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- Annual and semiannual cycles of CO₂ from multiple satellites and in situ data
- Information contents of satellite CO₂ retrievals and vertical structures for CO₂
- Comparisons of ground-based and satellite CO₂ with models

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CO₂ annual and semiannual cycles from multiple satellite retrievals and models

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Abstract Satellite CO₂ retrievals from the Greenhouse gases Observing SATellite (GOSAT), Atmospheric Infrared Sounder (AIRS), and Tropospheric Emission Spectrometer (TES) and in situ measurements from the National Oceanic and Atmospheric Administration - Earth System Research Laboratory (NOAA-ESRL) Surface CO₂ and Total Carbon Column Observing Network (TCCON) are utilized to explore the CO₂ variability at different altitudes. A multiple regression method is used to calculate the CO₂ annual cycle and semiannual cycle amplitudes from different data sets. The CO₂ annual cycle and semiannual cycle amplitudes for GOSAT X_{CO2} and TCCON X_{CO2} are consistent but smaller than those seen in the NOAA-ESRL surface data. The CO₂ annual and semiannual cycles are smallest in the AIRS midtropospheric CO₂ compared with other data sets in the Northern Hemisphere. The amplitudes for the CO₂ annual cycle and semiannual cycle from GOSAT, TES, and AIRS CO₂ are small and comparable to each other in the Southern Hemisphere. Similar regression analysis is applied to the Model for OZone And Related chemical Tracers-2 and CarbonTracker model CO₂. The convolved model CO₂ annual cycle and semiannual cycle amplitudes are similar to those from the satellite CO₂ retrievals, although the models tend to underestimate the CO₂ seasonal cycle amplitudes in the Northern Hemisphere midlatitudes and underestimate the CO₂ semiannual cycle amplitudes in the high latitudes. These results can be used to better understand the vertical structures for the CO₂ annual cycle and semiannual cycle and help identify deficiencies in the models, which are very important for the carbon budget study.

1. Introduction

As a result of fossil fuel emissions, atmospheric CO₂ demonstrates a positive trend, which varies from year to year with a range of 1.5–2 ppm from 1960 to 2014 [Keeling *et al.*, 1995; Sarmiento and Wofsy, 1999; Tans and Keeling, 2014]. Superimposed on this trend is an annual cycle resulting from the uptake and release of CO₂ by vegetation [Pearman and Hyson, 1980, 1981; Cleveland *et al.*, 1983; Bacastow *et al.*, 1985; Keeling *et al.*, 1996; Buermann *et al.*, 2007]. In addition to the trend and the annual cycle, atmospheric CO₂ also exhibits variability from synoptic scales to interannual timescales [Bacastow, 1976; Bacastow *et al.*, 1980; Keeling and Revelle, 1985; Keeling *et al.*, 1995; Enting, 1987; Feely *et al.*, 1987; Dettinger and Ghil, 1998; Dargaville *et al.*, 2000; Jiang *et al.*, 2010; Keppel-Aleks *et al.*, 2011; Wang *et al.*, 2011; Jiang *et al.*, 2013a].

The ground-based CO₂ measurement network has successfully been utilized to monitor the CO₂ concentrations and their trends at the surface on the hemispheric to global scale [GLOBALVIEW-CO₂, 2010]. However, the ground-based network does not have the resolution and coverage to characterize the physical processes that transport CO₂ throughout the atmospheric column and around the globe. Remote sensing observations from satellites provide new tools for studying the variations of atmospheric CO₂. Spectroscopic observations at thermal IR wavelengths are most sensitive to CO₂ variations in the middle troposphere [Chahine *et al.*, 2008; Kulawik *et al.*, 2010]. High-resolution spectra of reflected sunlight provide surface-weighted estimates of the column-averaged CO₂ dry air mole fraction [Crisp *et al.*, 2012].

Combining satellite and in situ observations and model simulations, it was found that the Madden-Julian Oscillation (MJO), Semiannual Oscillation (SAO), El Niño–Southern Oscillation (ENSO), monsoon, Northern Annular Mode (NAM), and South Atlantic Walker Circulation can influence CO₂ concentrations in the middle troposphere [Li *et al.*, 2010; Jiang *et al.*, 2010; Wang *et al.*, 2011; Jiang *et al.*, 2012, 2013a, 2015]. In addition to

the intraseasonal variability (e.g., MJO and SAO), ENSO, an important large-scale climate interannual variability, can influence CO₂ concentrations in the tropical region. During El Niño (La Niña) events, the atmospheric CO₂ growth rate increases (decreases) at surface stations [Keeling *et al.*, 1995; Jones *et al.*, 2001; Nevison *et al.*, 2008]. Using midtropospheric CO₂ data from Atmospheric Infrared Sounder (AIRS), Jiang *et al.* [2010] found that the ENSO can influence the CO₂ concentrations in the midtroposphere. Similar results are seen in Model for Ozone And Related chemical Tracers-2 (MOZART-2) convolved midtropospheric CO₂, although the amplitude and spatial pattern in the model CO₂ are somewhat different compared to those in the AIRS midtropospheric CO₂ [Jiang *et al.*, 2013a]. Midtropospheric CO₂ can also be modulated by the strength of monsoon as a result of change in the circulation. During strong (weak) monsoon years, there are more (less) midtropospheric CO₂ over the Indo-Pacific Ocean compared to normal monsoon years [Wang *et al.*, 2011].

