Orbiting carbon observatory (OCO-2) tracks 2-3 peta-grams increase of carbon release to the atmosphere during the 2014-2016 El Niño


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Key Points:
1. Near global data coverage of total column CO₂ by the Orbiting Carbon Observatory-2 (OCO-2)
2. JAMSTEC’s ACTM is used for simulating CO₂ growth rates measured by OCO-2, and ground-based TCCON and NOAA networks
3. Effect of the 2014-2016 El Niño event on CO₂ flux anomaly is estimated to be in the range of 2.2 – 3.3 PgC
Abstract. A powerful El Niño event in 2015-2016 -- the third most intense since the 1950s -- has exerted a large impact on the Earth’s natural climate system. Here, we analyze column-averaged CO₂ dry-air mole fraction (XCO₂) observations from the recently launched Orbiting Carbon Observatory-2 (OCO-2) satellite during the period from September 2014 to February 2016 (18 months) together with ground-based remote sensing and in situ observations. From the differences between observations and simulations from an atmospheric chemistry-transport model, we estimated, that relative to the mean annual fluxes for 2011-2013, this El Niño has contributed to an excess CO₂ flux from the Earth’s surface (land+ocean) to the atmosphere in the range of 2.24-3.32 PgC (1 Pg = 10¹⁵ g). This anomalous CO₂ flux results primarily from reduction in vegetation uptake due to drought and biomass burning. Improvements in modeling atmospheric-CO₂ are required to attribute CO₂ source changes at regional scales.

1. Introduction

Uncertainties in estimates of regional sources and sinks of carbon dioxide and other greenhouse gases derived from direct inventory methods or inferred from atmospheric observations has hindered the implementation of effective policy for reduction of emissions from anthropogenic activity [Ciais et al., 2013]. The large uncertainties can obscure the relative roles of management approaches for terrestrial biospheric fluxes and the energy intensity of the industrial activities in some countries. For example, the uptake and release of CO₂ by the tropical land biosphere has remained uncertain [Schimel et al., 2015] and the CO₂ emissions from industries in China are frequently revised by the state and international research communities [Olivier et al., 2015]. The atmospheric constraint is compromised by the sparseness of observational network and uncertainties in models employed for regional CO₂ flux calculations [Peylin et al., 2013 and references therein].

To improve the resolution and coverage of the atmospheric CO₂ measurements, NASA launched the OCO-2 satellite in July 2014. Since early September of 2014, OCO-2 has been routinely returning almost one million soundings each day over the...
sunlit hemisphere. While abundances of clouds and large aerosols preclude full-column measurements of CO$_2$ from most of these soundings, more than 10% ($\sim$100,000 soundings/day) yield estimates of the column-averaged dry air mole fraction, XCO$_2$, with single-sounding random errors near 0.5 parts per million (ppm). If regional scale biases are controlled to similar levels, these data can provide the precision and accuracy needed to characterize sources and sinks of CO$_2$ [Rayner and O’Brien, 2001].

The other factor that affects estimations of CO$_2$ fluxes from XCO$_2$ measurements is the biases in transport by chemistry-transport models (CTMs). This is being tested extensively using the XCO$_2$ observations from the first dedicated Greenhouse Gases Observing Satellite "IBUKI" (GOSAT), which was launched on 23 January 2009 by the Japan Aerospace Exploration Agency (JAXA) [Yokota et al., 2009]. Using multiple flux inversions of in situ and satellite CO$_2$ data, it is found that the model-model flux differences quickly increase to $>$100% of the annual flux on the scale of the subcontinental regions [Houweling et al., 2015]. Houweling et al. conclude that the differences in inversion-derived CO$_2$ fluxes are caused primarily by the underlying modeling components in the inversion system. The modeling components include a priori fluxes and uncertainty assumptions, screening and treatment of observational data, and transport models (see also Peylin et al. [2013]).

