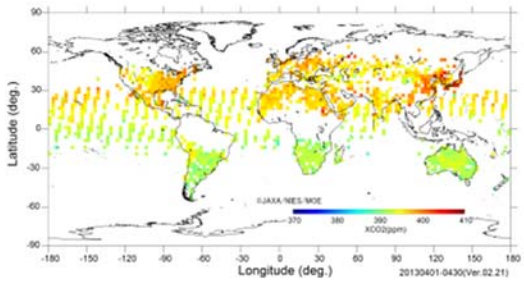
Released on November 16, 2015
Revised on November 30, 2015 (1st)
Revised on May 20, 2016 (2nd)
Revised on September 29, 2016 (3rd)
GOSAT Project, Satellite Observation Center, NIES

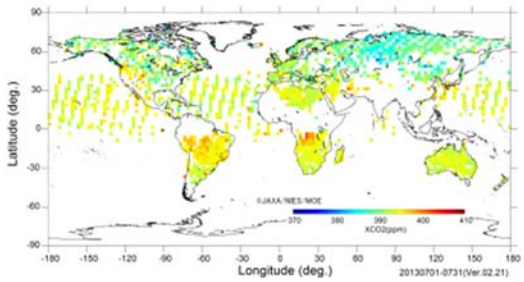
Calculation of whole-atmosphere monthly CO_2 mean concentration based on GOSAT observations

1. Introduction

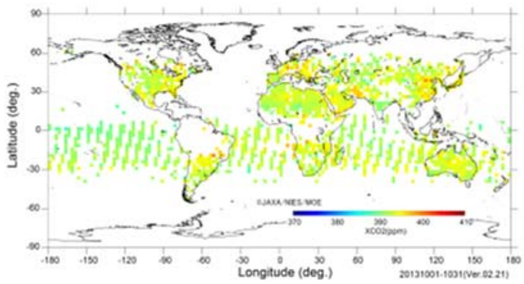
The concentration of carbon dioxide (CO_2) derived from space-based spectral measurements by GOSAT encompasses levels from the top of the atmosphere to the earth's surface; this is referred to as column-averaged dry air mole fraction of CO_2 or XCO_2. The column-averaged CO_2 concentration thus contains more information for understanding overall trends of CO_2 in the atmosphere than CO_2 measured at the surface. For the retrieval of XCO_2, measurement of light absorption spectra in the short-wave infrared (SWIR) radiation range is made with a Fourier Transform Spectrometer (FTS) onboard the satellite. These spectra are, however, only collected over sunlit parts of the globe without cloud cover and where the local solar altitude is above a specific threshold. Therefore, the area over which GOSAT XCO_2 data exist changes with season (Figure 1).



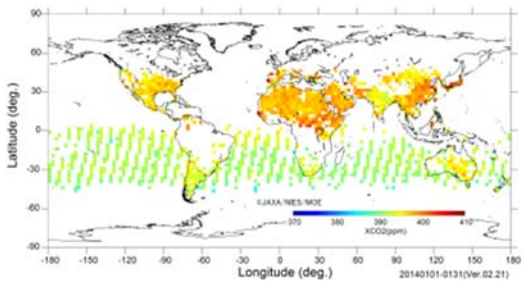
(a) April 2013（boreal spring）



(b) July 2013（boreal summer）



(c) October 2013（boreal fall）



(d) January 2014（boreal winter）

Figure 1. Distribution of GOSAT XCO_2 (GOSAT FTS SWIR Level 2 data product) gridded to

2.5-degree mesh and monthly averaged. Circles indicate the locations of XCO_2. The color shows the level of XCO_2 (low: blue; high: red).

Here, we considered an approach to estimate the whole-atmosphere mean CO_2 concentration from GOSAT XCO_2 data stored in GOSAT FTS SWIR Level 2 data product. The estimation approach is explained below.

