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Key Points:

- Nine global CO₂ atmospheric inversions are compared
- The CO₂ fluxes inferred from the satellite data show limited realism
- The satellite-inferred fluxes show large sensitivity to all input information

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Toward robust and consistent regional CO₂ flux estimates from in situ and spaceborne measurements of atmospheric CO₂

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Abstract We evaluate the robustness and consistency of global and regional posterior CO₂ flux estimates for 2010 inferred from two versions of bias-corrected CO₂ column retrievals from the Japanese Greenhouse Gases Observing Satellite (GOSAT). Six satellite-based inversions, generated from three atmospheric transport models and two independent Bayesian inference algorithms, facilitate a rigorous investigation of the uncertainty of the inverted fluxes. This ensemble shows hemispheric and regional differences in posterior flux estimates that are beyond 1 sigma uncertainties and in some regions are unrealistic. We recognize the importance of these satellite data in further understanding the contemporary carbon cycle but we argue that more resources should be invested in characterizing the errors of the prior fluxes, the systematic errors of the retrievals, and the systematic errors of the transport models, to improve confidence in the resulting posterior fluxes.

1. Introduction

Greenhouse Gases Observing Satellite (GOSAT) is the first Earth-orbiting satellite targeting carbon dioxide surface fluxes as its main scientific objective. Its dry air columnar mole fraction (X_{CO_2}) retrievals are already proven useful in their own right [e.g., Ross *et al.*, 2013]. Observation System Simulation Experiments have also shown that these data should significantly improve flux estimates inferred from surface data [e.g., Feng *et al.*, 2009], but achieving these improvements imposes stringent requirements on the size of acceptable retrieval and transport model biases [Chevallier *et al.*, 2005a, 2010]. Here we assess the usefulness of current GOSAT X_{CO_2} retrievals in this specific context using three transport models, two independent data assimilation techniques, and two X_{CO_2} retrieval algorithms. An ensemble of three inversions that assimilated surface air sample measurements serves as a reference for the satellite-based inversions. In the next section we briefly outline the models, algorithms, and data products used, and describe the experiments. In section 3, we report the results of our experiments. We conclude in section 4.

2. Data and Methods

We use X_{CO_2} retrieved from the measurements of backscattered sunlight at short-wave IR wavelengths made onboard the Japanese sun-synchronous GOSAT platform, launched in January 2009. We use two Bayesian X_{CO_2} retrieval algorithms that have been, respectively, developed by NASA's Atmospheric CO₂ Observations From Space project (ACOS, version 3.3) and by the University of Leicester (UoL, version 4). They differ in a number of subtle but meaningful respects, including prescreening, aerosol and cloud treatment, residual fitting, the simultaneous fitting of chlorophyll fluorescence, spectroscopy, post-retrieval filtering, and bias correction [Oshchepkov *et al.*, 2013]. We refer the reader to Osterman *et al.* [2013] and to Parker and the GHG-CCI project team [2013], respectively, for a detailed description of both products. For each GOSAT atmospheric sounding, they yield a statistically optimal estimation of X_{CO_2} , consistent with the radiance measurements, prior data and their uncertainties; a characterisation of its specific vertical weighting and of its uncertainty; and other variables that influence the radiances. Each product has been corrected a posteriori for known biases by the data providers. In order to further minimize the risk of heterogeneity in the data, hence of internal biases, we only take the GOSAT data acquired in "high gain" mode over land, leaving out the "medium gain" mode of GOSAT (that is used specifically over bright desert surfaces) and the ocean data (that

are acquired in sun-glint tracking mode). Consequently, inverted ocean fluxes are only loosely constrained by the data taken over land through the link established by the atmospheric transport model.

Under the assumption of unbiased Gaussian-distributed errors, atmospheric inversion systems will compute the best linear unbiased estimate of gridded fields of CO₂ surface fluxes and their associated error statistics. They exploit the atmospheric observations, a prior state of the CO₂ surface fluxes, a model of atmospheric transport, and statistical error models for the input information [e.g., Peylin *et al.*, 2013].

