

Evaluating Satellite Observed CO₂ Column by a 3-D Atmospheric Transport Model

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Abstract. Satellite remote sensing is the latest method of measuring atmospheric CO₂, which covers a wide range and makes periodic observation. But due to lack of ground-based observation sites, global satellite observed CO₂ column is not evaluated efficiently. This paper assess the applicability of using GEOS-Chem model to forward simulate atmospheric CO₂ for verifying Greenhouse Gas Observation SATellite (GOSAT) observed CO₂ column. It is shown that GEOS-Chem performs well in modelling atmospheric CO₂ and there are generally no significant differences between ground-based observation and model results. According to the comparison, the spatial and temporal distribution of XCO₂ agrees well between GOSAT and GEOS-Chem. GOSAT XCO₂ is turned out to be 2.6 ppm lower than the model results. The mean difference observed between GOSAT and GEOS-Chem varies from -1.8 to -3.1 ppm seasonally, with the standard deviation ranging from 1.4 to 2.1 ppm. And in general, the difference is larger in summer than that in winter, in land area than in sea area. It might have been caused by the different land-sea distribution and eco-system's changing with seasons.

1. Introduction

As one of the most important anthropogenic greenhouse gases, Atmospheric carbon dioxide (CO₂) has increased significantly since the beginning of the industrial revolution [1]. It is expected that further increase of CO₂ will definitely result in a warmer climate with adverse consequences, including rising sea levels and increasingly extreme weather events [2]. Currently, there are only a few satellite instruments orbiting the Earth which enable the retrieval of the column-averaged dry air mole fractions of atmospheric carbon dioxide (XCO₂). This is achieved by retrieving XCO₂ from measurements of reflected solar radiation in the near-infrared/shortwave –infrared (NIR/SWIR) spectral region (0.75-3μm). These instruments are SCIAMACHY onboard ENVISAT (launched in 2002) and TANSO onboard GOSAT (launched in 2009), which yield measurements of the relevant absorption bands of CO₂ in this spectral range [3-5]. GOSAT, the latest orbiting greenhouse gas observation satellite, is playing a pioneering role in the relatively new area of greenhouse gas observations from space [6]. Accurate analysis of GOSAT data is essential to initiate consistent long-term time series of CO₂ observation from space. However, due to lack of adequate ground-based observation stations, global validation of GOSAT XCO₂ is not sufficient [7, 8].

The use of global three-dimensional (3-D) models is an area of growing significance for understanding Earth's carbon cycle. GEOS-Chem is a global chemical transport model (CTM) that adopts the Goddard Earth Observing System (GEOS) assimilated meteorological fields from the

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National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office (GMAO). It is developed and used by research groups worldwide as a versatile tool application to a wide range of atmospheric composition problems [9]. This paper assess the applicability of the global atmospheric CO₂ concentration simulated by GEOS-Chem for verifying CO₂ retrieved from remote sensing satellite via the comparison with CO₂ column concentration obtained by the Total Carbon Column Observing Network (TCCON) based on the atmospheric spectral observations from ground.

2. CO₂ simulation with GEOS-Chem

2.1. Input dataset and simulation

The driven data contain the various met fields, emissions and other data that GEOS-Chem will use during the course of a simulation. The key inventories for GEOS-Chem CO₂ simulations are national fossil fuel and cement manufacture from CDIAC, biomass burning from GFEDv2, biofuel burning from Yevich, ocean exchange from Takahashi, balanced biosphere from CASA, residual annual terrestrial exchange, Shipping dataset from ICOADS, Aviation dataset from AEAP-SAGE and chemical source from Nassar [10]. In this work, all of these data is download with wget from Harvard archive (ftp.as.harvard.edu). The model is carried out with a supercomputer of Chinese Academy of Sciences.

The native vertical resolution of GEOS-5 meteorological fields is 72 hybrid eta levels, extending from the surface up to 0.01 hPa. The first 31 levels from the surface upward are pure sigma levels, the rest are fixed pressure levels. GEOS-Chem can be run at a reduced vertical resolution of 47 eta levels to minimize the amount of memory. Here the GEOS-Chem model (version 09-01-01) is used to forward simulate atmospheric CO₂ from the year 2008 to 2010. The simulation is carried out using GEOS-5 meteorological fields at 2°latitude × 2.5° longitude resolution, with 47 vertical hybrid-sigma levels being up to 0.01hPa.

2.2. GEOS-Chem CO₂

After dozens of hours of running the GEOS-Chem model, a 3-D CO₂ concentration dataset (GEOS-Chem CO₂) of the whole earth is obtained. The horizontal resolution of simulated CO₂ concentration data is 2° × 2.5°, at 47 vertical levels. The input meteorological data are updated every six hours, and the mixing depth and surface fields are updated every three hours. To save storage space of PC, the 6-hour mean CO₂ concentration data are transferred to daily mean data.