2. Estimation of whole-atmosphere mean CO_2 concentration

The data gaps found in the distribution of GOSAT XCO_2, as shown in Figure 1, must be filled out before the XCO_2 data can be used for the calculation of the whole-atmosphere mean CO_2. The gaps were filled by using latitudinal band mean XCO_2 calculated from three-dimensional CO_2 distribution based on atmospheric tracer transport modeling (GOSAT Level 4B data product).

2.1 Calibration of GOSAT XCO_2 data

For the evaluation of precision and accuracy, GOSAT XCO_2 values were compared with surface-based XCO_2 measurements taken at monitoring sites of the Total Carbon Column Observing Network [1] (TCCON; http://tccon.ornl.gov). Biases found through this data validation process were used to correct GOSAT XCO_2 values. These biases were found to be dependent on changes in the characteristics of the observational instruments, spectral measurement errors, and the version of the algorithm for retrieving GOSAT XCO_2 that went through several updates in the past. The versions of GOSAT FTS SWIR Level 2 data product used here, which cover different time periods, are as follows: V02.21 (May 2009 – May 2014); V02.31 (mid-June – mid-December 2014); V02.40 (February – early August 2015); V02.50 (early August – mid September 2015); V02.60 (mid-September 2015 and onward).

From the comparison to the TCCON data, biases in V02.21 data were found to be time-dependent to a small extent. The dependency is expressed as follows:

$$\text{Bias} = -1.76 + (2.30 \times 10^{-3} \times t) + (-7.83 \times 10^{-7} \times t^2) \quad \text{(ppm)}, \qquad (1)$$

where t represents days past since the launch of the satellite (January 23, 2009). The biases in V02.21 data were corrected using the above regression equation.

In the case of V02.31, the time-dependency of the biases was not considered since the time span is only half a year; the biases were corrected by raising all XCO_2 by 0.62 ppm, preliminary validation result compared with TCCON data. The same approach was applied to the half-year-long V02.40 data (raising all XCO_2 by 1.35 ppm). For V02.50 and V02.60,

XCO_2 values were raised by 0.52 ppm (preliminary validation result compared with TCCON data over the period between April 2009 and December 2015), as corresponding TCCON measurements are not made available yet [2].

The FTS instrument onboard GOSAT can switch the gain of the observed signal amplifier depending on the intensity of surface-reflected sunlight observed (high, medium, and low gains). The instrument uses the medium gain when measuring over highly reflective surfaces such as deserts, and switches the gain to high elsewhere over land and ocean. Therefore, GOSAT FTS SWIR Level 2 data product contains XCO_2 values based measurements with high gain over land, medium gain over land, and high gain over ocean. Past studies suggested that these three types of XCO_2 values, found in the same time periods and latitudinal bands, may have biases that differ slightly from one to another. Since the majority of the TCCON data used for the XCO_2 data validation are collected over land surfaces above which GOSAT takes measurements with high gain, biases found in XCO_2 values retrieved from measurements with high gain over land may be most reliable. We therefore selected these high-gain GOSAT XCO_2 values (biases corrected) for the estimation of whole-atmosphere mean CO_2.

Notes:

[1] A global network of monitoring sites where high-resolution Fourier transform infrared spectrometers are installed. Column-averaged concentrations of atmospheric trace gases, such as CO_2, methane, carbon monoxide, and nitrous oxide, can be retrieved from the spectral measurements by these instruments.

[2] At present, whole-atmosphere CO_2 mean concentrations estimated for the period after February 2015 are preliminary. These estimates are planned to be updated after the completion of the XCO_2 data validation activities.

2.2 Estimation of monthly XCO_2 distribution in longitudinal bands

GOSAT Level 4B data product stores the six-hourly three-dimensional distribution of CO_2 on a 2.5-degree mesh. These concentration data were obtained by simulating atmospheric CO_2 transport based on surface CO_2 flux data (GOSAT Level 4A product) estimated from GOSAT FTS SWIR Level 2 XCO_2 and surface-based CO_2 data over a period between June 2009 and May 2012. To estimate XCO_2 values over the entire surface of the globe, including the gaps seen in the GOSAT XCO_2 distribution, we estimated monthly latitudinal distribution of XCO_2 in several large areas from GOSAT Level 4B data product as follows.