Satellite missions provide global measurements of the atmospheric CO₂ [Chahine *et al.*, 2008; Kulawik *et al.*, 2010; Yokota *et al.*, 2009; Boesch *et al.*, 2011; Reuter *et al.*, 2011; Pagano *et al.*, 2014]. These global and continuous CO₂ data offer a unique opportunity to explore the CO₂ variability at different altitudes. In this paper, we will investigate the annual and semiannual cycles of CO₂ by combining models and multiple satellite CO₂ retrievals from the Greenhouse gases Observing SATellite (GOSAT) [Yokota *et al.*, 2009; Boesch *et al.*, 2011; Crisp *et al.*, 2012], Atmospheric Infrared Sounder (AIRS) [Chahine *et al.*, 2008], and Tropospheric Emission Spectrometer (TES) [Kulawik *et al.*, 2010], so we can better understand the CO₂ annual and semiannual cycles at different altitudes and over the global domain. We will discuss data and model in section 2 and present results in section 3.

2. Data and Models

CO₂ estimates retrieved from three different satellite instruments (GOSAT, AIRS, and TES) are used in this paper. Column-averaged CO₂ dry air mole fraction with more weighting near the surface is retrieved from the Thermal And Near infrared Sensor for carbon Observations-Fourier Transform Spectrometer (TANSO-FTS) on GOSAT. Midtropospheric CO₂ estimates are retrieved from the AIRS on the NASA Aqua satellite and from the TES on the NASA Aura satellite. The above CO₂ data sets are compared to CO₂ observations from surface in situ stations from the NOAA Earth System Research Laboratory (ESRL) network and the Total Carbon Column Observing Network (TCCON). There are three types of information in these data sets. NOAA-ESRL CO₂ data provide CO₂ information at the surface. AIRS and TES CO₂ data provide CO₂ information in the midtroposphere. GOSAT and TCCON CO₂ data provide estimates of the CO₂ column-averaged dry air mole fraction. The 3-D Model for Ozone And Related chemical Tracers-2, (MOZART-2) [Horowitz *et al.*, 2003; Jiang *et al.*, 2013a] and 3-D CarbonTracker [Peters *et al.*, 2007] are also used to explore the CO₂ annual cycle and semiannual cycle amplitudes at different pressure levels.

2.1. Satellite CO₂ Retrievals

2.1.1. GOSAT X_{CO2}

The GOSAT TANSO-FTS collects high-resolution spectroscopic observations of reflected sunlight in the CO₂ bands near 1.6 and 2.06 μm and by the 0.765 μm O₂ A band. Its circular, 0.0157-radian diameter, instantaneous field of view yields 10.5 km diameter footprints at nadir. Over land, and over the ocean at latitudes > 20° from the subsolar latitude, its two-axis (along-track/cross-track) pointing mechanism obtains soundings that are separated by ~155 km (five-point mode) or ~273 km (three-point mode [Shiomi *et al.*, 2008; Watanabe *et al.*, 2008; Kuze *et al.*, 2009]). Over the ocean at latitudes < 20° from the subsolar latitude, the pointing mechanism targets a glint spot to provide adequate sensitivity for X_{CO2} estimates. In this mode, it collects soundings at ~28 km intervals along the apparent path of the glint spot.

Column-averaged CO₂ dry air mole fraction (X_{CO2}) is retrieved from GOSAT data by the Atmospheric CO₂ Observations from Space (ACOS) team, using the optimal estimation approach developed for the Orbiting Carbon Observatory [Boesch *et al.*, 2006; Connor *et al.*, 2008; O'Dell *et al.*, 2012]. Data are available from <http://disc.sci.gsfc.nasa.gov/acdisc/data-holdings/acos-data-holdings>. GOSAT version B3.4 X_{CO2} is available from June 2009 to May 2013. GOSAT B3.4 X_{CO2} data used here have passed a preliminary quality filter and are recommended for the science data analysis. Comparison of X_{CO2} from ACOS GOSAT and TCCON shows that they usually agree within 1–2 ppm on regional scales [Nguyen *et al.*, 2014]. We regrid the GOSAT CO₂ to 2° (latitude) × 2° (longitude).

Table 1. Summary of Time Periods and Spatial Coverage for Different CO₂ Data Sets

Type	Data	Time Period	Latitude Range
Satellite CO ₂	GOSAT X _{CO2} [Crisp <i>et al.</i> , 2012]	Jun 2009 to May 2013	50°S–82°N
	TES midtropospheric CO ₂ [Kulawik <i>et al.</i> , 2010]	Sep 2004 to Jun 2011	40°S–45°N
	AIRS midtropospheric CO ₂ [Chahine <i>et al.</i> , 2008]	Sep 2002 to Dec 2013	60°S–90°N
Surface CO ₂	NOAA ESRL CO ₂ [GLOBALVIEW-CO ₂ , 2010]	Different time periods for different stations	90°S–85°N
	TCCON CO ₂ [Washenfelder <i>et al.</i> , 2006]	Different time periods for different stations	45°S–79°N

