Temporal and spatial distribution of tropospheric CO_2 over China based on satellite observations during 2003-2010

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ABSTRACT Mid-troposphere CO_2 data retrieved by the AIRS (Atmospheric Infrared Sounder) were validated with five ground-based stations and aircraft measurements in the Northern Hemisphere. AIRS CO_2 products show good agreement with ground and aircraft observations. The data had a monthly average accuracy better than 3 ppmv. In this study, the spatial and temporal distribution of mid-troposphere CO_2 from January 2003 to December 2010 was analyzed based on this satellite product. The average concentration of atmospheric CO_2 was higher in the Northern Hemisphere than in the Southern Hemisphere. The yearly average results show a gradual increase from 2003 to 2010. In China, the annual growth rate was about 2 ppmv/a, similar to the United States, Europe, Australia and India, but was slightly lower than Canada and Russia. Mid-troposphere CO_2 concentrations were higher over northern China than over southern areas, due to differences in natural conditions and industrial layout. There were four centers of high CO_2 concentration between 35 and 45°N over China, with low concentrations over Yunnan Province. There was a significant seasonal CO_2 variation with peak concentration in spring and the lowest concentration in autumn.

KEYWORDS: mid-troposphere CO_2, satellite remote sensing, ground based validation, temporal and spatial distribution

Carbon dioxide (CO_2), is one of the most prominent greenhouse gases, and plays an important role in climate and climate change [1]. Releases from the ocean, animal respiration, burning of fossil fuels and land use change are the main sources of atmospheric carbon dioxide. CO_2 is removed by plants through photosynthesis, dissolution at the surface of the oceans, and carbon deposition [2, 3]. CO_2 concentration in the atmosphere has increased by 35% since the Industrial Revolution [4] due to human activities, such as the burning of oil, coal and gas, and deforestation. This CO_2 increase has a significant effect on global climate, ecology, and economy. In recent years, scientists have paid more attention to this important topic [5-15].

The limited spatial coverage of the current surface observation system is not sufficient to obtain regional and global distribution of CO_2 concentrations. Satellite observations with better spatial coverage can provide a stable, long time series, over wide regions, as well as ground to aerial three-dimensional information regarding atmospheric composition [16]. Currently the Atmospheric Infrared Sounder (AIRS) instrument, orbiting on Aqua satellite, has been approved to retrieve mid-troposphere CO_2 concentration data [17-20]. Distribution of mid-troposphere CO_2 is important for the study of the global carbon cycle and the effects of human activities on the atmosphere.

In this paper, the trend, seasonal and regional variations in mid-troposphere CO_2 concentrations over China are presented based on the AIRS CO_2 findings.

1 Instrument and data source

The AIRS is an infrared spectrometer/radiometer that covers the 3.7-15.4μm spectral range with 2378 spectral channels. Low instrument noise and hyper-spectral data from AIRS have been used to produce global profiles on temperature, water vapor, carbon dioxide and other trace gases. These data provide important constraints on modeling the global distribution and transport of these gases. The satellite data in this paper come from NASA's official AIRS mid-troposphere CO_2 retrieval product site (http://airs.jpl.nasa.gov/AIRS_CO2_Data/). This AIRS product used cloud-cleared radiances to conduct retrieval under cloudy conditions and tested the RMS of adjacent 2 by 2 spots to control quality [21]. The spatial resolution of our CO_2 retrieval is 90 by 90 km^2 in the nadir. Extensive work has been conducted to validate the AIRS mid-troposphere CO_2 product.

The data from five ground-based are available at the World Data Centre for Greenhouse Gases (WMO WDCGG) web site (http://gaw.kishou.go.jp/wdcgg/wdcgg.html). The Assekrem, Mauna Loa, Niwot Ridge and Waliguan stations used a flask method to sample the air, while the Plateau Rosa station used a continuous method to sample. More details about the observations can be found elsewhere [15].

2 Results and discussion

2.1 Ground-based validation of the AIRS CO_2 product

AIRS retrieval CO_2 employs a set of 15 μm spectrum channels with a CO_2sensitivity of around 500 hPa. Based on the fact that CO_2 is well-mixed in the atmosphere, here we used the AIRS mid-troposphere CO_2 to represent troposphere CO_2 concentration. To assess accuracy of AIRS CO_2 retrievals, we compared AIRS monthly average retrieval results from five ground-based station observations, the altitude of which were above 2700km in the Northern Hemisphere. AIRS results are consistent with the ground-based observations. Table 1 gives the average bias, standard deviation, correlation coefficient, and growth rate per annum for both the ground and satellite observations over these years. The correlation coefficients are higher than 0.77 for all five stations, the bias is about 0.62 ppmv, and the monthly average standard deviation is less than 3.0 ppmv. The annual mean carbon dioxide growth rate for ground observations was 1.98 ppmv, which is slightly lower than the satellite 2.08 ppmv/a, but the difference is less than 1.5%.

Table 1. Comparison between ground-based and satellite measurements during 2003–2010.