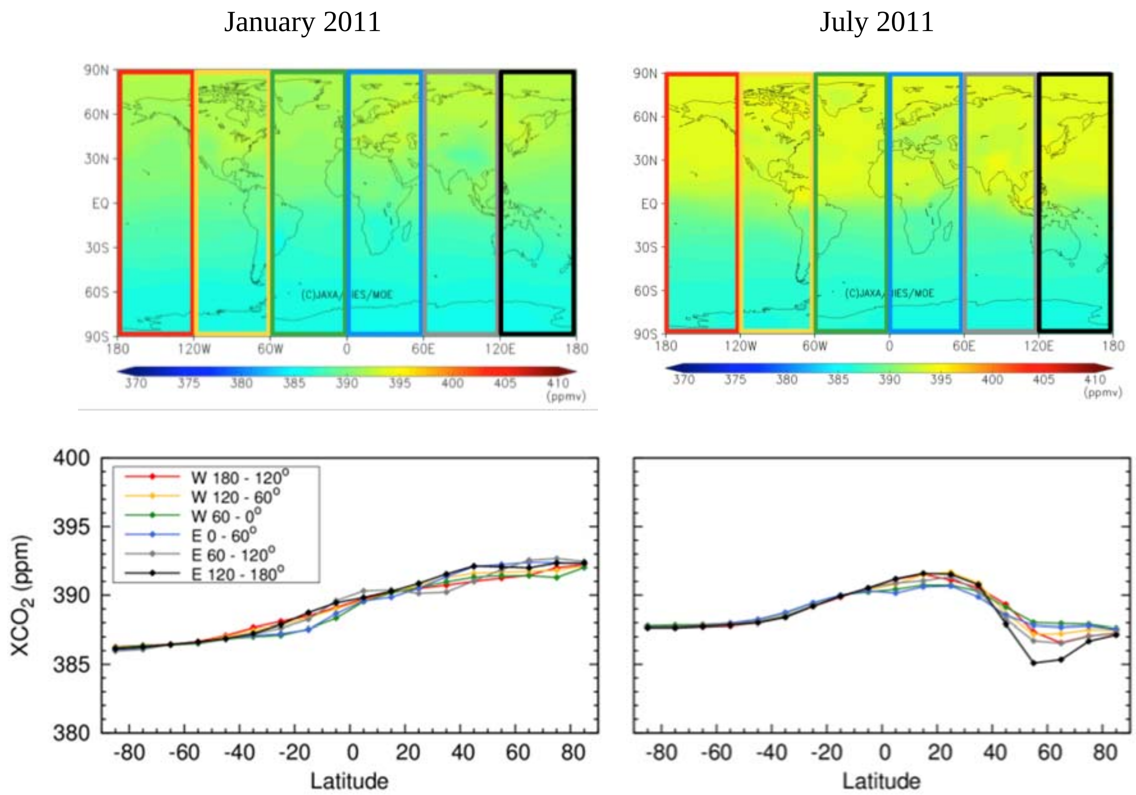


Figure 2. Upper panel: distribution of monthly mean model-simulated XCO_2 for January and July 2011. Lower panel: XCO_2 averaged over a 10° latitude×60° longitude grid box in each of the colored large areas, as shown in the upper panel. The line color indicates the location of each area.

First, we divided the globe into six large areas, each has a width of 60° longitude (see upper panel of Figure 2). Within each of the large areas, we defined 18 grid boxes with a size of 10° latitude by 60° longitude. We then calculated the monthly mean of model-simulated XCO_2 (GOSAT Level 4B data) over each of these grid boxes (lower panel of Figure 2).