2.3 GEOS-Chem XCO₂

Combined with the GEOS-5 column averaging kernels, CO₂ column concentration (XCO₂) is calculated from the 47 layers CO₂ profile with the following formula:

$$XCO_2 = \sum_{i=1}^n CO_2^i \bullet w_i \quad (1)$$

where CO_2^i represents CO₂ concentration of the i th layer, w_i is the column averaging kernels of the i th layer.

3. Verification of GEOS-Chem Simulating CO₂ by Ground-based observation

3.1 Validate GEOS-Chem CO₂ with WDCGG CO₂

The World Data Centre for Greenhouse Gases (WDCGG), which is operated by the Atmospheric Environment Division (AED) of the Japan Meteorological Agency (JMA) under the framework of the framework of the Global Atmosphere Watch (GAW), gathers data about greenhouse gases and related tracer measurements from observation stations, archives and then disseminates these data. The WDCGG CO₂ data are mainly measured from flask samples at stationary platform, which reflects CO₂ concentration near earth surface and the measurement precision is within ±0.35ppm.

Here 43 valid GAW stations during the simulating period are used to evaluate the precision of GEOS-Chem model near the earth surface. It is shown that there are generally no significant differences between WDCGG CO₂ and the model results. The typical daily mean bias between model results and WDCGG CO₂ is within 3.2 ± 2.0 ppm, approximate to 0.82% ($\sim 0.82\%$), and the correlation coefficient is above 0.65. This corresponds well to Feng's study from year 2003 to 2006 [11]. GEOS-Chem model shows a good performance in simulating CO₂ concentration near the earth surface.

3.2 Validate GEOS-Chem XCO₂ with TCCON XCO₂

3.2.1. TCCON XCO₂. TCCON is a ground-based network of Fourier Transform Spectrometers (FTS) that precisely measure total columns of CO₂, CO, CH₄, N₂O, H₂O, HF and other gases [12]. The TCCON instruments measure the absorption of direct sunlight by atmospheric gases in the near infrared (NIR) spectral region. An enormous effort is put into minimizing errors in this external information, and the resulting total columns are precise. The error of XCO₂ is believed to be within 0.25% [13]. In this work, TCCON XCO₂ data are obtained from TCCON Data Archive at <http://tcon.ipac.caltech.edu/>, operated by the California Institute of Technology, and the observation data at each site are transferred to daily mean to indicate the daily CO₂ column concentration.

3.2.2. GEOS-Chem XCO₂ compared with TCCON XCO₂. Fifteen TCCON sites are adopted, which are distributed worldwide and have data among year 2008 to 2010. Figure 1 shows the comparison between model results and the ground based observations.

