paired synthetic inversions of INV_ACOS_MOD_NOEU

and INV_ACOS_MODONLYEU.

For INV_UOL, when we replace the X₂CO₂ data out-

side Europe by the a posteriori INV_TCCON model simu-

lations, European uptake is reduced to 0.67 GtC a⁻¹

(INV_UOL_MODNOEU, Table 1), indicating an exter-

nal contribution of nearly 90 % to the enhanced uptake of

0.82 GtC a⁻¹. Together with Fig. 3, these results suggest that

GOSAT inversions result in an overestimated CO₂ inflow.

This will subsequently lead to the fitted European flux hav-

ing to compensate, via mass balance, by being erroneously

low even when un-biased GOSAT X₂CO₂ data are assimilated

over the immediate European region. We find similar effects

in the quasi-regional inversions (Fig. A1 in Appendix A),

where only observations within the European region are as-

similated, with flux estimates from INV_TCCON or from

INV_ACOS being used to provide lateral boundary condi-

tions around Europe.

Figure 3. Monthly mean observed and model a posteriori model

CO₂ mole fractions (ppm) below 3 km above Amsterdam (the top

panel) and Moscow (the bottom panel) airports during 2010, re-

spectively (Machida et al., 2008). The three sets of a posteriori

model concentrations are inferred from three inversion experi-

ments: INV_TCCON (red line), INV_ACOS (green line), and INV_UOL

(blue line). The broken magenta line represents a model simulation

where the European fluxes from INV_ACOS inversion are replaced

by INV_TCCON estimates.

<table>
<thead>
<tr>
<th>Month</th>
<th>CO₂ (ppm)</th>
<th>Amsterdam (52.3N, 4.8E)</th>
<th>Moscow (55.4N, 37.9E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>384</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
<tr>
<td>Feb</td>
<td>385</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
<tr>
<td>Mar</td>
<td>385</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
<tr>
<td>Apr</td>
<td>384</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
<tr>
<td>May</td>
<td>384</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
<tr>
<td>Jun</td>
<td>384</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
<tr>
<td>Jul</td>
<td>384</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
<tr>
<td>Aug</td>
<td>384</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
<tr>
<td>Sep</td>
<td>384</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
<tr>
<td>Oct</td>
<td>384</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
<tr>
<td>Nov</td>
<td>384</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
<tr>
<td>Dec</td>
<td>384</td>
<td>INV_TCCON</td>
<td>INV_ACOS</td>
</tr>
</tbody>
</table>

For INV_UOL, when we replace the X₂CO₂ data out-

side Europe by the a posteriori INV_TCCON model simu-

lations, European uptake is reduced to 0.67 GtC a⁻¹

(INV_UOL_MODNOEU, Table 1), indicating an exter-

nal contribution of nearly 90 % to the enhanced uptake of

0.82 GtC a⁻¹. Together with Fig. 3, these results suggest that

GOSAT inversions result in an overestimated CO₂ inflow.

This will subsequently lead to the fitted European flux hav-

ing to compensate, via mass balance, by being erroneously

low even when un-biased GOSAT X₂CO₂ data are assimilated

over the immediate European region. We find similar effects

in the quasi-regional inversions (Fig. A1 in Appendix A),

where only observations within the European region are as-

similated, with flux estimates from INV_TCCON or from

INV_ACOS being used to provide lateral boundary condi-

tions around Europe.
Figure 4. Monthly European biospheric flux estimates (GtC) from two groups of sensitivity experiments (top panel, Table 1). Black, green and red solid lines denote the a priori and the INV_ACOS and INV_TCCON inversions, respectively. Differences between INV_TCCON inversion and sensitivity inversions (bottom panel): (1) INV_ACOS_MOD_ALL (yellow), where all GOSAT retrievals are replaced by the model simulations forced by INV_TCCON a posteriori fluxes; (2) INV_ACOS (green), where original GOSAT ACOS retrievals are assimilated; (3) INV_ACOS_NOEU (blue) where all the GOSAT retrievals outside the European region are replaced by the INV_TCCON simulations; and (4) INV_ACOS_MOD_ONLYEU (cyan) where only GOSAT retrievals within the European region are replaced by the INV_TCCON simulations.

