The influence of tropospheric biennial oscillation on mid-tropospheric CO_2

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[1] Mid-tropospheric CO_2 retrieved from the Atmospheric Infrared Sounder (AIRS) was used to investigate CO_2 interannual variability over the Indo-Pacific region. A signal with periodicity around two years was found for the AIRS mid-tropospheric CO_2 for the first time, which is related to the Tropospheric Biennial Oscillation (TBO) associated with the strength of the monsoon. During a strong (weak) monsoon year, the Western Walker Circulation is strong (weak), resulting in enhanced (diminished) CO_2 transport from the surface to the mid-troposphere. As a result, there are positive (negative) CO_2 anomalies at mid-troposphere over the Indo-Pacific region. We simulated the influence of the TBO on the mid-tropospheric CO_2 over the Indo-Pacific region using the MOZART-2 model, and results were consistent with observations, although we found the TBO signal in the model CO_2 is to be smaller than that in the AIRS observations. **Citation:** Wang, J., X. Jiang, M. T. Chahine, M.-C. Liang, E. T. Olsen, L. L. Chen, S. J. Licata, T. S. Pagano, and Y. L. Yung (2011), The influence of tropospheric biennial oscillation on mid-tropospheric CO_2, *Geophys. Res. Lett.*, *38*, L20805, doi:10.1029/2011GL049288.

1. Introduction

[2] Carbon dioxide is the most important anthropogenic greenhouse gas in the atmosphere and there is a serious concern that its continued increase could have an adverse climatic impact [see, e.g., *Intergovernmental Panel on Climate Change*, 2007]. Current and future satellite missions are and will be making global measurements of atmospheric CO_2 with unprecedented precision, spatial resolution and coverage to characterize CO_2 sources and sinks on regional scales and its transport around the globe [see, e.g., *Yokota et al.*, 2009; *Boesch et al.*, 2011]. It is important to identify and quantify spatiotemporal patterns of the natural variability of CO_2 before carrying out inversions for net CO_2 sources and sinks associated with anthropogenic activities. Recent studies have identified CO_2 natural variability arising from El Niño [*Jiang et al.*, 2010], Madden Julian Oscillation [*Li et al.*, 2010], and synoptic weather in the mid-latitudes [*Keppel-Aleks et al.*, 2011].

[3] A previous study [*Li et al.*, 2005] revealed that more CO could appear in the upper troposphere over the Tibetan Plateau and Southwest China during Asian summer monsoon seasons. In this paper, we focus on investigating the influence of TBO on the Atmospheric Infrared Sounder (AIRS) CO_2 data in the mid-troposphere. Over the Indo-Pacific region, TBO is one of the climate systems that influence atmospheric circulation. TBO is defined as a tendency for a relatively strong monsoon to be followed by a relatively weak one over India and Australia [*Mooley and Parthasarathy*, 1984; *Yasunari and Suppiah*, 1988; *Yasunari*, 1990, 1991; *Tian and Yasunari*, 1992; *Shen and Lau*, 1995; *Webster et al.*, 1999]. TBO occurs in the season prior to the monsoon and involves coupled land–atmosphere–ocean processes over a large area of the Indo-Pacific region [*Meehl*, 1997]. Observations show that the signals of the TBO appear not only in the Indian-Australian rainfall records, but also in the tropospheric circulation, sea surface temperature (SST), and upper-ocean thermal fields [*Yasunari*, 1991; *Ropelewski et al.*, 1992; *Lau and Yang*, 1996; *Chang and Li*, 2001]. TBO is an important component of the tropical ocean–atmosphere interaction system, which is separated from the El Niño–Southern Oscillation [*Chang and Li*, 2000]. From the TBO theory [*Chang and Li*, 2000], the warming in the western Pacific induces not only a strong monsoon but also a stronger Western Walker Cell and thus a surface westerly anomaly over the Indian Ocean. This westerly anomaly helps the cold sea surface temperature anomalies (SSTA) to persist through the succeeding seasons, leading to a weaker Asian monsoon and weaker Western Walker Cell in the following summer. The Western Walker Cell blows from the Indian Ocean to the western Pacific and creates a convergence area with the Eastern Walker Cell at the Indo-Pacific region [*Meehl and Arblaster*, 2002]. The SSTA resemble those resulting from El Niño–La Niña conditions [*Chang and Li*, 2000]. El Niño has been found to influence atmospheric CO_2 in the mid-troposphere as a result of a change in the circulation [*Jiang et al.*, 2010]. TBO is expected to influence the atmospheric CO_2 in the mid-troposphere as well. In this paper, we used AIRS mid-tropospheric CO_2 data and a chemistry-transport model to investigate the influence of TBO on the mid-tropospheric CO_2 over the Indo-Pacific region.