Regions from 80°S to the South Pole have similar geographical features and are also away from major sources and sinks of CO_2; monthly mean XCO_2 over these regions are thus relatively stable and can serve as a reference in calculating the latitudinal distribution of model-simulated XCO_2. For each of the six large areas, we calculated the vector deviation ***D*** as follows:

D*(year, month, latitudinal-grid, longitudinal-grid)*
= (mean XCO_2 over each 10°lat.×60°lon. grid box) – (mean XCO_2 over 80°S-90°S). (2)

We calculated ***D*** for all months between June 2009 and May 2012 (three years). For every month from January to December, we then computed the mean of ***D*** (described as $\boldsymbol{D}_{mean}$) over the three-year period. $\boldsymbol{D}_{mean}$*(month, lat.-grid, lon.-grid)* values were used for the estimation of monthly global XCO_2 described in Section 2.3. Samples of the latitudinal distribution of $\boldsymbol{D}_{mean}$ are shown in Figure 3 (January and July).

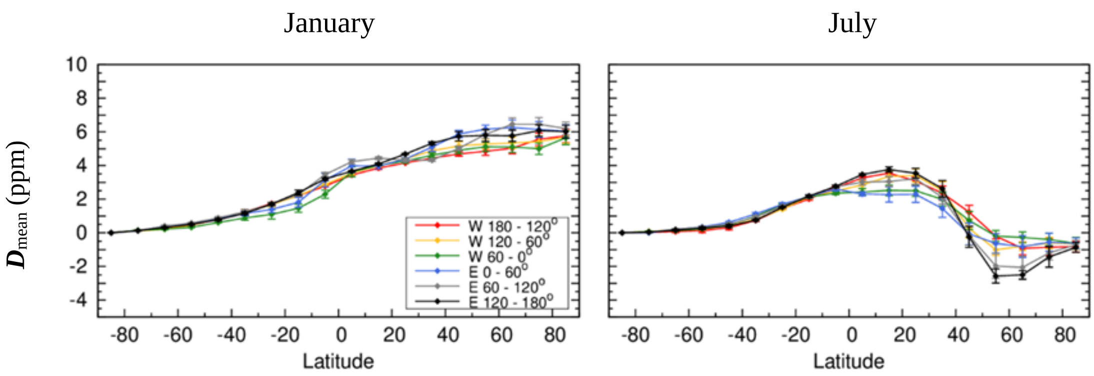


Figure 3. Mean deviation ($\boldsymbol{D}_{mean}$) of grid-box (10°×60°) mean XCO_2 from southern (80°S-90°S) XCO_2 (model-simulated XCO_2). Latitudinal distribution for each of the large areas defined in Figure 2 is shown (same color scheme used). Distribution for January (left) and July (right) are presented. Error bars indicate the standard deviation of model-simulated XCO_2 over the three-year period.

2.3 Estimation of monthly global XCO_2

For each of the six large areas defined in Section 2.2, we then calculated monthly mean GOSAT XCO_2 (biases were corrected as in Sect. 2.1) over each 10°×60° grid box. The monthly mean value was calculated if the number of GOSAT XCO_2 found in a given grid box in a month was greater than five.

To obtain gap-filled distribution of XCO_2, we used the following regression equation and found vector value ***a*** by the least squares method:

$$\text{(monthly mean GOSAT } XCO_2 \text{ over } 10°\times60° \text{ grid boxes)} = \boldsymbol{a}(\textit{year, month}) + \boldsymbol{D}_{mean}(\textit{month, lat.-grid, lon.-grid}). \quad (3)$$

Value ***a***, common for all the six large areas, is an estimated monthly mean XCO_2 concentration over the 80°S-90°S region. Using ***a***, we estimated monthly mean XCO_2 over 10°×60° grid boxes as the sum of ***a*** and $\boldsymbol{D}_{mean}$. The latitudinal distribution of the estimated XCO_2 as well as monthly mean GOSAT XCO_2 for 10° ×60° grid boxes, are shown in Figure 4.

