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Elevated uptake of CO2 over Europe inferred from GOSAT XCO2 retrievals: a real phenomenon or an artefact of the analysis?

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Elevated uptake of CO_2 over Europe inferred from GOSAT X_{CO_2} retrievals: a real phenomenon or an artefact of the analysis?

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ACPD

15, 1989–2011, 2015

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 understanding of regional CO_2 fluxes, particularly at tropical and high northern latitudes, has not significantly improved for more than 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 $< O(10\,000\,\text{km})$ (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) show a standard deviation of 1.6–2.0 ppm (e.g., Parker et al., 2012). Their global biases are typically smaller than 0.5 ppm (Oshchepkov 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. 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).

ACPD
15, 1989–2011, 2015

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., 2013; 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 observation errors, atmospheric transport errors and aggregation errors (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. 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 of uncharacterized regional biases.

We report the results from a small set of experiments that show systematic bias can cause a large difference between fluxes over Europe inferred from GOSAT and those inferred from in situ data. In the next section we provide an overview of the inverse model framework used to interpret in situ data (flask and TCCON) and GOSAT X_{CO_2} data. In Sect. 3, we describe and present results from two groups of experiments that characterize the role of systematic bias in regional flux estimates. 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), and run it at a horizontal resolution of $4^\circ \times 5^\circ$, 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 Transform Kalman Filter (ETKF) (Feng et al., 2009, 2011) to estimate regional fluxes from in situ or GOSAT observations for three years from 2009–2011, but we focus on 2010 to minimize errors

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
15, 1989–2011, 2015

Elevated uptake of CO_2 over Europe inferred from GOSAT X_{CO_2} retrievals

L. Feng et al.

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 6 sub-regions; we estimate fluxes for 199 regions compared to 144 regions used in previous studies (Feng et al., 2009; Chevallier et al., 2014).

In all inversion experiments we assume the same set of a priori flux inventories, including: (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 Randerson, 2004). We assume that the a priori uncertainty is proportional to the combination of the current biospheric emissions (70 %) and the annual variations (30 %), with the aggregated global flux uncertainty scaled to 1.6 $GtC\,a^{-1}$.

The control in situ inversion experiment (INV_TCCON) includes surface flask observations at 76 sites (Feng et al., 2011) and, to improve observation constraints, total column X_{CO_2} retrievals from all the TCCON sites of the GGG2012 dataset (see https://tccon-wiki.caltech.edu for more details). We use daytime mean TCCON retrievals (09:00 to 15:00 LT) with their errors determined by the standard deviations about that daytime mean. Including TCCON observations with the flask observations increases the annual net uptake over Europe from 0.47 to 0.56 $GtC\,a^{-1}$ for 2010, which mainly reflects larger summer uptake. Evaluation of the INV_TCCON a posteriori model concentrations agrees well with the independent HIAPER Pole-to-Pole Observations (HIPPO) aircraft measurements below 5 km (Wofsy et al., 2010), with a small bias of 0.04 ppm, and a sub-ppm standard deviation of 0.87 ppm (not shown).

For the two control GOSAT inversions, we use two independent data sets: (1) X_{CO_2} retrievals from JPL ACOS team (v3.3) (Osterman et al., 2013) (INV_ACOS); and (2) the full-physics X_{CO_2} retrievals (v4.0) from the University of Leicester (Cogan et al., 2012) (INV_UOL). For both data sets, we assimilate only the H gain data over land

ACPD
15, 1989–2011, 2015

regions, and apply the bias corrections suggested by the data providers. We double the reported observation errors, as suggested by the retrieval groups.