2. Data and Model

2.1. Data

[4] In this paper, we used mid-tropospheric CO_2 retrievals from the AIRS to investigate the influence of the TBO on

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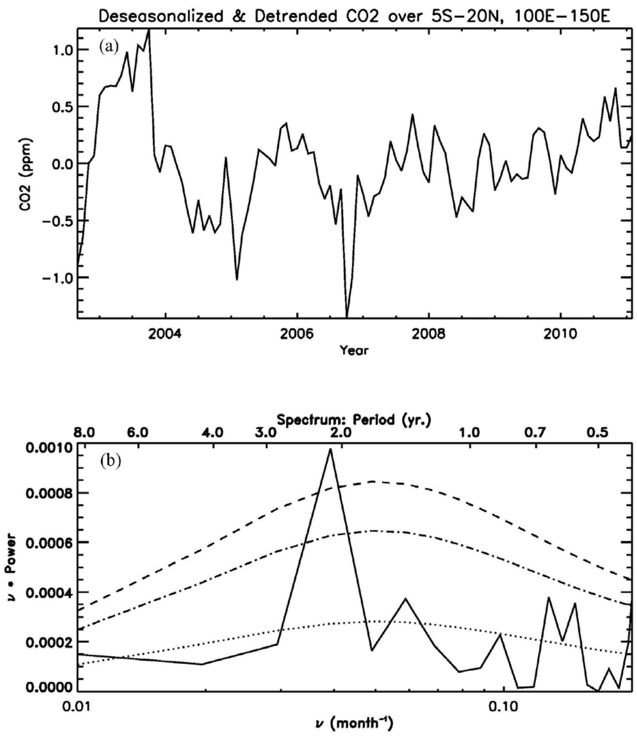

Figure 1. (a) Deseasonalized and detrended AIRS CO_2 averaged over 5°S - 20°N, 100°E - 150°E. (b) The power spectrum of deseasonalized and detrended AIRS CO_2 averaged over 5°S - 20°N, 100°E - 150°E. Dotted line is the mean red-noise spectrum, dash-dot line and dashed line shows 10% and 5% significance levels.

the mid-tropospheric CO_2. Mixing ratios of AIRS mid-tropospheric CO_2 are retrieved by the Vanishing Partial Derivative Method [*Chahine et al.*, 2005, 2008]. The maximum sensitivity of AIRS mid-tropospheric CO_2 retrievals is between 500 hPa and 300 hPa. AIRS Version 5 CO_2 retrieval products are available from 60°S to 90°N over land and ocean, day and night from the Goddard Earth Sciences Data and Information Services Center. It spans from September 2002 to the current date. We regridded AIRS Level 2 Standard Product CO_2 to 2° × 10° (latitude by longitude).