2.1.2. AIRS Midtropospheric CO₂

AIRS is a cross-track scanning grating spectrometer aboard on Aqua with 2378 channels from 3.7 to 15.4 μm with a 45 km × 45 km field of view at nadir [Aumann *et al.*, 2003]. The mixing ratios of AIRS midtropospheric CO₂ are retrieved using the Vanishing Partial Derivative Method (VPD) [Chahine *et al.*, 2005, 2008; Olsen and Licata, 2015]. AIRS midtropospheric CO₂ retrievals are available over land and ocean and under clear and cloudy conditions. AIRS midtropospheric CO₂ retrievals are available at 2° (latitude) × 2.5° (longitude) from September 2002 to December 2013. The maximum sensitivity of AIRS midtropospheric CO₂ retrieval is from 500 hPa to 300 hPa [Chahine *et al.*, 2008]. The midtropospheric CO₂ retrieved via the VPD method captures the correct CO₂ annual cycle and trend and agrees well with the aircraft CO₂ from CONTRAIL [Chahine *et al.*, 2005], INTEX-NA, and SPURT with a precision ~1–2 ppm [Olsen *et al.*, 2008].

2.1.3. TES Midtropospheric CO₂

TES is an imaging infrared FTS aboard on the Aura satellite, which was launched in July 2004. The TES spectral region extends from 660 cm⁻¹ to 2260 cm⁻¹ with a spectral resolution of 0.06 cm⁻¹ [Beer, 2006; Bowman *et al.*, 2006]. Midtropospheric CO₂ data from this instrument are available from 40°S to 45°N and from September 2004 to June 2011. Peak sensitivity of TES midtropospheric CO₂ data is at 511 hPa. The estimated error for TES midtropospheric CO₂ is ~10 ppm for a single target and ~1.3 ppm for the monthly mean average on spatial scales of 20° (latitude) × 30° (longitude) [Kulawik *et al.*, 2010]. Comparison between TES CO₂ with ocean surface stations from GLOBALVIEW-CO₂ reveals a correlation of 0.6. TES midtropospheric CO₂ measurements captures the correct CO₂ latitudinal gradient [Kulawik *et al.*, 2010]. Kulawik *et al.* [2010] compared TES midtropospheric CO₂ to CONTRAIL aircraft CO₂, AIRS midtropospheric CO₂, and CarbonTracker model CO₂ and found similar annual cycles between TES midtropospheric CO₂ and others. TES midtropospheric CO₂ also correlates well with the Carbon Tracker model CO₂ at the surface and 5 km [Kulawik *et al.*, 2010].

2.2. Surface CO₂ Observations

Besides the three satellite CO₂ data sets, we also use precise in situ CO₂ measurements. In situ CO₂ measurements include surface flask measurements from the NOAA Earth System Research Laboratory (ESRL) network [Tans *et al.*, 1998] and TCCON [Washenfelder *et al.*, 2006; Macatangay *et al.*, 2008; Wunch *et al.*, 2011]. Site information for the NOAA ESRL surface CO₂ is available at http://www.esrl.noaa.gov/gmd/dv/site/site_table.html. TCCON stations use a high spectral resolution FTS to record the absorption of direct sunlight by CO₂, O₂, and other gases. Under clear sky conditions, measurement precision for the TCCON column CO₂ is ~0.1% [Washenfelder *et al.*, 2006]. There are 20 operational sites between Ny Alesund, Norway (79°N), and Lauder, New Zealand (45°S) (<http://www.tcon.caltech.edu/>). Table 1 summarizes time periods and spatial coverage for all data sets.

2.3. Models

In this paper, two different models (MOZART-2 and CarbonTracker) are used to explore the CO₂ annual cycle and semiannual cycle. The MOZART-2 model is driven by the meteorological inputs every 6 h from the European Center for Medium range Weather Forecast (ECMWF)-Interim Reanalysis data from 1991 to 2012. Advection is computed every 20 min with a flux form semi-Lagrangian method [Lin and Rod, 1996]. The horizontal resolution of MOZART-2 is 2.8° (latitude) × 2.8° (longitude) with 45 vertical levels extending up to approximately 50 km altitude. MOZART-2 is built on the framework of the Model of Atmospheric Transport and Chemistry (MATCH). Advection, convective transport, boundary layer mixing, and wet and dry depositions are well represented in the MATCH model. Prescribed CO₂ sources and sinks are used as the model boundary conditions. The exchange of CO₂ between biosphere and atmosphere is calculated from the Carnegie-Ames Stanford Approach (CASA) biogeochemical model, which includes the effects of weather,