As a performance indicator for our ability to fit fluxes to observed X_{CO_2} concentrations, we compare a posteriori model concentrations with GOSAT X_{CO_2} retrievals and show that INV_ACOS and INV_UOL agree much better than INV_TCCON. For example, the bias against ACOS X_{CO_2} retrievals is −0.39 ppm for INV_TCCON and 0.03 ppm for INV_ACOS with a corresponding reduction in the standard deviation from 1.70 to 1.58 ppm. However, comparison of GOSAT a posteriori concentrations against independent HIPPO measurements is worse than INV_TCCON with a positive bias of 0.42 and 0.62 ppm for INV_ACOS and INV_UOL, respectively, which are mainly caused by the overestimation of CO_2 concentrations (~ 1.5–2.0 ppm) at low latitudes.

3 Results

Figure 1 and Table 1 compare the monthly and annual natural fluxes in 2010 over Europe for the three inversion experiments (INV_TCCON, INV_ACOS, and INV_UOL). The three inversions show similar summer uptake values in July 2010 (0.69 GtC m^{-1} for INV_TCCON and ~ 0.71 GtC m^{-1} for GOSAT inversions), but the GOSAT inversions have an annual net uptake of about 1.18 ± 0.13 GtC a^{-1} compared to the in situ inversion of 0.56 ± 0.1 GtC a^{-1}. Figure 1 also shows significant differences between the monthly flux estimates in early spring and winter when there is only sparse GOSAT observation coverage over Europe, particularly over northern Europe. Both INV_UOL and INV_ACOS have a cumulative total of about 0.48 GtC more uptake than INV_TCCON during February–April of 2010, and a further 0.30 (INV_UOL) to 0.38 GtC (INV_ACOS) more uptake accumulated over the following summer and autumn. This larger uptake is partially cancelled out by larger emissions (0.17–0.25 GtC) at the end of 2010.

Figure 2 shows our evaluation of these flux estimates by comparing the a posteriori model concentrations with independent descending and ascending profile observations over two European airports from the CONTRAIL experiment (Machida et al., 2008).

ACPD
15, 1989–2011, 2015

We calculated monthly mean CONTRAIL measurements during 2010 using data below 3 km, where there is greater sensitivity to local surface fluxes. Our current model resolution precludes small-scale sources (or sinks) so we expect model bias. We find that INV_TCCON agrees best with CONTRAIL observations, in particular at the beginning of the 2010, partially reflecting the poor GOSAT X_{CO_2} coverage over Europe during the winter and early spring. Figure 2 also shows an additional model experiment forced by a hybrid flux (denoted by the magenta broken line) where the INV_TCCON a posteriori fluxes outside Europe are replaced by the results from INV_ACOS. The resulting CO_2 concentrations from these hybrid fluxes are, as expected, higher than the a posteriori model concentrations from INV_ACOS because of the larger European emission estimates from INV_TCCON. But they are also systematically higher than the INV_TCCON simulation, in particular in the spring of 2010, although the same European fluxes are used to force these two simulations, indicating an overestimate in the CO_2 transported into the European region in GOSAT inversions. This highlights the sensitivity of the European flux estimate to lateral boundary conditions. Further comparison of the INV_TCCON simulation and the hybrid run reveals that bias in the inflow into the European domain can affect the atmospheric X_{CO_2} gradient across this region. In the INV_TCCON simulation, the mean X_{CO_2} difference 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 X_{CO_2} 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 sensitivity tests (see Table 1). First, we replaced all or part of the GOSAT X_{CO_2} retrievals assimilated in INV_ACOS with a model forced by the a posteriori fluxes from INV_TCCON. In the INV_ACOS_MOD_ALL inversion, for which we replace all GOSAT data with CO_2 concentrations inferred from INV_TCCON, we reproduce INV_TCCON with small exceptions at the beginning of 2010, reflecting the seasonal variation in GOSAT coverage. In a related experiment INV_ACOS_MOD_NOEU for which we replace X_{CO_2} retrievals outside Europe with the model simulations, the

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
ACPD
15, 1989–2011, 2015
Elevated uptake of CO_2 over Europe inferred from GOSAT X_{CO_2} retrievals
L. Feng et al.

