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 (X_{CO2}) and surface CO₂ measurements. Assimilation of GOSAT X_{CO2} 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 X_{CO2} 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 X_{CO2} 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 2005 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 (X_{CO2}) (Kuze et al. 2012). Owing to frequent occurrence of clear skies, semi-arid regions are covered by more number of GOSAT X_{CO2}; therefore, reliable estimates of CO₂ uptake are expected from the assimilation of the GOSAT X_{CO2}.

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 X_{CO2}. We aimed to identify the effects of X_{CO2} 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

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Fig. 1. Maps showing (a) the number of Greenhouse gases Observing SATellite (GOSAT) X_{CO_2} data points per each $5^\circ \times 5^\circ$ grid cell over the analyzed period (41 months from Jun 2009–Oct 2012). The overlaid red circles indicate the locations of CO₂ measurement sites (GLOBALVIEW-CO₂: GV) chosen for this study (212 sites); and (b) the three semi-arid regions of the Southern Hemisphere analyzed in this study.

(VISIT) (Ito 2008); 2) monthly ocean–atmosphere CO₂ fluxes generated from observations of surface ocean CO₂ partial pressure (pCO_2) (Valsala and Maksyutov 2010); 3) monthly biomass burning emissions estimated from an empirical relationship between biomass burning emission (the Global Fire Emissions Database (GFED) version 3.1 (van der Werf et al. 2010)) and burnt area (GFED burnt area version 4.0 (Giglio et al. 2013)), and; 4) monthly fossil fuel CO₂ emissions obtained by merging the Open source Data Inventory of Anthropogenic CO₂ emissions (ODIAC) (Oda and Maksyutov 2011) and the Carbon Dioxide Information Analysis Center datasets (Andres et al. 2011).

The NIES global atmospheric tracer Transport Model (NIES-TM) was used for performing forward simulations of atmospheric CO₂ (Takagi et al. 2011; Maksyutov et al. 2013). Atmospheric transport was driven by a real-time operational analysis dataset of the Japan Meteorological Agency (JMA) Climate Data Assimilation System (JCDAS) (Onogi et al. 2007).

The GOSAT inversion integrates satellite-based atmospheric CO₂ concentrations with surface-based data. The values of X_{CO_2} used in this study were retrieved from high-resolution spectra of reflected sunlight in shortwave infrared (SWIR) spectral wavebands collected by the Thermal And Near infrared Sensor for carbon Observation Fourier-Transform Spectrometer (TANSO-FTS) onboard the GOSAT satellite (publicly available as GOSAT FTS SWIR Level 2 data product). Details on the X_{CO_2} retrieval approach can be found in a report by Yoshida et al. (2013). The GLOBALVIEW-CO₂ surface-based CO₂ data (GLOBALVIEW-CO₂, 2013); hereafter referred to as GV) were used in conjunction with the GOSAT X_{CO_2} values to constrain the regional surface CO₂ fluxes.

2.2 Analysis

Using the GOSAT L4A monthly surface CO₂ flux (version 02.03), we evaluated recent net CO₂ flux in semi-arid regions of the Southern Hemisphere. We specifically considered three semi-arid regions, i.e., South America, South Africa (including Namibia, Botswana, and Zimbabwe), and Australia (including New Zealand) (Fig. 1b). These semi-arid regions were classified based on the regional boundary definition used in the TransCom atmospheric tracer transport model intercomparison project (Gurney 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 X_{CO_2} retrievals are found because of frequent occurrence of clear skies associated with semi-arid regions (Fig. 1a). In order to characterize the effect of the GOSAT X_{CO_2} retrievals, net CO₂ flux from the inversion constrained only by GV data (GV-only inversion) was compared with the GOSAT inversion. The study period was set to three years (June 2009–May 2012). Taking into account the seasonal cycle in the Southern Hemisphere, the annual period was set to run from June to May of the following year.

To understand the effect of the GOSAT X_{CO_2} retrievals on semi-arid net CO₂ flux estimates, seasonal variations in net CO₂ flux by the GOSAT inversion were evaluated in conjunction with the uncertainty reduction rate (UR), which represents the degree of contribution from the GOSAT X_{CO_2} retrievals in constraining regional fluxes. Based on Takagi et al. (2011), UR was calculated as follows:

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

where σ_{GV} and $\sigma_{GV+GOSAT}$ are the uncertainties in the monthly CO₂ exchanges estimated from the GV dataset and from both the GV dataset and X_{CO_2} retrievals.

3. Results

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

Fig. 2. Mean annual net CO₂ flux (Pg C yr^{-1} ; June 2009–May 2012) for globe and semi-arid regions in the Southern Hemisphere by the GOSAT inversion (L4A: GOSAT+GV) and ground-based CO₂ measurement only inversion (GV only).

