Impact of ENSO on variability of global CO₂ concentration retrievals from GOSAT and AIRS

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Abstract. The correlations between the growth rate of atmospheric CO₂ concentrations and the El Niño–Southern Oscillation (ENSO) events are well known. However, investigations of the influence ENSO events on global CO₂ concentrations remain poorly constrained in space. Here, we employ atmospheric CO₂ concentrations retrieved from the Greenhouse Gases Observing Satellite (GOSAT) and the Atmospheric Infrared Sounder (AIRS) to investigate the impact of ENSO events on the spatial patterns during July 2009–April 2014. Empirical orthogonal function decomposition was applied to the CO₂ concentration series and it showed that the spatial patterns of the GOSAT data compare well with those of the AIRS data. GOSAT and AIRS CO₂ concentrations exhibit a significant increase during warm ENSO episodes. Furthermore, we directly observed significant variations between the two datasets in the onset and mature phases of ENSO. Specifically, during the onset phase, the GOSAT CO₂ concentration decreases more remarkably over high latitudes compared with the AIRS data. During the mature stage, the GOSAT CO₂ concentration is reduced over the Atlantic and Pacific oceans, whereas the AIRS CO₂ concentration is reduced over North Asia and enhanced over the Pacific Ocean. The differences between the GOSAT and AIRS data for the ENSO decay phase are small. Using the high-resolution spatial and temporal observations available from GOSAT and AIRS data, our study demonstrates that the impact of ENSO on CO₂ spatial patterns is significant and requires further investigation.

1. Introduction

Carbon dioxide (CO₂) has been accumulating in the atmosphere since the pre-industrial period, mainly due to the burning of fossil fuels and human activities, which has led to increasing surface temperatures, rising sea levels and an increase in the occurrence of extreme weather conditions [1]. In addition to the long-term increasing trend due to the burning of fossil fuels, the atmospheric CO₂ concentration also exhibits a seasonal trend resulting from the seasonal growth and decay of land plants [2]. Furthermore, the atmospheric CO₂ concentration also shows variability on intraseasonal to interannual timescales [3].

The El Niño–Southern Oscillation (ENSO) is the strongest natural climate variability signal, which is characterized by anomalous sea surface warming and cooling in the eastern and central Pacific [4]. ENSO events are well known to be associated with a variety of anomalous weather patterns around the globe and leave an imprint on the global carbon cycle. It has been shown that the interannual variability in atmospheric CO₂ is mostly due to the effect of ENSO, based on singular spectrum analysis of the Mauna Loa and South Pole data [5] and on principal component analysis (PCA) of the rate of CO₂ growth derived from 89 stations in the GLOBALVIEW–CO₂ dataset [6]. High CO₂ growth rates correspond to El Niño climate conditions, and low growth rates to La Niña [7]. Moreover, Qian
et al. [8] revealed that the global atmospheric CO2 growth rate and the multivariate ENSO index (MEI) exhibit a six-month lag.

In recent years, CO2 concentration retrievals from different satellites have been used to determine the global atmospheric CO2 spatial patterns, which can be used to track CO2 variability at different locations. Using CO2 concentration retrievals from the Atmospheric Infrared Sounder (AIRS), it has been found that ENSO influences the mid-tropospheric CO2 concentrations [9–11]. By analyzing CO2 data obtained from AIRS over seven years, Ruzmaikin et al. [12] found the first principal component has a timescale typical for ENSO. In addition to AIRS measurements, Sun et al. [13] investigated the spatial pattern of CO2 over South America based on GOSAT data. Chatterjee [14] showed the gradients in the response of different tropical Pacific Ocean regions with OCO-2 data.

These studies indicate that ENSO events can either directly affect the growth rate of atmospheric CO2 or the spatial distribution of CO2 concentrations over regions. Although the ENSO cycle originates in the equatorial Pacific, its impact is felt globally as a result of its regional teleconnections. However, investigations of the relationship between ENSO events and global CO2 concentrations are lacking. The CO2 concentration retrievals from AIRS and GOSAT provide an opportunity to examine this relationship. In this study, we use AIRS and GOSAT data to analyze the CO2 spatial patterns and the response of CO2 during different ENSO episodes across the globe. The spatial patterns for each ENSO stage during warm and cold episodes are also analyzed.