differences between the GOSAT and in situ inversions are significantly reduced, particularly over the period with limited observation coverage, although the actual X_{CO_2} retrievals are still assimilated over Europe. The simulated GOSAT data outside of Europe reduces the estimate of European uptake from 1.20 to 0.89 GtC a^{-1}. In other words, the GOSAT observations outside the European region are responsible for about 50 % (0.31 GtC a^{-1}) of the total enhanced European sink (0.64 GtC a^{-1}) with the remainder (0.33 GtC a^{-1}) due to observations taken directly over Europe. For INV_UOL, when we replace the X_{CO_2} data outside Europe by the a posteriori INV_TCCON model simulations, European uptake is reduced to 0.69 GtC a^{-1} (INV_UOL_MOD_NOEU, Table 1), indicating an external contribution of over 80 % to the enhanced uptake of 0.60 GtC a^{-1}. We have also investigated the contribution from regions outside of Europe to the European flux estimate using quasi-regional inversions where only observations over Europe have been assimilated (see Appendix A).

Second, we crudely demonstrate how regional bias could explain the remaining discrepancy of 0.33 GtC a^{-1} between GOSAT and INV_TCCON inversions over Europe. In our experiment INV_ACOS_SPR_0.5ppm, we add 0.5 ppm to the GOSAT ACOS retrievals within Europe taken in February–April, inclusively, which effectively reduces the uptake by 0.09 GtC a^{-1} from 1.20 to 1.11 GtC a^{-1}. Similarly, when a 0.5 ppm bias is added to the GOSAT data taken in June–August we find a larger reduction of 0.14 GtC a^{-1} for the summer peak uptake (INV_ACOS_SUM_0.5ppm). 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 using an online data assimilation approach. We assimilate the GOSAT X_{CO_2} retrievals with the in situ flask and TCCON observations in two separate experiments: INV_ACOS_INS and INV_UOL_INS (Table 1). We also include as control variables monthly GOSAT X_{CO_2}

regional biases from 11 TransCom land regions (Gurney et al., 2002). Compared to the off-line comparisons between GOSAT X_{CO_2} retrieval and model concentrations, the main advantage of our online bias estimation is that the uncertainties associated with errors in flux estimates can be taken into account. To investigate the spatial pattern of the X_{CO_2} biases within Europe, we split Europe into West Europe (west of 20° E) and East Europe (east of 20° E). We assume a priori that monthly biases are 0.0 ± 0.5 ppm.

The annual European carbon flux estimates in 2010 for INV_ACOS_INS and INV_UOL_INS are 0.61 ± 0.08 and 0.66 ± 0.08 GtC a^{-1}, respectively, which are close to the in situ control estimate of 0.56 ± 0.1 GtC a^{-1}. This suggests that the coarse coverage of in situ observations is unlikely to be the main reason for the associated smaller estimate of European uptake.

Figure 4 shows the estimated monthly biases in ACOS and UOL X_{CO_2} retrievals over East and West Europe during 2010. Monthly biases are typically smaller than 0.5 ppm, but have different seasonal cycles over East and West Europe. We find that after correcting for these biases the annual European uptake estimate from INV_ACOS is reduced by 0.18 GtC a^{-1}, representing more than half of the contribution from GOSAT observations within Europe. This result is consistent with the sensitivity tests. The effect of bias correction is much smaller for INV_UOL (0.03 GtC a^{-1}), which is mainly due to the positive biases in the summer time over West Europe. The differences in GOSAT X_{CO_2} retrievals and their effects on regional flux estimates have also been investigated in previous studies (e.g., Takagi et al., 2014).

5 Discussion and Conclusions

We used an ensemble Kalman Filter to infer regional CO_2 fluxes using three different data sets: (1) surface in situ flask and TCCON observations; (2) GOSAT X_{CO_2} retrievals by JPL ACOS team; and (3) GOSAT X_{CO_2} retrievals by University of Leicester. Our results, consistent with previous studies, show that these GOSAT data in a global context

ACPD
15, 1989–2011, 2015

are consistent with a significantly larger European uptake than inferred from in situ data during 2010.