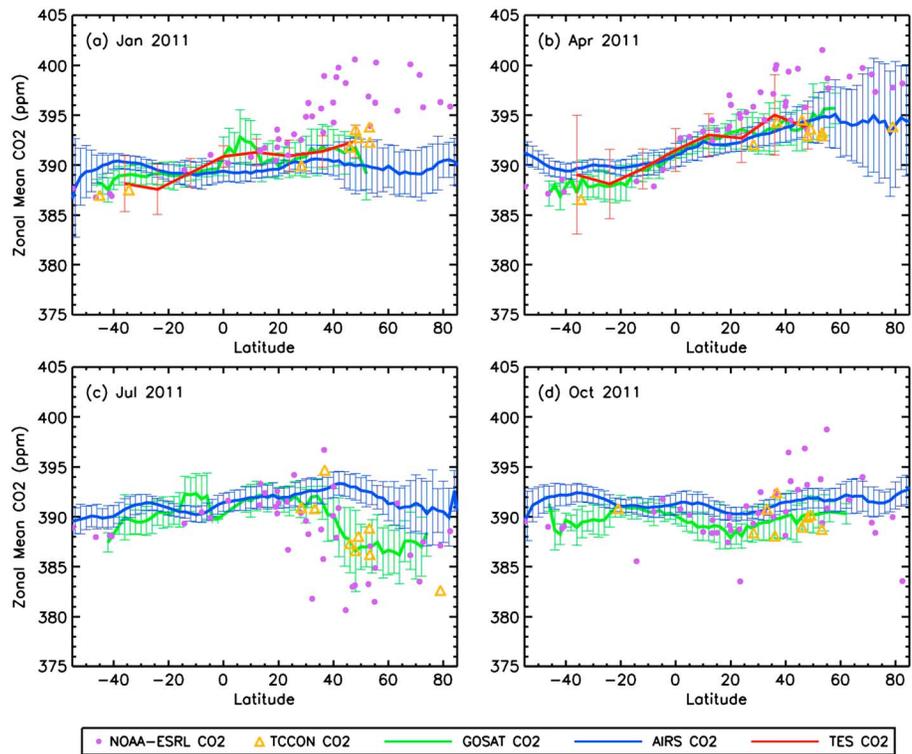


Figure 1. Zonal mean CO₂ in (a) January 2011, (b) April 2011, (c) July 2011, and (d) October 2011. Blue line is zonal mean AIRS midtropospheric CO₂. Red line is zonal mean TES midtropospheric CO₂. Green line is zonal mean GOSAT X_{CO₂}. Error bars are the standard deviations of CO₂ at each latitudinal band. Purple dots are surface CO₂ from NOAA ESRL network. Orange triangles are TCCON X_{CO₂}.

satellite observed Normalized Difference Vegetation Index, and fire on biosphere processes [Olsen and Randerson, 2004; van der Werf et al., 2006; Giglio et al., 2006; Keppel-Aleks et al., 2012]. Air-to-sea exchange of CO₂ is from Takahashi et al. [1997]. The fire module in the model is based on Global Fire Emissions Database Version 3.1 (GFEDv3.1) [Randerson et al., 2013]. Fossil fuel CO₂ emissions are from the Carbon Dioxide Information and Analysis Center [Boden et al., 2013].

CarbonTracker 2013 has a global resolution of 3° (longitude) × 2° (latitude). Transport Model 5 (TM5) is used to represent transport in CarbonTracker. Winds used to drive TM5 are from the ECMWF operational forecast model and the ECMWF-Interim Reanalysis. Ocean uptake of CO₂ is taken from ocean inversions [Jacobson et al., 2007] and direct measurements of seawater pCO₂ [Takahashi et al., 2009]. The exchange between biosphere and atmosphere is from CASA biogeochemical model. The fire module in CarbonTracker is from GFEDv3.1 [Randerson et al., 2013]. Fossil fuel CO₂ emissions are from the Miller fossil fuel emission inventory [Miller et al., 2012] and ODIAC fossil fuel emission inventory [Oda and Maksyutov, 2011]. Surface CO₂ observations from NOAA-ESRL Cooperative Global Air Sampling Network and the CSIRO Air Sampling Network are assimilated in CarbonTracker. 3-D mole fractions of CO₂ can be downloaded from ftp://aftp.cmdl.noaa.gov/products/carbontracker/co2/.

3. Results

We have conducted an intercomparison for three satellite CO₂ data sets (GOSAT X_{CO₂}, AIRS midtropospheric CO₂, and TES midtropospheric CO₂) with in situ CO₂ observations (NOAA-ESRL surface CO₂ and TCCON X_{CO₂}) to check the information contents of three satellite CO₂ data sets in Figure 1. The averaging kernels for the GOSAT X_{CO₂} and TES CO₂ are peaked closer to the surface compared with that from AIRS midtropospheric CO₂. While these vertical sensitivity differences preclude the cross validation of these remote sensing data sets, they provide a unique opportunity to study the CO₂ variability at different altitudes on regional to global scales. Zonal mean CO₂ for the GOSAT X_{CO₂}, AIRS midtropospheric CO₂, and TES midtropospheric

CO₂ in January 2011, April 2011, July 2011, and October 2011 are shown in Figure 1. Error bars in Figure 1 are the standard deviations for the zonal mean CO₂ at each latitudinal band. In general, the zonal average CO₂ for the three satellites show less variability than the NOAA-ESRL surface CO₂. The GOSAT and TES results are consistent with the TCCON X_{CO₂} data.

