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Elevated uptake of CO₂ over Europe inferred from GOSAT X_{CO₂} retrievals

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

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Abstract

Estimates of the natural CO₂ flux over Europe inferred from in situ measurements of atmospheric CO₂ mole fraction have been used previously to check top-down flux estimates inferred from space-borne dry-air CO₂ column (X_{CO_2}) retrievals. Recent work has shown that CO₂ fluxes inferred from X_{CO_2} data from the Japanese Greenhouse gases Observing SATellite (GOSAT) have a larger seasonal amplitude and a more negative annual net CO₂ balance than those inferred from the in situ data. The causes of this enhanced European CO₂ uptake have since become the focus of recent studies. We show this elevated uptake over Europe could largely be explained by mis-fitting data due to regional biases. We establish a reference in situ inversion that uses an Ensemble Kalman Filter (EnKF) to assimilate surface flask data and the X_{CO_2} data from the surface-based Total Carbon Column Observing Network (TCCON). The same EnKF system is also used 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 $1.18 \pm 0.1 \text{ GtC a}^{-1}$ compared to a value of $0.56 \pm 0.1 \text{ GtC a}^{-1}$ for our control inversion that uses only in situ data. To reconcile these two estimates, we have performed a series of numerical experiments that assimilate observations with 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 50–80% of the elevated European uptake in 2010 inferred from GOSAT data is due to retrievals outside the immediate European region, while most of the remainder can be explained by a sub-ppm retrieval bias over Europe. We have used data assimilation techniques to estimate monthly GOSAT X_{CO_2} biases from the joint assimilation of in situ observations and GOSAT X_{CO_2} retrievals. We find a monthly varying bias of up to 0.5 ppm can explain an overestimate of the annual sink of up to 0.18 GtC a^{-1} .

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1 Introduction

Observed atmospheric variations of carbon dioxide (CO₂) 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 CO₂ 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 CO₂ columns using short-wave IR wavelengths. Validation of current X_{CO₂} 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_{CO₂} (Liu et al., 2014).

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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 CO₂ fluxes (Takahashi et al., 2009); and (4) 3 hourly terrestrial biosphere-atmosphere CO₂ 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_{CO₂} retrievals from all the TCCON sites of the GGG2012 dataset (see <https://tcon-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_{CO₂} retrievals from JPL ACOS team (v3.3) (Osterman et al., 2013) (INV_ACOS); and (2) the full-physics X_{CO₂} 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

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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 $\sim 0.71 \text{ GtC m}^{-1}$ for GOSAT inversions), but the GOSAT inversions have an annual net uptake of about $1.18 \pm 0.13 \text{ GtC a}^{-1}$ compared to the in situ inversion of $0.56 \pm 0.1 \text{ GtC a}^{-1}$. 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).

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differences between the GOSAT and in situ inversions are significantly reduced, particularly over the period with limited observation coverage, although the actual X_{CO₂} 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_{CO₂} 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_{CO₂} 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_{CO₂}

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regional biases from 11 TransCom land regions (Gurney et al., 2002). Compared to the off-line comparisons between GOSAT X_{CO₂} 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_{CO₂} 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_{CO₂} 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_{CO₂} 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 CO₂ fluxes using three different data sets: (1) surface in situ flask and TCCON observations; (2) GOSAT X_{CO₂} retrievals by JPL ACOS team; and (3) GOSAT X_{CO₂} retrievals by University of Leicester. Our results, consistent with previous studies, show that these GOSAT data in a global context

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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Table 1. The magnitude and uncertainty of the European annual CO₂ biosphere flux (GtCa⁻¹) from 15 inversion experiments.