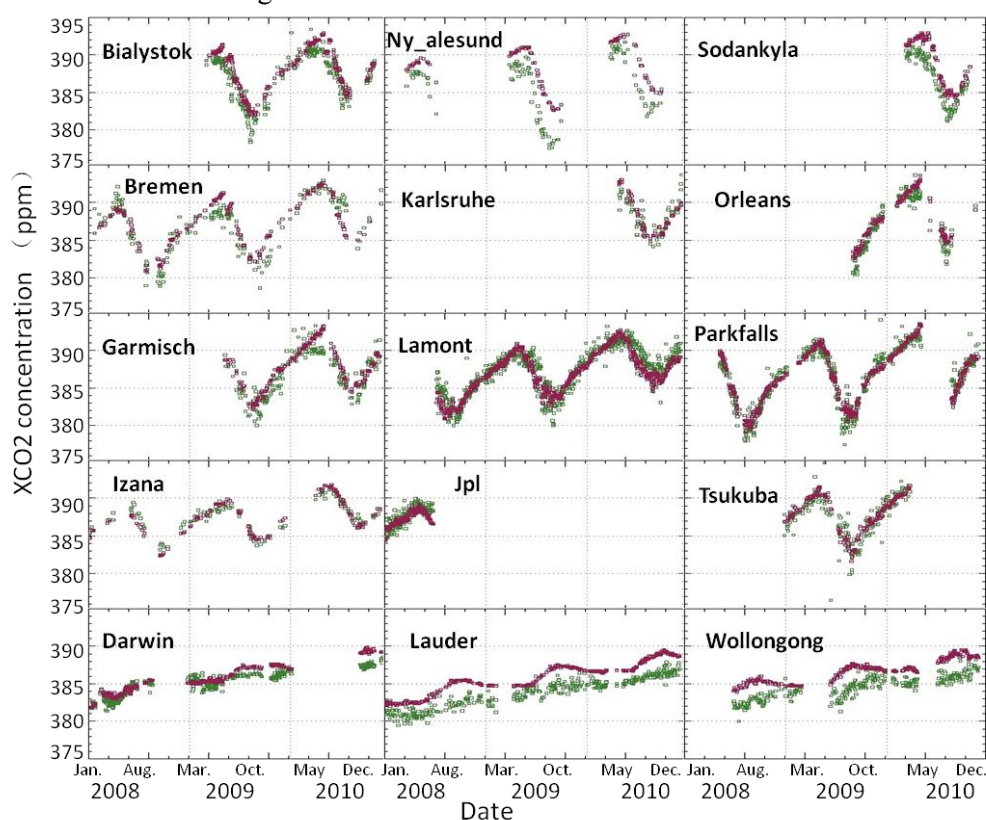


Figure 1. Comparison of GEOS-Chem XCO₂ (in red) time series of daily means with ground based FTS measurements (in green) at 15 TCCON sites for the years 2008-2010. The location of TCCON sites is shown in Figure 2. And the complete results are summarized in Table 1.

Table 1 indicates the comparison result between the TCCON XCO₂ data and GEOS-Chem XCO₂ data. And the bias of GEOS-Chem XCO₂ data reveals some distribution patterns. The daily bias of

high altitude is larger than that of low altitude. In Ny alesund site in North frigid zone area, GEOS-Chem XCO₂ data amounts to the maximum of 2.85ppm, 0.8%. In lower altitude, whereas, between 60°N and 60°S where the GOSAT satellite data footprints are most concentrated, the XCO₂ data bias between that of the GEOS-Chem and the total 13 TCCON sites amounts to 0.6±0.8 ppm with higher precision. It's evident from the table and figure that GEOS-Chem XCO₂ and TCCON XCO₂ are closely related to each other in each of the site. GEOS-Chem model proves to be worldwide efficient in simulating atmospheric CO₂ column concentration.

Table 1. Statistics of GEOS-Chem XCO₂ minus TCCON XCO₂ during 2008 to 2010

Station name	Lat	Lon	Number of days involved	Correlation coefficient	Mean & Std (ppm)
Ny_alesund	78.92	11.92	102	0.932	2.85±1.64
Sodankyla	67.37	26.63	107	0.949	2.10±1.01
Bialystok	53.23	23.03	240	0.907	1.37±1.29
Bremen	53.1	8.85	186	0.895	1.28±1.63
Karlsruhe	49.1	8.44	69	0.816	1.10±1.43
Orleans	47.97	2.11	157	0.950	1.11±1.09
Garmisch	47.48	11.06	194	0.900	1.20±1.31
Park Falls	45.94	-90.27	498	0.953	0.83±1.13
Lamont	36.6	-97.49	695	0.903	0.99±1.25
Tsukuba	36.05	140.12	179	0.839	1.02±1.51
Jpl	34.2	-118.18	154	0.715	0.81±0.93
Izana	28.3	-16.48	129	0.953	0.57±0.71
Darwin	-12.43	130.89	375	0.922	0.83±0.78
Wollongong	-34.41	150.88	279	0.793	2.20±0.96
Lauder	-45.04	169.68	354	0.933	2.02±0.78
Global Mean:					1.35±0.65

4. Evaluating GOSAT-XCO₂ with GEOS-Chem simulated XCO₂

4.1. GOSAT XCO₂

GOSAT nominally performs a cross-track scanning pattern with an instantaneous field of view (IFOV) of 15.8 mrad, equivalent to ~10.5 km diameter projected onto the Earth's surface. The standard mode consists of five cross-track points separated by ~158 km until August 2010. This has since been changed to three points to reduce pointing errors caused by micro-vibrations which are most extreme at the largest off-nadir pointing angles. The spectral radiance data obtained from TANSO FTS, a major sensor onboard GOSAT, are nominally processed to Level 2 (L2) CO₂ column abundance products with NIES algorithm, which contain column averaged volume mixing ratios of carbon dioxide (XCO₂). Initial validation of the L2 products was completed and the products were made public as version 00.xx on February, 2010. In order to avoid possible inaccuracy, the processing algorithms are improved and applied to the Level 1B data. New versions of the L2 products were released to the public from August 24, 2010 as ver.01.xx in quasi real time. Based on the positive conclusion of the FTS L2 validation committee held on April 19, 2012, GOSAT project starts releasing the new FTS L2 product ver.02.xx at <https://data.gosat.nies.go.jp/>, which have been processed with a new ver.02 NIES algorithm. Here ver.02.xx CO₂ product from June 2009 to May 2010 is collected, and the data are resampled to GMAO 2°×2.5° horizontal grid (GOSAT XCO₂) in accordance with resolution of GEOS-Chem.

