Hurricane Rainfall Patterns in Houston and Miami
Global Atmospheric CO\textsubscript{2} Concentrations Simulated by GEOS-Chem: Comparison with GOSAT, Carbon Tracker and Ground-Based Measurements

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Abstract: Accurate quantification of the distribution and variability of atmospheric CO\textsubscript{2} is crucial for a better understanding of global carbon cycle characteristics and climate change. Model simulation and observations are only two ways to globally estimate CO\textsubscript{2} concentrations and fluxes. However, large uncertainties still exist. Therefore, quantifying the differences between model and observations is rather helpful for reducing their uncertainties and further improving model estimations of global CO\textsubscript{2} sources and sinks. In this paper, the GEOS-Chem model was selected to simulate CO\textsubscript{2} concentration and then compared with the Greenhouse Gases Observing Satellite (GOSAT) observations, CarbonTracker (CT) and the Total Carbon Column Observing Network (TCCON) measurements during 2009–2011 for quantitatively evaluating the uncertainties of CO\textsubscript{2} simulation. The results revealed that the CO\textsubscript{2} simulated from GEOS-Chem is in good agreement with other CO\textsubscript{2} data sources, but some discrepancies exist including: (1) compared with GOSAT retrievals, modeled XCO\textsubscript{2} from GEOS-Chem is somewhat overestimated, with 0.78 ppm on average; (2) compared with CT, the simulated XCO\textsubscript{2} from GEOS-Chem is slightly underestimated at most regions, although their time series and correlation show pretty good consistency; (3) compared with the TCCON sites, modeled XCO\textsubscript{2} is also underestimated within 1 ppm at most sites, except at Garmisch, Karlsruhe, Sodankylä and Ny-Ålesund. Overall, the results demonstrate that the modeled XCO\textsubscript{2} is underestimated on average, however, obviously overestimated XCO\textsubscript{2} from GEOS-Chem were found at high latitudes of the Northern Hemisphere in summer. These results are helpful for understanding the model uncertainties as well as to further improve the CO\textsubscript{2} estimation.

Keywords: GEOS-Chem model; GOSAT satellite; CarbonTracker; XCO\textsubscript{2}

1. Introduction

As one of the most important anthropogenic greenhouse gases, the CO\textsubscript{2} concentration in the Earth’s atmosphere has increased by 40% since pre-industrial times because of human activities [1,2]. Global warming caused by atmospheric CO\textsubscript{2} concentrations has gained much attention from climate scientists throughout the world [3,4]. An increased knowledge of the carbon cycle is necessary to predict and mitigate climate change [3,4]. Thus, it is extremely important to accurately quantify the distribution and variability of the global CO\textsubscript{2} sources and sinks [4]. Model simulation and observations provide two effective ways to quantitatively estimate CO\textsubscript{2} fluxes and concentrations with high accuracy, but the existing in situ measurements of atmospheric CO\textsubscript{2} are sparse and even absent.
in some regions (e.g., oceans and polar regions) so that large uncertainties exist in the estimation of global CO$_2$ sources/sinks if only using ground-based data [5,6]. Satellite remote sensing provides an advantageous technique to derive the CO$_2$ column-averaged dry air mole fractions (XCO$_2$) for atmospheric inversions on the global and regional scales.

Currently, the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) from Europe [7], the Greenhouse gases Observing Satellite (GOSAT) from Japan [8], the Orbiting Carbon Observatory-2 (OCO-2) from the United States of America [9] and the TanSAT from China [10] are four typical satellite sensors that can derive XCO$_2$ with significant sensitivity in the boundary layer [7]. Among these instruments, SCIAMACHY mainly measures the global trace gases in the troposphere and stratosphere, including CO$_2$ and CH$_4$ [7], but unfortunately, it has been lost since 2012. The GOSAT as well as the recently launched OCO-2 and TanSAT are specifically designed to accurately estimate atmospheric CO$_2$ and CH$_4$ [8,9]. Moreover, CO$_2$ retrieval algorithms have also been developed based on these instruments, for example, the NASA’s Atmospheric CO$_2$ Observations from Space (ACOS) team has applied the OCO retrieval algorithm to the GOSAT Level 1B data [6,11] to produce XCO$_2$ data (hereinafter called GOSAT/ACOS XCO$_2$). These XCO$_2$ data from satellite are very useful to improve estimations of CO$_2$ concentrations and further constrain the model simulations, thereby reducing uncertainties of CO$_2$ sources and sinks. However, due to cloud contamination and limitations of observation modes, the available data number of XCO$_2$ retrievals is very limited [12,13]. Morino et al. [14] pointed out that only about 10% of the GOSAT data points can be used for the XCO$_2$ retrievals. Consequently, these limited CO$_2$ observations could bring additional uncertainties into atmospheric inversion models [15].

Model simulation is another essential tool to quantify the spatio-temporal characteristics of CO$_2$ concentrations and fluxes. Unlike limited satellite observations, it can provide full-coverage atmospheric CO$_2$ concentrations on a global scale. In early studies, two-dimensional transport models were frequently used to estimate the distribution of CO$_2$ fluxes [16], while, in recent decades, three-dimensional (3-D) models have been developed to estimate the distribution as well as interannual variations of CO$_2$ fluxes [16]. Considering the large differences between models, robust estimation of model transport error has become a serious concern [17]. TransCom 3 found that the significant source of uncertainty in CO$_2$ inversion calculations was mainly due to the CO$_2$ flux inventories in transport models by intercomparing CO$_2$ inversion differences among 17 different models [16]. Chevallier et al. emphasized that the uncertainties in models probably limits the utility of the model system for further carbon cycle research [17].

To better estimate the uncertainty in CO$_2$ model inversion, several studies have also assessed the differences between observations and models [15,18,19]. Li et al. [18] compared the differences of atmospheric CO$_2$ concentration in East Asia between the Community Multiscale Air Quality Modeling System (CMAQ) and GOSAT observations to evaluate the uncertainties in model simulation. Saito et al. [20] reported that the latitude-time variations of XCO$_2$, CH$_4$ and N$_2$O and the transport processes in troposphere and stratosphere were well modeled by an atmospheric general circulation model (AGCM)-based chemistry-transport model (ACTM), which was confirmed through comparisons to TCCON (Total Carbon Column Observing Network). Particularly, GEOS-Chem, as a global 3-D chemical transport model, which plays an important role in characterizing the distribution and variability of global atmospheric CO$_2$ [21], has also been evaluated using surface carbon dioxide monitoring network, aircraft, and satellite observations. For example, Feng et al. [22] evaluated the GEOS-Chem model using GLOBALVIEW, CONTRAIL aircraft and AIRS satellite data. Lindqvist et al. [23] compared the seasonal cycle of ACOS retrievals with the University of Edinburgh model (assimilating two GOSAT retrievals into GEOS-Chem, referred as UoE) in the Northern Hemisphere. Recently, Zhang et al. [24] modeled the HASM XCO$_2$ by fusing the TCCON measurements with GEOS-Chem XCO$_2$ model and compared them with satellite observation. These studies have compared the differences of atmospheric CO$_2$ between GEOS-Chem and other observations in terms of spatial variation, regional bias and latitudinal gradient by seasons. However, the CO$_2$ characteristics of
GEOS-Chem model simulation (e.g., seasonal cycle amplitude as well as model errors, especially CO₂ overestimation in the high latitudes in summer) have not been fully investigated and inter-compared with multi-source CO₂ data. These inter-comparisons are quite important to quantitatively evaluate model uncertainties and improve the CO₂ flux estimate in GEOS-Chem. Therefore, it is necessary to further compare the CO₂ characteristics from GEOS-Chem with multi-source CO₂ data including observations and other model results to understand uncertainties of CO₂ simulation.