[5] Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Climatology Project (GPCP V2.1) precipitation data were also used to construct the Indian monsoon rainfall index. Variability is consistent between TRMM and GPCP precipitation data. We included two data sets in the paper, for the TRMM and GPCP precipitation data cover different time periods. TRMM precipitation data are available at 0.25° × 0.25° (latitude by longitude) from 50°S to 50°N from 1998 to 2010. TRMM calibrated precipitation data combine precipitation estimates from different instruments (TMI, AMSR-E, SSM/I, AMSU-B) [*Huffman et al.*, 2007]. GPCP Version 2.1 precipitation data are obtained by merging infrared and microwave satellite estimates of precipitation with rain gauge data from more than 6,000 stations [*Huffman et al.*, 2009]. GPCP global monthly mean precipitation data are from 1979 to 2009 with spatial resolution 2.5° × 2.5° (latitude by longitude). Precipitation data in the monsoon season (June to September, JJAS) were used to calculate the Indian monsoon rainfall index (area mean of JJAS rainfall in 5°N ~ 40°N, 60°E ~ 100°E), which determines monsoon strengths in different years [*Meehl and Arblaster*, 2002]. A relatively strong monsoon is defined when the precipitation (P_i) is higher than the adjacent two years ($P_{i-1} < P_i > P_{i+1}$). A relatively weak monsoon is defined when the precipitation is lower than the adjacent two years ($P_{i-1} > P_i < P_{i+1}$).

2.2. Model

[6] We used a three-dimensional (3-D) chemistry-transport model, Model of Ozone and Related Chemical Tracers version 2 (MOZART-2), to investigate the TBO signal in the mid-tropospheric CO_2. ECMWF-Interim meteorological data were used to drive the MOZART-2. The horizontal resolution is 2.8° (latitude) × 2.8° (longitude) and there are 45 vertical levels extending up to approximately 50 km altitude [*Horowitz et al.*, 2003]. MOZART-2 is built on the framework of the Model of Atmospheric Transport and Chemistry (MATCH). MATCH includes representations of advection, convective transport, boundary layer mixing, and wet and dry deposition. The surface boundary condition for MOZART-2 is the climatological CO_2 surface fluxes from biomass burning, fossil fuel emission, ocean, and biosphere used by *Jiang et al.* [2008a]. There is no interannual variability in CO_2 surface fluxes.

3. Results and Discussion

[7] To investigate the variability of the mid-tropospheric CO_2 over the Indo-Pacific region, we have calculated the deseasonalized and detrended AIRS mid-tropospheric CO_2 over 5°S-20°N, 100°E-150°E. The result is shown in Figure 1a. The seasonal cycle was removed by subtracting monthly mean CO_2 from the data. We then removed a linear trend from the deseasonalized CO_2. The power spectrum of the deseasonalized and detrended CO_2 is shown in Figure 1b. In addition to the high frequency signals, there is also a signal around two years in the power spectrum, which is within the 5% significance level. The two-year signal in the deseasonalized and detrended mid-tropospheric CO_2 may be related to the TBO. The statistical significance of signals in the power spectrum was obtained by comparing the amplitude of a spectral peak to the mean red noise spectrum [*Gilman et al.*, 1963; *Jiang et al.*, 2008b].

[8] To further investigate the possible relation between the TBO and the mid-tropospheric CO_2, we calculated AIRS detrended mid-tropospheric CO_2 during the monsoon season (JJAS), and compared it with the detrended Indian monsoon rainfall index derived from TRMM precipitation for JJAS. Our results are shown in Figure 2. The correlation coefficient between two time series is 0.58 (4% significance level). In-phase variations show that there is more CO_2 in the mid-troposphere during the strong monsoon years (2003, 2005, 2007, and 2010), and less CO_2 during the weak monsoon years (2004, 2006, and 2008). *Li et al.* [2010] had found that the surface CO_2 concentration is higher than the mid-tropospheric CO_2 concentration at 10–12 km in the winter season. We compared surface CO_2 at Guam (13.45°N, 144.8°E) with CONTRAIL aircraft CO_2 (10–12 km) in the summer season (JJAS) from 1994 to 2008. The 15-year averaged CO_2 difference between the surface and aircraft in

