The Effect of GOSAT Observations on Estimates of Net CO₂ Flux in Semi-Arid Regions of the Southern Hemisphere

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Abstract

Greenhouse gases Observing SATellite (GOSAT) is the operational satellite dedicated to atmospheric CO₂ observations. Assimilation of data provided by GOSAT is expected to yield reliable CO₂ fluxes in semi-arid regions because of frequent observations owing to clear skies. Here we estimated net CO₂ flux over semi-arid regions of the Southern Hemisphere using the GOSAT column averaged CO₂ (XCO₂) and surface CO₂ measurements. Assimilation of GOSAT XCO₂ indicated that semi-arid regions are integral components of recent terrestrial CO₂ uptake, accounting for 44% globally. Compared with estimates assimilated from surface measurements, estimates by GOSAT XCO₂ suggest a 50% reduction in the semi-arid CO₂ uptake, amounting to 1.1 Pg C yr⁻¹. Significant estimation differences occurred for South America and South Africa, where the GOSAT makes frequent measurements but where surface CO₂ measurements are limited. In comparison, the two estimates varied less in Australia, where more surface measurements are available. These results suggest that GOSAT XCO₂ is effective at regulating excess estimates of semi-arid CO₂ uptake in regions that are less constrained by surface CO₂ measurements. To promote understanding of climate change effects in semi-arid regions, it is important to continue monitoring trends in CO₂ uptake with GOSAT.

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1. Introduction

The terrestrial biosphere uptakes ~2.5 Pg C (petagrams of carbon) of atmospheric CO₂ annually, amounting to 25% of annual anthropogenic CO₂ emissions (Le Quéré et al. 2013). Until recently, assessment results based on both models and field observations were in agreement that boreal and temperate ecosystems in northern middle–high latitudes and tropical ecosystems were the dominant contributors to net terrestrial CO₂ uptake (e.g., McGuire et al. 2009; Phillips et al. 2009; Pan et al. 2011). However, following recent effects of climate change, there is growing evidence that this may no longer hold true. Some models have suggested that the CO₂ sequestration capability of arctic tundra and boreal forest ecosystems in northern high latitudes has weakened over the last decade (Hayes et al. 2011), while satellite-remote sensing data have inferred that ecosystems in high latitudes no longer effectively uptake CO₂ under the increased temperature conditions of recent decades (Piao et al. 2014). Similarly, studies have suggested that persistent drying since 2000 has degraded CO₂ uptake in tropical regions such as the Amazon Basin (Hilker et al. 2014), with ecosystem productivity in the area having decreased extensively following severe droughts in 2003 and 2010 (Zeng et al. 2008; Xu et al. 2011; Parazoo et al. 2013).

In contrast, it has been suggested that semi-arid ecosystems are under a substantial positive change in net CO₂ uptake, largely due to increased availability of water resources (Poulter et al. 2014; Ahlström et al. 2015). Multi-model estimates indicate that interannual variations and trends in recent terrestrial CO₂ uptake are dominated by semi-arid ecosystems (Ahlström et al. 2015). Furthermore, work using a process model simulation has suggested that semi-arid regions in the Southern Hemisphere have been particularly influenced by climate change, specifically it was found that semi-arid regions in South America, South Africa, and Australia accounted for 51% of the global net CO₂ sink in 2011 (Poulter et al. 2014).

However, these recent reports about large changes in CO₂ uptake in semi-arid regions need to be interpreted with caution because of the limited availability of validation data. For example, eddy covariance measurements of net ecosystem exchange are significantly limited in semi-arid regions, particularly in the Southern Hemisphere. Satellite remote sensing provides information about vegetation activities (e.g., vegetation indices) at a global scale, but these data only serve as indirect proxies of net CO₂ flux (Piao et al. 2013).

Greenhouse gases Observing SATellite (GOSAT) CO₂ inversion is a potentially useful product for evaluating recent CO₂ flux in semi-arid regions. GOSAT was launched by the Japanese Aerospace Exploration Agency (JAXA) in January 2009 and is the first operational satellite to provide global atmospheric CO₂ concentrations in the form of column-averaged dry air molar fractions (XCO₂) (Kuze et al. 2012). Owing to frequent occurrence of clear skies, semi-arid regions are covered by more number of GOSAT XCO₂; therefore, reliable estimates of CO₂ uptake are expected from the assimilation of the GOSAT XCO₂.