An ensemble transform Kalman filter, developed by the University of Edinburgh (UoE), is one of our two systems. It estimates monthly fluxes over 144 global regions [Feng *et al.*, 2009, 2011] and uses the global chemistry transport model GEOS-Chem (v8-02-01). GEOS-Chem is run at a spatial resolution of 4° latitude × 5° longitude and 47 vertical layers, driven by GEOS-5 assimilated meteorology data from the Global Modeling and Assimilation Office global circulation model based at NASA Goddard Space Flight Center. We use the following prescribed prior flux inventories: (1) monthly fossil fuel emissions [Oda and Maksyutov, 2011] scaled to the global annual totals provided by the Carbon Dioxide Information Analysis Center (CDIAC, http://cdiac.ornl.gov/ftp/ndp030/global.1751_2010.ems), (2) weekly biomass burning emissions (GFED v3.0), (3) monthly oceanic surface CO₂ fluxes [Takahashi *et al.*, 2009], and (4) three hourly terrestrial biosphere-atmosphere CO₂ exchange [Olsen and Randerson, 2004]. We assume that prior error standard deviations are 80% of prior monthly land fluxes and 60% of prior oceanic surface fluxes. We assume that prior errors for these regional flux estimates are spatially correlated with each other, with a correlation length of 700 km over land and 1800 km over oceans. We have also included temporal error correlations with a correlation length of 1 month. As a result, the aggregated error standard deviation for prior annual flux estimates is about 3.2 (0.8) GtC yr⁻¹ for the global land (ocean). Following Feng *et al.* [2011], we assimilate atmospheric CO₂ observations at 71 surface sites (termed in situ hereafter) to estimate monthly surface fluxes for 36 months (from January 2009 to end of 2011). We also use the same system to digest the two versions of GOSAT X_{CO₂} retrievals (without the surface data) for 31 months from June 2009 to December 2011. The length of the inversion window avoids edge effects for the period studied (year 2010). We will refer to the results using this inversion system as UoE.

A variational inversion formulation, developed by Laboratoire des Sciences du Climat et de l'Environnement (LSCE), is our second approach to infer surface fluxes from the X_{CO₂} measurements [Chevallier *et al.*, 2005b]. It estimates 8 day grid point daytime/nighttime CO₂ fluxes and the grid point total columns of CO₂ at the initial time step of the inversion window. The error statistics of the estimate is computed by a robust randomization approach. This inversion scheme relies on the global tracer transport model LMDZ [Hourdin *et al.*, 2006], driven by the wind analyses from the European Centre for Medium-Range Weather Forecasts. The model is used here either at the horizontal resolution 3.75° longitude × 2.5° latitude with 19 vertical layers or at the horizontal resolution 3.75° longitude × 1.9° latitude with 39 vertical layers. The 19-layer version is the default transport model of this system. The inversion system follows the configuration used by Chevallier *et al.* [2011]. The prior fluxes are different from the UoE values, with the exception of the global annual total of fossil fuel emissions from CDIAC and the ocean flux climatology of Takahashi *et al.* [2009]. The associated error covariance matrix includes spatial and temporal correlations. When aggregated over the global lands (oceans) and the year, the assigned total 1 sigma uncertainty for the prior fluxes amounts to 2.8 (0.7) GtC yr⁻¹. The LSCE air sample inversion is an update of the study by Chevallier *et al.* [2011] who used 91 in situ site records over the globe. The LSCE GOSAT inversions (excluding surface data) are straightforward applications of this configuration to the X_{CO₂} measurements from June 2009 until September 2011 within a common analysis window. We will refer to the results using this inversion system as LSCE-19 or LSCE-39 depending on the vertical resolution of the underlying transport model.