As shown in Figure 1a, the NOAA-ESRL surface CO₂ measurements and the TCCON X_{CO₂} data show that there is more CO₂ in the Northern Hemisphere (NH) than in the Southern Hemisphere (SH) in January. The latitudinal gradients of CO₂ are smaller in the satellite CO₂ (AIRS midtropospheric CO₂, TES midtropospheric CO₂, and GOSAT X_{CO₂}) than the NOAA-ESRL surface CO₂. The GOSAT data extend only to ~50° latitude due to the lack of sunlight. January is the winter (summer) in the NH (SH). Release of CO₂ from biospheric respiration increases the atmospheric CO₂ concentrations near the surface in the fall and winter seasons; as a result, the atmospheric CO₂ concentrations are high in January in the NH. CO₂ uptake from vegetation in the summer removes CO₂ from the atmosphere and decreases the near-surface CO₂ concentrations in the SH in January. TCCON and GOSAT X_{CO₂} retrievals are sensitive to the full atmospheric column and are similar. The CO₂ north-south gradient in the NOAA-ESRL CO₂ is higher than those from the GOSAT and TCCON X_{CO₂}, and the TES and AIRS midtropospheric CO₂, because the amplitude of the seasonal CO₂ variability decreases rapidly with altitude above the CO₂ surface sources/sinks. Surface CO₂ values are lower in the NH polar region than those at midlatitudes in January because the largest fossil fuel emissions sources are at midlatitudes [Oda and Maksyutov, 2011; Boden et al., 2013], and CO₂ biospheric respiration is suppressed by the low temperature and snow/ice cover in the polar region. The midtropospheric CO₂ values are lower in the NH polar region than those at midlatitudes during this season, which is partly related to the transport of stratospheric low-CO₂ air into the midtroposphere over the NH polar region [Jiang et al., 2013b].

In April (Figure 1b), the latitudinal gradients of CO₂ have the same sign among GOSAT X_{CO₂}, AIRS midtropospheric CO₂, TES midtropospheric CO₂, TCCON X_{CO₂}, and NOAA-ESRL surface CO₂. There is more CO₂ in the NH high latitudes in April as a result of building up of fossil fuel emissions and biomass burning in the winter season. The NOAA-ESRL surface CO₂ measurements are higher than those from GOSAT X_{CO₂} and the AIRS and TES midtropospheric CO₂ in the NH. The concentration of CO₂ is low at NH high latitudes in July due to the uptake of CO₂ by the biosphere [Pearman and Hyson, 1981; Keeling et al., 1996, see Figure 1c]. The CO₂ concentrations are lower in the surface NOAA-ESRL CO₂ than those in the satellite CO₂ retrievals (GOSAT X_{CO₂}, TCCON X_{CO₂}, and AIRS midtropospheric CO₂) in the NH in July. CO₂ concentrations increase again in the NH high latitudes in October [Keeling et al., 1996; Giglio et al., 2006; Randerson et al., 2013] as shown in Figure 1d. The differences among the three satellite CO₂ retrievals are related to the different vertical sensitivities of the three satellite CO₂ observations.

In Figure 2, we compared zonal mean CO₂ time series from three satellite CO₂ retrievals and the NOAA-ESRL surface CO₂. CO₂ annual cycle amplitudes are larger in the NH than that in the SH, because the amplitudes of the CO₂ annual cycles from biospheric photosynthesis and respiration are larger in the NH than that in the SH [Cleveland et al., 1983]. CO₂ seasonal cycle amplitudes also change as a function of time as shown in Figure 2. To better reveal CO₂ annual cycle amplitudes as a function of latitude, we have applied a multiple regression method to all data sets. We regressed CO₂ data to the trend, annual, and semiannual oscillation. We decomposed CO₂ concentrations, X , at each location using the following empirical model [Jiang et al., 2013a]:

$$X(t) = A_0 + A_1NP_1(t/N - 1) + A_2N^2P_2(t/N - 1) + A_3N^3P_3(t/N - 1) + C_1 \cos(2\pi t) + S_1 \sin(2\pi t) + C_2 \cos(4\pi t) + S_2 \sin(4\pi t) \quad (1)$$

where t is time, N is the half length of the time period, the values P_1 , P_2 , and P_3 are the first, second, and third Legendre polynomials. The coefficients A_0 , A_1 , A_2 , and A_3 are the mean value, the trend, the acceleration in the trend, and the coefficient for P_3 , respectively. We added the third Legendre function to better fit the data sets. Annual and semiannual cycles are represented by the harmonic functions. C_1 and S_1 are the amplitudes of the annual cycle, while C_2 and S_2 are the amplitudes of the semiannual cycle.