	Ground-base Station			*Annual growth rate (ppmv/a)*		*Mean (ppmv)*		*Average deviation (ppmv)*	*Monthly average standard deviation (ppmv)*	*R*
	lat	**lon**	**h(m)**	**Ground**	**Satellite**	**Ground**	**Satellite**			
Assekrem	**23.27**	**5.63**	**2710**	**1.995**	**2.076**	**380.734**	**379.822**	**0.912**	**1.609**	**0.922**
Mauna Loa	**19.54**	**-155.58**	**3397**	**1.992**	**2.034**	**380.786**	**379.286**	**1.500**	**1.598**	**0.915**
Niwot Ridge	**40.05**	**-105.59**	**3523**	**2.018**	**2.149**	**381.293**	**380.811**	**0.482**	**2.614**	**0.806**
Plateau Rosa	**45.93**	**7.70**	**3480**	**1.935**	**2.040**	**380.729**	**381.007**	**-0.278**	**2.976**	**0.771**
Waliguan	**36.28**	**100.9**	**3810**	**1.977**	**2.100**	**381.209**	**380.730**	**0.479**	**2.692**	**0.806**
Average				**1.983**	**2.080**	**380.950**	**380.331**	**0.619**	**2.298**	**-**

Validation results show that the AIRS retrieved mid-troposphere CO_2 product was consistent with ground-based. The entire average month bias was less than 3 ppmv, which confirms the ability of AIRS to track the 5 ppmv seasonal variation in atmospheric CO_2 [18]. Furthermore, the annual growth rate obtained from the satellite is about 2 ppmv, which is similar to that from ground observations. This demonstrates that AIRS data can provide reliable inter-annual variation information for atmospheric CO_2. Many previous studies also have shown that AIRS mid-troposphere CO_2 data have the ability to obtain spatial and temporal distribution of CO_2 in the atmosphere [17-19].

2.2 Global Troposphere CO_2 distribution

Based on the 2003–2010 AIRS retrieval data, the global average distribution of CO_2 is shown in Figure 1. CO_2 concentration in the Northern Hemisphere was higher than in the Southern Hemisphere, with the highest levels occurring in 5 regions: (1) northern China, (2) Europe, (3) central United States, (4) southeast Canada and (5) the nearby sea region of Alaska. These high CO_2 concentration belts may be closely related to human activities and long-distance atmospheric pollution transport [17]. The lowest CO_2 concentration belt is in the 15°S-15°N Atlantic region, which extends eastward to Southern Africa and westward to the Pacific Ocean, west of South America.

Table 2 shows the increase in the average CO_2 concentration in these seven areas from 2003 to 2010. The average value for these areas was similar at about 380ppmv. The highest annual growth rate was found in Russia (2.35ppmv/a), followed by Canada (2.24 ppmv/a). The rates for the other regions, including China were lower than 2.20 ppmv/a.

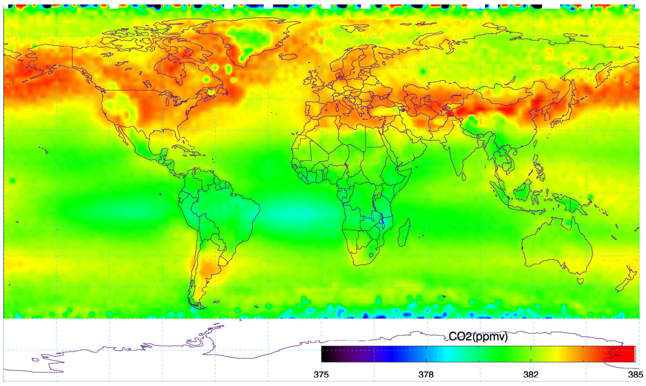


Figure 1. Mid-troposphere CO_2 concentrations averaged during 2003–2010 throughout the world.

Table 2. Mid-troposphere CO_2 concentration statistics for typical countries during 2003–2010.

	Arear		Mean	Monthly	Annual	Seasonal
	Longitude	Latitude	(ppmv)	average Variance (ppmv)	growth rate (ppmv/a)	fluctuation (ppmv)
America	122.5~72.5˚W	33~48˚N	383.01	5.10	2.17	4.52
Cananda	130~90˚W	50~65˚N	383.07	5.46	2.24	9.30
China	90~120˚E	22~42˚N	382.32	5.05	2.13	5.21
Russian	45~135˚E	56~70˚N	382.15	6.13	2.35	14.00
Australia	120~150˚E	30~20˚S	381.71	4.89	2.08	4.30
Europe	0~30˚E	40~60˚N	383.00	5.18	2.17	6.24
India	72.5~85˚E	14~30˚N	381.62	4.91	2.08	4.37

2.3 Spatial and temporal distribution of troposphere CO_2 over China

The average distribution of CO_2 over China during 2003–2010 is shown in Figure 2. The highest CO_2 level was in northern China with significant enhancements in 35°N-45°N range. This distribution is very similar to modeled results [17]. The highest concentration levels occurred in four regions: (1) Northeast Plain, (2) Inner Mongolia, (3) the Taklimakan Desert and (4) the Tarim Basin. In addition to the surface CO_2 emission and sink, atmospheric transport also causes a high CO_2 belt in China. Figure 2 shows that the high CO_2 belt runs parallel to the geopotential height contours, which confirms high CO_2 related to high latitude atmospheric transportation in the Northern Hemisphere [17].

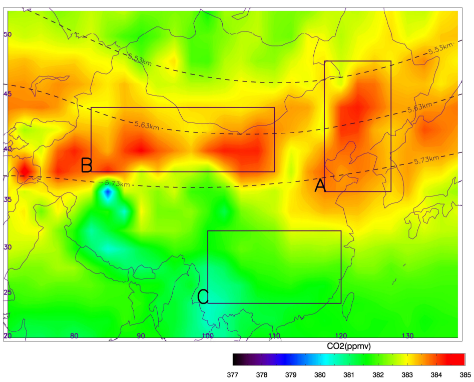


Figure 2, Mid-troposphere CO_2 concentration averaged during 2003–2010 over China

Figure 3 shows monthly variation in CO_2 concentration for three typical areas (A, 36-48°N, 117.5-127.5°E, Northeast China; B, 38-44°N, 82.5-110°E, Northwest; C, 24-32°N, 100-120°E, Southeast) during 2003–2010. The results show similar seasonal variation and an overall increasing trend from 2003 to 2010 in all the different areas. However, the seasonal fluctuation in the southeast is smaller than in the northeast and northwest.

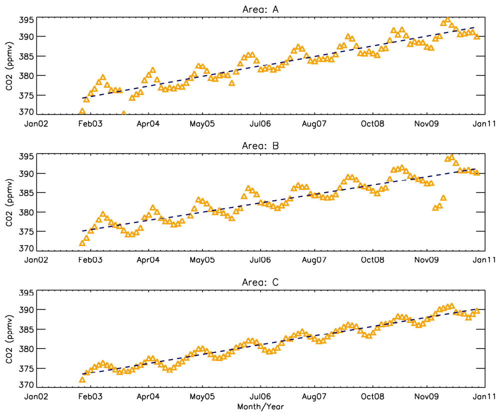
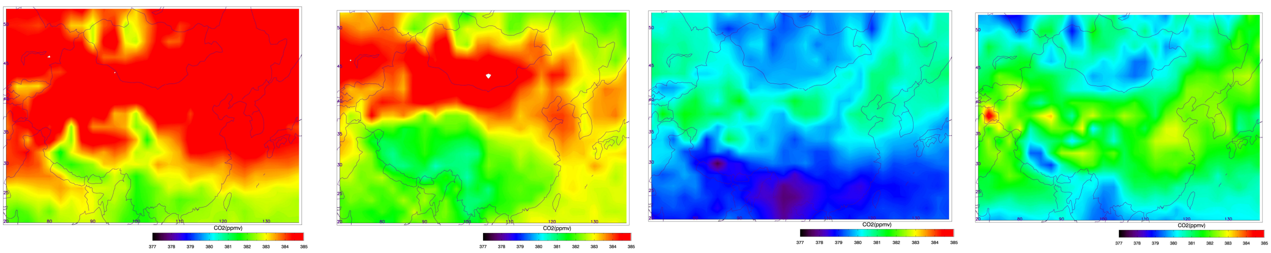


Figure 3, Monthly variations in mid-troposphere CO_2

2.4 Seasonal variation in Mid-troposphere CO_2

Middle troposphere CO_2 concentrations have showed significant seasonal variation in CO_2 over China (Figure 4; spring: March-May, summer: June-August, autumn: September-November, winter: December-February of the next year). Significant seasonal variation in CO_2 in the Northern Hemisphere was closely related to exchange between the atmosphere and the earth's biosphere [23].



(a) Spring (b) summer (c) Autumn (d) winter

Figure 4, Seasonal variation in mid-troposphere CO_2 over China based on AIRS data during 2003–2010

3 Conclusions

Mid-troposphere CO_2 product retrieved by the AIRS (Atmospheric Infrared Sounder) are validated by five ground-based stations in the Northern Hemisphere. This satellite mid-troposphere CO_2 product has been used to study the spatial and temporal distribution over China. The main results of this study can be summarized as fellow:

1) The AIRS mid-troposphere CO_2 data show consistency with ground-based observation . The monthly average bias is less than 3 ppmv, which validates the ability of the AIRS product to capture seasonal CO_2 concentration change precisely.

2) CO_2 concentration is higher in the Northern Hemisphere than in the Southern Hemisphere. The CO_2 concentration annual growth rate for China is about 2 ppmv, which is similar to the United States, Europe, Australia and India, but slightly lower than Canada and Russia. This rate still has some uncertainty because of limited satellite data.

3) Mid-troposphere CO_2 is higher in the north than in the south over China, and significant enhancements are seen at four centers in the range 35°N-45°N. The Yunnan area is the lowest CO_2 concentration center.

4) A rise in Mid-troposphere CO_2 occurs over China in the spring, when the Northern Hemisphere Greenup begins, and

reaches a minimum in autumn when the quantity of biomass undergoing photosynthesis is the greatest.

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