We showed using sensitivity experiments that 50–80 % of the enhanced European uptake of CO_2 is determined by a positive model bias of CO_2 being transported into Europe, due to the assimilation of GOSAT X_{CO_2} data outside of Europe. This model bias is supported by a comparison of GOSAT a posteriori X_{CO_2} concentrations with independent aircraft observations. The main consequence of the elevated CO_2 inflow into the European domain is that mass balance dictates that the European uptake must be increased, even if GOSAT X_{CO_2} retrievals within the European domain are not biased. Adding an additional 0.5 ppm to INV_ACOS X_{CO_2} data outside the European region increases European annual net uptake from 1.20 to 1.53 $GtC\,a^{-1}$, while the same increase to the INV_TCCON in situ observations outside Europe only increases the annual net uptake by 0.14 GtC from 0.56 to 0.70 $GtC\,a^{-1}$. Erroneous interpretation of X_{CO_2} data can result from analyses if unbiased boundary conditions are not addressed because biases in the model inflow can affect both the background concentrations and the internal X_{CO_2} gradients.

We showed using sensitivity tests that sub-ppm bias can explain the remaining 0.33 $GtC\,a^{-1}$ flux difference between INV_ACOS and the in situ inversion after accounting for biased boundary conditions. By assimilating the in situ and GOSAT observations to estimate surface fluxes and monthly X_{CO_2} biases, we infer a monthly bias that is typically less than 0.5 ppm over East and West Europe corresponding to an overestimated sink of 0.18 $GtC\,a^{-1}$. The inferred monthly biases for UOL X_{CO_2} are also not the same as the ACOS X_{CO_2} data, particularly over West Europe during the summer months. This level of sensitivity of regional flux estimates to time-varying sub-ppm biases highlights the challenges we face as a community when evaluating X_{CO_2} retrievals using current observation networks.

Flux estimates are also sensitive to a priori assumptions, idiosyncrasies of applied inversion algorithms, and the underlying model atmospheric transport (Chevallier et al., 2014; Peylin et al., 2014; Reuter et al., 2014). The presence of regional biases further complicates the inter-comparisons of flux estimates based on different inversion approaches. In our assimilation of ACOS retrievals, we find that doubling the a priori flux error (INV_ACOS_DBL_ERR) increases the estimated European uptake from 1.20 to $1.55\,\mathrm{GtC\,a^{-1}}$, reflecting the increased vulnerability to the X_{CO_2} biases both within and outside Europe particularly when using weak a priori constraints. In contrast, doubling the a priori flux errors only increases the uptake by 0.09 to $0.7\,\mathrm{GtC\,a^{-1}}$ for the joint data assimilation (INV_ACOS_INS_DBL_ERR), with very little changes in the estimated biases (not shown).

This study highlights the adverse effects of regional biases in current GOSAT X_{CO_2} retrievals that can attract erroneous interpretation of resulting regional flux estimates. A thorough evaluation of the X_{CO_2} retrievals using independent and sufficiently accurate/precise observations is urgently required to increase the confidence of regional CO_2 flux estimates inferred from space-based observations. Our study suggests that inferring flux estimates in a limited spatial domain like Europe, the observational density outside this domain is crucial. International networks such as TCCON have focused on establishing observation sites in remote regions and reducing inter-station biases, which represent an important activity within the broader carbon cycle science community.

Appendix A: Quasi-regional flux inversion

To investigate the contributions from X_{CO_2} retrievals within Europe to the European CO_2 flux estimate, we have performed two quasi-regional flux inversions: INV_ACOS_EU, and INV_UOL_EU (Table 1). In these two inversions, we use the a posteriori flux estimates from the reference in situ inversion INV_TCCON as the a priori. We also use the same a priori error for the 12 European sub-regions as the global inversion experiments of INV_UOL and INV_ACOS. However, we reduce the a priori error for other sub-regions by a factor of 2/3 to limit the influence of observations taken over Europe

ACPD
15, 1989–2011, 2015

on other regions. In these two experiments, we only assimilate GOSAT X_{CO_2} retrievals in 2010 over Europe.