Second, we crudely demonstrate how regional bias could explain the remaining discrepancy of up to 0.30 GtC a\(^{-1}\) between GOSAT and in situ inversions over Europe. In our experiment INV_ACOS_SPR_0.5ppm, we add a bias of +0.5 ppm to the GOSAT ACOS retrievals within Europe taken in February–April, inclusively, which effectively reduces the uptake by 0.1 GtC a\(^{-1}\) from 1.40 to 1.30 GtC a\(^{-1}\). Similarly, when the bias of +0.5 ppm is added to the GOSAT data taken in June–August we find a larger reduction of 0.15 GtC a\(^{-1}\) (INV_ACOS_SUM_0.5ppm), partially due to a larger a priori uncertainty and denser GOSAT coverage during the summer. These results emphasize the importance of characterizing sub-ppm regional bias to avoid erroneous flux estimates.

4 Bias estimation

Here we demonstrate a simple approach to quantify systematic bias in \(X_{\text{CO}_2}\) retrievals based on a simple on-line bias correction scheme. We assimilate the GOSAT \(X_{\text{CO}_2}\) retrievals together with the surface and TCCON observations in two experiments: INV_ACOS_INS and INV_UOL_INS (Table 1). We also include monthly GOSAT \(X_{\text{CO}_2}\) regional biases over 11 TransCom land regions (Gurney et al., 2002) as parameters to be inferred together with surface fluxes from the joint assimilation of in situ and satellite observations. To investigate the spatial pattern of the \(X_{\text{CO}_2}\) biases within Europe, we split Europe into West Europe (west of 20° E) and East Europe (east of 20° E). We assume that a priori for monthly biases is 0.0 ± 0.5 ppm. For simplicity, we have assumed that the a priori errors for regional \(X_{\text{CO}_2}\) biases are not correlated. Compared to the off-line comparisons between GOSAT \(X_{\text{CO}_2}\) retrieval and model concentrations, the main advantage of the on-line bias estimation is that the uncertainties associated with error in flux estimates can be partially taken into account. However, biases derived by this approach reflect the systematic difference between the model simulation and GOSAT data over large (continental) regions, which also contain systematic model errors (such as the atmospheric transport and representation errors). In addition, the inversion results are affected by the relative weights assigned to different data sets, as well as by the relative prior uncertainty assumed for surface fluxes and for the observation bias. The seasonal variation of the mean \(X_{\text{CO}_2}\) concentration is an important sign of the underlined biosphere seasonal cycle. We show in Appendix A that when we inflate the a priori uncertainty for the assumed observation bias, the observation constraints on flux estimate will become weaker. Also, the on-line bias correction is only effective for detecting and correcting bias at specified patterns, which may increase the sensitivity to other uncharacterized systematic errors. Despite these weaknesses, a joint data assimilation approach can exploit complementary constraints from in situ and satellite \(X_{\text{CO}_2}\) data: for example there are few GOSAT observations over northern Europe during autumn and winter months, while Eastern Europe has few in situ observations. We have also limited the a priori uncertainty for the monthly observation biases to 0.5 ppm. Figure C1 (Appendix C) shows, for example, the inferred monthly mean bias for March 2010.

In the joint inversions INV_ACOS_INS and INV_UOL_INS, the annual European uptake is estimated to be 0.62 and 0.67 GtC a\(^{-1}\), respectively (Table 1), which is close to the reference value of 0.58 GtC a\(^{-1}\) inferred from the in situ observations. To test the impact of the on-line bias correction, we set the a priori uncertainty of regional \(X_{\text{CO}_2}\) bias to 0.01 ppm so that on-line bias correction is effectively turned off. As a result, the annual European uptake for INV_ACOS_INS is increased by 0.15 GtC to 0.77 GtC a\(^{-1}\), which is close to INV_ACOS_MOD_NOEU, but about 55% of the GOSAT only inversions (1.40 GtC a\(^{-1}\)).

Figure 5 shows the estimated monthly biases in ACOS and UOL \(X_{\text{CO}_2}\) retrievals over East and West Europe during 2010. Monthly biases are typically smaller than 0.5 ppm over the two regions, but have different seasonal cycles. Additional experiment shows that after ACOS \(X_{\text{CO}_2}\) data over Europe have been corrected for the inferred biases, the European annual uptake by INV_ACOS is reduced by
shows that reducing ACOS XCO2 biases (ppm) results in a significant increase in European annual uptake from 1.40 to 0.98 GtC a\(^{-1}\). ERRONEOUS interpretation of XCO2 data can result from analyses if biased boundary conditions are not addressed. However, as shown in Appendix A, a gross mis-characterization and correction of bias may weaken observation constraints, which can also lead to erroneous flux estimates.