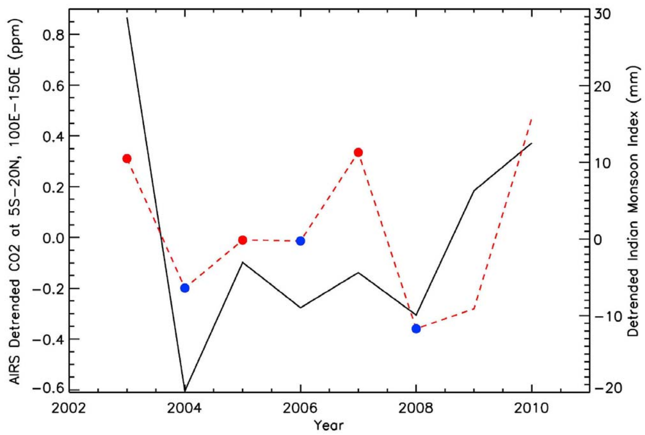

Figure 2. Detrended AIRS mid-tropospheric CO_2 averaged at 5°S-20°N, 100°E-150°E in JJAS from 2003 to 2010 (black solid line) and detrended Indian monsoon index calculated from TRMM precipitation data (red dashed line). Red dots are strong monsoon years and blues dots are weak monsoon years. Correlation coefficient between AIRS CO_2 and monsoon index is 0.58 (4%).

the summer season (JJAS) is 0.5 ± 0.2 ppm. This confirms that surface CO_2 concentrations are higher than that in the mid-troposphere. The transport of surface CO_2 into the mid-troposphere over the Indo-Pacific region is determined by the strength of the upwelling. From the theory of TBO [*Chang and Li*, 2000], the warming in the western Pacific induces not only a strong monsoon but also a stronger Western Walker Cell. Since the Western Walker Cell is stronger during a strong monsoon year [*Chang and Li*, 2000], it will result in enhanced CO_2 transportation from the surface to the mid-troposphere due to the strong upwelling. So there is more mid-tropospheric CO_2 over the Indo-Pacific region during a strong monsoon year. During a weak monsoon year, the Western Walker Cell is weaker and less CO_2 will be transported to the mid-troposphere, thus less mid-tropospheric CO_2 is seen over the Indo-Pacific region during a weak monsoon year. Results shown in Figure 2 are not contaminated by the influence from El Niño or La Niña, for El Niño and La Niña occur in the winter seasons of 2005, 2008, and 2010, which do not overlap with Monsoon seasons (JJAS).

[9] We chose the strong and weak monsoon years to investigate spatial patterns of AIRS mid-tropospheric CO_2. The mean value of AIRS detrended mid-tropospheric CO_2 in the strong monsoon years (mean value of CO_2 in JJAS of 2003, 2005, 2007, and 2010) is shown in Figure 3a. The mean value of AIRS detrended mid-tropospheric CO_2 in weak monsoon years (mean value of CO_2 in JJAS of 2004, 2006 and 2008) is shown in Figure 3b. In Figures 3a and 3b, high concentrations of the mid-tropospheric CO_2 over the Indo-Pacific region correspond to the upwelling area of the Western and Eastern Walker Cells. During strong monsoon years, there is more mid-tropospheric CO_2 over the Indo-Pacific region. During weak monsoon years, though the value of CO_2 over Indo-Pacific region remains high, the CO_2 value is smaller comparing with that in strong monsoon years. Figure 3c reveals the difference in mid-tropospheric CO_2 between strong and weak monsoon years. There is more mid-tropospheric CO_2 over the Indo-Pacific region and the South China Sea during strong monsoon years. The Student-t test was used to calculate the statistical significance of the difference for mid-tropospheric CO_2 concentrations in strong and weak monsoon years. Mid-tropospheric CO_2 differences between strong and weak monsoon years are statistically significant when the t-value is larger than a certain value t_0. There are 16 months in the strong monsoon group and 12 months in the weak monsoon group. The number of degrees of freedom for the CO_2 difference between two groups is 16 + 12 − 2 = 26. When the t-value is larger than 1.7, the results are within the 10% significance level, which are highlighted by blue areas in Figure 3d.