For this reason, the overall objective of this study was to simulate atmospheric CO₂ using GEOS-Chem and inter-compare the characteristics of CO₂ simulation with GOSAT/ACOS XCO₂ data, CarbonTracker CO₂ modeling system and TCCON site measurements during the years of 2009–2011. The remainder of this paper is organized as follows: Section 2 describes the data and models used in this study; Section 3 introduces the methods to compare the simulated XCO₂ from GEOS-Chem and other CO₂ data with the results presented in Section 4 along with the comparisons between XCO₂ from GEOS-Chem and that of GOSAT/ACOS, CarbonTracker as well as TCCON measurements. The results are discussed in Section 5 and the conclusions are presented in Section 6.

2. Data and Models

2.1. Datasets

2.1.1. GOSAT XCO₂ Observations

The GOSAT, the first satellite specifically used to accurately monitor CO₂ and CH₄ [8], was successfully launched on 23 January 2009. It includes a Thermal and Near-infrared Sensor for Carbon Observation Fourier Transform Spectrometer (TANSO-FTS, JAXA, Tokyo, Japan) and a Cloud and Aerosol Imager (CAI, JAXA, Tokyo, Japan). TANSO-FTS mainly measures greenhouse gases in both the Short-Wave InfraRed (SWIR) region (0.76, 1.6 and 2.0 µm) and a wide Thermal InfraRed (TIR) band (5.5–14.3 µm) at a spectral resolution of 0.2 cm⁻¹ [8]. TANSO-CAI monitors the clouds and aerosols within the TANSO-FTS’s field of view [8]. In recent years, some CO₂ retrieval algorithms, e.g., NIES [25], ACOS [6], and UOL-FP [26] have been developed based on the GOSAT satellite. Operational GOSAT/ACOS CO₂ products from the NASA’s Atmospheric CO₂ Observations from Space team have been released and are publicly available. Currently, the version 7.3 of the GOSAT/ACOS XCO₂ L2 data [27] is the newest one. Considering the potential deficiencies in M-gain and ocean glint retrievals, only the H-gain land data of GOSAT/ACOS are used in this study. Before incorporating GOSAT/ACOS XCO₂ data in this study, data filtering and bias corrections recommended by GOSAT/ACOSv7.3 data users guide [27] were applied for scientific purpose.

2.1.2. Total Carbon Column Observing Network (TCCON) XCO₂ Measurements

The Total Carbon Column Observing Network (TCCON) is a global network of ground-based Fourier transform spectrometers that measure atmospheric columns of the gases CO₂, CO, CH₄, H₂O and others [28–30]. Wunch et al. [28] compared the XCO₂ data retrieved from TCCON with integrated aircraft profiles and found an accuracy of approximately 1 ppm in these data. TCCON provides critical ground-based data for validation and bias correction of retrieved CO₂ from satellites [28,29], e.g., the calibration of ACOS XCO₂ retrievals from GOSAT [11]. In this study, TCCON XCO₂ retrievals of the newest GGG2014 version at fourteen sites during January 2009–December 2011 were used to evaluate XCO₂ results from the GEOS-Chem model. Sites selected for this study are: Lamont [31], Park Falls [32,33], Białystok [34,35], Orleans [36,37], Garmisch [38,39], Bremen [40], Sodankylä [41,42], Ny–Ålesund, Izaña [43], Eureka [44], Karlsruhe [45] sites located in the Northern Hemisphere (NH), Wollongong [46], Darwin [47,48], and Lauder [49] sites located in the Southern Hemisphere (SH), were used in this study.


2.2. Model Description

2.2.1. GEOS-Chem Model Description

GEOS-Chem is a global three-dimensional (3-D) chemical transport model (CTM) driven by assimilated meteorological fields from the Goddard Earth Observing System (GEOS-5) of the NASA Global Modeling and Assimilation Office [50]. The original GEOS-Chem CO\textsubscript{2} simulation was developed by Suntharalingam et al. [51]. Nassar et al. [21] have completed a major update of CO\textsubscript{2} simulations of GEOS-Chem model, which improved the CO\textsubscript{2} flux inventories and added CO\textsubscript{2} emissions from international shipping and aviation. In this study, the GEOS-Chem model (v9-02) was used to simulate global atmospheric CO\textsubscript{2} from 2005 to 2011.

Since the setting of initial CO\textsubscript{2} concentration has a significant impact on the simulated results, it is necessary to select the appropriate CO\textsubscript{2} concentration to initialize the model. In this study, the CO\textsubscript{2} concentration on January 2005 was initially set as 375 ppm on the global scale similar to Nassar et al. [21]. Four years after initialization, a more reasonable CO\textsubscript{2} distribution pattern was generated to again drive the model calculation. Finally, the global atmospheric CO\textsubscript{2} distribution is effectively simulated and available for the years of 2009–2011 in this study. The simulated CO\textsubscript{2} included 47 vertical levels with a horizontal grid resolution of $2^\circ \times 2.5^\circ$ latitude/longitude. The time period of CO\textsubscript{2} simulation is set at 13:00 $\pm$ 2 h local time to match the overpass time of the GOSAT satellite.

The input surface CO\textsubscript{2} fluxes include: (1) fossil fuel burning and cement manufacture from an inventory developed at the Carbon Dioxide Information and Analysis Centre (CDIAC) [52]; (2) Monthly biomass burning from the third version of the Global Fire Emission Database (GFEDv3) [53]; (3) Terrestrial biospheric exchange in the model including two components: a balanced biosphere computed by the CASA biospheric model and the residual annual terrestrial exchange obtained by inverse modeling in the TransCom 3 project [21,54,55]. The CASA Net Ecosystem Productivity (NEP) output is used as Net Ecosystem Exchange (NEE) in the GEOS-Chem model simulation [21]. It should be noted that these balanced biospheric fluxes contribute no net annual uptake of CO\textsubscript{2}, but they make the greatest contribution to the seasonal cycle of atmospheric CO\textsubscript{2} over most of the globe with the largest impact in the Northern Hemisphere [21]. The residual annual terrestrial exchange is based on the TransCom CO\textsubscript{2} inversion results adjusted with GFEDv2 fire emissions and account for the total annual sum of biospheric uptake and emission of CO\textsubscript{2} [21]; (4) The ocean fluxes of CO\textsubscript{2} from Takahashi et al. [56]. Other fossil fuel emissions from international shipping and aviation have also been included in the GEOS-Chem simulation [21]. The CO\textsubscript{2} module and sources/sinks inventories is described in detail by Nassar et al. [21].