Here, we analyze early OCO-2 observations of XCO$_2$ during the powerful El Niño event extending from 2014 through 2016. The efficiency of the terrestrial ecosystem at absorbing atmospheric carbon dioxide (CO$_2$) depends on the availability of sunlight, soil moisture (fed by precipitation), and optimal air temperature. Thus droughts and high temperatures associated with El Niño reduce the ability of the terrestrial ecosystem to assimilate carbon while additional release by frequent occurrence of fires further reduce the uptake of carbon by the terrestrial biosphere [Bacastow et al., 1980; van der Werf et al., 2004; Patra et al., 2005a,b]. A carbon flux of 227±66 TgC during the two months has been derived from MOPITT CO$_2$ observations [Huijnen et al., 2016], and a value of 340 TgC for a larger tropical Asian region and all of 2015 has been derived from active fire observations [Kaiser et al., 2016]. These anomalies are much smaller than those ($\sim$1 PgC) estimated for the 1997/1998 El Niño event [van der Werf et al., 2004; Patra et al., 2005a]. The
equatorial east Pacific Ocean experiences weaker ventilation of deep-water CO₂ during an El Niño, thus a negative CO₂ flux anomaly, but the effect of El Niño on global total CO₂ flux anomalies is not clear [Wanninkhof et al., 2013 and references therein]. No partitioning of land and ocean fluxes will be made in this study.

Here, we present a first analysis of XCO₂ observations from OCO-2 extending from 2014 through 2016. The OCO-2 observations along with CTM simulations are used to make an early impact assessment of the ongoing El Niño event on the terrestrial carbon cycle. Comparisons with in situ and ground-based remote sensing observations provide a test of the robustness of the estimated carbon exchange based on the OCO-2 observations.

2. Materials and methods

We used the bias corrected measurements of XCO₂ from the ‘OCO-2 7 LITE LEVEL 2’ files (Mandrake et al. [2015]; updated document at http://disc.sci.gsfc.nasa.gov/OCO-2/documentation/oco-2-v7; last accessed: 5 May 2016). These files only include those soundings that have passed the cloud screens and converged (xco2_quality_flag = 0). In addition, only those soundings that have a warn level (WL) less than 10 and air mass factor (AMF) less than 3.5 are used in this analysis, but no distinction is made for the different viewing modes of nadir, glint or target. All the data for the period extending from 06 September 2014 to 29 February 2016 are combined into 2.5°×2.5° grid boxes at monthly time intervals for the convenience of analysis. Any grid containing less than 3 OCO-2 soundings (N) is set to be undefined. The limits for WL and AMF are chosen after testing different cut-off levels for making the gridded dataset. For example, use of AMF < 2.5 or < 3.5 did not produce large numbers of XCO₂ differences greater than ±1 ppm at most latitude bands (except at the high latitude edge of the satellite orbit) in all months. Similarly, XCO₂ differences greater than ±1 ppm were not found frequently for selection of WL < 5 or WL < 10. Various sensitivities of these data screening parameters are shown in the Supplementary Information (Fig. S2-S11).
In addition, we have used selected measurements of XCO$_2$ from the ground-based Total Carbon Column Observing Network (TCCON; Wunch et al. [2011]) and CO$_2$ from the NOAA cooperative global air sampling network [Dlugokencky et al., 2015; Product: obspack_co2_1_CarbonTracker-NRT_v2.0_2016-02-12]. We have used the XCO$_2$ data from TCCON sites at Lauder (45°S, 170°E), Reunion Is (21°S, 55°E), Darwin (12°S, 131°E), Ascension Is (8°S, 14°W), Lamont (37°N, 97°W) and Park Falls (46°N, 90°W). The in situ CO$_2$ data are taken from Cape Grim (41°S, 145°E), Samoa (14°S, 171°W), Ascension Is (8°S, 14°W), Seychelles (5°S, 55°E), Barbados (13°N, 59°W), Mauna Loa (20°N, 156°W), Barrow (71°N, 157°W) and Alert (82°N, 62°W). Details of the ground measurement sites used in this study are given in Table S1.

The four-dimensional (4D) distribution of CO$_2$ mole fractions are simulated using the Center for Climate System Research/National Institute for Environmental Studies/Frontier Research Center for Global Change (CCSR/NIES/FRCGC) atmospheric general circulation model (AGCM)-based CTM (i.e., JAMSTEC’s ACTM; e.g., Patra et al. [2011]). ACTM is run at a horizontal resolution of T106 spectral truncations (~1.125×1.125°), and 32 sigma-pressure vertical levels. The following CO$_2$ flux tracers are simulated by ACTM with an aim to encompass the observed CO$_2$ growth rates during October 2014 to February 2016 (Table 1):

a. **Flux CYC64**: This simulation is performed using the inverted land and ocean fluxes for the year 2008 from 64 land and ocean regions [Patra et al., 2011]. Details of the inversion methodologies are given in Supplementary Information.