[10] We used the MOZART-2 model to investigate the TBO signal in the model mid-tropospheric CO_2. The AIRS mid-tropospheric CO_2 weighting function was applied to MOZART-2 CO_2 vertical profiles and the weighted MOZART-2 CO_2 were averaged over 5°S-20°N, 100°E-150°E in JJAS from 1991 to 2008. Figure 4a is the time series of MOZART-2 detrended mid-tropospheric CO_2 concentration averaged over 5°S-20°N, 100°E-150°E in JJAS and detrended Indian monsoon rainfall index calculated from GPCP from 1991 to 2008. MOZART-2 mid-tropospheric CO_2 is highly correlated with the Indian monsoon rainfall index. The correlation coefficient is 0.56 (4% significance level). We chose two strong monsoon years (1996 and 2007) and two weak monsoon years (1999 and 2002) from the MOZART-2 model to investigate the influence of the TBO on the mid-tropospheric CO_2. Differences of the MOZART-2 mid-tropospheric CO_2 between strong and weak monsoon years (Figure 4b) demonstrate that there is more mid-tropospheric CO_2 over the Indo-Pacific area during strong monsoon years, which is similar to our analysis using the AIRS mid-tropospheric CO_2. However, the mid-tropospheric CO_2 difference due to the strength of monsoon is smaller in the MOZART-2 compared to that from the AIRS CO_2. *Jiang et al.* [2008a] found that the 3-D chemistry-transport models (MOZART-2 and GEOS-Chem) underestimate the amplitude of the CO_2 seasonal cycle in the mid-troposphere as seen in the aircraft data, which is consistent with results found in the column-averaged CO_2 by *Yang et al.* [2007]. *Jiang et al.* [2008a] also found that the convective mass flux, which is very important for the correct simulation of CO_2 in the mid-troposphere, tends to be too weak in the model. This may be the same reason for the underestimation of the simulated TBO signal in the MOZART-2 CO_2. In addition, the simulation of TBO signal might be improved in the future when we include correct CO_2 interannual variability at the surface.

4. Conclusions

[11] This work reveals that the concentration of the mid-tropospheric CO_2 can be influenced by the strength of the monsoon for the first time. The relationship between the TBO and variations of mid-tropospheric CO_2 concentrations over the Indo-Pacific region is established. Time series of AIRS mid-tropospheric CO_2 correlate well with the TBO index, showing that during strong (weak) monsoon years, there are more (less) CO_2 in the mid-troposphere over Indonesia due to the strong (weak) Western Walker Cell. This suggests that the strength of the circulation influences CO_2 concentration in the mid-troposphere. MOZART-2 mid-tropospheric CO_2 results are consistent with those from the