We also showed using sensitivity tests that sub-ppm bias can explain the remaining 0.30 GtC a\(^{-1}\) flux difference between the in situ inversion and INV_ACOS after accounting for biased boundary conditions. By simultaneously assimilating the in situ and GOSAT observations to estimate surface fluxes and monthly XCO2 biases, we infer a monthly observation bias that is typically less than 0.5 ppm over East and West Europe, but is able to cause an elevated sink of up to 0.20 GtC a\(^{-1}\). The inferred monthly biases for UOL XCO2 are not the same as the ACOS XCO2 data, particularly over West Europe during the summer months. This level of sensitivity of regional flux estimate to time-varying sub-ppm observation bias highlights the challenges we face as a community when evaluating XCO2 retrievals using current observation networks.

Flux estimates are sensitive to a priori assumptions, idiosyncrasies of applied inversion algorithms, and the underlying model atmospheric transport (Chevallier et al., 2014; Peylin et al., 2013; Reuter et al., 2014). The possible presence of regional observation biases further complicates the inter-comparisons of flux estimates based on different inversion approaches, as they may have different sensitivities to certain observation biases. In our assimilation of ACOS XCO2 retrievals, we find that doubling the a priori flux error (INV_ACOS_DBL_ERR) increases the estimated European uptake from 1.40 to 1.61 GtC a\(^{-1}\), consistent with the hypothesis on the increased vulnerability to the observation biases both within and outside Europe when using weak a priori constraints. In contrast, doubling the a priori flux errors only increases the uptake by 0.05 to 0.67 GtC a\(^{-1}\) for the joint data assimilation (INV_ACOS_INS_DBL_ERR), with very little changes in the estimated biases (not shown). Examples in Appendix A also demonstrate different responses to regional and sub-regional biases before and after an online scheme is used to correct the systematic error across Europe. These differences emphasize the need for a closer examination of the responses of the inversion systems to the assimilated observations, as well as to their possible biases, to help understand the inter-model variations in estimated regional fluxes.

Complicated interactions between observations and the assimilation system also mean that our present study does not exclude other possible causes for the elevated European uptake reported by previous research from assimilation of GOSAT data. Instead, it highlights the adverse effects of possibly uncharacterized regional biases in current GOSAT XCO2 retrievals that can attract erroneous interpretation of resulting regional flux estimates. A more thorough evaluation

**Figure 5.** Estimates of monthly CO2 biases (ppm) in GOSAT ACOS (green) and UOL (blue) XCO2 retrievals over (top) West (West of 20\(^{\circ}\) E) and (bottom) East (East of 20\(^{\circ}\) E) Europe. The black vertical lines represent the uncertainty.
of the XCO₂ retrievals using independent and sufficiently accurate and/or precise observations is urgently required to increase the confidence of regional CO₂ flux estimates inferred from space-based observations. Without additional observations, we cannot rule out either the lower European uptake estimate of around 0.6 GtC a⁻¹ (inferred from the in situ inversion INV_TCCON and the joint inversion INV_ACOS_INS and INV_UOL_INS) or the higher European uptake estimate of around 1.40 GtC a⁻¹ (inferred from GOSAT data). There is also no sufficient reason to believe that the mean value among these diverse estimates is more reliable, because our study suggests that small systematic errors can result in significant differences in the estimated fluxes, and the influences of random errors have also not been fully quantified. The observational density required to infer flux estimates over a limited spatial domain such as Europe is crucial. For the time frame of this analysis, the TCCON network provided good coverage for Europe, North America, Southeast Asia and Australia and New Zealand. Great efforts were also taken to reduce inter-station biases. In future the TCCON measurement network may be supported by smaller, more mobile FTIR instruments, which can be established, at least on a campaign basis, in tropical and high latitude locations where observational gaps are greatest.