4.2. Evaluate GOSAT XCO₂ with model results.

We compare one year of GOSAT XCO₂ with CO₂ column concentration from the GEOS-Chem. Overall, GOSAT XCO₂ agrees well with GEOS-Chem XCO₂ in the spatial and temporal distribution. There shows high correlations of the seasonal varies with a correlation coefficient up to 0.82. The CO₂ column concentration is declining in the summer and increasing in the rest seasons. The maximum XCO₂ comes in May for both dataset, 388.6 ppm from GOSAT observation and 390.4 ppm from model results. While, the minimum of GSOAT XCO₂ 383.2 ppm appears in September and the model 385.3 ppm appears in August. The annual XCO₂ variation amplitude from GOSAT observation is 5.4 ppm, greater than 5.1 ppm from GEOS-Chem simulation. The monthly mean difference observed between GOSAT and GEOS-Chem varies from -1.8 to -3.1 ppm seasonally, with the standard deviation ranging from 1.4 to 2.1 ppm. GOSAT XCO₂ turns out to be 2.6 ± 0.5 ppm lower than the model results.

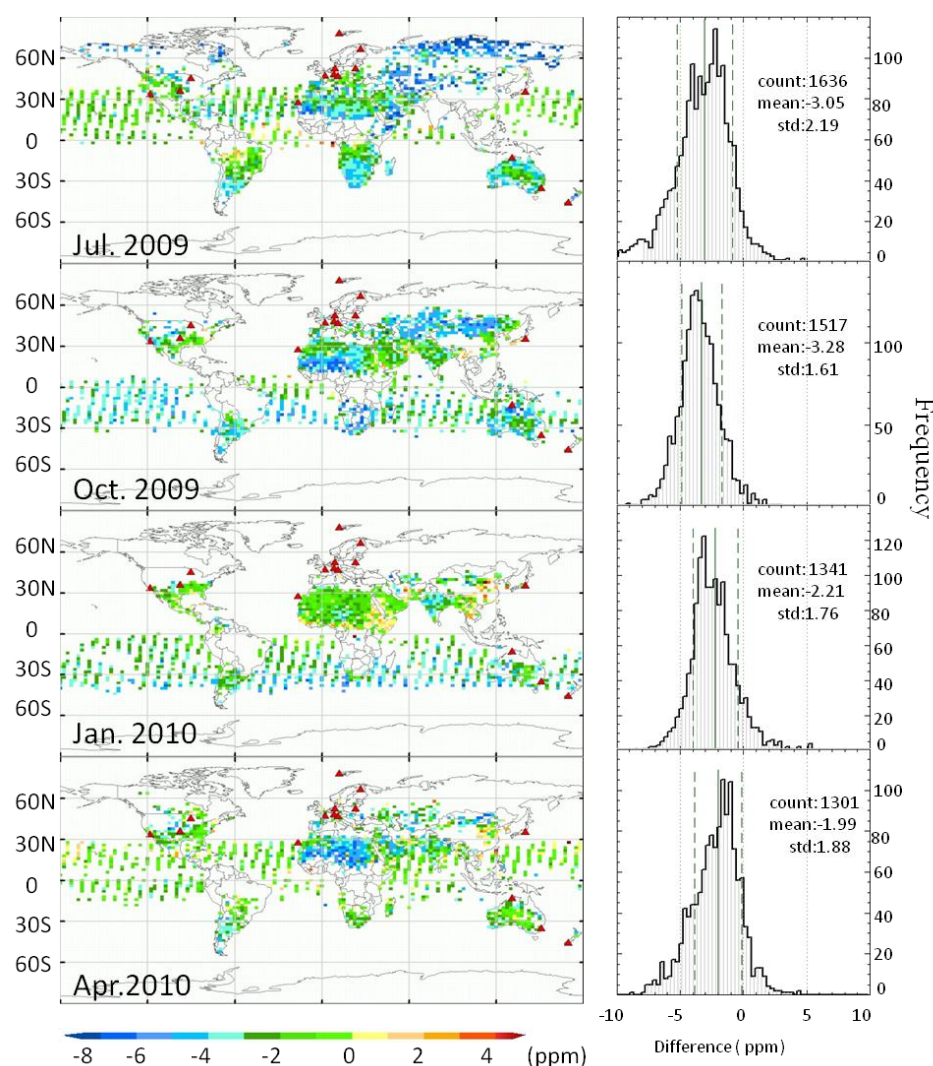


Figure 2. Comparison of XCO₂ retrieved from GOSAT data with GEOS-Chem XCO₂ calculations and the corresponding histogram. The red triangles indicate the location of TCCON sites. The *count* shows the number of grids that contain three or more GOSAT footprints in certain month, *mean* represents the mean XCO₂ difference, and *std* gives the standard deviation of the difference.