Name	Data	Flux (GtCa ⁻¹)	Uncertainty (GtCa ⁻¹)
INV_TCCON	In-situ Flask and TCCON X _{CO₂}	-0.56	0.1
INV_ACOS	ACOS X _{CO₂} retrievals	-1.20	0.13
INV_UOL	UOL X _{CO₂} retrievals	-1.16	0.13
INV_ACOS_MOD_ALL	Model simulation of ACOS X _{CO₂} by using INV_TCCON posterior fluxes	-0.60	0.13
INV_ACOS_MOD_NOEU	As INV_ACOS_MOD_ALL but the real ACOS X _{CO₂} retrievals are assimilated within Europe.	-0.89	0.13
INV_UOL_MOD_NOEU	As INV_UOL, but outside the Europe, UOL X _{CO₂} retrievals are replaced with INV_TCCON simulations.	-0.69	0.13
INV_ACOS_MOD_ONLYEU	Only X _{CO₂} retrievals within EU are replaced by INV_TCCON simulations	-0.90	0.13
INV_ACOS_SPR_0.5ppm	ACOS X _{CO₂} 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 _{CO₂} 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 _{CO₂} retrievals and In-situ flask and TCCON data	-0.61	0.08
INV_UOL_INS	UOL X _{CO₂} retrievals and in-situ flask and TCCON data	-0.66	0.08
INV_ACOS_DBL_ERR	ACOS X _{CO₂} retrievals but the prior flux errors have been doubled	-1.55	0.15
INV_ACOS_INS_DBL_ERR	GOSAT ACOS X _{CO₂} 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 _{CO₂} retrievals over the European region	-0.87	0.16
INV_UOL_EU	Only UOL X _{CO₂} retrievals over the European region.	-0.70	0.16

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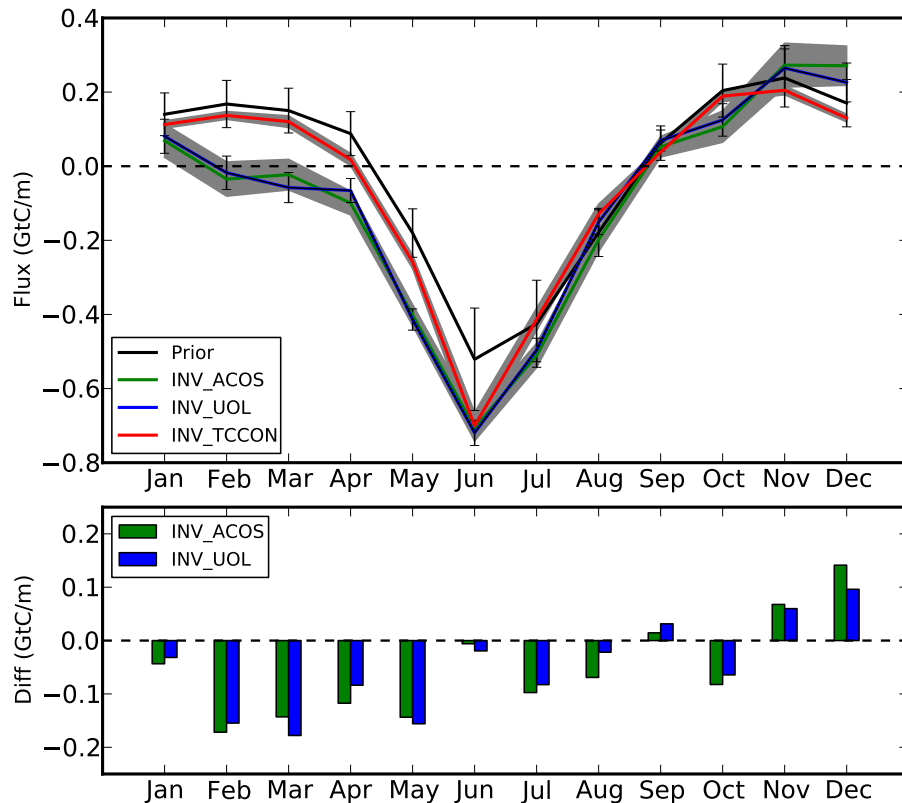


Figure 1. Monthly a posteriori estimates (GtC m^{-1}) for European biospheric fluxes in 2010 using three inversion experiments (top panel): (1) INV_TCCON (red line), (2) INV_ACOS (green line), and INV_UOL (blue line). The black line denotes a priori values. The vertical black lines and grey shading denotes the uncertainties of the corresponding a priori or a posteriori flux estimates, respectively. Differences in monthly CO₂ uptake (GtC m^{-1}) between INV_TCCON and two GOSAT inversions (bottom panel): INV_ACOS (green bars) and INV_UOL (blue bars).