The amplitudes for the CO₂ annual cycle ($\sqrt{C_1^2 + S_1^2}$) and the CO₂ semiannual cycle ($\sqrt{C_2^2 + S_2^2}$) are plotted in Figures 3a and 3b, respectively. The CO₂ annual cycle amplitudes are ~5–10 ppm for the NOAA-ESRL surface CO₂ in the NH, which is almost a factor of 2 larger than those derived from the satellite CO₂ retrievals. The annual cycle amplitudes of the GOSAT X_{CO₂} are consistent with those from TCCON X_{CO₂}. For these two

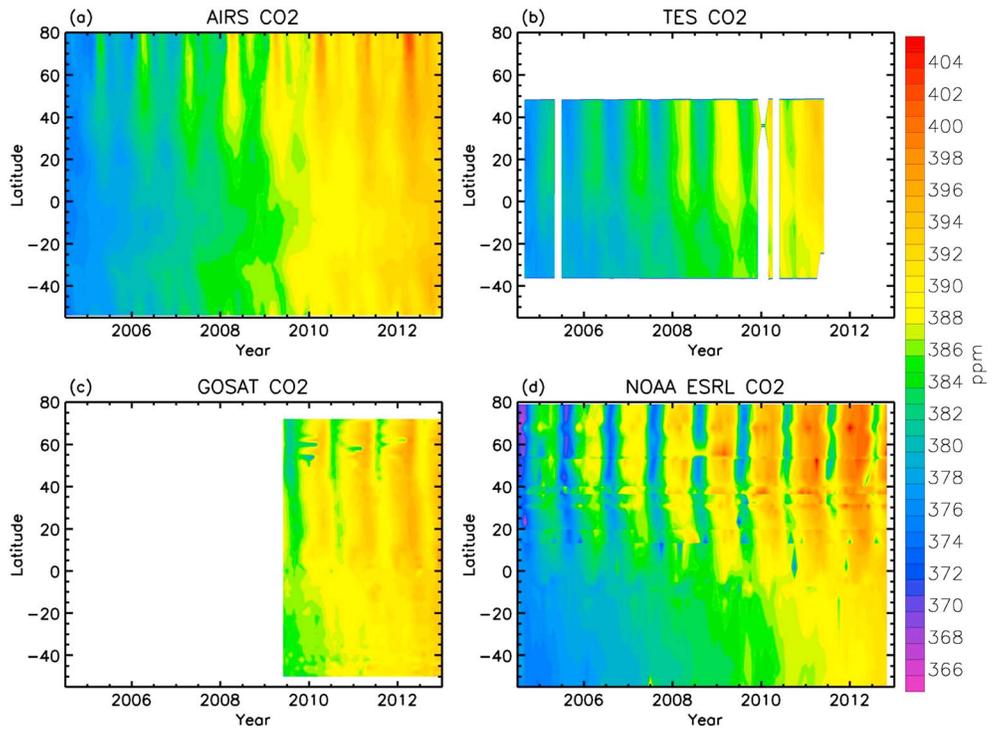


Figure 2. (a) Zonal mean AIRS midtropospheric CO₂, (b) zonal mean TES midtropospheric CO₂, (c) zonal mean GOSAT X_{CO2}, and (d) surface NOAA-ESRL CO₂.

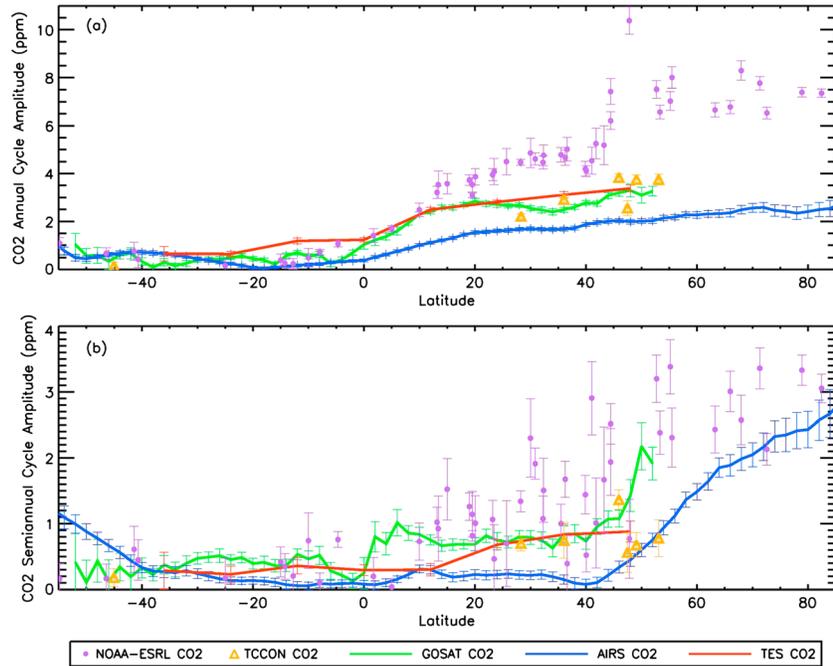


Figure 3. (a) Latitudinal distributions of CO₂ annual cycle amplitudes. (b) Latitudinal distributions of CO₂ semiannual cycle amplitudes. Blue lines are results from AIRS midtropospheric CO₂. Green lines are results from GOSAT X_{CO2}. Purple dots are results from NOAA-ESRL surface CO₂. Orange triangles are results from TCCON X_{CO2}. Error bars are the uncertainties of CO₂ annual cycle and semiannual cycle amplitudes derived from the multiple regressions.