This study investigated recent net CO₂ flux of semi-arid regions in the Southern Hemisphere, namely South America, South Africa, and Australia, using assimilation (i.e., CO₂ inversion) based on the GOSAT XCO₂. We aimed to identify the effects of XCO₂ on estimates of net CO₂ flux by comparing the results with estimates from assimilation based only on surface CO₂ measurements.

2. Materials and methods

2.1 GOSAT-based flux estimates

Monthly estimates of net CO₂ flux for 64 sub-continental and ocean-basin regions (42 tiles for land and 22 tiles for ocean; Fig. 1a) are publicly distributed by the National Institute for Environmental Studies (NIES) GOSAT Project as GOSAT Level 4A data product (GOSAT L4A). The regional flux estimates are obtained by optimizing a priori flux estimates such that model-predicted concentrations given by an atmospheric transport model concur with the corresponding observations (Maksyutov et al. 2013). The a priori flux dataset, atmospheric transport model, and CO₂ observation data for constraining model simulations used in this estimation approach (GOSAT inversion) are briefly explained below.

The a priori flux dataset used for GOSAT inversion comprises four components: 1) daily net ecosystem exchange (NEE) predicted by the Vegetation Integrative Simulator for Trace gases...
June to May of the following year. The annual period was set to run from June 2009–May 2012. Taking into account the seasonal cycle in the Southern Hemisphere, we specifically considered three years (2010–2012), which were modified to be close to the classification used in Poulter et al. (2002), except that the classification for South Africa was modified to be close to the classification used in Poulter et al. (2014). Over these three regions, more GOSAT XCO$_2$ retrievals were available, resulting in that the former constitutes 84% and the latter 44% of the observations.

To understand the effect of the GOSAT XCO$_2$ retrievals on semi-arid net CO$_2$ flux estimates, seasonal variations in net CO$_2$ flux by the GOSAT inversion were evaluated in conjunction with the uncertainty reduction rate (UR), which represents the degree of contribution from the GOSAT XCO$_2$ retrievals in constraining regional fluxes. Based on Takagi et al. (2011), UR was calculated as follows:

$$UR(\%) = \left(1 - \frac{\sigma_{GV+GOSAT}}{\sigma_{GV}} \right) \times 100$$

where $\sigma_{GV}$ and $\sigma_{GV+GOSAT}$ are the uncertainties in the monthly CO$_2$ exchanges estimated from the GV dataset and from both the GV and GOSAT datasets, respectively.

### 3. Results

Both GOSAT and GV-only inversions showed that the semi-arid regions make a large contribution to global terrestrial CO$_2$ uptake, but the level of contribution is largely different between the two inversions (Fig. 2). Over the study period, mean annual global CO$_2$ budgets were similar between the GOSAT and GV-only inversions ($-2.52$ Pg C yr$^{-1}$ and $-2.64$ Pg C yr$^{-1}$, respectively). However, CO$_2$ uptake in semi-arid regions, as given by the GV-only inversion ($-2.20$ Pg C yr$^{-1}$), was nearly two times larger than that given by the GOSAT inversion ($-1.11$ Pg C yr$^{-1}$), resulting in that the former constitutes 84% and the latter 44% of the observations.
the global CO₂ uptake.

Over the study period, the GOSAT and GV-only inversions relatively agree in seasonal variations of global net CO₂ flux, with similar amplitudes of CO₂ sink-source patterns (Fig. 3a). In semi-arid regions in the Southern Hemisphere, the two inversions exhibited similar variation patterns of net CO₂ flux, but variations of the GOSAT inversion were associated with weaker CO₂ sinks and stronger CO₂ sources than those of the GV-only inversion (Fig. 3b). These differences in seasonal variations between the GOSAT and GV-only inversions are more clearly illustrated scatter plots (Figs. 3c and 3d). Global net CO₂ fluxes of the two inversions were closely in line with the 1:1 line, with a slope of 0.97. Meanwhile in semi-arid regions in the Southern Hemisphere, it was found that the overall distribution of net CO₂ fluxes was shifted toward the GOSAT inversion, despite a slope was close to the 1:1 line (i.e., 1.05).