The resulting monthly European fluxes are compared to the INV_ACOS and INV_UOL in Fig. A1. The quasi-regional fluxes show much less uptake during the first half of 2010 compared to the fluxes inferred by the global inversions, resulting in a significant reduction of the European net annual uptakes. The net annual uptake for ACOS X_{CO_2} data is reduced from 1.20 to 0.87 $GtC\,a^{-1}$, and more interestingly, the uptake for UOL has been reduced from 1.16 to 0.70 $GtC\,a^{-1}$. As a result, the gap between ACOS and UOL estimates is now tripled from about 0.06 $GtC\,a^{-1}$ for the global inversions to 0.17 $GtC\,a^{-1}$, reflecting the differences between ACOS and UOL X_{CO_2} retrievals.

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ACPD
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ACPD
15, 1989–2011, 2015

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ACPD

15, 1989–2011, 2015

Elevated uptake of CO_2 over Europe inferred from GOSAT X_{CO_2} retrievals

L. Feng et al.

Table 1. The magnitude and uncertainty of the European annual CO_2 biosphere flux ($GtC\,a^{-1}$) from 15 inversion experiments.

Name	Data	Flux ($GtC\,a^{-1}$)	Uncertainty ($GtC\,a^{-1}$)
INV_TCCON	In-situ Flask and TCCON X_{CO_2}	−0.56	0.1
INV_ACOS	ACOS X_{CO_2} retrievals	−1.20	0.13
INV_UOL	UOL X_{CO_2} retrievals	−1.16	0.13
INV_ACOS_MOD_ALL	Model simulation of ACOS X_{CO_2} by using INV_TCCON posterior fluxes	−0.60	0.13
INV_ACOS_MOD_NOEU	As INV_ACOS_MOD_ALL but the real ACOS X_{CO_2} retrievals are assimilated within Europe.	−0.89	0.13
INV_UOL_MOD_NOEU	As INV_UOL, but outside the Europe, UOL X_{CO_2} retrievals are replaced with INV_TCCON simulations.	−0.69	0.13
INV_ACOS_MOD_ONLYEU	Only X_{CO_2} retrievals within EU are replaced by INV_TCCON simulations	−0.90	0.13
INV_ACOS_SPR_0.5ppm	ACOS X_{CO_2} retrievals, but 0.5 ppm bias has been added to the European data in Feb, Mar, and Apr.	−1.11	0.13
INV_ACOS_SUM_0.5ppm	ACOS X_{CO_2} retrievals but 0.5 ppm bias has been added to the European data in Jun, Jul, and Aug.	−1.06	0.13
INV_ACOS_INS	ACOS X_{CO_2} retrievals and In-situ flask and TCCON data	−0.61	0.08
INV_UOL_INS	UOL X_{CO_2} retrievals and in-situ flask and TCCON data	−0.66	0.08
INV_ACOS_DBL_ERR	ACOS X_{CO_2} retrievals but the prior flux errors have been doubled	−1.55	0.15
INV_ACOS_INS_DBL_ERR	GOSAT ACOS X_{CO_2} retrievals and In-situ flask and TCCON data but the prior flux errors have been doubled	−0.70	0.1
INV_ACOS_EU	Only ACOS X_{CO_2} retrievals over the European region	−0.87	0.16
INV_UOL_EU	Only UOL X_{CO_2} retrievals over the European region.	−0.70	0.16