The above figure indicates the distribution patterns of the difference between GOSAT XCO₂ data and GEOS-Chem XCO₂ data. The differences are consistent with a normal distribution. It's reflected

that GOSAT XCO₂ data is worldwide lower than GEOS-Chem XCO₂ data and the bias changes along with time and space. In summer, GOSAT XCO₂ concentration data is ~7ppm lower than GEOS-Chem XCO₂ concentration data in the central and north Asian area, southern European area and equatorial African region. It's ~2ppm lower in a majority of the rest areas and ~3ppm lower in some areas. It's similar in autumn when GOSAT XCO₂ data concentration is ~6ppm lower than GEOS-Chem XCO₂ concentration in Central Asia, equatorial African region, south Africa and parts of South America. It's slightly ~1ppm lower in the eastern coastal regions of Asia and east coast of North America region. In some rare areas, GOSAT XCO₂ concentration data is ~2ppm higher than GEOS-Chem XCO₂ concentration. In winter GOSAT XCO₂ concentration is concentrated on low altitude areas in both south and north hemispheres. Except in the eastern coastal regions of Asia and equatorial African region, GEOS-Chem XCO₂ concentration is relatively higher, which reaches ~5ppm in middle and low altitude ocean in south hemisphere. In spring, except in southeast coastal area and Region of South America, GOSAT XCO₂ concentration is lower than GEOS-Chem XCO₂ concentration and reaches a minimum of ~5ppm in Central Africa and Central Asia and parts of the Americas.

The annual mean difference in the ocean area is -2.2 ppm, with a standard deviation of 1.2 ppm. While in the continent area the difference is -2.6 ppm, with a standard deviation of 1.9 ppm. The difference over ocean is lower and much more stable than that over global land. The precision of CO₂ column retrieved from GOSAT is affected by the measurement quality as well as the ground surface condition and the aerosol optical thickness. These factors vary with land-sea distribution, and the ecological system has a seasonal change, and thus leads to the different status of satellite retrieval processing. Further meticulous work needs to be done on analyzing the retrieval algorithm with the input parameters at areas that display distinct difference.

5. Conclusions

This manuscript presents and discusses the comparison between a global one year dataset of XCO₂ retrieved from GOSAT using the NIES retrieval algorithm and results from a GEOS-Chem simulation which is validated by ground based flask measurements (WDCGG) and FTS observations (TCCON).

It is demonstrated that there are generally no significant differences between ground-based observation and model results. The typical bias near ground surface CO₂ concentration between model results and 43 WDCGG sites is within 3.2 ± 2.0 ppm, ~0.82%, with correlation coefficients above 0.65. And the bias between the model simulation and CO₂ column concentration from the 15 global TCCON sites is 1.35 ± 0.65 ppm, ~0.35%, with correlation coefficients above 0.85. In lower altitude, whereas, between 60°N and 60°S where satellite data site is most concentrated, the bias between that of the GEOS-Chem and the total 13 TCCON sites amounts to 0.6 ± 0.8 ppm with higher precision. The results indicate that GEOS-Chem which performs well in modeling global atmospheric CO₂ concentration can be applied for the verification and assessment of CO₂ retrieved from satellite observation.

According to the comparison, GOSAT XCO₂ agrees well with GEOS-Chem XCO₂ in the spatial and temporal distribution. There is a high correlation of the seasonal varies with correlation coefficient up to 0.82. The CO₂ column concentration is declining in the summer and increasing in the rest seasons. The monthly mean difference observed between GOSAT and GEOS-Chem varies from -1.8 ppm to -3.1 ppm seasonally, with the standard deviation ranging from 1.4 ppm to 2.1 ppm. GOSAT XCO₂ turns out to be 2.6 ± 0.5 ppm lower than the model results.

The differences between the GOSAT and GEOS-Chem CO₂ column show a temporal and spatial pattern. And in general, the difference is larger in summer than that in winter, in land area than in sea area. It might have been caused by the different land-sea distribution and eco-system's changing with seasons. Further work remains to be done on analyzing the GOSAT retrieval algorithm with relevant input parameters at the regions that displays distinct difference. This will improve the precision of the retrieval results from satellite and broaden the use of the products.

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