b. **Flux IAV84**: Monthly-mean CO$_2$ fluxes for 84 land and ocean regions corresponding to year 2011 are taken from an 84-region inverse model [as used in Thompson et al., 2016].

c. **Flux GFAS**: The fire-related daily CO$_2$ emissions are taken from the Global Fire Assimilation System (GFAS) version 1.2 [Kaiser et al., 2012]. The GFAS emissions are added to IAV84 fluxes from October 2014 onwards, and is used here as a proxy for anomalous CO$_2$ emission, not specifically as a quantification of fire emission. Since more than 80% of GFAS emissions occur in the 20°S-20°N, this is regarded as a surrogate for tropical land flux anomaly.
Interannually varying a priori emissions for fossil fuel consumption and cement production (FFC) are taken from EDGAR4.2 [Olivier et al., 2015]. Same for all 3 cases. The spatial distribution of emissions for 2010 is repeated for all the later years with a 0.2 PgC yr$^{-1}$ increase globally. This assumption of emission increase rate has an identical but compensatory effect on the estimation of interannual variations in CO$_2$ fluxes.

The CO$_2$ flux tracer simulations are started on 01 January 2005. We then combine the CO$_2$ flux tracers to get 4D CO$_2$ concentrations, as ACTM_CYC64 (=FFC+CYC64), ACTM_IAV84 (=FFC+IAV84), ACTM_IAV84+GFAS (=FFC+IAV84+GFAS).

These 3 combinations of model CO$_2$ concentrations allow us to cover the whole range of XCO$_2$ increase observed by OCO-2 and TCCON, and CO$_2$ at NOAA sites. The model CO$_2$ values are adjusted by -1.80, -1.45 and -1.45 ppm, respectively, for ACTM_CYC64, ACTM_IAV84 and ACTM_IAV84+GFAS on 01 September 2014, coinciding with the start of data collection by OCO-2. This adjustment leads to no flux correction for September 2014. The vertical profiles of CO$_2$ are first sampled at the location and time of individual OCO-2 measurements, and then convolved with the a priori profiles and averaging kernels of OCO-2 and TCCON for calculating ACTM XCO$_2$ values.

It should be noted here that the ACTM_IAV84 simulation successfully simulated the CO$_2$ concentrations for the time evolution and tropospheric profiles over Asia for the period of 2007-2012 [Thompson et al., 2016]. Also shown here are the CO$_2$ growth rates, well simulated by ACTM_IAV84 at the selected TCCON and NOAA ground-based measurement sites for January 2013 to mid-2014 (Fig. S12 and S13). Thus, any differences in time evolution during the period September 2014 to February 2016 of OCO-2 data analysis can be attributed to excess CO$_2$ releases associated with the El Niño event, relative to the 2011-2013 mean.
Table 1: Global total CO$_2$ fluxes used in the 3 ACTM simulations (column 2-6), and estimated flux corrections (column 7-10) for different time windows given in column 1 (Units: PgC). Note here that these values are not strictly mass balanced as the XCO$_2$ differences are weighted by area of the 3 latitude bands, without knowing whether the mismatches at high latitudes in particular extend to the poles on either side. CO$_2$ flux corrections for AMF and WL sensitivity are given in Table S2.

<table>
<thead>
<tr>
<th>Time window</th>
<th>A priori CO$_2$ fluxes used for ACTM simulations</th>
<th>Patra et al. (2005b)</th>
<th>CO$_2$ flux corrections from OCO-2 – ACTM differences$^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FFC</td>
<td>CYC64</td>
<td>IA-V84</td>
</tr>
<tr>
<td>Oct-Dec 2014</td>
<td>2.44</td>
<td>3.36</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Jan-Dec 2015</td>
<td>9.98</td>
<td>-2.86</td>
<td>-6.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan-Feb 2016</td>
<td>1.70</td>
<td>0.64</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct14-Feb16</td>
<td>14.1</td>
<td>1.14</td>
<td>-5.36</td>
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<td></td>
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$^5$ Range estimated from two different fits, with (Flux anomaly = 0.3539 + 1.4935 × MEI amplitude change) or without (= -1.0756 + 2.4579 × MEI amplitude change) the La Niña years