3. Results

3.1. In Situ Inversions

We first examine the in situ inversion results that provide a benchmark for the level of agreement expected from the GOSAT data described below. Figure 1a shows that there is some consistency of large-scale CO₂ fluxes inferred by in situ inversions using different assumed prior fluxes, atmospheric transport models, and inverse models. Atmospheric growth rates (summing natural and fossil fuel contributions), corresponding to 2.086 GtC ppm⁻¹, range from 2.4 (UoE) to 2.5 ppm yr⁻¹ (LSCE-19 and LSCE-39) for year 2010 and agree with the NOAA estimate of 2.44 ± 0.06 ppm yr⁻¹ (<http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html>).

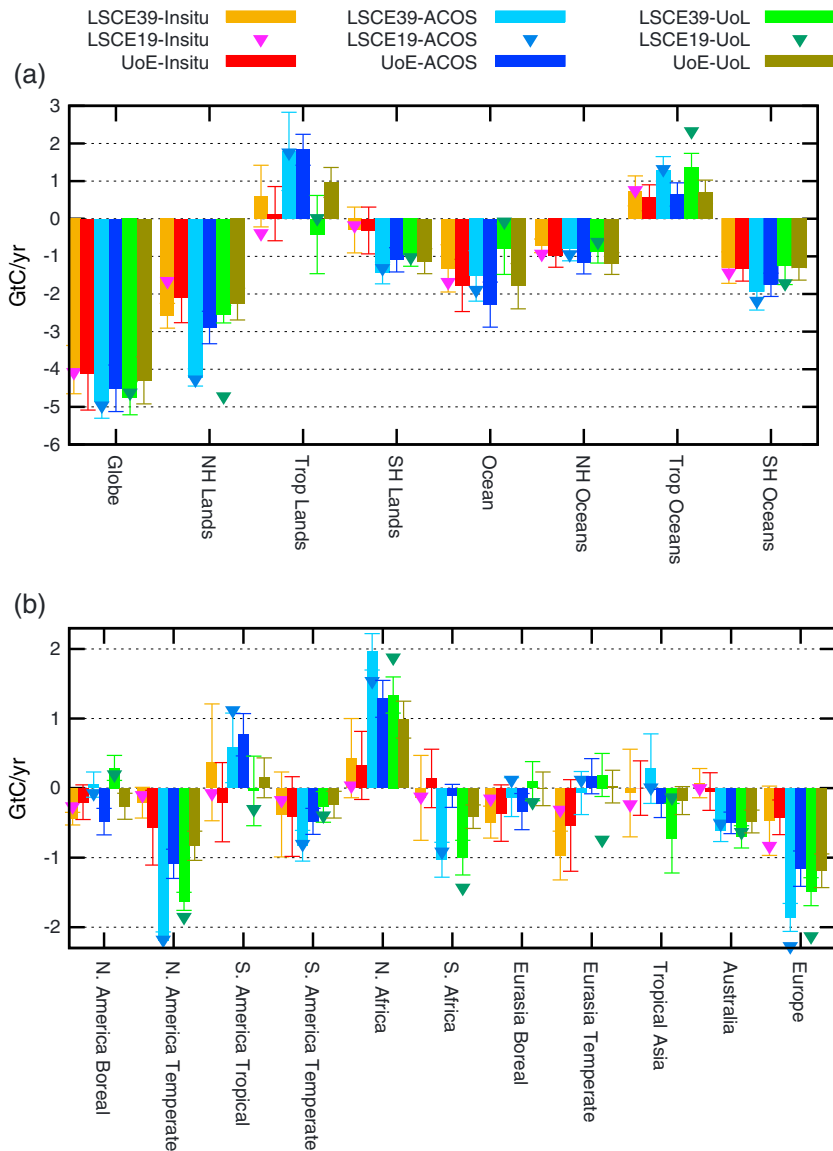


Figure 1. Large-scale annual mean natural (fossil fuel removed) CO₂ budgets of the nine atmospheric inversions from the UoE, LSCE-39, and LSCE-19 inversion systems, with in situ data and two GOSAT products (ACOS and UoL) for 2010 with their respective 1 sigma uncertainty (except for LSCE-19). NH (SH) corresponds to latitudes north (south) of 20°N (20°S). A positive flux is a flux to the atmosphere.