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ACPD

15, 1989–2011, 2015

Elevated uptake of CO_2 over Europe inferred from GOSAT X_{CO_2} retrievals

L. Feng et al.

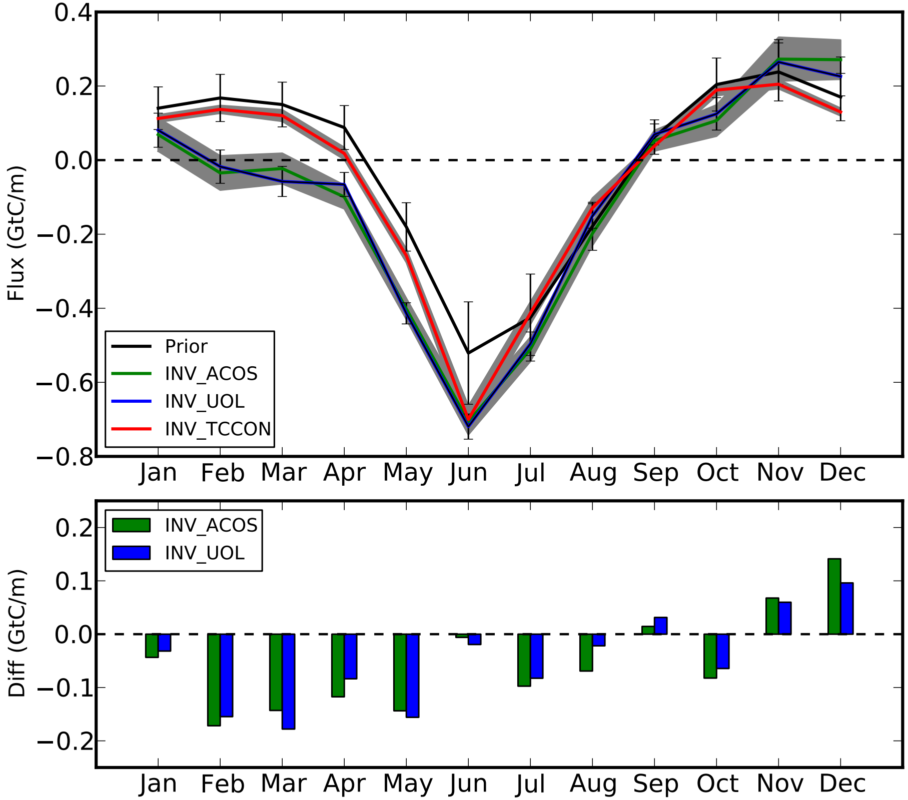

Figure 1. Monthly a posteriori estimates (GtC m^{-1}) for European biospheric fluxes in 2010 using three inversion experiments (top panel): (1) INV_TCCON (red line), (2) INV_ACOS (green line), and INV_UOL (blue line). The black line denotes a priori values. The vertical black lines and grey shading denotes the uncertainties of the corresponding a priori or a posteriori flux estimates, respectively. Differences in monthly CO_2 uptake (GtC m^{-1}) between INV_TCCON and two GOSAT inversions (bottom panel): INV_ACOS (green bars) and INV_UOL (blue bars).