2.2.2. CarbonTracker

CarbonTracker (CT) is a CO\textsubscript{2} data assimilation system built by the National Oceanic and Atmospheric Administration (NOAA, Silver Spring, MD, USA), Earth System Research Laboratory (ESRL, Boulder, CO, USA) and uses the Transport Model 5 (TM5) offline atmospheric tracer transport model to propagate surface emissions [57]. CarbonTracker CO\textsubscript{2} profiles of CT2013B and CT2016 version during 2009–2011 were collected for comparison with modeled CO\textsubscript{2} of the GEOS-Chem model in this study. The CT provides global CO\textsubscript{2} profiles of 25 vertical levels with $3^\circ \times 2^\circ$ longitude/latitude grids and 3-h temporal resolution [58].

The input CO\textsubscript{2} fluxes used in CarbonTracker contain: (1) two fossil fuel emissions from Miller and ODIAC datasets. These two datasets provide similar global emissions for each year, but differ in spatial and temporal distribution [59]; (2) biomass burning based on CASA-GFED [59], which is similar to that used in GEOS-Chem; (3) two terrestrial biosphere flux; for CT2013B from CASA-GFEDv2 and GFEDv3; for CT2016 from GFEDv4 and GFED_CMS. It reported that CASA-GFEDv3 product has a smaller seasonal cycle than the older CASA-GFEDv2 [59]; (4) The ocean fluxes of CO\textsubscript{2} from Takahashi et al. [56] and ocean inversions (OIF) [59,60] results; (5) assimilation of in situ observations including tall towers, flasks sampled by the NOAA Cooperative Air Sampling Network, and continuous measurements
from partners [59]. A comparison of CO₂ input parameters among CT2013B, CT2016 and GEOS-Chem is shown in Table 1.

Table 1. Comparison of resolution, input surface CO₂ fluxes, transport models and assimilated observation Among CT2013B, CT2016 and GEOS-Chem.

<table>
<thead>
<tr>
<th>Models</th>
<th>Resolution</th>
<th>Biospheric Flux</th>
<th>Fossil Fuel</th>
<th>Transport Model</th>
<th>Biomass Burning</th>
<th>Assimilated Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEOS-Chem</td>
<td>2° × 2.5° lat/lon × 47</td>
<td>CASA/GFEDv3</td>
<td>CDIAC</td>
<td>GEOS5</td>
<td>CASA/GFEDv3</td>
<td>no</td>
</tr>
<tr>
<td>CT2013B</td>
<td>2° × 3° lat/lon × 25</td>
<td>CASA/GFEDv3 and GFEDv2</td>
<td>CDIAC and Miller</td>
<td>TM5</td>
<td>CASA/GFEDv3 and GFEDv2</td>
<td>in situ data</td>
</tr>
<tr>
<td>CT2016</td>
<td>2° × 3° lat/lon × 25</td>
<td>CASA/GFEDv4 and GFED_CMS</td>
<td>CDIAC and Miller</td>
<td>TM5</td>
<td>CASA/GFEDv4 and GFED_CMS</td>
<td>in situ data</td>
</tr>
</tbody>
</table>

3. Methodology

It is well known that different CO₂ products cannot be directly compared with each other as a result of their different data sources and samplings methods. For example, CO₂ products retrieved from GOSAT/ACOSv7.3 are CO₂ column-averaged dry air mole fraction (XCO₂) concentrations, while the modeled results from GEOS-Chem are CO₂ profiles with 47 vertical layers. Considering these discrepancies, an adjustment must be conducted before comparing them with each other. In this study, the model-simulated CO₂ profiles were converted to XCO₂ by using averaging kernel and a priori profile of GOSAT/ACOS according to Rodgers and Connor [61] for comparing with GOSAT observations. The adjustment equation is expressed as follows:

\[
XCO₂^m = XCO₂^a + \sum_j h_j a_j (y_m - y_a)_j
\]  

where XCO₂^m refers to the transformed model XCO₂, XCO₂^a is the GOSAT/ACOS a priori XCO₂, \( h \) denotes pressure weighting function, \( a \) is the GOSAT/ACOS v7.3 column averaging kernel, \( y_m \) is the simulated CO₂ vertical profile, \( y_a \) is the GOSAT/ACOS v7.3 a priori CO₂ profile.

The detailed adjustment method was performed as follows. First, the GEOS-Chem CO₂ profiles were extracted and interpolated to the corresponding time and locations of the GOSAT/ACOS v7.3 XCO₂ data. After interpolation according to the GOSAT/ACOS pressure levels, the simulated CO₂ profiles have the same layers as a priori CO₂ profiles of the GOSAT/ACOS. Then, the interpolated CO₂ profiles from the GEOS-Chem model are convolved with the averaging kernel of GOSAT/ACOS to obtain XCO₂ as in Equation (1). These transformed XCO₂ from the GEOS-Chem model are then compared with GOSAT/ACOSv7.3 XCO₂ data in terms of their spatial and temporal characteristics as well as time series variations.

Furthermore, modeled CO₂ from both GEOS-Chem and CarbonTracker are CO₂ profiles with different vertical levels (e.g., GEOS-Chem for 47 layers and CarbonTracker for 25 layers). To better compare them with each other on the global scale, their CO₂ profiles are uniformly transformed to XCO₂ according to the weighting pressure-averaged method described by O’Dell et al. [6]:

\[
XCO₂ = \hat{h}^T \hat{u}
\]

where \( \hat{u} \) is the CO₂ profiles from the CarbonTracker or GEOS-Chem model on discrete pressure levels and \( \hat{h} \) is the pressure weighting function. The specific conducted method of \( \hat{h} \) is described in O’Dell et al. [6].

In addition, to compare modeled CO₂ from GEOS-Chem with TCCON XCO₂ measurements, the GEOS-Chem CO₂ profiles should be transferred to XCO₂ by using TCCON column averaging kernels and a priori CO₂ profiles [28,62,63]. The averaging kernel correction formula is similar to Equation (1). Here, the model-simulated CO₂ profiles are extracted and integrated to XCO₂ within ±2.5° latitude and ±2.5° longitude of each TCCON site. XCO₂^m denotes the integrated
XCO$_2$ from GEOS-Chem; XCO$_2$ is the TCCON a priori XCO$_2$; $h$ is pressure weighting function; $a$ is the TCCON column averaging kernel, which is a function of pressure and the solar zenith angle; $y_m$ is the simulated CO$_2$ profile; $y_a$ is the TCCON a priori CO$_2$ profile. The detailed method is described in Wunch et al. [28].