Inspecting zonal mean flux estimates provides further insight. In north of 20°S, there is a larger range of posterior estimates for continental regions than for the oceans, as expected, because both systems assign larger prior uncertainty to the land fluxes than to the ocean fluxes. The in situ inversions agree less in the Northern Hemisphere lands: LSCE-39 infers a natural sink much larger ($2.6 \pm 0.3 \text{ GtC yr}^{-1}$) than the two other inversions (1.7 GtC yr^{-1} for LSCE-19 and 2.1 GtC yr^{-1} for UoE). This larger sink is compensated at the global scale by larger tropical natural emissions and by smaller ocean uptake, but within the 1 sigma uncertainty range.

Figure 1b shows that this level of agreement of posterior flux estimates inferred from the in situ data extends to most subcontinental-scale regions, with consistent results within the posterior error statistics. Note that the posterior errors are often large compared to the flux for regions with limited in situ data. Our region definition follows the commonly used tiling of the globe of the Atmospheric Tracer Transport Model Intercomparison Project (TransCom3) [Gurney *et al.*, 2002]. Temperate Eurasia is seen as the main source of discrepancy for the Northern Hemisphere land budgets: LSCE-39 diagnoses a natural uptake there

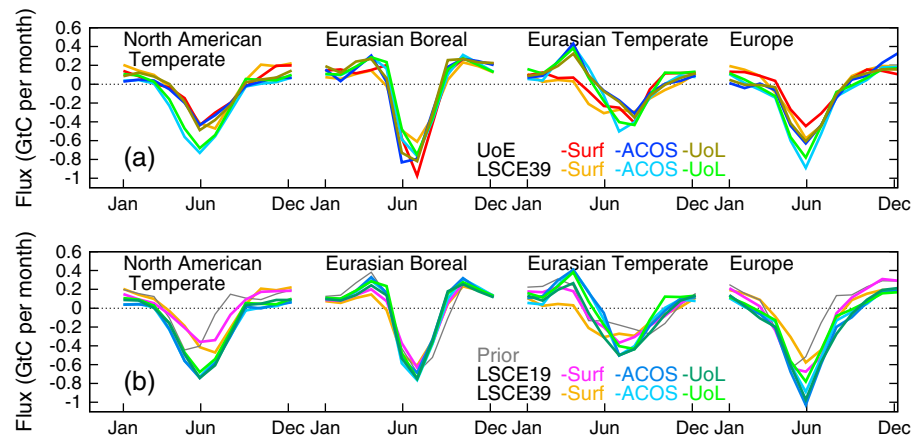


Figure 2. Regional seasonal CO₂ flux estimates in four of the regions of Figure 1. (a) Comparison of the UoE and the LSCE-39 results. (b) Comparison of the LSCE-19 results, the LSCE-39 results, and the LSCE prior fluxes. A positive flux is a flux to the atmosphere.

($1.0 \pm 0.3 \text{ GtC yr}^{-1}$) that is two to three times larger than the other two inversions. There are no specific regional differences between the in situ inversions over the ocean basins (not shown).

Figures 2a and 2b display the corresponding monthly flux estimates in four of the TransCom3 land regions. It corroborates the information given by the annual budgets about the relative agreement between the three in situ inversions, despite some differences in the phasing and the amplitude of the seasonal cycles and despite notably large increments to the prior fluxes (the LSCE prior fluxes are shown in Figure 2b). It shows that the larger annual uptake of LSCE-39 seen in temperate Eurasia corresponds to much reduced autumn emissions compared to UoE and to much reduced winter emissions compared to LSCE-19 (i.e., UoE and LSCE-19 agree in the annual total but not in the seasonal cycle). We also notice that the summer uptake in Europe is smaller with UoE than with LSCE-39 but it is larger in boreal Eurasia. Overall, the two LSCE in situ inversions are not closer to each other than to UoE, illustrating the large influence of transport uncertainty in the differences between the inversions, as the two versions of LMDZ mainly differ by their vertical resolution.