The whole-atmosphere monthly mean CO_2 concentration was obtained by calculating a weighted average of the estimated XCO_2 values. Weight was assigned to each estimated XCO_2 value according to the latitude of its 10°×60° grid box center as

$$\text{weight} = \cos(-85° + 10° \times n), \quad (4)$$

where n is an integer that indicates the north-to-south location of the grid box in a given large area (0-17).

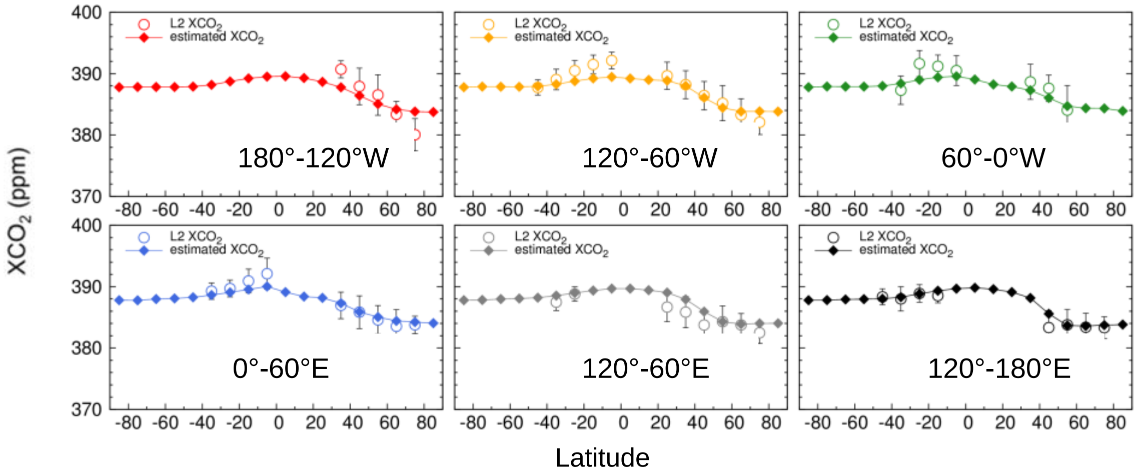


Figure 4. Latitudinal distribution of monthly mean GOSAT XCO_2 (circle) and estimated XCO_2 (diamond).

3. Trend line of whole-atmosphere monthly mean CO_2

The result obtained in this analysis shows that the whole-atmosphere monthly mean CO_2 rises continually, showing seasonal oscillations. The trend line of the time series of the whole-atmosphere monthly mean CO_2 can be obtained by calculating mean seasonal variation and subtracting it from the time series (red line in the upper part of Figure 5). A trend line value for a given month is nearly equal to a one-year average.

The slope of the derived trend line is not constant over the analyzed period. The red line in the lower part of Figure 5 shows the CO_2 annual growth, which is given by taking the time derivative of the trend line. The growth rate was small in 2011, and became large from late 2012 to early 2013. Overlaid onto the figure are a trend (blue line) derived from measurements taken at surface-level sites operated by US National Oceanic and Atmospheric Administration (NOAA) and the annual CO_2 growth calculated (Dlugokencky and Tans, NOAA/ESRL (data available at www.esrl.noaa.gov/gmd/ccgg/trends/)). Both growth rate curves (red and blue) show similar changes, although their phases are slightly different from one another. At each of the NOAA monitoring sites, high-precision CO_2 measurement is guaranteed with the use of reference CO_2 gases. The reasonable agreement of both results (red and blue) suggests long-term stability of the space-based CO_2 observation by GOSAT.