4. Results and Discussion

4.1. Comparison with GOSAT/ACOS XCO$_2$ Retrievals

Satellite measurements (e.g., GOSAT) can provide spatiotemporal distribution characteristics of global atmospheric CO$_2$ and have the potential to improve model flux estimation. Motivated by this, we compare modeled CO$_2$ from GEOS-Chem with GOSAT/ACOSv7.3 retrievals over land in this study to evaluate the uncertainties of CO$_2$ simulations. However, atmospheric CO$_2$ data from GOSAT/ACOS are XCO$_2$ concentrations, while those from the GEOS-Chem model are CO$_2$ profiles with 47 vertical levels. For comparison between them, the model-simulated CO$_2$ profiles were transformed to XCO$_2$ according to the time and location of GOSAT/ACOS retrievals based on the method in Section 3. It is noted that the CO$_2$ data used in this study during the period of March 2010 to February 2011, are divided by seasons in this study: spring (MAM, March–May), summer (JJA, June–August), autumn (SON, September–November), and winter (DJF, December 2010–February 2011). From Figure 1, obviously sparse spatial coverage is observed in GOSAT/ACOSv7.3 XCO$_2$ distribution because of some factors, e.g., cloud contamination or limitations of GOSAT observation modes as well as solar zenith angles [13,26].

![Figure 1](image-url)

**Figure 1.** Comparison of XCO$_2$ simulated with GEOS-Chem and GOSAT/ACOSv7.3 XCO$_2$ products during March 2010–February 2011. Seasonal averaged XCO$_2$ concentrations are shown for GEOS-Chem, GOSAT/ACOSv7.3 and their differences (GEOS-Chem − ACOS): (a): MAM; (b): JJA; (c): SON; (d): DJF. Unit: ppm.
Figure 1 also reveals that seasonal variations of XCO₂ in the NH are apparent for the GEOS-Chem model and GOSAT/ACOSv7.3, with the higher CO₂ concentrations occurred in MAM and DJF as well as the lower ones in JJA and SON. There was no significant seasonal variation found in the SH. The cause of these significant seasonal variations in the NH may be mainly that strong photosynthesis by vegetation in JJA and SON results in the decay of the CO₂ concentration and winter heating leads to higher XCO₂ concentration in MAM and DJF [13,64].

As presented in Figure 1, although the spatial distribution characteristics are consistent between GEOS-Chem and GOSAT/ACOS on the whole, the differences are evident in each season. For example, XCO₂ from GEOS-Chem is overestimated relative to that of GOSAT/ACOSv7.3 at many regions, especially in the SH and high latitude region in the NH. However, underestimated XCO₂ is found in the middle latitude region of the NH, particularly in SON.

Furthermore, there are consistent latitudinal variations between GEOS-Chem and GOSAT/ACOS v7.3 retrievals in Figure 2. Nevertheless, some discrepancies are obvious between them (GEOS-Chem − GOSAT/ACOS), which vary from 0.2 ppm to 0.78 ppm, with the largest difference (0.78 ppm) in summer. The result in Figure 2 also shows that overestimated XCO₂ from GEOS-Chem were found, especially in the SH as well as 55° N–65° N latitude band in JJA, with largest overestimated value point-by-point even up to 2.88 ppm in the 20° S latitude band in winter. However, underestimated XCO₂ was observed over tropical region of the NH in MAM and DJF, as well as middle latitude region of NH in JJA and SON. For underestimated XCO₂ over tropical region in MAM and DJF, it may be affected by satellite retrieval errors due to tropical cloud during these seasons. This result is also in good agreements with Cogan et al. [26]. Few data is found in the high latitude of the NH for GOSAT/ACOS XCO₂ in DJF due to the effect of large solar zenith angles in GOSAT observation. In addition, it can also be seen from Figure 2 that the standard deviation of GOSAT/ACOSv7.3 is relatively larger than GEOS-Chem, which indicates the larger discrete variation of GOSAT/ACOS retrievals.

The seasonal correlation coefficients of XCO₂ between GOSAT/ACOS and GEOS-Chem in Figure 3 show that best correlation (R = 0.80) is found in MAM and the poorest correlation (R = 0.52) in SON. Cogan et al. [26] also found that GEOS-Chem (v08-02) showed highest correlation with GOSAT observation (UoL-FP retrievals) in MAM.
Cogan et al. [26] also found that GEOS-Chem (v08-02) showed highest correlation with GOSAT observation (UoL-FP retrievals) in MAM.

**Figure 3.** Scatter plots of XCO$_2$ retrievals of GOSAT/ACOS v7.3 versus XCO$_2$ simulation from GEOS-Chem during March 2010–February 2011. (a)–(d) indicate MAM, JJA, SON and DJF respectively. Unit: ppm.

In addition, as shown in Figure 4, the time series variations of XCO$_2$ from GEOS-Chem in the NH during April 2009–December 2011 show good agreement with those of GOSAT/ACOSv7.3, but monthly averaged XCO$_2$ in the SH is obviously overestimated by GEOS-Chem (even up to 2.5 ppm in April 2011). Overall, the average bias between GEOS-Chem and GOSAT/ACOS is 0.78 ppm (GEOS-Chem – GOSAT/ACOS) on the global land during April 2009–December 2011. From Figure 4, in the NH, the CO$_2$ seasonal cycle dependence of GOSAT/ACOSv7.3 is stronger than GEOS-Chem in JJA.

**Figure 4.** The time series variations of monthly averaged XCO$_2$ for April 2009–December 2011 in the NH and SH between GOSAT/ACOS and GEOS-Chem. The green line denote the GOSAT/ACOS XCO$_2$ retrievals in the NH and the orange one is in the SH; the two blue lines refers to the XCO$_2$ simulated from GEOS-Chem in the NH and SH respectively.

Monthly averaged XCO$_2$ result in Table 2 and time series variations of the NH in Figure 4 also reveal the largest difference (1.2 ppm) between GEOS-Chem and GOSAT/ACOS found in JJA. This phenomenon coincides with the seasonal drawdown of XCO$_2$ and therefore may be connected
to the biospheric fluxes in the GEOS-Chem model. Li et al. [18] stated that the uncertainty in the terrestrial biosphere has a strong effect on CO$_2$ simulations in summer.

Table 2. Statistics of the number of XCO$_2$ data (N), standard deviation (STD) and averaged biases (Bias) for GEOS-Chem (G-C), GOSAT/ACOS (G-A for GEOS-Chem – ACOS) over the global land during March 2010–February 2011. Unit: ppm.

