Atmospheric Environment 188 (2018) 50–59

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Spatial and temporal distribution of NO_2 and SO_2 in Inner Mongolia urban agglomeration obtained from satellite remote sensing and ground observations

Caiwang Zheng[a], Chuanfeng Zhao[a,c,*], Yanping Li[b,**], Xiaolin Wu[a], Kaiyang Zhang[a], Jing Gao[d], Qi Qiao[b], Yuanzhe Ren[e], Xi Zhang[b], Fahe Chai[b]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Global Change and Earth System Science, Beijing Normal University, Beijing, 100875, China
[b] Chinese Research Academy of Environmental Sciences, Beijing, 100012, China
[c] Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, 91125, USA
[d] Rinpoche (Beijing) Technology Co., Ltd, Beijing, 100094, China
[e] The Inner Mongolia Autonomous Region Environmental Monitoring Center Station, Hohhot, 010011, China

A R T I C L E I N F O

Keywords:
NO_2
SO_2
OMI
Inner Mongolia
Long-term trend
Spatial distribution

A B S T R A C T

Nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) are important pollution gases which can affect air quality, human health and even climate change. Based on the combination of tropospheric NO_2 and SO_2 column density products derived from OMI satellite with the ground station observations, this study analyzed the spatial-temporal distribution of NO_2 and SO_2 amount in Inner Mongolia urban agglomerations. It shows that NO_2 increased continually from 2005 to 2011 at a rate of 14.3% per year and then decreased from 2011 to 2016 at a rate of −8.1% per year. SO_2 increased from 2005 to 2007 with a rate 9.7% per year. While with a peak value in 2011, SO_2 generally showed a decreasing trend of −1.6% per year from 2007 to 2016. With regard to the spatial pattern, the highest levels of NO_2 occur in Hohhot and Baotou, followed by Wuhai and Ordos, the least in Bayannur. Compared with NO_2, the spatial distribution of SO_2 is slightly different. The pollution of SO_2 is the most serious in Wuhai, followed by Hohhot and Baotou, and the lightest in Ordos and Bayannur. The diurnal variations of NO_2 and SO_2 are basically the same, which decrease from 0:00 to 6:00, then increase to a peak value at 8:00, and decrease from 8:00 to 15:00. The diurnal variation of NO_2 and SO_2 is highly related to the diurnal variation of both anthropogenic emission and boundary layer height. Differently, the long-term spatial-temporal distribution of NO_2 and SO_2 are more closely related to human activities.

1. Introduction

In the past decades, coupled with China's burgeoning economy is the terrible air pollution (Chan and Yao, 2008), which is mainly caused by China's industrial explosive growth and urbanization development. Air pollutants can be divided into two forms, particulate matter (PM) and gaseous pollutants. PM has attracted great public concern because of its severe health impact (Yuan et al., 2012; Chang, 2012), especially for cardiovascular and respiratory disease, as well as reduced visibility caused by smog. Gaseous pollutants, such as sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3), also play very important roles in our atmospheric environment and get more and more attentions (Hao et al., 2007; Wang et al., 2012).

NO_2 and SO_2 are both important trace gases and play a significant role in the complex atmospheric chemistry process of the troposphere, causing a series of urban environmental pollution problems such as acid rain, haze and photochemical smog (WHO, 2000; IPCC, 2007; He et al., 2007; Shon et al., 2011). The secondary sulfate and nitrate particulate is formed by oxidation of gas granules, contributing to the particle concentration in the air and thus influencing the radiative budget and climate (Kajino et al., 2011). They can also promote the formation of acid rain and cause the decrease of crop yields and destruction of ecology (Richter et al., 2006; Dickerson et al., 2007). NO_2 is primarily released by anthropogenic emissions, which contain the industrial burning of fossil fuels such as coal, oil and gas, vehicle exhaust, biomass burning, and electricity generation. In terms of natural sources, it is

* Corresponding author. State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Global Change and Earth System Science, Beijing Normal University, Beijing, 100875, China.
** Corresponding author.
E-mail addresses: czhao@bnu.edu.cn (C. Zhao), leeyp@craes.org.cn (Y. Li).

https://doi.org/10.1016/j.atmosenv.2018.06.029
Received 19 March 2018; Received in revised form 15 June 2018; Accepted 17 June 2018
Available online 18 June 2018
1352-2310/

emitted from soils through the decomposition process of nitrates and can also be produced by lightning (Richter and Burrows, 2002; Cheng et al., 2012). Similarly, SO_2 is released into the atmosphere through both natural and anthropogenic emissions. Natural sources mainly refer to volcanic eruptions while anthropogenic sources include the burning of fossil fuels containing sulfur for domestic heating and the power generation for industrial activities (Zhang et al., 2017).