Our joint data assimilation approach assimilates in situ and space-borne observations. It also provides estimates of systematic differences between XCO₂ retrievals and the inversion system at regional/sub-regional scales. However the resulting differences will include the observation biases and deficiencies in the underlying inversion approach. To achieve consistent flux estimates inferred from assimilating multiple data sets using different inversion approaches, we need to better quantify observation and model errors, and need to better understand the sensitivity of each inversion system to the assimilated observations as well as to their possible biases. It is difficult to develop a robust bias correction scheme before properly characterizing observation biases and the responses by the inversion system.
Appendix A: Quasi-regional flux inversion

To further study the contributions from $X_{CO_2}$ retrievals within and outside Europe we have performed quasi-regional flux inversions to infer the European uptake of $CO_2$ in 2010, based on the same EnKF approach as the global flux inversions. In contrast to the global experiments (Table 1), for the quasi-regional inversions we assimilate observations only over Europe, and assign a small a priori flux uncertainty to any region outside Europe in order to minimize the influence of observations taken over Europe on other regions. Consequently, a posteriori flux estimates outside of Europe are close to their a priori values. We use the a posteriori fluxes from INV_TCCON as the a priori estimates for 12 sub-regions in Europe, and assume their uncertainty is two thirds of that we use for the global flux inversions. This is because the a posteriori estimates from INV_TCCON have already been refined by in situ data.

To investigate the influence of lateral boundary conditions on the quasi-regional flux inversions, we use two different sets of a posteriori estimates to define fluxes outside Europe: (1) INV_TCCON (INV_BD_TCCON) and (2) INV_ACOS (INV_BD_ACOS). Figure A1 shows that INV_BD_ACOS has a higher annual uptake of 1.58 GtC a$^{-1}$ than INV_BD_TCCON with an uptake of 0.79 GtC a$^{-1}$ (Table A1), with differences larger during the first half of 2010. The estimate for INV_BD_ACOS is similar to its global inversion counterpart INV_ACOS. Large differences between INV_BD_ACOS and INV_BD_TCCON highlight the importance of accurate lateral boundary conditions to a regional European inversion.

We use on-line bias correction schemes to reduce the adverse impacts from incorrect boundary conditions around Europe. Similar to Reuter et al. (2014), we estimate monthly observation biases across Europe using our quasi-regional flux inversion system. Here, we introduce a monthly bias to remove the systematic difference between model and GOSAT observations across the whole European region, and assume an associated a priori uncertainty of 100 ppm (Reuter et al., 2014). This is different from our previous bias assumption of 0.5 ppm over East and West Europe for INV_ACOS_INS. Compared to INV_ACOS_INS, we also do not assimilate any in situ observations as additional constraints. Figure A1 shows that such a bias correction scheme (INV_BD_ACOS_BC) successfully reduces European uptake of $CO_2$ during 2010 to 0.96 GtC a$^{-1}$ from 1.58 GtC a$^{-1}$ for INV_BD_ACOS. Table A1 shows that after applying the bias correction scheme, INV_BD_ACOS_BC and INV_BD_TCCON_BC are consistent (0.94 GtC a$^{-1}$ vs. 0.96 GtC a$^{-1}$) despite different lateral boundary conditions provided by INV_ACOS and from INV_TCCON. But INV_BD_TCCON_BC (0.94 GtC a$^{-1}$) has 0.15 GtC a$^{-1}$ more uptake than INV_BD_TCCON (0.79 GtC a$^{-1}$). We find a similar difference using UOL data (not shown), which infer an annual uptake of 0.71 GtC a$^{-1}$ (0.56 GtC a$^{-1}$) with (without) the on-line bias correction.

We next examine the effectiveness of the inversion system that uses an on-line bias correction with large a priori uncertainty. Generally, large a priori uncertainty for biases will lead to the eventual loss of constraint by the observed mean $CO_2$ concentration across Europe. The weakened constraint can be seen by the enlarged posterior error (by 0.04 GtC a$^{-1}$) for INV_BD_TCCON_BC. In additional OSSEs (Table A2) we find that the loss of such a constraint can result in large systematic errors in estimated fluxes.