2. DATA AND METHODS
The GOSAT satellite was launched on 23 January 2009 and was the first satellite dedicated to monitoring atmospheric CO2 and methane (CH4) from space [15]. It is based on the thermal and near infrared sensor for carbon observation Fourier transform spectrometer (TANSO-FTS). L3 data are generated by interpolating and extrapolating the FTS L2 data and estimating the distribution of XCO2 for each month on a global scale. L3 global CO2 products are available from June 2009 to July 2015, but are missing data for June 2014, December 2014, January 2015 and February 2015. After an improvement of the retrieval algorithm from v01.xx to 02.xx, the accuracy and precision of GOSAT SWIR XCO2 has been improved significantly. The bias and standard deviation of GOSAT v02.xx XCO2 were estimated to be about –1.48 ppm and 2.09 ppm against the ground-based FTS XCO2 data from the Total Carbon Column Observing Network (TCCON) sites [16].

AIRS is the first in a new generation of high-spectral-resolution infrared sounder instruments aboard the Aqua research mission. It is mounted on the sun-synchronous, near-polar orbiting satellite and wavenumbers in the range 690–725 cm⁻¹ are used for retrievals of the CO2 mixing ratio in the mid-troposphere [17]. The spatial resolution of AIRS CO2 retrievals is 2.0° × 2.5° (latitude by longitude) from 60°S to 90°N. AIRS mid-tropospheric CO2 has also been compared with CONTRAIL aircraft CO2 and there is a bias of 0.1 ppm with a standard deviation of 1.8 ppm [18].

Considering the continuity and comparability of AIRS and GOSAT data, we used CO2 monthly mean data from July 2009 to April 2014. Regions around the South Pole (60°–90°S) are excluded, which are either poorly covered by the retrievals or have large retrieval errors. The kriging interpolation method was used to predict the missing values. Long-term in situ records of atmospheric CO2 concentrations obtained from the Mauna Loa Observatory (MLO) from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) are for comparison with the AIRS and GOSAT data. ENSO episodes are selected based on the definition of Ocean Niño Index (ONI) data.

3. RESULTS AND DISCUSSION

3.1 Spatiotemporal characteristics of CO2
The interannual variation of the monthly mean CO2 concentration from July 2009 to April 2014 is shown in Figure 1. The CO2 concentrations during the observation period show a clear increasing trend as well as clear seasonal fluctuations, with peaks occurring in April and May, and lows occurring
in July and August. The mean GOSAT CO₂ concentration is about 389 ppm, generally lower than that of the AIRS data by 3 ppm. The peak-to-trough variation amplitude of the GOSAT CO₂ matches that of AIRS, with small amplitude. The mean CO₂ concentration for the AIRS and MLO data is 392.7 and 392.3 ppm, respectively. This small discrepancy may be due to the similar retrieval height. However, the values from the MLO show larger fluctuations due to they were retrieving in the Northern Hemisphere (NH) satellites rather than in both hemispheres.

Furthermore, we can see that hemispheric differences are evident. Larger CO₂ concentrations from GOSAT measurement appear in Central Africa, East Asia and West Asia in response to the effects produced by both natural sources and intense human activities over these regions [19]. AIRS CO₂ has a zonal distribution pattern with high values in mid- and high latitudes of the NH, which may be strongly influenced by surface sources and large-scale circulations of mid-latitude NH pollution belts [20]. The enhanced CO₂ concentrations over the Southern Hemisphere (SH) are probably due to contributions from multiple processes, including fires in Australia and the uptake of CO₂ at the ocean surface [21].

Figure 1. (a) Time-series of monthly mean CO₂ concentration for 58 months from AIRS, MLO and GOSAT (in ppm); (b) The spatial distribution of monthly mean GOSAT CO₂; (c) The spatial distribution of monthly mean AIRS CO₂. Units: ppm

3.2 CO₂ spatial pattern during different ENSO episodes

ENSO is the dominant mode of interannual variability that originates in the tropical Pacific but influences regional weather and climate variability all over the world. Studies have shown that ENSO events can affect the spatial distribution of CO₂ concentrations over regions. Therefore, we further examine the impact of ENSO on CO₂ spatial patterns. Three ENSO episodes during our study period were selected: a warm period (July 2009 to April 2010), a cold period (July 2010 to April 2011 and July 2011 to April 2012) and a neutral period (July 2012 to April 2013 and July 2013 to April 2014). The linear trend is removed from the GOSAT and AIRS CO₂.

Figure 2. GOSAT CO₂ for ENSO neutral warm episode (a); cold episode (b) and neutral episode (c).

Figure 3. AIRS CO₂ for ENSO neutral warm episode (a); cold episode (b) and neutral episode (c).

The GOSAT CO₂ spatial distributions during the ENSO episodes are shown in Figure 2. In the warm episode (Figure 2(a)), the CO₂ concentration in tropical Africa and East and West Asia is higher...
than during the cold and neutral episodes (Figure 2(b,c)). In the cold episode, the subtropical Pacific Ocean and Atlantic Ocean CO₂ concentrations are significantly greater than in the warm and neutral episodes. The results indicate that warm episodes have a notable impact on land, while cold episodes have a greater impact on ocean regions.