<table>
<thead>
<tr>
<th>Month</th>
<th>Num</th>
<th>G-C</th>
<th>STD$^{\text{G-C}}$</th>
<th>ACOS</th>
<th>STD$^\text{A}$</th>
<th>Bias$^{\text{G-A}}$</th>
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<td>03/2010</td>
<td>2286</td>
<td>389.74</td>
<td>1.48</td>
<td>389.33</td>
<td>2.90</td>
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<tr>
<td>04/2010</td>
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<td>1.72</td>
<td>389.81</td>
<td>3.54</td>
<td>0.26</td>
</tr>
<tr>
<td>05/2010</td>
<td>3339</td>
<td>389.82</td>
<td>1.46</td>
<td>389.37</td>
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<td>0.46</td>
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<tr>
<td>06/2010</td>
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<td>388.87</td>
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<td>3880</td>
<td>388.32</td>
<td>1.57</td>
<td>388.43</td>
<td>1.80</td>
<td>$-$0.11</td>
</tr>
<tr>
<td>11/2010</td>
<td>3167</td>
<td>389.08</td>
<td>1.02</td>
<td>389.08</td>
<td>1.82</td>
<td>0.00</td>
</tr>
<tr>
<td>12/2010</td>
<td>2598</td>
<td>390.14</td>
<td>0.66</td>
<td>389.96</td>
<td>1.98</td>
<td>$-$0.17</td>
</tr>
<tr>
<td>01/2011</td>
<td>2232</td>
<td>390.98</td>
<td>0.73</td>
<td>390.74</td>
<td>2.44</td>
<td>0.25</td>
</tr>
<tr>
<td>02/2011</td>
<td>1908</td>
<td>391.21</td>
<td>1.05</td>
<td>391.21</td>
<td>2.80</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Additionally, the result from Table 2 indicates that monthly averaged biases (GEOS-Chem—GOSAT/ACOS) during March 2010–December 2011 ranging from $-$0.11 ppm to 1.23 ppm. However, Lei et al. [19] found that the bias between GEOS-Chem and GOSAT (NIES algorithm) XCO$_2$ could be up to around 3.3 ppm. This discrepancy between our study and Lei et al. [19] could be due to different retrieval algorithms of GOSAT and different version of GEOS-Chem model simulation.

From Table 2, the monthly averaged standard deviation of GOSAT/ACOSv7.3 XCO$_2$ is relatively larger (even up to 3.5 ppm) than that of XCO$_2$ simulated from GEOS-Chem, indicating the more discrete variation of GOSAT/ACOSv7.3 XCO$_2$ than those of GEOS-Chem. This phenomenon is similar to the result shown in Figure 2. The reason for more discrete variations of GOSAT/ACOS XCO$_2$ may be that, on the one hand, the GEOS-Chem model is not better to capture complicated dynamic variations of XCO$_2$ than satellite observations [15]. On the other hand, the retrieval errors on satellite observations [23,26] could lead to large uncertainties in the GOSAT/ACOSv7.3 XCO$_2$.

4.2. Comparison with CarbonTracker XCO$_2$

Satellite XCO$_2$ retrievals are useful in analyzing XCO$_2$ variability and informing carbon cycle science. Nonetheless, their limited observations probably lead to uncertainties in further interpreting their scientific significance [65]. Unlike satellite XCO$_2$ retrievals, model simulations (e.g., GEOS-Chem) can provide full-coverage maps of CO$_2$ concentrations on the global or regional scale. To further compare the differences between GEOS-Chem and CarbonTracker, global CO$_2$ profiles from GEOS-Chem, CT2013 and CT2016 are converted to XCO$_2$ using Equation (2) in this section. In view of a high similarity of input surface fluxes in GEOS-Chem and CT2013B, we mainly analyze the spatial distribution, seasonal correlation and time series variations of XCO$_2$ between GEOS-Chem and CT2013B.

The spatial distribution of XCO$_2$ between GEOS-Chem and CT2013B in Figure 5 indicates that significant seasonal variations of global atmospheric CO$_2$ are found from these two model simulations. The difference (GEOS-Chem – CT2013B) result shows that the seasonal averaged XCO$_2$ of GEOS-Chem is slightly underestimated relative to that of CT2013B at most regions on the global scale, apart from eastern China and middle Africa in MAM, SON and DJF; northern South America as well as high latitude of the NH in JJA. Here, we simply analyze the overestimated effect in these regions. From Figure 6, limited assimilated observation sites for CT2013B are found in these regions, therefore, the assimilated effect of CT2013B is small and not discussed in these regions. From Table 1,
GEOS-Chem used ODIAC as fossil fuel emission input, and CT2013B simultaneously used ODIAC and Miller dataset. CT2013B document [59] reported that large fossil emission differences between ODIAC and Miller datasets were found in eastern China, although ODIAC and Miller have similar global emissions for each year. Overestimated $\text{XCO}_2$ from GEOS-Chem over eastern China may be due to the effect of fossil fuel emission inventory differences. For middle Africa and northern South America, overestimated $\text{XCO}_2$ from GEOS-Chem is probably related to spatial distribution differences in terrestrial biosphere fluxes between GFED3 and GFED2. These spatial differences between GFED3 and GFED2 were also described by CT2013 document [59]. For more details, please see the CT2013 document [59]. For the high latitude region in the NH, the difference of biosphere fluxes and fossil fuel emission in this region used in GEOS-Chem and CT2013B is very small according to CT2013B document [59], but transport models are different. Therefore, overestimated $\text{XCO}_2$ from GEOS-Chem in summer for the high latitudes of NH are likely affected by atmospheric transport and local fluxes.

![Comparison of global XCO2 simulated with GEOS-Chem and CT2013B during March 2010–February 2011. Seasonal averaged XCO2 concentrations are shown for GEOS-Chem, CT2013B and their difference (GEOS-Chem – CT2013B). (a) MAM; (b) JJA; (c) SON; (d) DJF. Unit: ppm.](image)

**Figure 5.** Comparison of global $\text{XCO}_2$ simulated with GEOS-Chem and CT2013B during March 2010–February 2011. Seasonal averaged $\text{XCO}_2$ concentrations are shown for GEOS-Chem, CT2013B and their difference (GEOS-Chem − CT2013B). (a) MAM; (b) JJA; (c) SON; (d) DJF. Unit: ppm.
which mainly located at high latitude of the NH as shown in Figure 5. The whole, but remarkably overestimated XCO$_2$.

The seasonal correlation in Figure 7 shows that the highest correlation of XCO$_2$ (up to 0.98) between GEOS-Chem and CT2013B is found in MAM, with an average bias of $-0.59$ ppm, while the poorest correlation also reached approximately 0.93 in SON, with the smallest average bias of $-0.37$ ppm. The XCO$_2$ from these two models show very good correlation for each season on the whole, but remarkably overestimated XCO$_2$ for GEOS-Chem (more than 6 ppm) are found in Figure 7b, which mainly located at high latitude of the NH as shown in Figure 5.

Figure 7. Scatter plots of XCO$_2$ from CarbonTracker (CT2013B) versus that of GEOS-Chem during March 2010–February 2011. (a)–(d) indicate MAM, JJA, SON and DJF respectively. Unit: ppm.