In these OSSEs, we assume the a priori estimates for 12 European sub-regions to be the same as the a priori used by INV_TCCON. Similar to INV_BD_TCCON, we set the fluxes outside the European region to be the a posteriori estimates by INV_TCCON. We assimilate the INV_TCCON model ACOS $X_{CO_2}$ retrievals over Europe, to test the ability of the system to recover the "true" European flux (defined by INV_TCCON) from the assumed a priori that we define as the CASA model. Without the on-line bias correction, the quasi-regional inversion INV_REG_ENKF reproduces the truth for most months (Fig. A2), and the associated annual uptake of 0.55 GtC a$^{-1}$ compared to the true value of 0.58 GtC a$^{-1}$. If we also estimate monthly $X_{CO_2}$ bias with a large a priori uncertainty of 100 ppm (INV_REG_BC), the a
posteriori European uptake is systematically underestimated for almost all months in 2010 (Fig. A2). Consequently, the a posteriori annual uptake is about 0.38 GtC a\(^{-1}\), which is 35 % smaller than the true uptake (Table A2). Weakening the observation constraint also enlarges the a posteriori uncertainty from 0.22 GtC a\(^{-1}\) for INV_REG_ENKF to 0.27 for INV_REG_BC. But we find that increases in the estimated a posteriori uncertainty (by 0.05 GtC a\(^{-1}\)) are smaller than the increase in the systematic deviation from the true annual uptake (by 0.19 GtC a\(^{-1}\)).

More importantly, we find that the derived annual uptake is not linearly correlated to the assumed true fluxes.

In experiment INV_REG_BC_SP (Table A2) we replace the true fluxes (defined by INV_TCCON) over the first 3 of 12 European sub-regions, which are at the southern part of Europe (roughly south of 47\(^\circ\) N), with values from CASA model. As a result, the new true fluxes have an annual uptake of about 0.48 GtC a\(^{-1}\) across Europe, which is about 18 % (0.1 GtC a\(^{-1}\)) lower than the original one defined by INV_TCCON for INV_REG_BC. We then regenerate model ACOS X\(_{\text{CO}}\) data by running GEOS-Chem driven by the new hybrid true fluxes. However, after assimilating the new model X\(_{\text{CO}}\) data, INV_REG_BC_SP infers an annual uptake of 0.37 GtC a\(^{-1}\), which is almost the same as the posterior estimate (0.38 GtC a\(^{-1}\)) of INV_REG_BC, failing to reproduce the 18 % decrease from the true value of 0.58 GtC a\(^{-1}\) assumed for INV_REG_BC to the 0.48 GtC a\(^{-1}\) assumed for INV_REG_BC_SP. In contrast, the quasi-inversion without on-line bias correction (INV_REG_ENKF_SP) well reproduces such a decrease. The bias correction across Europe can also increase the sensitivity to sub-regional biases. To illustrate this we added 1 ppm bias to the simulated observations during June to August of 2010 over south-west Europe between 35 to 42\(^\circ\) N and 15\(^\circ\) E to 20\(^\circ\) W (mostly over Spain and Italy). Without an on-line bias correction, adding the 1 ppm bias over the south-west strip leads to a small change (0.01 GtC a\(^{-1}\)) in the annual uptake: a (slightly) reduced uptake in the first half of 2010 is largely compensated by a slightly enhanced uptake in the second half of 2010. Conversely, when we use an on-line bias correction with large prior errors (INV_REG_BC_1ppm), the 1 ppm positive bias increases the uptake by about 0.24 GtC in June, July and August. This implies that without the constraint from the mean concentration across the whole European region, the inversion system is free to interpret the higher concentrations over the small south-west strip as the signal of more uptakes over other larger parts of Europe. As a result, the annual uptake changes from an underestimation of 35 % by INV_REG_BC to an overestimation of 15 % by INV_REG_BC_1ppm (0.65 GtC a\(^{-1}\)) (Table A2).
Table A2. The same as Table A1 but for Observation System Simulation Experiments, where we assimilate synthetic ACOS X$_{CO_2}$ from model simulations forced by the assumed “true” fluxes.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Flux (GtC a$^{-1}$)</th>
<th>Uncertainty (GtC a$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INV_REG_ENKF</td>
<td>Synthetic ACOS data over Europe are assimilated to infer monthly fluxes over 12 European sub-regions, which prior estimates are assumed to be same as INV_ACOS (i.e., CASA model). Here we assume the true fluxes be a posteriori of INV_TCCON inversion.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INV_REG_BC</td>
<td>The same as INV_REG_ENKF, but estimates for monthly bias are included as additional parameters.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INV_REG_ENKF_1ppm</td>
<td>The same as INV_REG_ENKF, but 1 ppm bias is added to the synthetic observations over a strip at south-west Europe for 3 months from June to August in 2010.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INV_REG_BC_1ppm</td>
<td>The same as INV_REG_BC, 1 ppm bias is added to the synthetic observations over a strip at south-west Europe for 3 months from June to August in 2010.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INV_REG_ENKF_SP</td>
<td>The same as INV_REG_ENKF, but the “true fluxes” over the first 3 of the 12 European sub-regions are replaced by CASA model values.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INV_REG_BC_SP</td>
<td>The same as INV_REG_ENKF_SP, but with on-line bias correction with assumed prior uncertainty of 100 ppm.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In summary, our quasi-regional inversion experiments highlight the sensitivity of regional flux inversions to the accurate description of the boundary conditions around the domain. Using an on-line bias correction can be helpful when the bias has been properly characterized. Over-correcting the bias can weaken the observation constraints, and possibly increase sensitivity to other small-scale unknown biases. We have also tested bias correction schemes using a different inversion algorithm (the Maximum A Posteriori (MAP) approach, Fraser et al., 2014), and found similar deficiencies when the a priori uncertainty of the regional observation bias is assumed to be very large. Our studies cannot prove or disprove Reuter et al. (2014), but it does highlight previously unrecognized limitation to the approach. The diversity of results reached under different assumptions associated with observation biases and emission spatial patterns highlight the importance of investigating the interaction between observation and the inversion system for achieving consistent flux estimates in the future from assimilation of the up-coming observations from OCO-2 satellite as well as from the improved in situ networks.