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 (Fig. 4f). Corresponding to those regional differences in net CO₂ fluxes, regional differences in UR were identified in the semi-arid regions. The inclusion of the GOSAT X_{CO2} retrievals effectively reduced uncertainty in the South American and South African estimates: 10% and 22% on average, respectively (Figs. 4a and 4b). Compared to those two regions, UR was least profound in Australia: ~4% on average (Fig. 4c).

4. Discussions

This study has highlighted the effects of GOSAT X_{CO2} 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 X_{CO2} 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 X_{CO2} retrievals significantly affected CO₂ uptake in South America and South Africa. Corresponding to these uptake reductions, large UR ($\geq 10\%$) values were also noted for these regions. In previous work, CO₂ inversions based on five GOSAT X_{CO2} retrievals processed with different algorithms indicated a similar result, i.e., large UR ($\geq 10\%$) 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 X_{CO2} retrievals was low in this region. We regard that these influences of the GOSAT X_{CO2} 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: $R^2 = 0.42$ and 0.37 , respectively, with $p < 0.01$), while no clear relationship was identified for Australia (Fig. 5c: $R^2 = 0.08$, $p > 0.05$).

Regional differences in the effects of X_{CO2} retrievals are attributable to the availability of surface CO₂ measurements. The GOSAT X_{CO2} 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 X_{CO2} 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

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.

Fig. 4. Seasonal variations in net CO₂ 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 X_{CO2} retrievals is shown, along with seasonal variations in net CO₂ 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.

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 X_{CO2} retrievals. Besides Australia, a previous study also identified a similar situation in North America, with this region characterized by a high availability of the X_{CO2} retrievals but also covered by dozens of GV sites (Maksyutov et al. 2013).

It should be noted that, for the study regions, the GOSAT X_{CO2}

retrievals affected appreciably the magnitude of net CO₂ 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 CO₂ 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 CO₂ uptake for both the

Fig. 6. Seasonal anomalies of net CO_2 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 CO_2 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.

two inversions (Fig. 6a), which is largely due to the contribution from Australia as consistent with the indication by previous works (Poulter et al. 2014; Detmers et al. 2015) (Fig. 6d). However, this result does not necessarily suggest that seasonal variations are always unaffected by the GOSAT X_{CO_2} retrievals, because, contrary to this study, the inclusion of the GOSAT X_{CO_2} retrievals significantly enhanced anomalies of net CO_2 flux in response to increased temperature in the case of Siberia (Kondo et al. 2015). To fully characterize the effect of the GOSAT X_{CO_2} retrievals, it is important to continue validation studies, including evaluation of the spatio-temporal effects on biases inherited in the GOSAT X_{CO_2} on net CO_2 flux estimation.

5. Outlook

It was encouraging to find that net CO_2 fluxes varied significantly in regions characterized by the strong effect of the GOSAT X_{CO_2} retrievals (high URs). In conjunction with previous work, which also analyzed the effect of the GOSAT X_{CO_2} retrievals (e.g., Guerlet et al. 2013; Parazoo et al. 2013; Saeki 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

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 X_{CO_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 (Houweling 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 X_{CO_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 X_{CO_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 X_{CO_2} and simulated CO_2 .

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References

- Ahlström, A., and co-authors, 2015: The dominant role of semi-arid ecosystems in the trend and variability of the land CO_2 sink. *Science*, **348**, 895–899, doi:10.1126/science.aaa1668.
- Andres, R. J., J. S. Gregg, L. Losey, G. Marland, and T. A. Boden, 2011: Monthly, global emissions of carbon dioxide from fossil fuel combustion. *Tellus*, **63B**, 309–327, doi:10.1111/j.1600-0889.2011.00530.x.
- Basu, S., M. Krol, A. Butz, C. Clerbaux, Y. Sawa, T. Machida, H. Matsueda, C. Frankenberg, O. P. Hasekamp, and I. Aben, 2014: The seasonal variation of the CO_2 flux over Tropical Asia estimated from GOSAT, CONTRAIL, and IASI. *Geophys. Res. Lett.*, **41**, 1809–1815, doi:10.1002/2013GL059105.
- Basu, S., S. Guerlet, A. Butz, S. Houweling, O. Hasekamp, I. Aben, P. Krummel, P. Steele, R. Langenfelds, M. Torn, S. Biraud, B. Stephens, A. Andrews, and D. Worthy, 2013: Global CO_2 fluxes estimated from GOSAT retrievals of total column CO_2 . *Atmos. Chem. Phys.*, **13**, 8695–8717, doi:10.5194/acp-13-8695-2013.
- Deng, F., and co-authors, 2014: Inferring regional sources and sinks of atmospheric CO_2 from GOSAT X_{CO_2} data. *Atmos. Chem. Phys.*, **14**, 3703–3727, doi:10.5194/acp-14-3703-2014.
- Detmers, R. G., O. Hasekamp, I. Aben, S. Houweling, T. T. van Leeuwen, A. Butz, J. Landgraf, P. Köhler, L. Guanter, and B. Poulter, 2015: Anomalous carbon uptake in Australia as seen by GOSAT. *Geophys. Res. Lett.*, **42**, 8177–8184, doi:10.1002/2015GL065161.