The AIRS CO₂ spatial distributions during the ENSO episodes are shown in Figure 3. Significant differences can be found over the NH high latitudes (40°–60°N) and the Atlantic Ocean from South America to Africa (0°–20°S) between the values for the warm and neutral episodes and the values for the cold episode. The values over Northeast Asia, eastern North America and the Atlantic Ocean are found to be enhanced in the warm episode and reduced in the cold and neutral episodes. The difference between the highest and lowest values in the cold episode is larger than that in the warm episode. ENSO has a greater impact in the GOSAT data than in the AIRS data.

Furthermore, we illustrate the CO₂ spatial variability during different stages of both ENSO warm and cold episodes. To reveal the changes in CO₂ during an ENSO episode, we subtract the neutral episode from the warm and cold episodes, respectively. As both warm and cold episodes begin in July and end in April of the following year, the results for September, December and March are shown to represent the onset, mature and decay stages of ENSO, respectively. For the GOSAT data (Figure 4), during the onset stage, CO₂ in the warm episode decreases by about 4–6 ppm over the mid–high latitude land and ocean regions (40°–80°N) in the NH, whereas it decreases by 1–2 ppm in the cold episode. During the mature stage, higher values in the warm episode move southward to the mid–latitudes and concentrate in the Pacific and Atlantic oceans. Synchronized with the warm episode, higher values in the cold episode also move to the Pacific and Atlantic oceans, but with a weaker magnitude. During the decay stage, the differences over land are not obvious while the values over the subtropical Pacific Ocean during the warm episode are significantly enhanced. There is a significant
influence on the high latitudes in the NH and Pacific Ocean during the onset and mature stages of an ENSO warm phase.

Meanwhile, for the AIRS data (Figure 6), during the onset stage, CO₂ decreases significantly in Northern Asia and northern United States during the warm episode, while the variations in the cold episode are slight. During the mature stage, CO₂ in the warm episode decreases by about 4 ppm over Northern Asia, which is 2 ppm in the cold episode. It is worth noting that CO₂ in the cold episode decreases by 4 ppm in Pacific Ocean, whereas it is enhanced in warm episode. During the decay stage, the CO₂ patterns in the warm and cold episodes are similar. These results demonstrate that a warm ENSO episode has a remarkable impact on Northern Asia and the Pacific Ocean, especially in its onset and mature stages. ENSO regions in the AIRS data are more pronounced compared with GOSAT data.

![Figure 5. AIRS CO₂ patterns processes in ENSO warm (a,c,e) and cold (b,d,f) episode.](image)

4. CONCLUSION

Using data retrieved from AIRS and GOSAT measurements, we analyze the spatial-temporal patterns of atmospheric CO₂ concentration and their variations in various ENSO episodes. We find that the spatial patterns of 58 month GOSAT CO₂ are mostly related to strong CO₂ emissions, while AIRS CO₂ is distributed zonally, increasing from the tropics to the high latitudes and reaching a maximum at 40–60°N. There is an overall increase in CO₂ concentration during the warm ENSO episode, while there is an overall decrease during the cold ENSO episode for both the GOSAT and AIRS data. The analysis of CO₂ variations in different ENSO stages shows that the differences are significant during the onset and mature phases. For the GOSAT measurements, we directly observe a decrease in CO₂ concentration over high latitudes (about 4–6 ppm) during the ENSO warm onset phase. During the ENSO warm mature stage, CO₂ centers move to the mid- and low latitudes, especially in the Atlantic and Pacific oceans (>6 ppm). During the ENSO warm decay phase, CO₂ concentrations are significantly enhanced over the high latitudes and subtropical Pacific Ocean. For the AIRS measurements, CO₂ decreases significantly over Northern Asia and the northern United States during the ENSO warm onset stage. During the ENSO warm mature stage, CO₂ concentration decreases by
about 4 ppm over Northern Asia and the Pacific Ocean. The differences between the GOSAT and AIRS data for the decay phase in both ENSO warm and cold episodes are small.

ENSO influences atmospheric and oceanic circulation, precipitation, temperature and fire emissions [22–23]. Wang et al. [24] suggested that environmental factors, such as forest cover, vegetation, fire emissions and temperature, could determine the spatial distribution of CO₂ on a large scale. Therefore, CO₂ anomalies may be attributed to a combination of terrestrial sources, such as global biosphere uptake, soil and plant respiration, and fire emissions, as well as oceanic sources. As no model simulations were used to derive the distribution of CO₂, the reasons discussed in this paper need further investigation.

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