3.2. GOSAT Inversions

The growth rates of the six GOSAT inversions are smaller than the NOAA or surface-inversion estimates: they vary between 2.1 ppm yr^{-1} (LSCE-39 assimilating ACOS data) and 2.3 ppm yr^{-1} (UoE assimilating UoL data). At the hemispheric scale (Figure 1a), we see neither overall consistency of the GOSAT inversions with each other (despite similar posterior misfit statistics for a given GOSAT product assimilated by different inversion systems, not shown), nor consistency of some of the GOSAT inversions with the surface-based inversions. For instance, LSCE-19 infers nearly no ocean uptake with UoL ($0.1 \pm 0.6 \text{ GtC yr}^{-1}$) due to a very large tropical ocean source, while UoE assimilating ACOS suggests a sink of $2.3 \pm 0.6 \text{ GtC yr}^{-1}$. Tropical lands are seen as a strong and consistent natural source ($\sim 1.9 \text{ GtC yr}^{-1}$) in the three ACOS inversions, but much less so with UoL (LSCE-39 even suggests a small natural sink, associated with a relatively large tropical ocean source). In this sense, the UoL-based inversions are more consistent with in situ inversions for tropical lands. Both LSCE systems diagnose a very large uptake in the Northern lands with ACOS ($>4 \text{ GtC yr}^{-1}$). UoE infers an uptake less than 3 GtC yr^{-1} with the same data, in line with UoE and LSCE-39 results using UoL, while LSCE-19 with UoL infers a very large uptake. In the Southern lands, the six GOSAT inversions show an uptake of about 1.2 GtC yr^{-1} , while the uptake is about 0.2 GtC yr^{-1} in the three in situ inversions.

At the annual regional scale (Figure 1b), the inverted budgets significantly differ (>1 sigma) across the ensemble of nine inversions in five out of the 11 land regions: (1) North American temperate (the uptake found by the two LSCE systems assimilating GOSAT is $>1.5 \text{ GtC yr}^{-1}$, while the other inversions have an uptake $< 1.1 \text{ GtC yr}^{-1}$ and $< 0.6 \text{ GtC yr}^{-1}$ for in situ inversions); (2) North Africa (the natural emissions inferred by the six GOSAT-based inversions are $\sim 1.0 \text{ GtC yr}^{-1}$, while they are $\sim 0.5 \text{ GtC yr}^{-1}$ with the in situ data); (3) South Africa ($\sim 1.0 \text{ GtC yr}^{-1}$ uptake found by the two LSCE systems with GOSAT, much larger than with UoE or with the in situ inversions); (4) Eurasia temperate (near-neutral natural budget found by five out of six GOSAT inversions, but significant uptake found by the three in situ inversions); and (5) Europe ($1.2\text{--}1.8 \text{ GtC yr}^{-1}$ uptake

found by the six GOSAT inversions, i.e., two to three times larger than the in situ inversions). Over the oceans (not shown), differences between the nine inversions are smaller than over lands and are found over the Northern Ocean, the tropical basins, and the Southern Ocean, with larger flux gradients inferred by the two LSCE inversions than by UoE, showing the role of assigned prior error statistics (see section 2) in these areas where no direct GOSAT observations are assimilated and where the same prior fluxes are used in all inversions.

The seasonal cycles from GOSAT over midlatitude and high-latitude land regions (Figure 2) agree well with each other and with the in situ inversions in terms of phase. However, in terms of amplitude, they notably regroup by inversion system (LSCE or UoE) rather than by data source, despite significantly different annual budgets when using the same inversion system. This grouping appears throughout the year, i.e., even outside the winter period when low-sunlight conditions limit the availability of the retrievals. It occurs despite large inversion increments to the prior fluxes (see the LSCE prior fluxes in Figure 2b). It is hardly sensitive to the version of the transport model used within a same inversion system (compare, e.g., Figures 2a and 2b for North American temperate region or North American boreal region during the uptake period). These elements imply that the posterior seasonal flux differences are driven by the prior error statistics (including those implied by the state vector definition), even though they do not appear to play such a dominant role with the in situ data.