3. Results and discussion

Figure 1 shows the latitude-time distributions of XCO$_2$ obtained from NASA’s OCO-2 instrument and the differences with JAMSTEC’s ACTM simulations for the period from September 2014 through February 2016. The OCO-2 minus ACTM results are
shown for three combinations of terrestrial and oceanic CO$_2$ fluxes, namely, CYC64 (Fig. 1b), IAV84 (Fig. 1c) and IAV84+GFAS (Fig. 1d). The simulated XCO$_2$ growth rates by ACTM_CYC64 and ACTM_IAV84 overestimated (typically by ~0.5 ppm) and underestimated (by up to 2.0 ppm), respectively, the observed growth rate over this 18-month period. The underestimation of ACTM_IAV84 develops most strongly during Sep-Nov 2015. The ACTM_IAV84+GFAS simulation most closely follows the OCO-2 observations, compensating in particular for the underestimation after Nov 2015. All ACTM simulations use the same emissions from FFC at the rate of ~10 PgC yr$^{-1}$ (Table 1). However, the annual total land and ocean fluxes vary (-2.86, -6.29, and -4.29 PgC yr$^{-1}$, respectively, for CYC64, IAV84 and IAV84+GFAS cases). Because the ACTM_IAV84 simulation closely follow the evolution of atmospheric CO$_2$ measured from the ground based networks until the mid-2014, the flux (FFC+IAV84) is well balanced for CO$_2$ growth rate prior to the onset of this El Niño event.

**Figure 1:** Latitude-time distribution of XCO$_2$ (in ppm) measured from OCO-2 (a) and their differences with 3 cases of ACTM simulations (b, c, d). Further analysis with separation for soundings over land and water surfaces suggest that the positive model biases in the high latitudes arise mainly over the ocean surface (Fig. S6).

Figures 2a, 2b and 2c show comparisons of XCO$_2$ as measured by OCO-2 and simulated by ACTM as zonal means for three broad latitude ranges for the period from September 2014 through February 2016. The latitude bands of 10°S-10°N (hereinafter referred to as tropics) and 10°-90° cover 88.6 and 210.7 million km$^2$, respectively. When combined into 2.5°×2.5° grid boxes, as described above, the OCO-2 data coverage for the latitude bands poleward of 10° varies from 30% to 50% of the total area. We have also checked the XCO$_2$ differences corresponding to the three different longitude bands, i.e., the Americas (180°W-20°W), Africa (20°W-
60°E) and Asia (60°W-180°W). The region south of 10°S has the largest model–
observation mismatches, with values up to 2 ppm, with major contributions from the
American and Asian sectors, during April to August 2015. The ACTM_IAV84
simulation, on the other hand, most closely follows the OCO-2 observations until July
2015 for the region north of 10°N (Fig. 2a), suggesting that the FFC emissions are
reasonably prescribed at an increase of 0.2 PgC yr$^{-1}$ during 2014-2016 in the ACTM
simulations and that the large model-observation mismatches at the later time are
arising from the deficiencies in biospheric fluxes, both from land and ocean.

Figure 2: Time series of zonal mean XCO$_2$ observations and ACTM simulations for
three broad latitude bands (top row). Further separation in to zonal bands of America
(180°W-20°W), Africa/Europe (20°W-60°E) and Asia/Oceania (60°E-180°E)
continents are shown in Fig. S7. The comparison of ACTM simulations with TCCON
XCO$_2$ and NOAA CO$_2$ trends are shown in the middle and bottom rows, respectively
(ref. Fig. S12 and S13 for comparisons at more sites for longer time periods).

Figures 2g, 2h and 2i suggest the best match between the model and measurements
are found for the ACTM_IAV84+GFAS simulation with the NOAA in situ
observations. We found no systematic bias in CO$_2$ increase over the period of the first
and last months of this analysis. Although the ACTM_IAV84+GFAS simulation
underestimates the atmospheric XCO$_2$ measured by TCCON during November 2014
to July 2015, the observed and model values agree relatively well by the end of 2015
on an average for all the sites considered here (Fig. 2d, e, f). Although the
ACTM_IAV84+GFAS simulation very well describes the time evolution of observed XCO$_2$ in the tropics and most times for the region north of $10^\circ$N (mostly within 0.1 ppm), systematic underestimations of about 0.4 ppm are seen outside the tropics by February 2016.