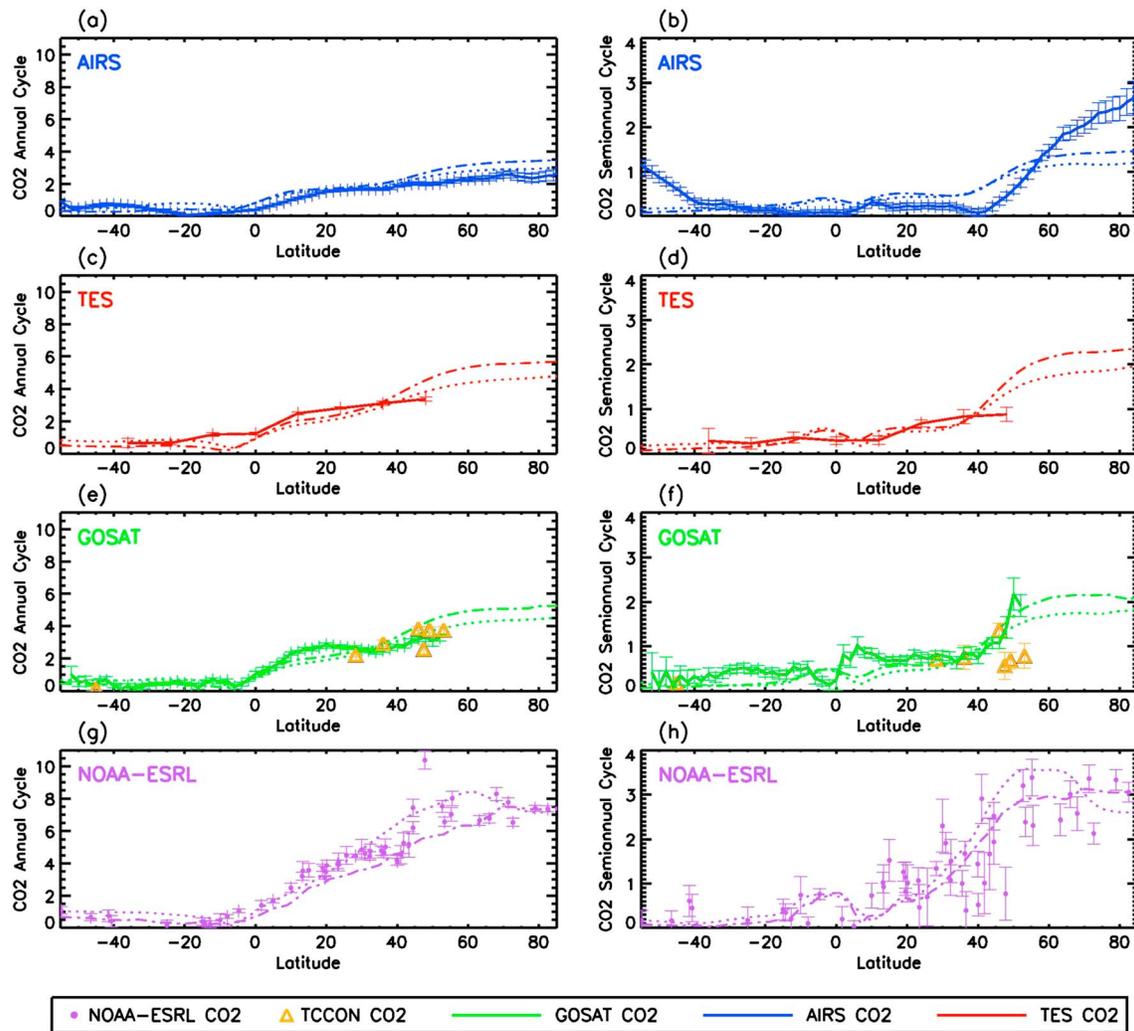


Figure 4. (a) Comparison of annual cycle amplitudes between AIRS midtropospheric CO₂ and model convolved CO₂, (b) comparison of semiannual cycle amplitudes between AIRS midtropospheric CO₂ and model convolved CO₂, (c and d) comparisons of annual and semiannual cycle amplitudes between TES midtropospheric CO₂ and model convolved CO₂, (e and f) comparisons of annual and semiannual cycle amplitudes between GOSAT X_{CO2} and model convolved CO₂, and (g and h) comparisons of annual and semiannual cycle amplitudes between NOAA-ESRL surface CO₂ and model surface CO₂. Dotted lines are convolved model CO₂ from MOZART-2. Dash-dotted lines are convolved model CO₂ from CarbonTracker. Units are in ppm.

X_{CO2} data sets, the NH (SH) annual cycle amplitudes are about 2–3 ppm (0.5–1 ppm). TES CO₂ annual cycle amplitudes are similar to GOSAT X_{CO2} in the NH. The NH CO₂ annual cycle amplitude is smallest in the AIRS midtropospheric CO₂. Since the CO₂ annual cycle amplitudes are small in the SH, the differences of CO₂ annual cycle amplitudes between different satellite CO₂ retrievals are correspondingly small.

Amplitudes for CO₂ semiannual cycle are shown in Figure 3b. The CO₂ semiannual signal is largest at the surface, for the source for the semiannual signal in CO₂ is mostly related to the CO₂ exchange between biosphere and atmosphere at the surface [Jiang et al., 2012]. The CO₂ semiannual signals are consistent between the GOSAT and TCCON CO₂, which are smaller than that from the surface NOAA-ESRL CO₂. The semiannual signal is smaller in the AIRS midtropospheric CO₂ than GOSAT CO₂ and TES CO₂.