Further investigation on three semi-arid regions in the Southern Hemisphere illustrated regional differences in net CO₂ flux by the GOSAT and GV-only inversions. In South America and South Africa, two inversions exhibited similar seasonal variation patterns (Figs. 4a and 4b), but as indicated by scatter plots, these distributions tended to lean toward the GOSAT inversion (Figs. 4d and 4e). Meanwhile, seasonal variations of the GOSAT and GV-only inversions for Australia were nearly identical (Fig. 4c), with a slope and intercept of the regression in line with the 1:1 line (i.e., 1.05).

Regional differences in the effects of XCO₂ retrievals are attributable to the availability of surface CO₂ measurements. The GOSAT XCO₂ retrievals were consistently available within and in the vicinity of all three semi-arid regions (Fig. 1a). However, the UR in Australia barely exceeded 5%, unlike in South America and South Africa (Fig. 3). This is because the GOSAT XCO₂ retrievals were more effective in regions under-sampled by surface observation networks (i.e., GV sites) (Maksyutov et al. 2013). In Australia, besides the four surface observation sites, aircraft observations

4. Discussions

This study has highlighted the effects of GOSAT XCO₂ retrievals on CO₂ uptake estimates for semi-arid regions in the Southern Hemisphere. The significant semi-arid CO₂ uptake indicated in previous work (i.e., Poulter et al. (2014)) was noted in our results obtained with the inversion assimilating the GOSAT XCO₂ retrievals. For the period from June 2009 to May 2012, both the GOSAT and GV-only inversions indicated that a large proportion of global CO₂ uptake is attributable to the three Southern Hemisphere semi-arid regions, the value of 84% indicated by the GV-only inversion is notably high, while the estimate by the GOSAT inversion (44%) is closer to the 2011 estimate (51%) of Poulter et al. (2014).

From the comparison of the GOSAT L4A and GV-only inversions, we found that use of the GOSAT XCO₂ retrievals significantly affected CO₂ uptake in South America and South Africa. Corresponding to these uptake reductions, large UR (≥ 10%) values were also noted for these regions. In previous work, CO₂ inversions based on five GOSAT XCO₂ retrievals processed with different algorithms indicated a similar result, i.e., large UR (≥ 10%) in South America and South Africa and large reductions in the CO₂ sink of South America (Takagi et al. 2014). In contrast to these two regions, the CO₂ budgets estimated by the GOSAT and GV-only inversions for Australia were less varied, indicating that the contribution of XCO₂ retrievals was low in this region. We regard that these influences of the GOSAT XCO₂ retrievals on net CO₂ fluxes are robust, as indicated by relationships between UR and differences between the GOSAT and GV-only inversions (Fig. 5). In South America and South Africa, UR and the differences in two inversions shows positive linear relationships with a statistical significance (Figs. 5a and 5b: R² = 0.42 and 0.37, respectively, with p < 0.01), while no clear relationship was identified for Australia (Fig. 5c: R² = 0.08, p > 0.05).

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Fig. 3. Seasonal variations in net CO₂ flux (Pg C yr⁻¹) for (a) globe and (b) semi-arid regions by the GOSAT inversion (L4A: red line for estimated values and red shading for uncertainties) and ground-based CO₂ measurement only inversion (GV only: black line for estimated values and grey shading for uncertainties) for the period June 2009—May 2012. Scatter plots of seasonal variations between the GOSAT and GV-only inversions for (a) globe and (b) semi-arid regions, with grey shading indicating the 95% confidence ellipse.
were available within and in the vicinity (see Fig. 1a). However, surface observations were limited in the other regions, with just two sites in South America and one site in South Africa. Therefore, the situation in Australia represents a case where the constraints by the GV data prevail over that by the GOSAT XCO$_2$ retrievals. Besides Australia, a previous study also identified a similar situation in North America, with this region characterized by a high availability of the XCO$_2$ retrievals but also covered by dozens of GV sites (Maksyutov et al. 2013).