ACPD
15, 1989–2011, 2015

Elevated uptake of CO_2 over Europe inferred from GOSAT X_{CO_2} retrievals

L. Feng et al.

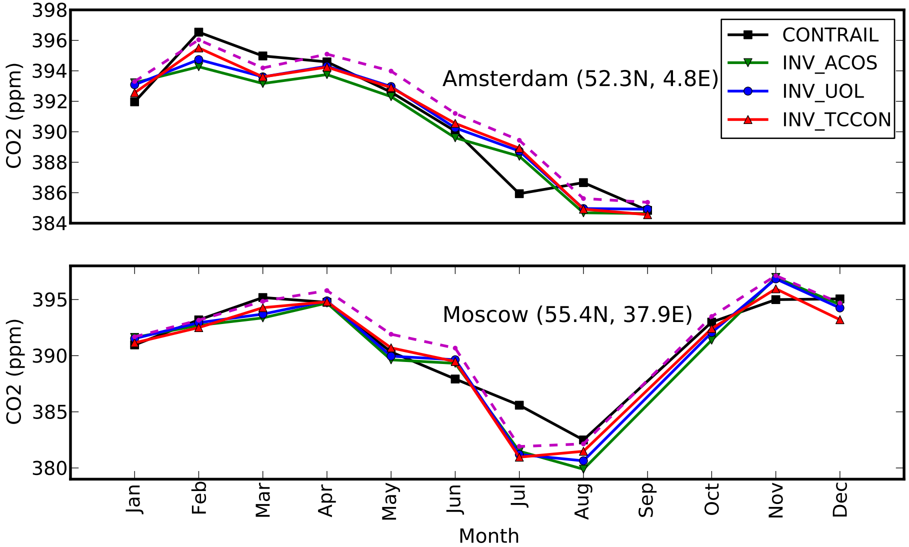

Figure 2. Monthly observed and a posteriori model CO_2 concentrations (ppm) < 3 km above Amsterdam and Moscow airports during 2010 (Machida et al., 2008). The three sets of a posteriori model concentrations are inferred from three inversion experiments: INV_TCCON (red line), INV_ACOS (green line), and 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.

ACPD
15, 1989–2011, 2015

Elevated uptake of CO_2 over Europe inferred from GOSAT X_{CO_2} retrievals

L. Feng et al.

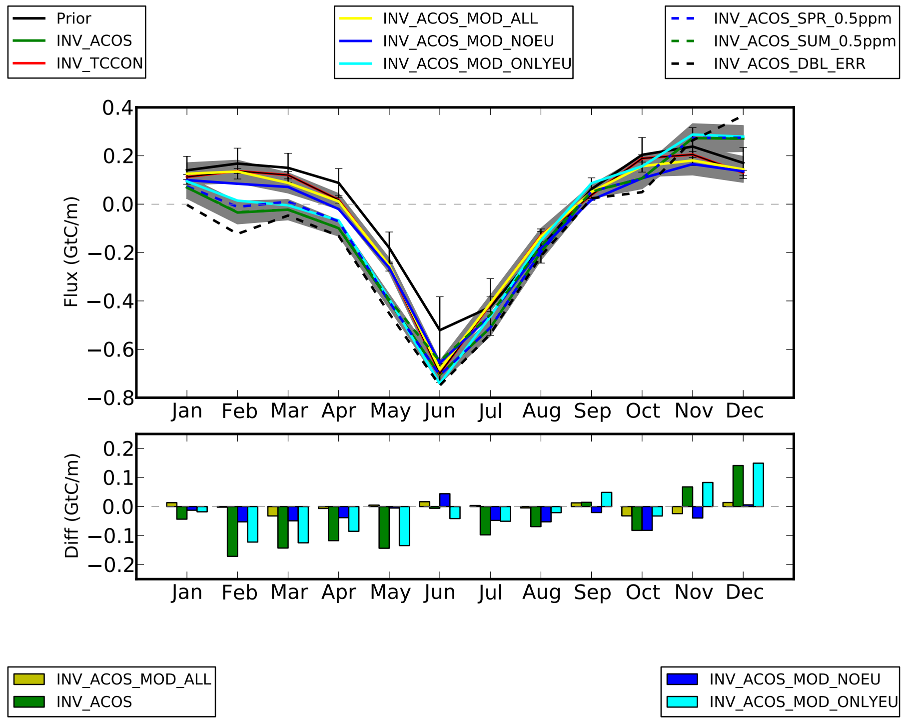

Figure 3. Monthly European biospheric flux estimates from two groups of sensitivity experiments (top panel, Table 1). Black, green and red solid lines denote the a priori and the INV_ACOS and INV_TCCON inversions, respectively. Differences between INV_TCCON inversion and sensitivity inversions (bottom 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.