Appendix B: Additivity of the increased European uptake estimates

In the framework of Kalman Filter data assimilation (Feng et al., 2009), posterior flux estimates are determined by

\[ f^u = f^f + K \left( y_{\text{obs}} - H \left( f^f \right) \right), \]  

where \( f^f \), \( f^u \) are the prior and posterior estimates of monthly regional surface CO$_2$ fluxes, respectively; \( y_{\text{obs}} \) represents the GOSAT (real or simulated) X$_{CO_2}$ retrievals. \( H \) is the observation operator for relating the surface fluxes to the observed GOSAT X$_{CO_2}$, which includes complicated atmospheric transporting as well as convolving of co-located model profiles with GOSAT averaging kernels (Feng et al., 2009; Chevallier et al., 2010). Here, the Kalman gain matrix \( K \) is given by

\[ K = BH^T \left( HH^T + R \right)^{-1}, \]  

where \( B \) is the a priori flux error covariance, \( R \) is the observation error covariance, and \( H \) is the Jacobian defined by

\[ H = \frac{\partial H(f^f)}{\partial f^f}. \]  

Although the atmospheric transport is non-linear, the dependence of model concentrations (such as the column mixing ratios X$_{CO_2}$) on the surface fluxes is nearly linear if we do not take into account any feedback of varying CO$_2$ concentrations on atmospheric dynamics (for example, Chevallier et al., 2010; Baker et al., 2006). As a result, the gain matrix is eventually independent of actual observation values, but will still be affected by the location and uncertainty of observations.

As described in the main text, we split the actual (or simulated) X$_{CO_2}$ observations into two parts: Part A for observations within Europe; and Part B for observations outside Europe. For the GOSAT inversions (such as INV_ACOS),
we denote the observation vector as
\[ y_{\text{obs}} = \begin{bmatrix} g^A \\ g^B \end{bmatrix}. \] (B4)

The corresponding posterior flux estimate is given as
\[ f^a_g = f^f + K \left( \begin{bmatrix} g^A \\ g^B \end{bmatrix} - H (f^f) \right). \] (B5)

In experiment INV_MOD_ALL, we replace the retrieved \( X_{\text{CO}_2} \) values by the reference model simulation (from INV_TCCON), so that the observation vector becomes
\[ y_{\text{obs}} = \begin{bmatrix} m^A \\ m^B \end{bmatrix}, \] (B6)

and the resulting flux estimates are:
\[ f^a_m = f^f + K \left( \begin{bmatrix} m^A \\ m^B \end{bmatrix} - H (f^f) \right). \] (B7)