Using the 3 cases of ACTM simulated in comparison with OCO-2 measurements, we conclude that the emission from GFAS of about 2.64 PgC is a good estimation for the 2015-2016 El Niño-induced extra carbon flux from vegetation fires, reduced net primary productivity and any errors in our assumed trends of anthropogenic (FFC) emissions during the period October 2014 – February 2016. Since the XCO$_2$ values consist of vertically-integrated information for the whole atmospheric column, simple approximations can be applied for estimating CO$_2$ flux corrections (in PgC month$^{-1}$) from sub-hemispheric atmospheric CO$_2$ burden differences (PgC) at monthly time interval.

$\text{Burden difference} = \sum (\text{XCO}_2 \text{difference} \times \text{area of the grid} \times \text{air density})$

$\text{CO}_2 \text{flux correction} = \frac{\text{d}(\text{Burden difference})}{\text{dt}}$

Where the XCO$_2$ difference is the observed minus model values (e.g., Fig. S14), area of the grid is latitude dependent and air density is calculated as the air mass overhead each 2.5 x 2.5 grid from ACTM air density. The difference in the burden mismatches between October and September 2014 is assigned to the flux correction for October 2014. In this simple method, we do not expect to resolve the evolution of flux corrections at less than a 1-month time resolution or the contrast between the continents and between land-ocean. However, this method is applicable for near real-time monitoring of biospheric health of Earth’s ecosystem without significant additional investment, minimal extrapolation in space and any assumption of overhead vertical profile.

This method of flux corrections is valid only for sub-hemispheric scales since the zonal transport circulates air masses several times around each of the 3 broad, zonal bands within one month. The transport effect is taken in to account only for the prior fluxes, and is excluded on the flux corrections. This method (also the formal inversion/assimilation models) suffers from the extrapolation of data to the missing observation grid boxes. For example, OCO-2 soundings covered a maximum of 70%,
70% and 60% of the 2.5×2.5° grid cells in the latitudes bands of 90°S-10°S, 10°S-10°N and 10°N-90°N, respectively. In the latitude bands poleward of 10°, monthly data coverage can be as low as 30% in the winter hemisphere (Table S2). Data coverage in the tropical latitudes suffers mainly from cloud cover, sometimes for longer than a month, and are extrapolated at modelers discretion. The fraction of missing data area will increase further when analyzed for smaller than 2.5°×2.5° grid sizes. Note that this method cannot be employed for the in situ measurement network without significant extrapolation in space and for the fact that the ground measurement sites do not cover the majority of the continental source regions [e.g., Dlugokencky et al., 2015].

The estimated CO₂ flux corrections are summarized in Table 1. For the IAV84 and IAV84+GFAS fluxes, the anomalous CO₂ emissions aggregated over the 18 months of OCO-2 operation are in the range of 2.24 and 3.32 (=2.64±0.68) PgC, respectively. The ACTM_IAV84+GFAS simulation very closely follow the OCO-2 XCO₂ observations over the tropics (Fig. 2b). The 0.68 PgC additional emissions required for fitting the observations in the extratropics, poleward of 10° in both hemispheres (Fig. 1d). For these flux estimations in the control case, missing areas are filled by the mean values of the observed – model differences for the 3 latitude bands. The lower range of values in the 3 right columns is obtained without extending model-observation mismatches to the missing data grids (1.45 and 3.15 PgC). The range of estimated CO₂ flux corrections corresponds well with the empirical calculation of the CO₂ flux anomaly (2.67-2.73 PgC) using its linear relationships with the MEI trend (Table 1; following Patra et al. [2005b]). From the model-observation comparisons of growth rates, the lower limit of 1.45 PgC is an underestimation. Our best estimate of the Earth-to-atmosphere CO₂ emission is 2.24-3.32 PgC over the period of October 2014 to February 2016, and 1.59-2.32 PgC for the year of 2015.

The annual total CO₂ residual fluxes for 2015 are then estimated as -3.34 (=−2.86 - 0.48), -3.70 (=−6.29 + 1.59) and -3.97 (=−4.29 + 0.32) PgC for the simulation cases ACTM_CYC64, ACTM_IAV84 and ACTM_IAV84+GFAS for the control data screening. The 2015 fluxes for ACTM_IAV84 case are only weakly sensitive when OCO-2 data are screened for AMF<2.5 (-3.91 = -6.29 + 1.38 PgC) or WL<5 (-3.90 = -6.29 + 1.39 PgC). The consistency over data screening and transport model case
provide us confidence on the adapted methodology for calculation of flux correction from model-observation mismatches in columnar data.