4. Discussion and Conclusions

The level of agreement shown by posterior estimates inferred from our nine inversions usually remains within the spread of the various inversion systems in the scientific community after they assimilate in situ data [Peylin *et al.*, 2013]. This agreement is particularly strong within our three in situ inversions that agree well within their posterior error statistics on most quantities studied. In comparison, large differences exist at most space-time scales when assimilating the GOSAT retrievals, even though the retrievals have been bias-corrected by the data producers.

The 2010 global growth rate inferred by assimilating the retrievals is smaller than the one reported by the surface measurements. The corresponding excessive uptake from the atmosphere is distributed in the ocean and in the midlatitude lands, in a way specific to each inversion. These areas also compensate for large emissions inferred in the tropical oceans by some inversions and in North Africa. The quantitative budgets very much depend on which retrieval product, which transport model, and which inversion system is used. A strong sink of 1.5 GtC yr^{-1} inferred in continental Europe is a robust feature of the six GOSAT inversion configurations studied and of the sensitivity tests that we have performed (varying the selection of the data and their assigned error statistics). This feature contradicts current knowledge about the European carbon budget [Schulze *et al.*, 2009]. A similar artifact was shown by an independent work [Basu *et al.*, 2013] that used a different GOSAT X_{CO_2} product and inversion scheme but did not explore its implications for scientific interpretation of these data. Since carbon mass is conserved in the global atmosphere, the lack of realism of a single regional budget inferred by a global inversion weakens the credibility of the inferred regional budgets elsewhere in the world. Actually, the large natural net emissions ($>1 \text{ GtC yr}^{-1}$) inferred in Northern Africa are also not realistic, considering that fire emissions alone likely amount to less than 0.7 GtC yr^{-1} [van der Werf *et al.*, 2010] despite their main role in the African carbon budget. Individually, the GOSAT inversions show other contradictions with current knowledge (e.g., about Northern America, the tropical lands, or the global ocean) [see Crevoisier *et al.*, 2010; Stephens *et al.*, 2007; Wanninkhof *et al.*, 2013]. By contrast, we find that the GOSAT inversions agree remarkably well with each other and with the in situ inversion for the phase (but not the amplitude) of the seasonal cycle over midlatitude and high-latitude land regions. The wide (therefore ambiguous) space-time sensitivity of X_{CO_2} to the surface fluxes allows the prior error statistics (variances and correlations) to drive the amplitude of this regional seasonal cycle. This implies that robust prior error statistics are needed to exploit the satellite retrievals at the monthly scale. At larger time-space scales, the inverted budgets are very sensitive both to the retrievals and to the transport model (and less to the prior error statistics), showing that consensus between the inversions can only be achieved by improving both.

Much better agreement was actually found by Chevallier *et al.* [2011] who compared an inversion assimilating sparse ground-based X_{CO_2} retrievals and one assimilating the in situ network: they did not report any obvious degradation brought by retrieval or transport inaccuracies, even though biases were found later in these

retrievals (https://tcccon-wiki.caltech.edu/Network_Policy/Data_Use_Policy/Data_Description#Laser_Sampling_Errors, accessed 16 November 2013). We therefore suggest that the high spatial density of the satellite data exacerbates the impact of regional biases of the transport models and of the retrievals. We argue that more resources should be invested in characterizing and subsequently minimizing X_{CO_2} retrieval error by substantially expanding X_{CO_2} validation efforts in different atmospheric environments. Such work will benefit from measurements taken by the second Orbiting Carbon Observatory (OCO-2), which is due to be launched in the second half of 2014. For the atmospheric transport models, it is not clear whether increasing the resolution of the current transport models would make them converge toward a satisfactory behavior [Prather *et al.*, 2008], or if new transport parameterizations are needed.

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