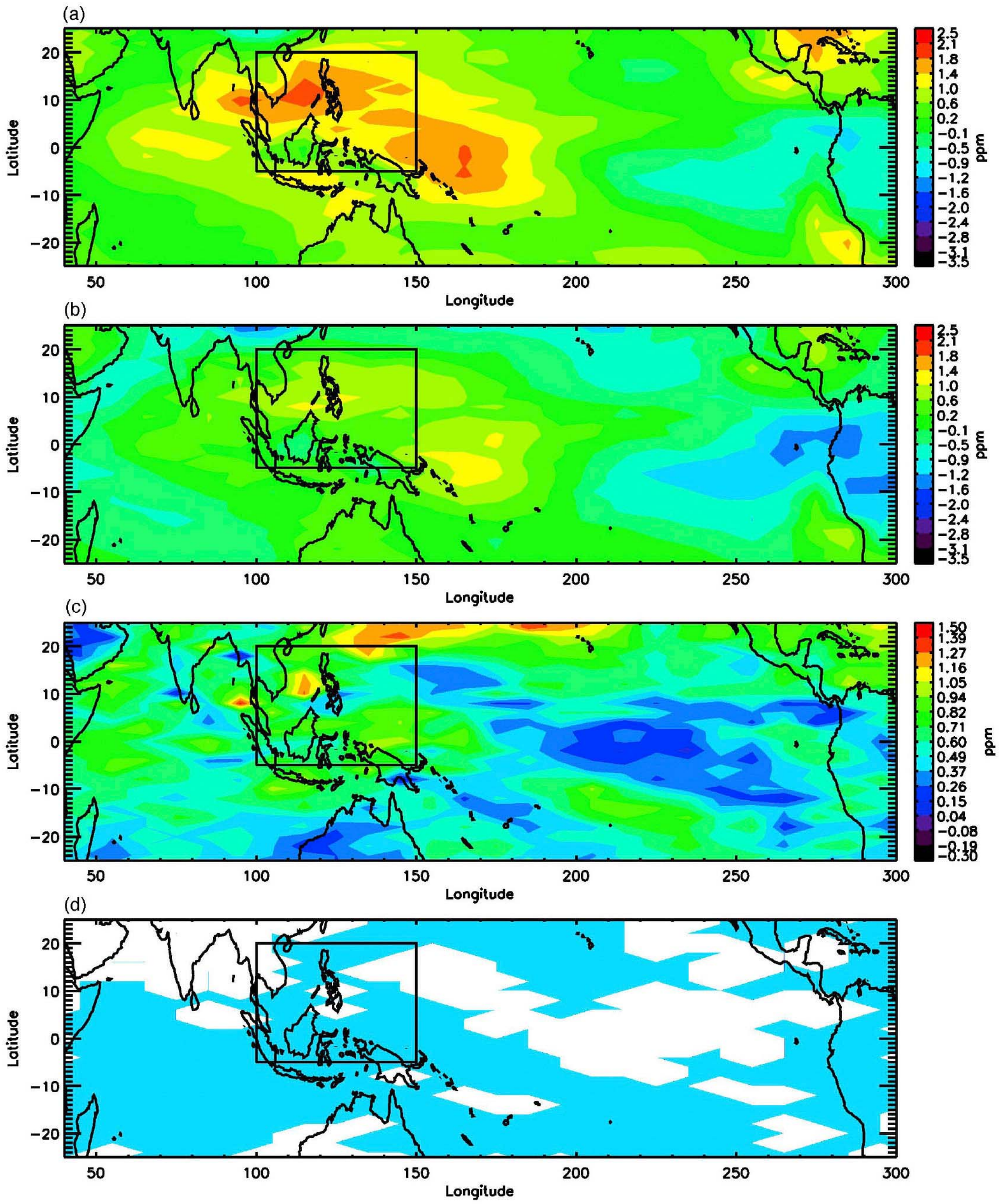

Figure 3. (a) The mean value of AIRS CO_2 concentration in strong monsoon years (JJAS of 2003, 2005, 2007, and 2010). (b) The mean value of AIRS CO_2 concentration in weak monsoon years (JJAS of 2004, 2006 and 2008). (c) CO_2 difference between the strong and weak monsoon years. (d) CO_2 differences within 10% significance level are highlighted in blue.