ACPD
15, 1989–2011, 2015

Elevated uptake of CO_2 over Europe inferred from GOSAT X_{CO_2} retrievals

L. Feng et al.

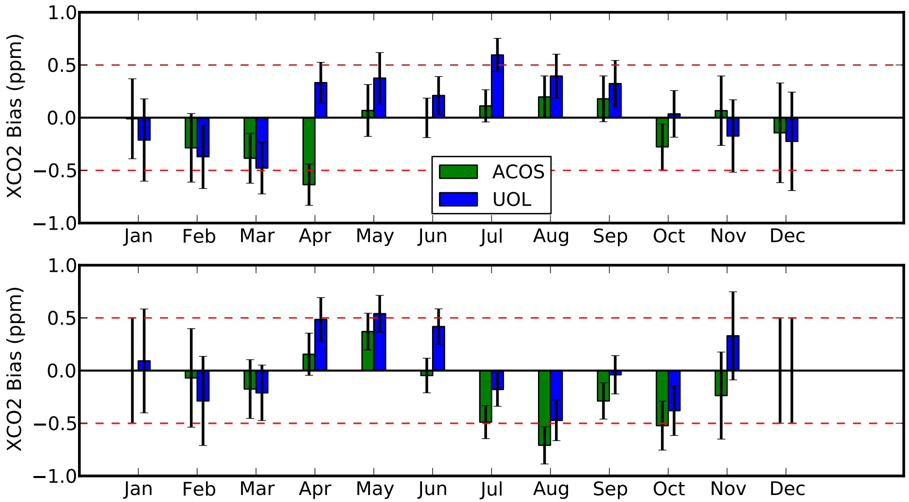

Figure 4. Estimates of monthly biases in GOSAT ACOS (green) and UOL (blue) X_{CO_2} retrievals over (top) West (West of 20° E) and (bottom) East (East of 20° E) Europe. The black vertical lines represent the uncertainty.

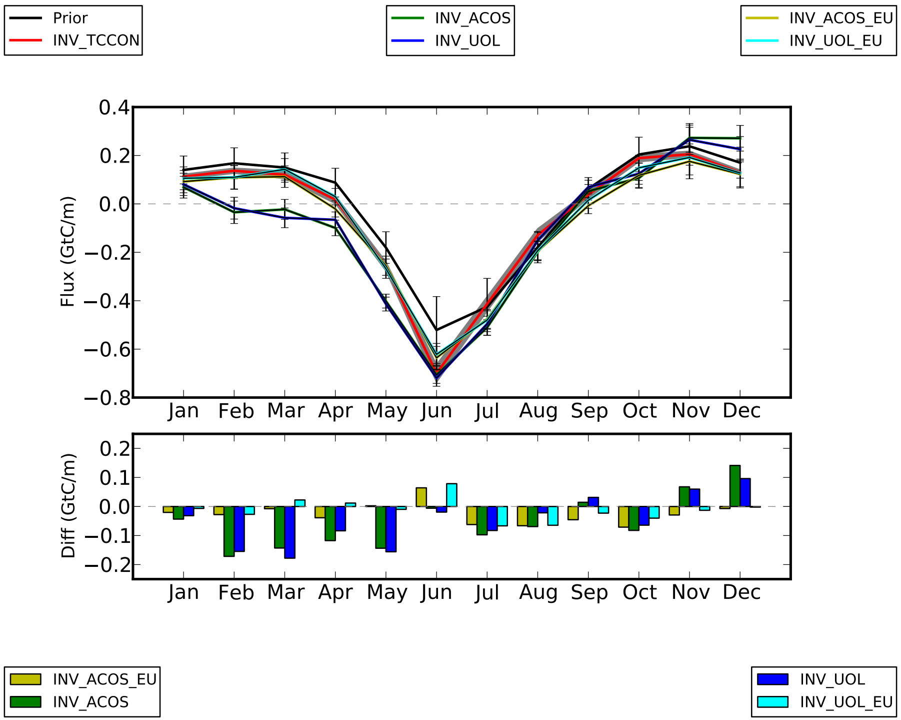

Figure A1. As Fig. 3, but for the comparisons between the quasi-regional inversions INV_ACOS_EU and INV_UOL_EU with three global inversions.

ACPD
15, 1989–2011, 2015

Elevated uptake of CO_2 over Europe inferred from GOSAT X_{CO_2} retrievals

L. Feng et al.