Similar multiple regression analysis has been applied to model CO₂ from MOZART-2 and CarbonTracker to check how well the models simulate the annual and semiannual cycles of CO₂ at different altitudes. First, we convolve GOSAT, TES, and AIRS averaging kernels with the MOZART-2 and CarbonTracker model vertical CO₂ profiles. Then we calculate the CO₂ annual cycle amplitude ($\sqrt{C_1^2 + S_1^2}$) and semiannual cycle amplitude ($\sqrt{C_2^2 + S_2^2}$) for model convolved CO₂ using the multiple regression method. Results for the annual cycle

and semiannual cycle amplitudes from the model convolved CO₂ are plotted against satellite and surface CO₂ in Figure 4. The convolved model CO₂ annual cycle amplitudes are shown in Figures 4a, 4c, 4e, and 4g. In the midlatitudes of the NH, the model convolved CO₂ annual cycle amplitudes are about 2–3 ppm, which are a little (~0.5 ppm) lower than the amplitudes seen in the satellite CO₂ retrievals from GOSAT and TES. In the midlatitudes of the NH, the model surface CO₂ annual cycle amplitudes are similar to those obtained from the NOAA-ESRL surface CO₂. The model convolved CO₂ annual cycle amplitude (blue line) is about 3 ppm in the NH high latitudes, which is close to that in the AIRS midtropospheric CO₂ as shown in Figure 4a. In the SH, the model results convolved with the remote sensing averaging kernels produce CO₂ annual cycle amplitudes between 0.5 and 1 ppm, which are similar to those from GOSAT, TES, and AIRS CO₂ retrievals. The values obtained by convolving the model CO₂ by the GOSAT averaging kernel are larger than the values obtained by convolving the model CO₂ by the AIRS CO₂ averaging kernel, because the GOSAT X_{CO₂} averaging kernel's maximum is closer to the surface than that for the AIRS CO₂ averaging kernel.

Semiannual cycle amplitudes for the MOZART-2 and CarbonTracker CO₂ are shown in Figures 4b, 4d, 4f, and 4h. Both models show CO₂ semiannual cycles that are larger in the NH than SH. The CO₂ semiannual cycle amplitude obtained by convolving the models with the GOSAT averaging kernel is about 0.5–2 ppm in the NH, which is similar to the measured GOSAT CO₂ semiannual cycle shown in Figure 4f. The amplitude of the CO₂ semiannual cycle obtained by convolving the models with the AIRS averaging kernel is about 0.5–1 ppm in the NH, which is weaker than that from AIRS CO₂ semiannual cycle in the high latitudes. In the SH, the amplitudes of the semiannual cycle in CO₂ obtained by convolving the model results with the AIRS averaging kernel is much weaker than in the NH, which is consistent with the observation. The difference of the CO₂ semiannual cycle amplitudes between AIRS midtropospheric CO₂ and model convolved CO₂ is ~0.5–1 ppm in the high latitudes and need further exploration with in situ CO₂ profile data in the future.

4. Conclusions

Recent satellite CO₂ retrievals offer a unique opportunity to study the CO₂ variability at different altitudes [Crisp *et al.*, 2012; Chahine *et al.*, 2008; Kulawik *et al.*, 2010]. In this paper, we have compared the satellite CO₂ retrievals with in situ CO₂ measurements (NOAA-ESRL surface CO₂ and TCCON X_{CO₂}). The latitudinal gradients and their seasonal variations are consistent with the vertical sensitivities of the observations and the rapid decay of the CO₂ variations with altitude. We have investigated the annual cycle and semiannual cycle amplitudes of CO₂ from the GOSAT X_{CO₂}, midtropospheric AIRS CO₂, midtropospheric TES CO₂, NOAA-ESRL surface CO₂, and TCCON X_{CO₂}. The CO₂ annual cycle and semiannual cycle amplitudes for GOSAT X_{CO₂} and TCCON X_{CO₂} are consistent but smaller than those seen in the NOAA-ESRL surface data. As expected, the CO₂ annual cycle and semiannual cycle amplitudes are larger in the NH than that in the SH. The CO₂ annual and semiannual cycles are smallest in the AIRS midtropospheric CO₂ compared with other data sets in the NH. The amplitudes for the CO₂ annual cycle and semiannual cycle from GOSAT, TES, and AIRS CO₂ are small and comparable to each other in the SH. Results obtained in this study can help us better understand the information contents of the satellite CO₂ retrievals and vertical structures for the CO₂ annual cycle and semiannual cycle. Comparisons of these ground-based and satellite observations with the MOZART-2 and CarbonTracker model illustrate how well the chemistry-transport models simulate the CO₂ annual cycles and semiannual cycles at different altitudes. With better CO₂ surface emission inventories and transport fields, we can better simulate CO₂ seasonal cycles at different altitudes in the future. These data/model comparisons can also be used to diagnose the deficiencies in the models and improve the CO₂ simulations, which is very important for understanding the carbon budget in the future.

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