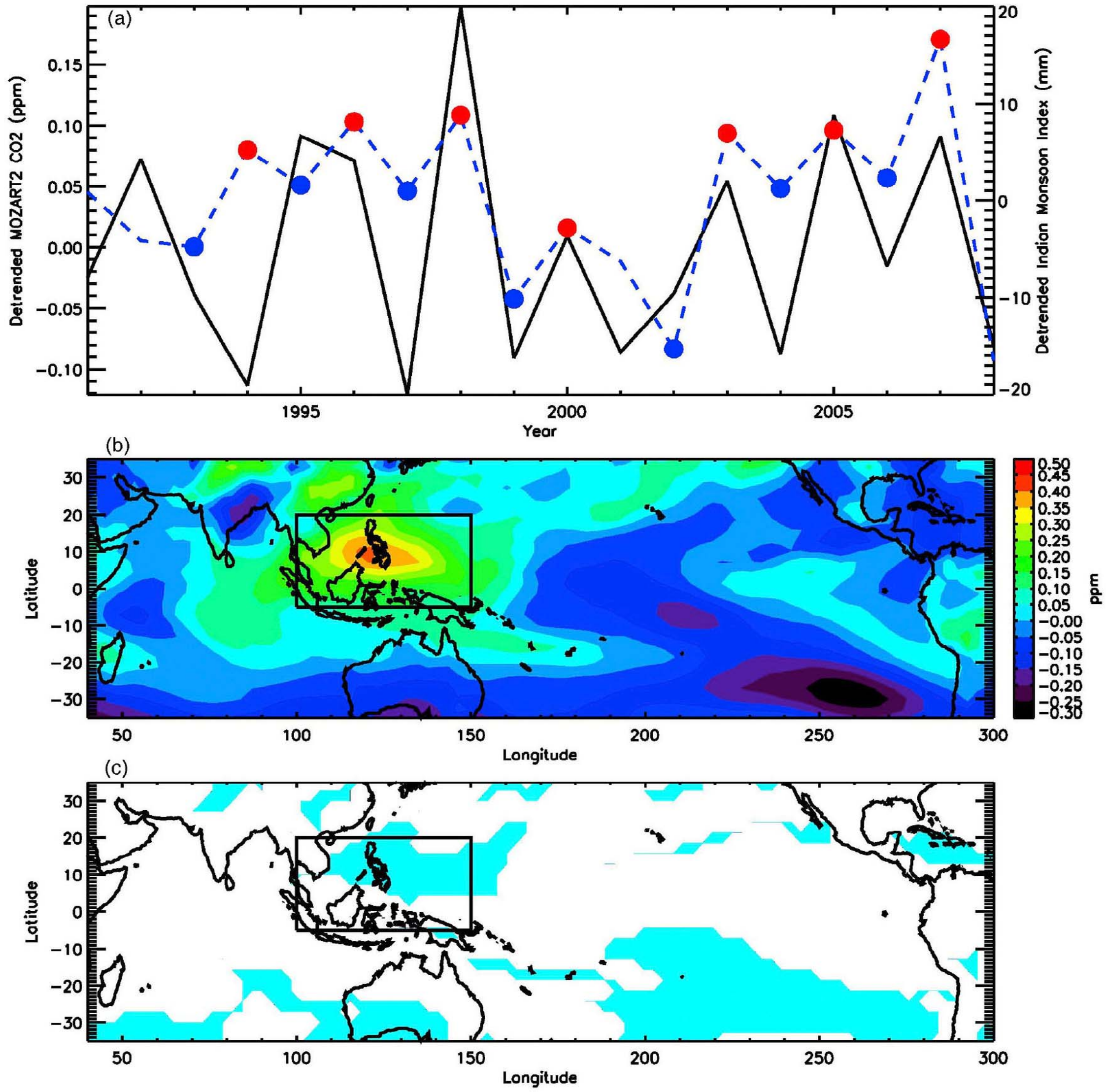

Figure 4. (a) MOZART-2 detrended mid-tropospheric CO_2 averaged at 5°S-20°N, 100°E-150°E (black solid line) and detrended Indian monsoon index derived from GPCP precipitation data (blue dashed line). Correlation coefficient between two time series is 0.56 (4%). (b) MOZART-2 CO_2 difference between strong monsoon years (1996 and 2007) and weak monsoon years (1999 and 2002) in JJAS. (c) MOZART-2 CO_2 differences within 10% significance level are highlighted in blue.

observation, although the signal simulated in the model is smaller than that from AIRS CO_2, indicating that TBO might not have been fully represented in the model. The correct identification of this natural variability of CO_2 is important for inferring the sources, sinks and transport of CO_2. In addition, as the quality and quantity of satellite CO_2 data improve [*Boesch et al.*, 2011], modeling the variations in the mid-tropospheric CO_2 as a response to monsoon offers a unique opportunity to diagnose deficiencies in chemistry-transport models.

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