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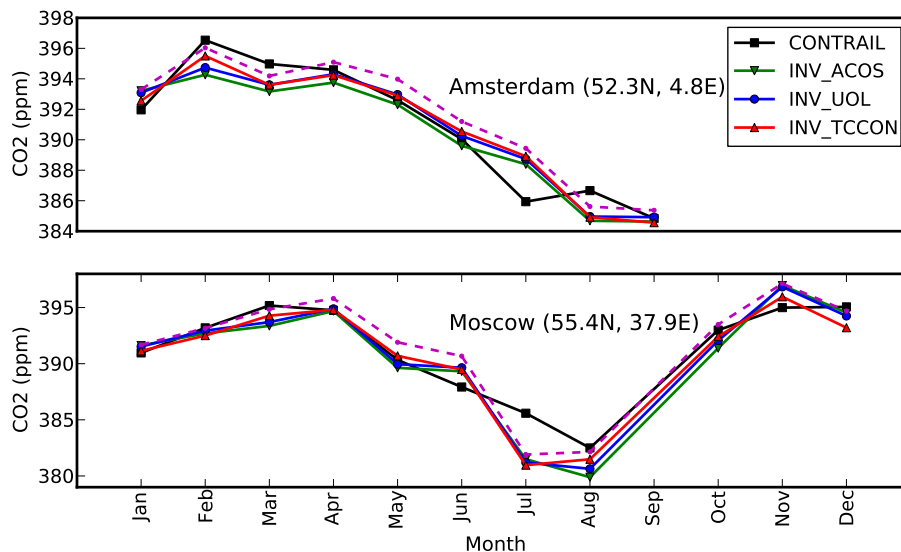


Figure 2. Monthly observed and a posteriori model CO₂ concentrations (ppm) < 3km above Amsterdam and Moscow airports during 2010 (Machida et al., 2008). The three sets of a posteriori model concentrations are inferred from three inversion experiments: INV_TCCON (red line), INV_ACOS (green line), and 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.

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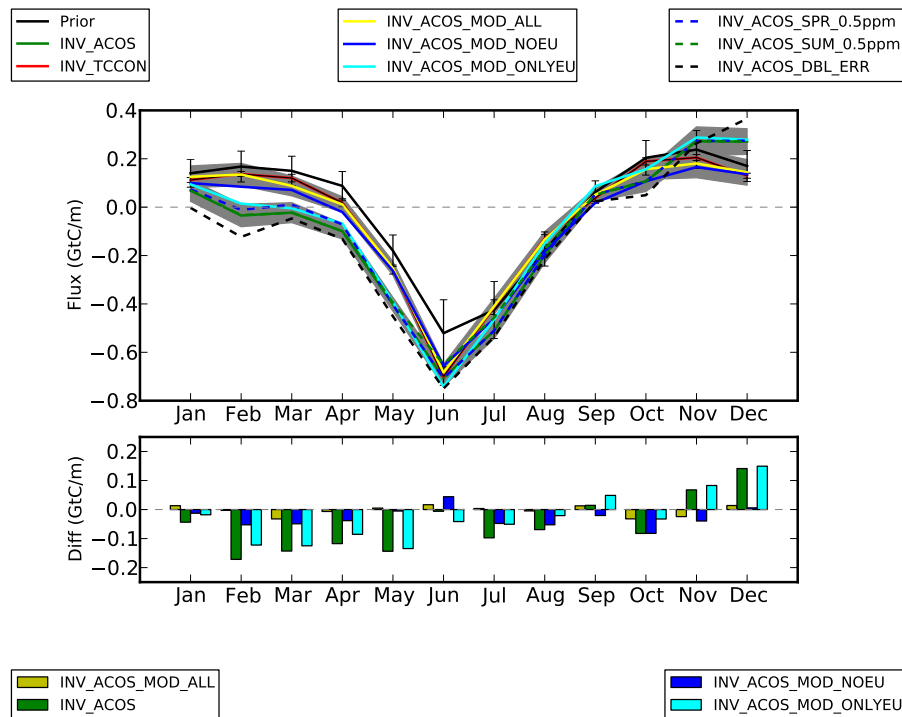


Figure 3. Monthly European biospheric flux estimates from two groups of sensitivity experiments (top panel, Table 1). Black, green and red solid lines denote the a priori and the INV_ACOS and INV_TCCON inversions, respectively. Differences between INV_TCCON inversion and sensitivity inversions (bottom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