Figure 8 shows that there is good agreement among GEOS-Chem, CT2013B and CT2016 with regard to the seasonal cycle of monthly averaged XCO$_2$ during 2009–2011. As presented in Table 1, both GEOS-Chem and CT2013B use CASA biospheric flux (GFED3 or GFED2) as their input surface flux. Lindqvist et al. [29] reported that biospheric flux is closely connected to seasonal cycle of CO$_2$. Nearly identical time series variation of XCO$_2$ in JJA and SON in Figure 8 between GEOS-Chem and CT2013B are probably influenced by similar biospheric flux components. This result was also reported by Lindqvist et al. [23]. However, CT2013B Document [59] have found that the newer CASA-GFEDv3 product has a smaller seasonal cycle than the older CASA-GFEDv2. Compared with the time series of
CT2013B, the global XCO$_2$ simulated from GEOS-Chem were slightly underestimated on the whole, which may be due to the newer CASA-GFEDv3 biospheric flux used in GEOS-Chem, as well as different transport models or the assimilation of observation data (e.g., GLOBALVIEW data) from CT2013B. Furthermore, the CT2013B show nearly identical variation with the CT2016 due to their similar input surface fluxes and transport models (shown in Table 1). However, due to the difference of biospheric flux version, their seasonal cycle shows a little discrepancies in JJA.

![Figure 8](image-url)  
**Figure 8.** The time series variations of monthly averaged XCO$_2$ and standard deviation for 2009–2011 among CT2013B, CT2016 and GEOS-Chem on the global scale. The orange line is the XCO$_2$ simulated from GEOS-Chem; the blue line refers to XCO$_2$ simulated from CT2016; the green line is the XCO$_2$ of CT2013B. Unit: ppmv.

For standard deviation, most of the monthly averaged XCO$_2$ from CT2013B shows a slightly larger discrete variation than the GEOS-Chem model. The larger discrete variation in CT2013B may be due to different transport models, as well as the assimilation of observation data (e.g., GLOBALVIEW data) in the CT2013B.

### 4.3. Comparison with TCCON XCO$_2$ Measurements

To further validate the GEOS-Chem CO$_2$ simulations, ground-based TCCON measurements during 2009–2011 were used in this study. Since TCCON measurements were XCO$_2$ observations, the model-simulated CO$_2$ profiles need to be first sampled at the location of TCCON observation and integrated to XCO$_2$ by using the TCCON averaging kernels and a priori profiles as described in Section 3. The ground-based XCO$_2$ retrievals from fourteen TCCON sites were compared to the modeled CO$_2$ from GEOS-Chem at around 13:00 ± 2 h local time.

The comparison result in Figure 9 shows that evident time series variations of XCO$_2$ from the GEOS-Chem model and TCCON sites are observed in the NH sites, e.g., Bialystok, Lamont, Park Falls, Garmisch, and Orleans. No obviously seasonal variations were found in Wollongong, Darwin and Lauder sites of the SH. The XCO$_2$ comparisons in Figure 10 and Table 3 reveal that the model bias at most sites is within ±1.0 ppm, except at Eureka (−1.2 ppm). The model bias is relatively smaller in the SH sites (<0.5 ppm) than those in the NH sites (<1.2 ppm). However, relative to GOSAT/ACOS, the model bias is a litter larger in the SH than that in the NH. The result in Figure 10a and Table 3 also indicates that modeled XCO$_2$ from GEOS-Chem are underestimated at most sites, which shows good agreement with the result from comparison with CT2013B. Other studies also reported the underestimated effect of XCO$_2$ in model simulation (e.g., ACTM, TM5 models) [20,66]. However, overestimated XCO$_2$ from GEOS-Chem are found at some sites, including Garmisch (+0.79 ppm), Karlsruhe (+0.03 ppm), Sodankylä (+0.68 ppm) and Ny-Ålesund (+0.37 ppm). As for Garmisch, complex geographical terrain (valleys) at station probably result in model overestimation. For Sodankylä and Ny-Ålesund sites in the far north, model overestimation of CO$_2$ is likely caused by atmospheric transport and local fluxes that has been discussed in Section 4.2. This result is also
similar to the performance of the NIES TM model, which shows a larger bias (+1.22 ppm) for $\text{XCO}_2$ over Sodankylä [67].

Figure 9. Comparison of $\text{XCO}_2$ from GEOS-Chem (yellow dots) and ground-based TCCON $\text{XCO}_2$ measurements (blue dots) during 2009–2011: (a) Lauder; (b) Wollongong; (c) Darwin; (d) Izaña; (e) Lamont; (f) Park Falls; (g) Garmisch; (h) Orleans; (i) Karlsruhe; (j) Bremen; (k) Bialystok; (l) Sodankylä; (m) Ny-Ålesund; (n) Eureka.

Figure 10. Bias and root-mean-square error (RMSE) of GEOS-Chem model vs. TCCON sites in 2010. (a) model bias; (b) RMSE. Unit: ppm.
Table 3. Statistics of number of XCO₂ data (N) at TCCON sites, averaged XCO₂, correlation coefficient (R), averaged bias (Bias) and root-mean-square error (RMSE) between GEOS-Chem (G-C) and TCCON during 2009–2011.

<table>
<thead>
<tr>
<th>Sites</th>
<th>N</th>
<th>TCCON</th>
<th>G-C</th>
<th>R</th>
<th>Bias</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lauder (45.04° N, 169.68° E)</td>
<td>28,453</td>
<td>387.04</td>
<td>386.96</td>
<td>0.92</td>
<td>–0.03</td>
<td>0.57</td>
</tr>
<tr>
<td>Wollongong (34.41° S, 150.88° E)</td>
<td>12,546</td>
<td>386.66</td>
<td>386.48</td>
<td>0.83</td>
<td>–0.18</td>
<td>0.98</td>
</tr>
<tr>
<td>Darwin (12.42° S, 130.88° E)</td>
<td>9451</td>
<td>386.78</td>
<td>386.66</td>
<td>0.95</td>
<td>–0.12</td>
<td>0.66</td>
</tr>
<tr>
<td>Izaña (28.37° N, 16.5° W)</td>
<td>4024</td>
<td>389.61</td>
<td>389.34</td>
<td>0.94</td>
<td>–0.27</td>
<td>0.65</td>
</tr>
<tr>
<td>Lamont (36.61° N, 97.49° W)</td>
<td>41,176</td>
<td>388.79</td>
<td>387.91</td>
<td>0.90</td>
<td>–0.90</td>
<td>1.32</td>
</tr>
<tr>
<td>Park Falls (45.95° N, 90.27° W)</td>
<td>19,857</td>
<td>388.05</td>
<td>387.83</td>
<td>0.93</td>
<td>–0.22</td>
<td>1.31</td>
</tr>
<tr>
<td>Garmisch (47.48° N, 11.06° E)</td>
<td>7714</td>
<td>388.39</td>
<td>389.16</td>
<td>0.87</td>
<td>0.79</td>
<td>1.47</td>
</tr>
<tr>
<td>Orleans (47.97° N, 2.11° E)</td>
<td>6934</td>
<td>388.30</td>
<td>388.13</td>
<td>0.90</td>
<td>–0.16</td>
<td>1.13</td>
</tr>
<tr>
<td>Karlsruhe (49.1° N, 8.4° E)</td>
<td>620</td>
<td>389.55</td>
<td>389.57</td>
<td>0.91</td>
<td>0.03</td>
<td>1.28</td>
</tr>
<tr>
<td>Bremen (53.10° N, 8.85° E)</td>
<td>3447</td>
<td>388.42</td>
<td>388.29</td>
<td>0.93</td>
<td>–0.14</td>
<td>1.56</td>
</tr>
<tr>
<td>Bialystok (53.23° N, 23.03° E)</td>
<td>11,933</td>
<td>388.41</td>
<td>388.09</td>
<td>0.95</td>
<td>–0.33</td>
<td>1.48</td>
</tr>
<tr>
<td>Sodankylä (67.37° N, 26.63° E)</td>
<td>16,936</td>
<td>386.68</td>
<td>387.35</td>
<td>0.97</td>
<td>0.68</td>
<td>1.53</td>
</tr>
<tr>
<td>Ny-Ålesund (78.92° N, 11.92° E)</td>
<td>857</td>
<td>387.76</td>
<td>388.13</td>
<td>0.92</td>
<td>0.37</td>
<td>2.21</td>
</tr>
<tr>
<td>Eureka (80.1° N, 86.4° W)</td>
<td>698</td>
<td>389.14</td>
<td>387.92</td>
<td>0.90</td>
<td>–1.23</td>
<td>1.86</td>
</tr>
</tbody>
</table>