- Giglio, L., J. T. Randerson, and G. R. van der Werf, 2013: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *J. Geophys. Res. Biogeosci.*, **118**, 317–328, doi:10.1002/jgrg.20042.
- GLOBALVIEW-CO₂, 2013: Cooperative Global Atmospheric Data Integration Project, updated annually. Multi-laboratory compilation of synchronized and gap-filled atmospheric carbon dioxide records for the period 1979–2012 (obspack_co2_1_GLOBALVIEW-CO2_2013_v1.0.4_2013-12-23). NOAA ESRL Global Monitoring Division, Boulder, Colorado, U.S.A. (Available online at <http://dx.doi.org/10.3334/OBSPACK/1002>, accessed 3 April 2016).
- Guerlet, S., S. Basu, A. Butz, M. Krol, P. Hahne, S. Houweling, O. P. Hasekamp, and I. Aben, 2013: Reduced carbon uptake during the 2010 Northern Hemisphere summer from GOSAT. *Geophys. Res. Lett.*, **40**, 2378–2383, doi:10.1002/grl.50402.
- Gurney, K. R., and co-authors, 2002: Towards robust regional estimates of CO₂ sources and sinks using atmospheric transport models. *Nature*, **415**, 626–630, doi:10.1038/415626a.
- Harris, I., P. D. Jones, T. J. Osborn, and D. H. Lister, 2014: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. *Int. J. Climatol.*, **34**, 623–642, doi:10.1002/joc.3711.
- Hayes, D. J., A. D. McGuire, D. W. Kicklighter, K. R. Gurney, T. J. Burnside, and J. M. Melillo, 2011: Is the northern high-latitude land-based CO₂ sink weakening? *Global Biogeochem. Cy.*, **25**, GB3018, doi:10.1029/2010GB003813.
- Hilker, T., A. I. Lyapustin, C. J. Tucker, F. G. Hall, R. B. Myneni, Y. Wang, J. Bi, Y. M. de Moura, and P. J. Sellers, 2014: Vegetation dynamics and rainfall sensitivity of the Amazon. *Proc. Natl. Acad. Sci. U. S. A.*, **111**, 16041, doi:10.1073/pnas.1404870111.
- Houweling, S., and co-authors, 2015: An intercomparison of inverse models for estimating sources and sinks of CO₂ using GOSAT measurements. *J. Geophys. Res. Atmos.*, **120**, 5253–5266, doi:10.1002/2014JD022962.
- Huete, A. R., K. Didan, T. Miura, E. P. Rodriguez, X. Gao, and L. G. Ferreira, 2002: Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.*, **83**, 195–213, doi:10.1016/S0034-4257(02)00096-2.
- Ito, A., 2008: The regional carbon budget of East Asia simulated with a terrestrial ecosystem model and validated using AsiaFlux data. *Agri. Forest Meteorol.*, **148**, 738–747, doi:10.1016/j.agrformet.2007.12.007.
- Kondo, M., K. Ichii, H. Takagi, and M. Sasakawa, 2015: Comparison of the data-driven top-down and bottom-up global terrestrial CO₂ exchanges: GOSAT CO₂ inversion and empirical eddy flux upscaling. *J. Geophys. Res. Biogeosci.*, **119**, doi:10.1002/2014JG002866.
- Kuze, A., H. Suto, K. Shiomi, M. Nakajima, and T. Hamazaki, 2012: Level 1 algorithms for TANSO on GOSAT: processing and on-orbit calibrations. *Atmos. Meas. Tech.*, **5**, 2447–2467, doi:10.5194/amt-5-2447-2012.
- Le Quéré, C., and co-authors, 2013: The global carbon budget 1959–2011. *Earth System Science Data*, **5**, 165–185, doi:10.5194/essd-5-165-2013.
- McGuire, A. D., L. G. Anderson, T. R. Christensen, S. Dallimore, L. Guo, D. J. Hayes, M. Heimann, T. D. Lorenson, R. W. Macdonald, and N. Roulet, 2009: Sensitivity of the carbon cycle in the Arctic to climate change. *Ecol. Monogr.*, **79**, 523–555, doi:10.1890/08-2025.1.
- Maksyutov, S., H. Takagi, V. K. Valsala, M. Saito, T. Oda, T. Saeki, D. A. Belikov, R. Saito, A. Ito, Y. Yoshida, I. Morino, O. Uchino, R. J. Andres, and T. Yokota, 2013: Regional CO₂ flux estimates for 2009–2010 based on GOSAT and ground-based CO₂ observations. *Atmos. Chem. Phys.*, **13**, 9351–9373, doi:10.5194/acp-13-9351-2013.