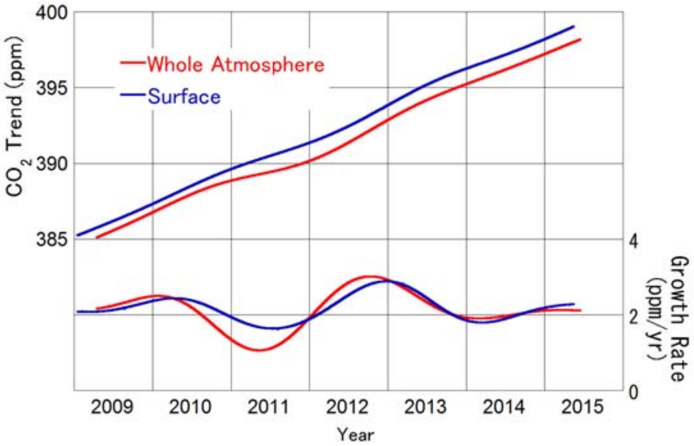


Figure 5. Whole-atmosphere mean CO_2 based on GOSAT XCO_2 data (red) and global mean CO_2 based on surface measurements (blue). Upper: CO_2 trend line. Lower: CO_2 annual growth.

4. Characteristics of whole-atmosphere mean CO_2

Figure 6 shows the whole-atmosphere monthly mean CO_2 values and their trend calculated using GOSAT FTS SWIR Level 2 data between May 2009 and April 2016. In December 2015, the whole-atmosphere monthly mean, which increases gradually with seasonal oscillation, reached the level of 400 ppm for the first time. The trend of the whole-atmospheric CO_2 mean, which increases monotonically, first exceeded 400 ppm in February 2016 based on the calculation result including GOSAT data up to April 2016.

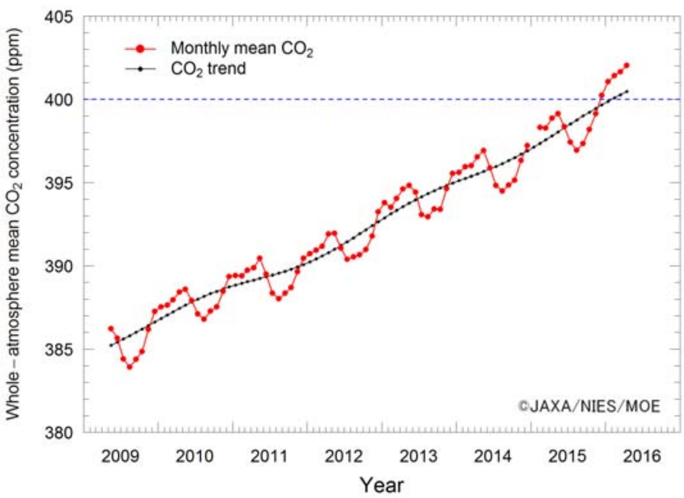


Figure 6. Whole-atmosphere monthly mean CO_2 (red dots) and their trend (black diamonds).

Appendix: Summary of this revision (2nd rev.)

- Biases in GOSAT FTS SWIR Level 2 data product were updated based on the latest result of GOSAT data validation activities (Section 2.1).
- This lead to slight changes in the coefficients of Equation 1 (the time dependency of biases in V02.21 data product).
- The whole-atmosphere mean CO_2 was then re-calculated based on the above updated information.
- With this update, the extent of uncertainty associated with the whole-atmosphere CO_2 estimate must be re-evaluated, and thus Chapter 3 was withheld at this time.
- Chapter 4 (Characteristics of whole-atmosphere mean CO_2) was modified according to the new results released in May 2016.
- Figure 6 was updated with the new results released in May 2016.

Summary of this revision (3rd rev.)

- Chapter 4 (Characteristics of whole-atmosphere mean CO_2) was modified according to the new results released in September 2016.
- Figure 6 was updated with the new results released in September 2016.

Note that the calculation method of the whole-atmosphere monthly CO_2 mean concentration is just the same as the method described in the 2nd revision.

Acknowledgement

The GPV (Grid Point Value) weather forecast data, provided by the Japan Meteorological Agency, were used for the retrieval of GOSAT FTS SWIR Level 2 XCO_2. Also, for the validation of GOSAT XCO_2, surface-based XCO_2 data by the Total Carbon Column Observing Network (TCCON; http://tccon.ornl.gov) were used. Thanks are extended to these two organizations.