As presented in Table 3, XCO₂ from GEOS-Chem show strong correlation with the TCCON data (R > 0.83), indicating a good representation of transport and fluxes in GEOS-Chem for simulated CO₂. However, in the far north (Eureka and Sodankylä, Finland), the result show good correlation (R > 0.9) but the model bias is relatively high (>0.5 ppm), which is probably caused by atmospheric transport and local flux in high latitude of the NH. From Figure 10b and Table 3, the root-mean-square error (RMSE) also show small differences between GEOS-Chem and TCCON sites, with the largest RMSE (2.21 ppm) at the Ny-Ålesund site located in the far north. The RMSE is somewhat smaller at the SH stations than most of the NH sites, except Izaña site.

Seasonal biases can affect the seasonal cycle amplitude, and the seasonal cycle is important for biospheric flux attribution [68]. From Figure 11, in MAM and DJF, the modeled XCO₂ from GEOS-Chem are underestimated at most sites, except Garmisch and Izaña. However, similar to Figure 10 and Table 3, the overestimated XCO₂ occurred at the sites of high latitude of the NH in JJA, especially overestimated seasonal bias more than 1 ppm found at Sodankylä and Ny-Ålesund sites. This comparison result is also consistent with that of GOSAT/ACOS as well as CT2013B and probably related to transport model and local flux in GEOS-Chem.

Figure 11. Variations of seasonal biases between GEOS-Chem and TCCON sites during March 2010–December 2011: MAM, blue; JJA, green; SON; yellow and DJF, purple.

The seasonal cycle of XCO₂ is closely related to the biospheric fluxes that determine the global terrestrial net CO₂ sinks [23]. To compare the seasonal cycle of XCO₂ from GEOS-Chem and TCCON sites, we use the NOAA fitting software CCGCRV [69] to statistically fit the seasonal cycle and yearly
growth of XCO$_2$. Constrained by short time series or large data gaps, only seven sites in the NH are used to extract the seasonal cycle of XCO$_2$ in this study. It is noted that the detrended seasonal cycle is calculated by removing the long-term trends of XCO$_2$. From Figure 12, the seasonal cycles in GEOS-Chem XCO$_2$ are in good agreement with those of TCCON sites, for example, no apparent mismatches found at the Garmisch, Park Falls and Lamont sites. However, seasonal cycle amplitudes of XCO$_2$ are obviously underestimated by GEOS-Chem at some sites, such as Bialystok, Bremen and Sodankylä sites, which may be due to the biospheric fluxes or transport in model. The result also shows consistency with previous studies, reporting an underestimation of XCO$_2$ peak-to-trough amplitudes in models [23,66]. From Table 4, the average yearly growth rate varies from 1.90 ppm year$^{-1}$ to 2.37 ppm year$^{-1}$ for GEOS-Chem and TCCON measurements during 2009–2011. The GEOS-Chem model shows a lower XCO$_2$ growth rate than those of TCCON sites.

![Figure 12](image)

**Figure 12.** Seasonal cycles of XCO$_2$ are compared for GEOS-Chem and TCCON in the Northern Hemisphere during 2009–2011, which is calculated by removing the long-term trends of XCO$_2$ (gray dots for TCCON, black dots for GEOS-Chem); smoothed lines is fitting seasonal cycle (red for TCCON, green for GEOS-Chem).
Table 4. Comparison of the seasonal cycle amplitude and yearly growth rate between XCO$_2$ of GEOS-Chem and TCCON sites. Sites included Izaña, Lamont, Park Falls, Garmisch, Bremen, Bialystok, and Sodankylä.

<table>
<thead>
<tr>
<th>Sites</th>
<th>XCO$_2$ Amplitude (ppm)</th>
<th>Growth Rate (ppm year$^{-1}$)</th>
<th>Period</th>
</tr>
</thead>
</table>

We also investigate mean bias, RMSE and correlation coefficients between TCCON sites and GEOS-Chem as well as GOSAT/ACOS during April 2009–December 2011. Considering of CO$_2$ data availability at TCCON sites, only 9 TCCON sites including Bialystok, Bremen, Darwin, Garmisch, Lauder, Lamont, Orleans, Park Falls and Wollongong are used in this section. Similar to Cogan et al. [26], the averaging kernel and a priori have not been adopted in comparison between GOSAT/ACOS and TCCON sites, but they are used when comparing modeled CO$_2$ from GEOS-Chem with TCCON sites.

As shown by Figure 13, the overall correlations between XCO$_2$ from GEOS-Chem as well as GOSAT/ACOS and 9 TCCON sites are 0.93 and 0.74 respectively. The mean biases of XCO$_2$ is −0.06 ppm between GEOS-Chem and TCCON sites, and −0.2 ppm between GOSAT/ACOS and TCCON sites, and their RMSE is 1.19 ppm and 2.05 ppm respectively. The result show that the modeled XCO$_2$ from GEOS-Chem is underestimated on the whole by comparison with TCCON sites. Also, the result also indicate that XCO$_2$ retrievals from GOSAT/ACOSv7.3 show somewhat underestimated effect by comparison with TCCON sites, which may be due to retrieval errors or instrument issue of the GOSAT [23,26,68]. These results show good consistency with Section 4 and Cogan et al. [26].

Figure 13. The scatter plot of XCO$_2$ between GEOS-Chem as well as GOSAT/ACOS and 9 TCCON sites during April 2009–December 2011. (a) The scatter plot between XCO$_2$ from GEOS-Chem and XCO$_2$ from TCCON sites; (b) The scatter plot between XCO$_2$ from GOSAT/ACOS and XCO$_2$ from TCCON sites.
5. Discussion

In this study, the comparison method mainly considered the averaging kernels among different CO₂ data according to Wunch et al. [28]. While horizontal CO₂ variability and differences in spatial support should be also considered in the future due to their impact in inter-comparison between different remote sensing observations [70]. For example, TCCON provide XCO₂ observations at a point location, and GOSAT/ACOS observation represents an average XCO₂ within the footprint 10.5 km in diameter [70]. The differences in spatial support may introduce another uncertainties when directly comparing between model results and observations [70]. Tadić and Michalak reported that different spatial support can lead to differences exceeding 0.5 ppm even for co-located CO₂ observations [70]. To roughly estimate the uncertainty raised from the spatial support, we compared the differences between the XCO₂ of GOSAT/ACOS (or TCCON sites) and the spatially averaged XCO₂ of GOSAT/ACOS (or TCCON sites) in a 2° × 2.5° grid which is in line with the horizontal resolution of GEOS-Chem CO₂ results.