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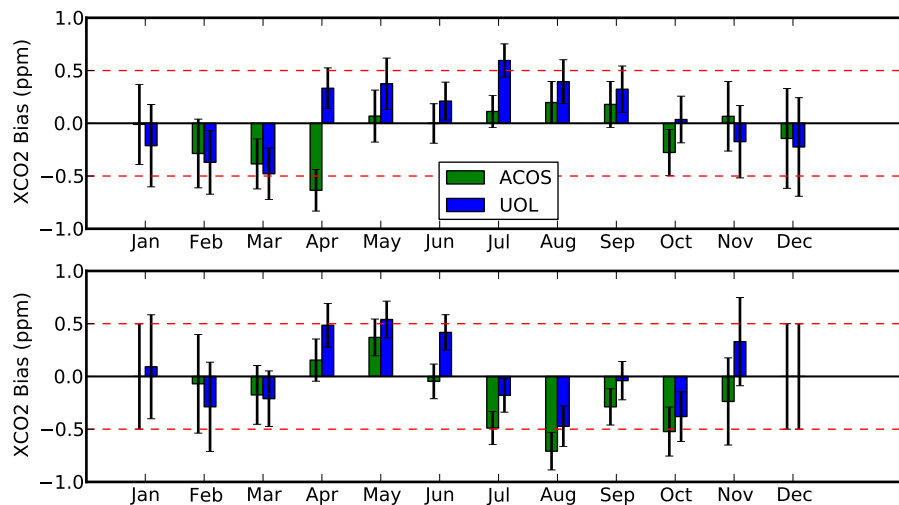


Figure 4. Estimates of monthly biases in GOSAT ACOS (green) and UOL (blue) XCO₂ retrievals over (top) West (West of 20° E) and (bottom) East (East of 20° E) Europe. The black vertical lines represent the uncertainty.

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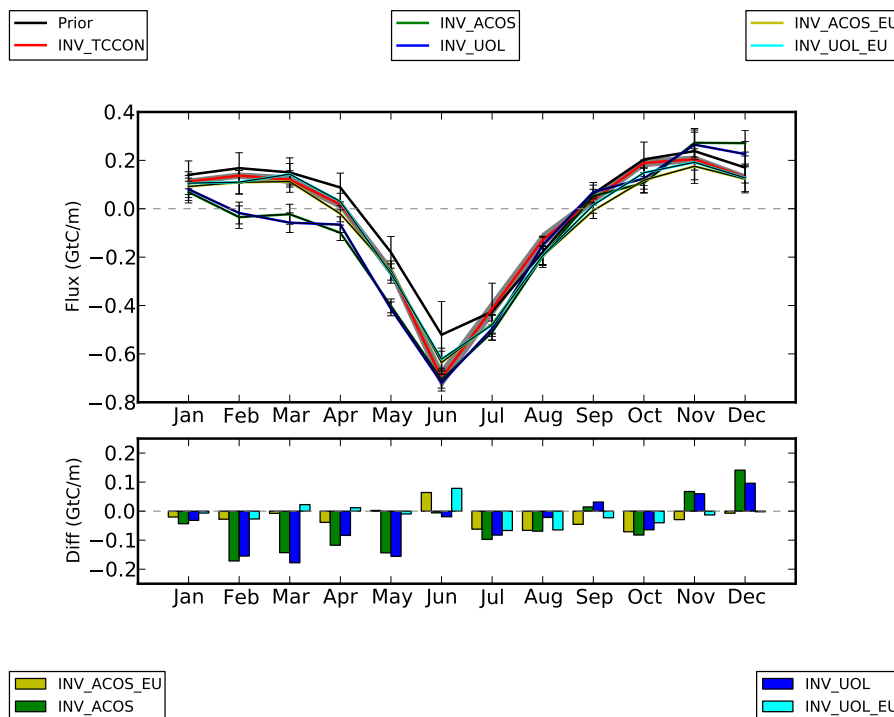


Figure A1. As Fig. 3, but for the comparisons between the quasi-regional inversions INV_ACOS_EU and INV_UOL_EU with three global inversions.

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