It should be noted that, for the study regions, the GOSAT XCO$_2$ retrievals affected appreciably the magnitude of net CO$_2$ flux, but not seasonal variations. This result implies that despite the difference in magnitude, both the GOSAT and GV-only inversions would show similar responses to climate anomalies. In Fig. 6, seasonal anomalies of net CO$_2$ flux by the GOSAT and GV-only inversions are quite similar for the semi-arid regions as expected. In particular, from the later part of 2010 to the early 2011, notable positive precipitation anomalies in the semi-arid regions promoted increases in vegetation activities represented by Normalized Difference Vegetation Index (NDVI) and in CO$_2$ uptake for both the

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**Fig. 4.** Seasonal variations in net CO$_2$ flux (Pg C yr$^{-1}$) for (a) South America and (b) South Africa, and (c) Australia by the GOSAT and GV only inversions for the period June 2009–May 2012. The rate of uncertainty reduction (UR: %) by the inclusion of GOSAT XCO$_2$ retrievals is shown, along with seasonal variations in net CO$_2$ flux. Scatter plots of seasonal variations between the GOSAT and GV-only inversions for (a) South America, (b) South Africa, and (c) Australia. Except URs, figure configurations are the same as in Fig. 3.

**Fig. 5.** Relationships between the rate of uncertainty reduction (UR: %) and differences in seasonal variations between the GOSAT and GV-only inversions for (a) South America, (b) South Africa, and (c) Australia, with grey shading indicating the 95% confidence ellipse.
observations on CO$_2$ flux estimates of the terrestrial carbon cycle. In particular for regions undergoing rapid change (e.g., semi-arid regions), it is important to continue monitoring trends in net CO$_2$ flux with GOSAT, also using observations from additional satellites dedicated to CO$_2$ monitoring, such as the Orbiting Carbon Observatory-2 (OCO-2).

On the same token, it is important to evaluate the semi-arid CO$_2$ sink using inversion systems different from this study (i.e., NIES-TM). Although effects of the GOSAT XCO$_2$ retrievals on CO$_2$ uptake were found similar regardless of different retrieval algorithms (Takagi et al. 2014), there are non-negligible differences among net CO$_2$ fluxes estimated by different inversion systems (Houwling et al. 2015). Thus, the result from this study needs to be regarded as one of potential results of GOSAT inversions and to be validated by other inversion systems in future.

Lastly, we stress importance in improving the retrieval and bias correction algorithms for the XCO$_2$ further, as performance of those algorithms directly affect results of the inversion (e.g., Basu et al. 2013). Particularly for regions constrained by only a few ground observations such as South America and South Africa, the accuracy of the XCO$_2$ becomes a critical factor to the inversion. Likewise, it is necessary to grow a network of ground observations for the semi-arid regions in future. This is crucial not only for strengthening constraints of the inversion system, but also for validation of the XCO$_2$ and simulated CO$_2$.

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5. Outlook

It was encouraging to find that net CO$_2$ fluxes varied significantly in regions characterized by the strong effect of the GOSAT XCO$_2$ retrievals (high URs). In conjunction with previous work, which also analyzed the effect of the GOSAT XCO$_2$ retrievals (e.g., Guerlet et al. 2013; Parazoo et al. 2013; Sacke et al. 2013; Basu et al. 2014; Deng et al. 2014; Kondo et al. 2015), the result of this study facilitates our understanding of the effect of satellite

![Fig. 6. Seasonal anomalies of net CO2 flux by the GOSAT and GV-only inversions for (a) semi-arid regions in the Southern Hemisphere, (b) South America, (c) South Africa, and (d) Australia. In addition to net CO2 flux, seasonal anomalies of precipitation from CRU TS 3.23 (Harris et al. 2014) and of Normalized Difference Vegetation Index (NDVI) from TERRA MODIS (Huete et al. 2002) that averaged for the regions in Fig. 1b are shown.](image-url)
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