From Figure 14, the differences (standard deviation) between GOSAT/ACOS XCO₂ observations and the corresponding averaged averaged XCO₂ (at a 2° × 2.5° grid) ranged from 0–0.3 ppm and mostly distributed at 0–0.05 ppm. To some extent, these differences can be deemed as the impact of spatial support. To further understand the impact of averaged XCO₂ at 2° × 2.5° grids, we recalculated the correlation, averaged bias and RMSE between GOSAT/ACOS and GEOS-Chem at GOSAT footprint scale (using averaging kernels but no spatial support was considered) and 2° × 2.5° scales (using averaging kernels and then calculating the average), respectively, using data of 2010 on the global land. Table 5 shows that the correlation (R) is less affected by the effect of spatial support, while the mean bias and RMSE can be impacted by different spatial support.

![Figure 14](image-url) The frequency histogram of differences (standard deviations) between GOSAT XCO₂ and the corresponding averaged XCO₂ at 2° × 2.5° grids on the global land in 2010.

<table>
<thead>
<tr>
<th>XCO₂</th>
<th>R</th>
<th>Bias</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEOS-Chem-ACOS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(using averaging kernels and NO average)</td>
<td>0.54</td>
<td>0.52</td>
<td>2.08</td>
</tr>
<tr>
<td>GEOS-Chem-ACOS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(using averaging kernels and then averaged)</td>
<td>0.53</td>
<td>0.38</td>
<td>1.83</td>
</tr>
</tbody>
</table>

Similarly, 14 TCCON sites were also used to estimate the uncertainties of the spatial support and they include Lamont, Park Falls, Bialystok, Orleans, Garmisch, Bremen, Sodankylä, Ny-Ålesund,
Izaña, Eureka, Karlsruhe, Wollongong, Darwin, Lauder. From Figure 15, the differences (standard deviation) between XCO₂ at 14 TCCON sites and averaged XCO₂ at 2° × 2.5° grids mainly ranged from 0–1.4 ppm and mostly distributed at 0–0.1 ppm. This result indicates that different spatial support may bring relatively large uncertainties when directly comparing TCCON sites and GEOS-Chem.

![Figure 15](image_url)

**Figure 15.** The frequency histogram of differences (standard deviations) between TCCON XCO₂ (14 sites) and the corresponding averaged XCO₂ in 2010 at 2° × 2.5° grids.

Also, the correlation, averaged bias and RMSE between XCO₂ from TCCON sites and GEOS-Chem in 2010 (Figure 16 and Table 6) were also calculated, which is similar to that of GOSAT/ACOS and GEOS-Chem. Similar to the comparison between GEOS-Chem and GOSAT, from Figure 16 and Table 6, we can see that the correlation is not affected by the spatial support, while the bias and RMSE is slightly affected.

![Figure 16](image_url)

**Figure 16.** The scatter plots between XCO₂ from TCCON sites and GEOS-Chem ((a) using averaging kernels without considering the spatial support; (b) using averaging kernels and then calculating the average) in 2010.

**Table 6.** Comparison between XCO₂ from GEOS-Chem and TCCON sites in 2010.

<table>
<thead>
<tr>
<th>XCO₂</th>
<th>R</th>
<th>Bias</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEOS-Chem-TCCON (using averaging kernels and no average)</td>
<td>0.87</td>
<td>−0.41</td>
<td>1.06</td>
</tr>
<tr>
<td>GEOS-Chem-TCCON (using averaging kernels and average)</td>
<td>0.87</td>
<td>−0.40</td>
<td>1.17</td>
</tr>
</tbody>
</table>

By comparing Figures 14 and 15, it is revealed that the impact of spatial support is more obvious for TCCON sites than that of GOSAT/ACOS measurements when comparing with GEOS-Chem results. This may be due to the spatial support of GOSAT/ACOS is more close to that of GEOS-Chem.
than TCCON. Furthermore, the correlation analysis between GEOS-Chem and TCCON sites (or GOSAT/ACOS) indicates that the spatial support has no obvious effect on the correlation coefficient. However, the mean bias and RMSE is indeed influenced by spatial support. Therefore, the uncertainties from spatial support should be pay enough attention in the future, especially for comparison with TCCON XCO$_2$ point observations.

6. Conclusions

Global atmospheric CO$_2$ concentrations were effectively simulated by a global 3-D chemical transport model (GEOS-Chem) during the years of 2009–2011 and compared with XCO$_2$ data from the GOSAT satellite, CarbonTracker CO$_2$ modeling system and TCCON measurements in this study. The results indicate that the modeled XCO$_2$ from GEOS-Chem shows overall good consistency with GOSAT/ACOSv7.3, CarbonTracker, but the GEOS-Chem model overestimates XCO$_2$ values compared with the GOSAT/ACOSv7.3 XCO$_2$ retrievals at most regions, particularly in the SH and the high latitude of the NH.

The results also show that the monthly averaged XCO$_2$ of GEOS-Chem generally underestimate XCO$_2$ as compared to CarbonTracker, although they have a similar seasonal cycle. The discrepancies between the two models may be originated from a different transport model or the assimilation of observation in CarbonTracker. However, obvious overestimated XCO$_2$ from GEOS-Chem was found at the high latitudes of the Northern Hemisphere in JJA as compared with CarbonTracker or TCCON sites, which indicates that large uncertainties in GEOS-Chem over these regions probably because of the influences of atmospheric transport model and local flux. This phenomenon has been also reflected by comparison with GOSAT/ACOS.

Overall, although the simulated CO$_2$ from GEOS-Chem are in a good agreement with the GOSAT/ACOS retrievals, CarbonTracker and TCCON measurements, the discrepancies between them are considerable, e.g., the underestimation effect of XCO$_2$ in GEOS-Chem model, probably due to lack of constraints from measurements and affected by prior biosphere flux in model. Also, the obvious overestimated XCO$_2$ in the high latitude of the NH in JJA is needed to be concerned. Future work will need to assimilate observation data, e.g., GOSAT/ACOS or OCO-2, into the GEOS-Chem model to further optimize the CO$_2$ fluxes. These comparisons and analysis also indicated that GOSAT/ACOSv7.3 retrievals could underestimate the XCO$_2$. The uncertainties in satellite observations are necessary to quantify for further estimations of their assimilation into model systems. Furthermore, the uncertainties from spatial support should be carefully considered when inter-comparison among different observations and models.

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