- Oda, T., and S. Maksyutov, 2011: 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. *Atmos. Chem. Phys.*, **11**, 543–556, doi:10.5194/acp-11-543-2011.
- Onogi, K., and co-authors, 2007: The JRA-25 Reanalysis. *J. Meteor. Soc. Japan*, **85**, 369–432.
- Pan, Y., and co-authors, 2011: A large and persistent carbon sink in the world's forests. *Science*, **333**, 988–993, doi:10.1126/science.1201609.
- Parazoo, N. C., and co-authors, 2013: Interpreting seasonal changes in the carbon balance of southern Amazonia using measurements of XCO₂ and chlorophyll fluorescence from GOSAT. *Geophys. Res. Lett.*, **41**, 1809–1815, doi:10.1002/grl.50452.
- Phillips, O. L., and co-authors, 2009: Drought sensitivity of the amazon rainforest. *Science*, **323**, 1344–1347, doi:10.1126/science.1164033.
- Piao, S., and co-authors, 2013: Evaluation of terrestrial carbon cycle models for their response to climate variability and to CO₂ trends. *Glob. Change Biol.*, **19**, 2117–2132, doi:10.1111/gcb.12187.
- Piao, S., and co-authors, 2014: Evidence for a weakening relationship between interannual temperature variability and northern vegetation activity. *Nature Commun.*, **5**, 5018, doi:10.1038/ncomms601.
- Poulter, B., D. Frank, P. Ciais, R. B. Myneni, N. Andela, J. Bi, G. Broquet, J. G. Canadell, F. Chevallier, Y. Y. Liu, S. W. Running, S. Sitch, and G. R. van der Werf, 2014: Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle. *Nature*, **509**, 600–603, doi:10.1038/nature13376.
- Saeki, T., S. Maksyutov, M. Saito, V. Valsala, T. Oda, R. J. Andres, D. Belikov, P. Tans, E. Dlugokencky, Y. Yoshida, I. Morino, O. Uchin, and T. Yokota, 2013: Inverse modeling of CO₂ fluxes using GOSAT data and multi-year ground-based observations. *SOLA*, **9**, 45–50, doi:10.2151/sola.2013-011.
- Takagi, H., T. Saeki, T. Oda, M. Saito, V. Valsala, D. Belikov, R. Saito, Y. Yoshida, I. Morino, O. Uchino, R. J. Andres, T. Yokota, and S. Maksyutov, 2011: On the benefit of GOSAT observations to the estimation of regional CO₂ fluxes. *SOLA*, **7**, 161–164, doi:10.2151/sola.2011-041.
- Takagi, H., and co-authors, 2014: Influence of differences in current GOSAT XCO₂ retrievals on surface flux estimation. *Geophys. Res. Lett.*, **41**, 2598–2605, doi:10.1002/2013GL059174.
- Valsala, V., and S. Maksyutov, 2010: Simulation and assimilation of global ocean pCO₂ and air-sea CO₂ fluxes using ship observations of surface ocean pCO₂ in a simplified biogeochemical offline model. *Tellus*, **62B**, 821–840, doi:10.1111/j.1600-0889.2010.00495.x.
- van der Werf, G. R., J. T. Randerson, L. Giglio, G. J. Collatz, M. Mu, P. S. Kasibhatla, D. C. Morton, R. S. DeFries, Y. Jin, and T. T. van Leeuwen, 2010: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmos. Chem. Phys.*, **10**, 11707–11735, doi:10.5194/acp-10-11707-2010.
- Xu, L., A. Samanta, M. H. Costa, S. Ganguly, R. R. Nemani, and R. B. Myneni, 2011: Widespread decline in greenness of Amazonian vegetation due to the 2010 drought. *Geophys. Res. Lett.*, **38**, L07402, doi:10.1029/2011GL046824.
- Yoshida, Y., and co-authors, 2013: Improvement of the retrieval algorithm for GOSAT SWIR XCO₂ and XCH₄ and their validation using TCCON data. *Atmos. Meas. Tech.*, **6**, 1533–1547, doi:10.5194/amt-6-1533-2013.
- Zeng, N., J.-H. Yoon, J. A. Marengo, A. Subramaniam, C. A. Nobre, A. Mariotti, and J. D. Neelin, 2008: Causes and impacts of the 2005 Amazon drought. *Environ. Res. Lett.*, **3**, 014002, doi:10.1088/1748-9326/3/1/014002.