The gain matrix in Eq. (B7) is the same as Eq. (B5). Similarly, for INV_MOD_ONLYEU where GOSAT \( X_{\text{CO}_2} \) retrievals over Europe are replaced by model simulations, we have
\[ f^a_{mg} = f^f + K \left( \begin{bmatrix} m^A \\ m^B \end{bmatrix} - H (f^f) \right). \] (B8)

And for INV_MOD_NOEU where GOSAT \( X_{\text{CO}_2} \) retrievals outside Europe are replaced by model simulations, we have
\[ f^a_{gm} = f^f + K \left( \begin{bmatrix} m^A \\ m^B \end{bmatrix} - H (f^f) \right). \] (B9)

From Eqs. (B5), (B7), (B8), and (B9), we can directly obtain
\[ f^a_g - f^a_m = \left( f^a_{gm} - f^a_m \right) + \left( f^a_{gm} - f^a_m \right). \] (B10)

Equation (B10) demonstrates that elevated European uptake is the sum of the individual contributions from INV_MOD_NOEU and INV_MOD_ONLYEU. As discussed in Sect. 3, such additivity has also been found in our inversion results (Table 1), despite approximations in numerically solving posterior fluxes (Feng et al., 2009).

### Appendix C: Regional and sub-regional systematic errors inferred in joint data assimilation

In the joint data assimilation, we attempt to estimate and remove systematic errors at the regional and sub-regional scales from GOSAT \( X_{\text{CO}_2} \) retrievals. The assimilated \( X_{\text{CO}_2} \) retrieval can be described as
\[ y^c = y - \text{bias}(m,i), \] (C1)

where \( y \) represents GOSAT retrievals before the (extra) bias correction, and \( y^c \) is the bias-corrected \( X_{\text{CO}_2} \) data that we assimilate in our joint data assimilation experiments. For simplicity, we have assumed the regional (sub-regional) bias, \( \text{bias}(m,i) \) is a function only of month \( m \) and geographical region \( i \).

In the joint data assimilation experiments, we consider \( \text{bias}(m,i) \) as part of the state vector that we infer from assimilating in situ and satellite observations. Figure C1 shows the resulting bias (in ppm) for March 2010. Like other model and GOSAT inter-comparisons (see for example, Lindqvist et al., 2015), our results demonstrate a strong spatial dependence of the derived systematic errors. As discussed in Sect. 4, our results reflect the mean differences between the inversion system and \( X_{\text{CO}_2} \) retrievals at (sub) regional scales, which does not necessarily suggest that the GOSAT \( X_{\text{CO}_2} \) bias (as well as the coverage) within these (sub-) regions is homogeneous.

![Figure C1. Inferred regional bias (in ppm) for March 2010 over TransCom regions and two European (West and North) sub-regions.](atmos-chem-phys.net/16/1289/2016/)
Acknowledgements. Work at the University of Edinburgh was partly funded by the NERC National Centre for Earth Observation (NCEO). P. I. Palmer gratefully acknowledges funding from the NCEO and his Royal Society Wolfson Research Merit Award. Work at the University of Leicester was funded by NCEO and the European Space Agency Climate Change Initiative (ESA-CCI). The TCCON Network is supported by NASA’s Carbon Cycle Science Program through a grant to the California Institute of Technology. The TCCON stations from Bialystok, Orleans and Bremen are supported by the EU projects InGOS and ICOS-INWIRE, and by the Senate of Bremen. TCCON measurements at Eureka were made by the Canadian Network for Detection of Atmospheric Composition Change (CANDAC) with additional support from the Canadian Space Agency. The authors thank the NASA JPL ACOS team for providing their XCO₂ retrievals. We also thank the CONTRAIL and HIPPO team for their observations used in our validations. We thank G. J. Collatz and S. R. Kawa for providing NASA Carbon Monitoring System Land Surface Carbon Flux Products: http://nacp-files.nacarbon.org/nacp-kawa-01/. We are grateful to Hartmut Bösch, Chris O’Dell, and Thorsten Warneke for their helpful comments on the manuscript.

Edited by: M. Heimann

References


Oda, T. and Maksyutov, S.: A very high-resolution (1 km × 1 km) global fossil fuel CO₂ emission inventory derived using a point source database and satellite observations of nighttime lights, At-