Figure 3 shows the monthly variations in CO$_2$ flux corrections along with the number of ~1km$^2$ pixels with fire seen from the MODIS sensor onboard the Terra satellite. The positive CO$_2$ flux corrections show high coincidence with large fire counts, e.g., during September-October of 2014 and 2015, high CO$_2$ emissions are caused by fires in maritime tropical Asia (mainly Indonesia) and America and emission during March-April 2015 can be linked to fires in the continental tropical Asia (Thailand and the neighboring countries) (ref. also to Fig. S15-S16). As seen from Fig. 3b, more than 90% of global fires (black line) occur within the latitude band of 30°S-30°N (broken line), and are emitted as pulse in about a month time window. This result of anomalous XCO$_2$ increase during the 2015-2016 El Nino can be assigned to CO$_2$ emissions from the tropical land. However, this OCO-2-based study cannot quantitatively discriminate the relative roles of reduction in biospheric uptake due to warmer and drier climate, and emissions from biomass burning.

**Figure 3:** Global total CO$_2$ flux corrections as estimated from the OCO-2 and ACTM differences and global total GFAS emissions (a), and fire-pixel counts are shown for the Americas, Africa/Europe and Asia/Oceania sectors, in addition to the global and tropical latitudes (broken line) (b). Fire counts are taken from the Moderate-resolution Imaging Spectroradiometer (MODIS) Active Fire Products [Giglio et al., 2006].

Interestingly, although the time-integrated GFAS emissions are in good agreement with tropical XCO$_2$ increase, the timing of pulsed CO$_2$ emissions during the fire events are not well represented. The OCO-2 based flux correction time series can be decomposed in to two components as: 1) slowly varying biospheric flux anomaly, and 2) fast varying component with duration less than a couple months. Using this
decomposition, we estimate fire emissions to be ~0.7 PgC from the peaks in March, April, September and November of 2015, which is 30-44% of the total flux anomaly for the year 2015. The intense fire activity over the maritime Southeast Asia in October 2015 did not produce a positive CO$_2$ flux anomaly because of the missing OCO-2 data affected by aerosol plumes of fire products. Some of part of this emission is likely to have been detected in November 2015, spread over a wider area due to zonal mixing.

4. Conclusions and pitfalls

The powerful El Niño centering around 2015 has made a large impact on the Earth’s natural climate system, which in turn affected the terrestrial ecosystem. We analyzed the column-averaged CO$_2$ dry mole fraction (XCO$_2$) estimates from NASA’s OCO-2 observations collected between September 2014 and February 2016. We have also used the well-established TCCON ground-based XCO$_2$ and NOAA in situ CO$_2$ measurements in the analysis. Global simulations using JAMSTEC’s ACTM are performed for three combinations of terrestrial and oceanic CO$_2$ fluxes, and a common FFC emission field. We estimate that the El Niño event led to excess CO$_2$ release to the atmosphere in the range of 2.24-3.32 PgC during October 2014 to February 2016, compared to the reference period of 2011-2013, from the OCO-2 and ACTM XCO$_2$ differences. In year 2015, about 0.7 PgC is emitted from fires, which is in the range of 30-44% of total CO$_2$ flux anomaly.

Although the main goal of the OCO-2 satellite mission is to estimate regional (country scale) sources and sinks of CO$_2$, we identified two major issues needing immediate attention:

1) Handling of the data gaps in OCO-2 or other passive sensors for long-lived gases gives cause for concern as seen here (this issue is not serious for the short-lived species as their emission and chemical loss cycle is confined to a particular latitude band). Our estimates of CO$_2$ fluxes could vary by a factor of 2 depending on what area coverage is assumed for the extension of model-data differences towards the poles (Table 1).
2) Accounting for chemical production of CO$_2$ from methane (CH$_4$), carbon monoxide (CO) and biogenic volatile organic compounds (BVOCs). While most of their emissions occur in the tropics or northern hemisphere, a large fraction of about 1 PgC-CO$_2$ is produced away from the source regions (Fig. S17). Inclusion of regional distribution of chemical CO$_2$ source is required for regional source/sink attribution.

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Reference:


