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Analysis of the temporal and spatial distribution of atmospheric CO_2 in China

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सार - भूमंडलीय उष्णन मानवता के लिए एक बहुत बड़ा खतरा है और यह मुख्य रूप में मानव निर्मित ग्रीन हाउस गैसों के कारण होता है। पृथ्वी के वायुमंडल में कार्बन डाइआॉक्साइड और मिथेन के घनत्व का प्रेक्षण करने के उद्देश्य से वर्ष 2009 में ग्रीन हाउस गैस प्रेक्षण उपग्रह (GOAST) छोड़ा गया था इस शोध पत्र में जून 2009 से मई 2014 तक की अवधि में ग्रीन हाउस गैस प्रेक्षण उपग्रह से प्राप्त हुए स्तर एवं स्तर के डेटा उत्पादों के विश्लेषण के द्वारा चीन के तीन मुख्य क्षेत्रों (बीजिंग-टियांजिन-हेबेई क्षेत्र, यांग्त्ज़ी नदी डेल्टा और पर्ल नदी डेल्टा) में CO_2 के अस्थाई और स्थानिक वितरण के बारे में परिक्षण किया गया है हमारे परिणामों से यह पता चलता है कि इन क्षेत्रों में CO_2 की सांद्रता लगातार बढ़ रही है और इसका गहरा संबंध मानवीय गतिविधियों से इसके अलावा इन आंकडो को चीन सांख्यिकीय पुस्तिका 2013 में बीजिंग और शंघाई की कुल ऊर्जा खपत और अन्य सहायक डेटा से जनसंख्या घनत्व द्वारा मान्य किया गया है। कार्बन उत्सर्जन को कम करना अभी भी एक चुनौती पूर्ण कार्य है।

ABSTRACT. Global warming represents a huge threat to humanity and is mainly caused by man-made greenhouse gases. The Greenhouse Gases Observing Satellite (GOSAT) was launched in 2009 with the main purpose to observe densities of carbon dioxide and methane in the earth atmosphere. The following paper investigates temporal and spatial distribution of atmospheric CO_2 over the three main regions of China (Beijing-Tianjin-Hebei region, the Yangtze River Delta and Pearl River Delta) by analyzing Level 2 and Level 4 data products provided by GOSAT from June 2009 to May 2014. Our results indicated that the concentrations of CO_2 in these areas are constantly increasing and are closely related to human activities. In addition, these data were validated by the population density from "China Statistical Yearbook 2013", Beijing and Shanghai's total energy consumption and other auxiliary data. Reducing the carbon emissions still remains a challenging task.

Key words – CO_2, GOSAT, Spatial and temporal distribution, Beijing-Tianjin-Hebei region, Yangtze river delta, Pearl river delta.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has pointed out that the impacts of global warming are becoming clearer with each passing day and that global warming is mainly caused by man-made greenhouse gases (IPCC, Climate Change, 2013). Compared with the fourth assessment report published in 2007, the fifth assessment report states that the climate warming is much more serious than it was ever thought before, while the changes it brings occur at much faster pace than previously estimated.

In order to understand the global atmospheric carbon cycle, it is necessary to establish the global scale and real-time detection of greenhouse gases. Even though traditional methods are hugely precise and reliable, they are mainly single point observations influenced by geographical conditions. With the development of the atmospheric remote sensing observation technology, satellite monitoring is becoming ever more popular (Liu *et al.*, 2011).

Greenhouse gases Observing Satellite (GOSAT) (Yokota *et al.*, 2009), also known as Ibuki, was launched in 2009 by Japan Aerospace Exploration Agency and is mainly dedicated to greenhouse-gas-monitoring, *i.e.*, measuring of carbon dioxide and methane densities in the earth atmosphere. Ibuki includes two observation sensors on-board satellite, a Thermal and Near-infrared Sensor for carbon Observation Fourier Transform Spectrometer (TANSO-FTS) and a Cloud/Aerosol Imager (TANSO-CAI). TANSO-FTS is used to monitor greenhouse gases, while TANSO-CAI is used to collect the information on clouds and aerosols so as to improve the inversion precision of greenhouse gases (Kuze *et al*., 2009; Lei, *et al*., 2013).

Over recent years, numerous studies have focused on investigating temporal and spatial distribution of CO_2 and the global carbon cycle. Yokota *et al*., 2009 have found that CO_2 concentration in the northern hemisphere has higher hemispheric gradient compared to southern hemisphere. By comparing GOSAT with GEOS-Chem data, Cogan *et al.*, 2012 have concluded that the seasonal cycle and the spatial variability of them agree well. In addition, Butz *et al.*, 2011 have found low bias between GOSAT and ground-based observation data from the Total Carbon Column Observing Network (TCCON).

In the present study, we used the L2 direct observation data, the L4A global carbon flux analysis data from TANSO-FTS, the population density and total energy (coal) consumption from “China Statistical Yearbook 2013”, as well as other auxiliary data, to further analyze the spatial and temporal distribution of CO_2 in major regions of China. We also analyzed carbon fluxes in different climatic zones, as well as the relationship between human behaviour and the CO_2 concentrations over the major cities of China.

2. Data and study areas

2.1. *Data selection*

GOSAT data inversion method and the accuracy have been repeatedly verified by many scholars. GOSAT data and ground data coincide well, with relative accuracy of 1% for CO_2 (4 ppmv, 3-month average) and 2% for CH_4. This bias should become smaller as the algorithm becomes improved (Cogan *et al.*, 2012; Butz *et al.*, 2011; Dils *et al.*, 2014; Bu *et al.*, 2015).

GOSAT provides multi-level data: Level 1 data are based on spectral observation data from TANSO-FTS; Level 2 are CO_2 column concentrations derived from Level 1 data (NIES, 2012); FTS SWIR Level 3 data products are generated by interpolating, extrapolating and smoothing FTS SWIR Level 2 column-averaged mixing ratios of CO_2 and CH_4 on a monthly basis. A geostatistical calculation technique, known as Kriging, was applied

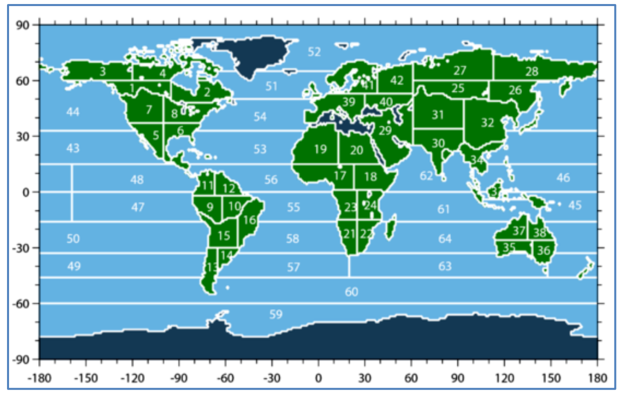

Fig. 1. The division of L4 global carbon flux assessment model

and the values were gridded to 2.5-degree cells. In this study, we used daily average column concentration L2 data for analysis. L2 data are available from June 2009; the inversion algorithm was updated from May 24, 2014 to June 16, 2014. To ensure the consistency and to exclude the impact of different algorithms, we used L2 data from June 2009 to May 2014.

The atmospheric CO_2 mixes well and has a continuous distribution. L4A data are derived from L2 data and ground station data; they are monthly CO_2 fluxes which can reflect seasonal variation of CO_2 at regional scale. The Level 4A data products provide monthly averaged source/sink strengths (fluxes) of CO_2 in 64 regions. These data come with uncertainties that are inversely estimated from the FTS SWIR Level 2 column-averaged mixing ratios, ground-based observational data and other meteorological data such as wind direction and velocity, using a global atmospheric transport model. There are 42 land areas and 22 marine areas as shown in Fig. 1.

2.2. *Study area*

According to geographical, environmental and economic development in China, three representative areas were selected for the present study: Beijing-Tianjin-Hebei region (38°~41° N, 115°~118° E), the Yangtze River Delta (30°~32° N, 120°~122°) and the Pearl River Delta (22°~23° N,111.5°~114.5° E). As shown in Fig. 1, Beijing-Tianjin-Hebei region and the Yangtze River Delta are in No. 32 area, while Pearl River Delta region is positioned in No. 34 area.

Beijing-Tianjin-Hebei region includes Beijing, Tianjin and eight cities of Hebei Province. The area has surface of approximately 200000 square kilometers and the total population of about 150 million. In 2014, GDP was about 6.6473 trillion RMB. This area is Chinese

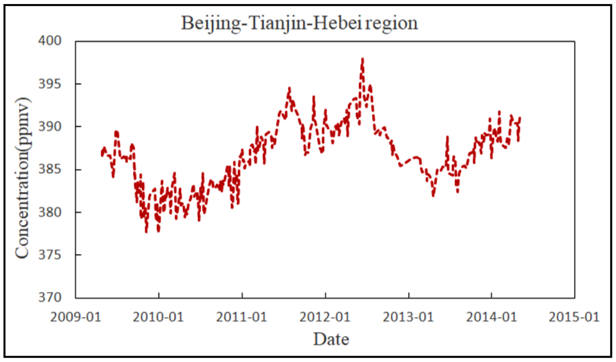

Fig. 2. The average daily column concentration of CO_2 in the Beijing-Tianjin-Hebei region

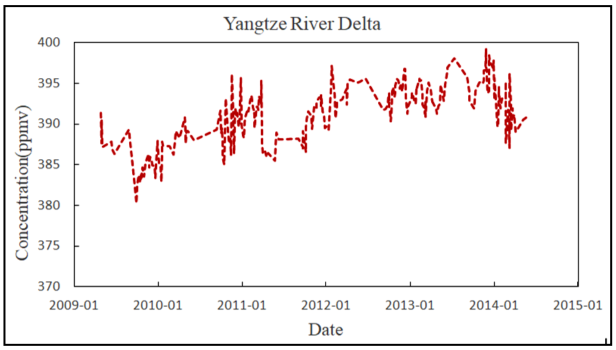

Fig. 3. The average daily column concentration of CO_2 in the Yangtze River Delta

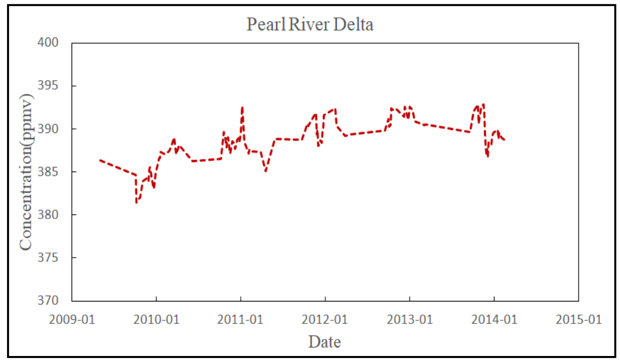

Fig. 4. The average daily column concentration of CO_2 in the Pearl River Delta region

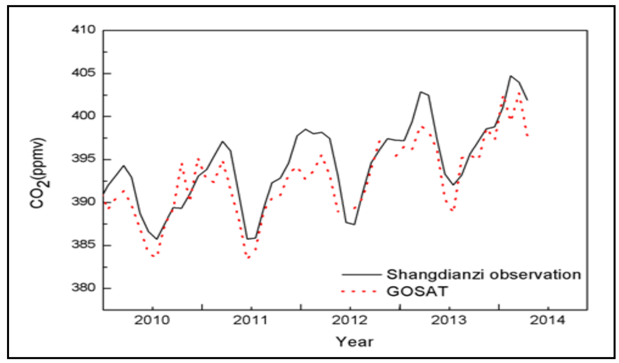

Fig. 5. Monthly average concentration of CO_2 from ground observation at Shangdianzi station and the GOSAT Data

political, cultural, technological innovation and international communication center, with many high-tech enterprises and heavy industries, such as automotive industry, electronic industry, machinery industry and metallurgical steel industry. Pearl River Delta region has advanced manufacturing and modern service industries of global influence. In January 26^{th}, 2015, the World Bank report revealed that the Pearl River Delta overtook Tokyo thus becoming the largest urban world area in both size and population. Yangtze River Delta is the alluvial plain and the largest Chinese economic zone. The central government regards it as the strongest economic center, the advanced manufacturing base and the important international gateway in Asia-Pacific area. So, these three areas are densely populated with the most developed economies in China.

2.3. *Data analysis*

The daily average column concentrations of CO_2 were obtained from the GOSAT L2 data. The concentrations and changes in CO_2 from June 2009 to May 2014 in the three regions of China are reported in Figs. 2-4. The number of actual observations was 297 days in region A; 266 days in region B; and 110 days in region C. (*i*) The number of surface observation points that are used to monitor the distribution of CO_2 concentrations is limited and unevenly distributed due to the satellite's operational status. Also, effective observation sites accounted for only 2% ~ 5% of all sites; (*ii*) The satellite is a sun-synchronous orbit, so the number of observations and observation times of satellites in the target area are not stable; (*iii*) L2 data are generated and provided on-demand basis according to acquisition time, position and observation mode; (*iv*) The weather affects the CO_2 concentration in the region. Consequently, days having valid data varied across different regions.

There are seven atmospheric observation stations in China, such as Mt. Waliguan and Shangdianzi Station. To confirm the reliability of data from GOSAT, we compared the monthly average concentrations of CO_2 from GOSAT data over Beijing with the observation data from Shangdianzi station. The Shangdianzi station is located in Beijing and it has been the regional atmospheric local station since 1988. The data were obtained from the World Data Center for Greenhouse Gases (WDCGG), which represent the average condition of the atmospheric

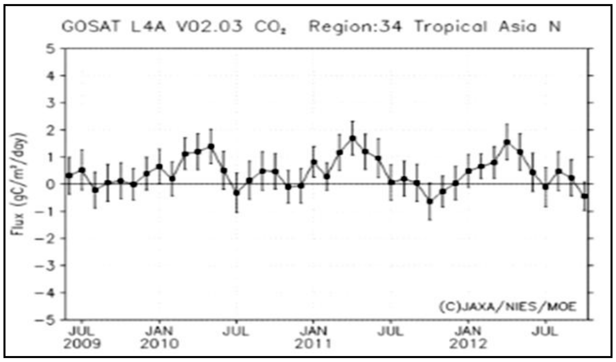

Fig. 6. Tropical Asia regional carbon flux

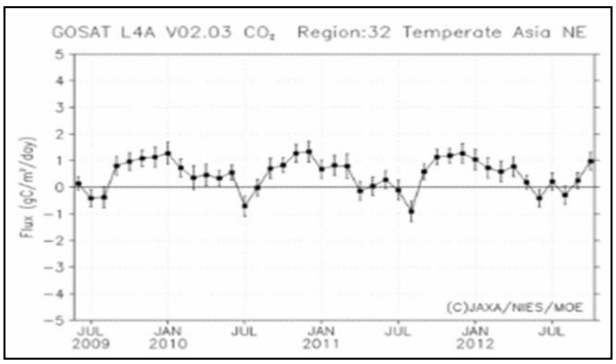

Fig. 7. Temperate Asia regional carbon flux

composition in Beijing-Tianjin-Hebei region. The surface CO_2 data were obtained with flask sampling first and then the samples were analyzed at Key Laboratory of Atmospheric Chemistry, China Meteorological Administration. These results are represented in Fig. 5 and they show a good consistency and the correlation coefficient of 0.897. Also, the monthly mean deviation was less than 5ppmv. Consequently, we were able to assure that the satellite data were valid and the deviation was acceptable.

Atmospheric CO_2 flux from June 2009 to October 2012 in the Asia temperate climate belt (No. 32 area) and the Asia tropical climate belt (No. 34 area) were shown in Figs. (6-7). The positive value indicated carbon source, while the negative value represented carbon sink. The annual variation was almost identical, with great changes over different seasons. In the tropical belt (Fig. 6), the largest value of carbon source occurred in spring and the lowest value of carbon sink appeared in summer. Species are abundant in the tropics and ecosystems are important for maintaining the carbon balance in nature. However, human activities (deforestation, etc.) have caused enormous damage to ecosystems in recent years. Therefore, the carbon source and sink may vary in the same month of different years. In the temperate belt

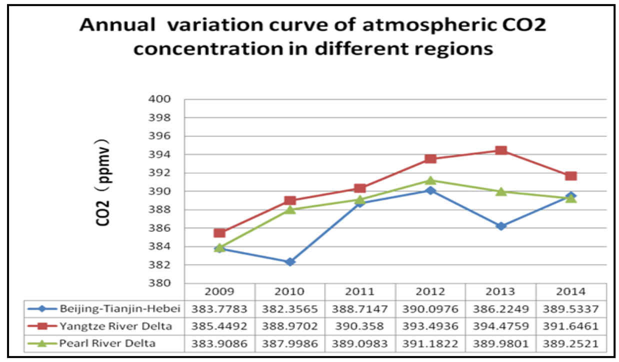

Fig. 8. Variation of average column concentration of atmospheric CO_2

(Fig. 7), the flux increased from the autumn to winter reaching the highest levels in December or January, which then decreased and reached the lowest levels in summer.

Both, the seasonal changes and the long-term trends are shown in Figs. 2-4. In Beijing-Tianjin-Hebei region, the CO_2 column concentration decreased from the summer 2009 to summer of 2010 and then it started increasing until the summer of 2012. Subsequently, it decreased during the next year. In Yangtze River Delta region and Pearl River Delta region, the rising trend was maintained during these several years. Even though Yangtze River Delta and Beijing-Tianjin-Hebei region are in temperate climate belt, the changes in CO_2 distribution were different. Pearl River Delta region is in the tropical climate belt, nonetheless the CO_2 concentration in Pearl River Delta region revealed similar changes as those in Yangtze River Delta. Consequently, the most probable factor that influences the CO_2 concentration could be the human activity which includes human factors like burning of the fossil fuels, usage of land, industrial emissions, government's policy and so on.

Fig. 8 shows the annual average concentrations in three regions, which were 394.4 ppmv in Yangtze River Delta region; 389.9 ppmv in the Pearl River Delta region; and 386.7 ppmv in the Beijing-Tianjin-Hebei region. According to 2013 statistical data, among the three areas the largest population was recorded in Yangtze River Delta and the smallest in Beijing-Tianjin-Hebei region, which was coherent with the annual average concentrations.

The main energy consumption rates from 2009 to 2012, for both Shanghai and Beijing, were provided by "China Statistical Yearbook" and are presented in Table 1 and Table 2. The total energy consumption in Shanghai increased by 13%, *i.e.*, it went from 157.66 million tons of standard coal in 2009 to 179.65 million tons of standard coal in 2011. The total number of energy consumption in

TABLE 1

Total energy consumption in Shanghai

Norm	2012	2011	2010	2009	Convert coefficient
Coal ($\times10^4$ t)	5703	6142	5875.52	5305.17	1kg Standard coal/kg
Coke ($\times10^4$ t)	673.17	714.15	717.08	677.68	0.9714kg Standard coal/kg
Crude oil ($\times10^4$ t)	2210.55	2134.69	2126.5	1937.18	1.4286 kg Standard coal/kg
Gasoline ($\times10^4$ t)	517.35	427.87	415.37	338.52	1.4714 kg Standard coal/kg
Kerosene ($\times10^4$ t)	402.74	400.5	399.07	353.11	1.4714 kg Standard coal/kg
Diesel ($\times10^4$ t)	568.99	532.96	509.04	483.19	1.4571 kg Standard coal/kg
Fuel ($\times10^4$ t)	640.15	6705.04	744.28	742.79	1.4286 kg Standard coal/kg
Oil gas ($\times10^9$ m^3)	64.38	55.43	45.01	33.52	$2.143\times10^{-}$ t/m^3
Power ($\times10^9$ kwh)	1353.45	1339.62	1295.87	1153.38	3.27×10^{-4} t/Kwh
Total standard coal quantity ($\times10^4$ t)	17820	17965	17393	15766	

TABLE 2

Total energy consumption in Beijing

Norm	2012	2011	2010	2009	Convert coefficient
Coal ($\times10^4$ t)	2270	2366	2634.62	2664.7	1 kg Standard coal/kg
Coke ($\times10^4$ t)	32.77	33.28	220.45	211.97	0.9714 kg Standard coal/kg
Crude oil ($\times10^4$ t)	1075.77	1105.08	1116.29	1162.93	1.4286 kg Standard coal/kg
Gasoline ($\times10^4$ t)	415.9	389.79	371.53	363.61	1.4714 kg Standard coal/kg
Kerosene ($\times10^4$ t)	443.33	419.88	392.63	341.934	1.4714 kg Standard coal/kg
Diesel ($\times10^4$ t)	215.82	241.12	237.42	240.18	1.4571 kg Standard coal/kg
Fuel ($\times10^4$ t)	78.16	74.64	66.69	42.4	1.4286 kg Standard coal/kg
Oil gas ($\times10^9$ m^3)	92.07	73.56	74.79	69.4	2.143×10^{-4} t/m^3
Power ($\times10^9$ kwh)	874.28	821.71	809.9	739.15	3.27×10^{-4} tkwh
Total standard coal quantity ($\times10^4$ t)	9505	9206	9565	9240	

Beijing was much lower than that in Shanghai. Shanghai and Beijing are typical representatives of Yangtze River Delta and Beijing-Tianjin-Hebei regions. The energy consumption directly contributes to the CO_2 concentration. The average CO_2 concentration in Beijing-Tianjin-Hebei region was much lower than that in Yangtze River Delta. The maximum difference was 8 ppmv and the minimum difference was 3 ppmv.

The annual average CO_2 concentration kept rising for these several years in both Yangtze River Delta and the Pearl River Delta. Nonetheless, the situation was somewhat different in Beijing-Tianjin-Hebei region. In this region the concentration was fluctuating because of the government's interference. Since 2008, when the Olympic Games were held, the Beijing government took a series of effective actions to protect the local environment. The rare blue sky appeared in Beijing during APEC China in 2014, which was also known as "APEC blue" phenomenon and which significantly revealed the powerful guiding role of the Chinese Government.

3. Conclusions

In the present paper, L2 and L4 data from the GOSAT satellite were used to analyze the CO_2 concentration in three major regions of China and the carbon fluxes in different climatic zones in Asia. The

CO_2 concentration varies heavily over different seasons and its annual average is proportional to the local population density and energy consumption. Moreover, the influences of the government regulatory policies are very considerable. So, both the government and the individuals must work together to bring effective measures that would help to control emissions, develop low-carbon economy and encourage low-carbon life.

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