Over the years, researchers began to realize the detrimental effects of NO_2 and SO_2 to human health and plants, thus carried out studies about these two polluted gases (Ul-Haq et al., 2015). Compared with traditional ground station measurements which can provide continuous observations of near surface pollutants for a long time, satellite remote sensing offers other advantages, such as a coverage of large area with high spatial continuity. The satellite observations allow us to study the long-term spatio-temporal distribution of NO_2 and SO_2, the characteristics of long-distance transport (Zhang et al., 2008), as well as the pollutant contribution from various sources (Wang et al., 2012; Lu et al., 2013). To effectively acquire information of atmospheric pollutants, a lot of on-board satellite instruments are designed, such as Global Ozone Monitoring Experiment (GOME), SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY), GOME-2 and Ozone Monitoring Instrument (OMI). OMI is widely used and has high spatial and temporal resolution (Krotkov et al., 2016; Levelt et al., 2018). As overviewed by Levelt et al. (2018), OMI has been applied to various study themes including air quality monitoring, detection of ozone, volcanoes, spectral solar radiation, and so on. For air quality monitoring, OMI can provide information of several key pollutants such as NO_2, SO_2, aerosols, and HCHO. Damiani et al. (2012) used the ground-based total ozone measurements from 2007 to 2009 in the Arctic to check the quality of OMI, GOME and SCIAMACHY satellite-based data, and found that there was a good agreement between satellite- and ground-based observations despite of some systematic biases. Ul-Haq et al. (2015) investigated temporal trends, seasonality, and anomalies of tropospheric NO_2 pollution over four basins in South Asia using OMI measurements during the period 2004–2015. Lamsal et al. (2015) quantified the NO_2 temporal trend from 2005 to 2013 over the United States using surface measurements and tropospheric NO_2 vertical column density (VCD) data from OMI products. Krotkov et al. (2016) expanded the study area and used the OMI observation to investigate the SO_2 and NO_2 pollution changes over different countries of the world for the period of 2005–2014.

There are also many studies regarding the OMI-observed SO_2 and NO_x emission trends over China (van der A et al., 2017; Liu et al., 2016, 2017; Cui et al., 2016; Li et al., 2010, 2017; Zhang et al., 2017). Li et al. (2010) found the large reduction of SO_2 emissions from Chinese power plants in 2005–2007 based on OMI observations, and Li et al. (2017) indicated that SO_2 emission have declined by 75% in China since 2007 using OMI observations, making China surpassed by India for the total anthropogenic SO_2 emissions. Liu et al. (2016) investigated the temporal variation of NO_x over China at a national level based on both OMI observations and emission inventories, and they found a deceasing trend of column NO_2 by 32% from 2011 to 2015. Liu et al. (2017) further investigated the NO_x emissions from 48 cities and seven power plants over China, and found an increase by 52% from 2005 to 2011 and a decrease by 21% from 2011 and 2015 based on OMI observations. van der A et al. (2017) studied the air quality trends from 2005 to 2015 and evaluated the effectiveness of air quality policy for SO_2 and NO_x emissions in China. Zhang et al. (2017) analyzed the long-term trend of spatial and temporal distribution of NO_2 and SO_2 column density in Henan Province using OMI product. Cui et al. (2016) indicated that western China experienced rapid growth of NO_2 during 2005–2013, including the Inner Mongolia city cluster region. Note that Cui et al. (2016) mainly focused on regional statistical study of NO_2 from 2005 to 2013 for several regions in western China. By contrast, there is no intensive study for the gaseous pollution of SO_2 and NO_2 with high city/county level resolution over the Inner Mongolia region so far.

Inner Mongolia accounts for 12.3% of the land area in China and is rich in natural resources, of which coal reserves rank the second place among thirty-four provinces in China, making it become China's important energy heavy chemical base (NBS, 2013). Industries such as thermal power, chemical engineering and metallurgy impose a heavy burden on air quality. Various types of air pollutants have been increasing in recent years. Particularly, the amount of coal burning has increased greatly in winter heating period, making the air quality worse. As indicated by Cui et al. (2016), the increasing trend rate of NO_2 in 2005–2013 is as high as 10.2 ± 1.3% per year for the Inner Mongolia region. Currently, the first pollution-contributing factor is particulate matter, which is mainly from natural coal ash emission, dust and automobile exhaust emissions; and the second is SO_2 (IMESB, 2006). How to make a balance between the energy structure modulation and the improvement of air quality is an essential issue for public interests. To do that, we first need to obtain detailed pollution status over this region, such as SO_2 and NO_2. Therefore, this study aims to investigate the long-term trend and spatial distribution characteristics of NO_2 and SO_2 in Inner Mongolia urban agglomerations using both OMI measurements and ground-station observations.

The paper is organized as follows. Section 2 describes the data and method. Section 3 analyzes the spatial-temporal trends of NO_2 and SO_2 at cities in Inner Mongolia, and section 4 summarizes the findings.

2. Data and method

2.1. Study region

Inner Mongolia is the third largest province in China, with an area of about 1,183,000 km^2, population of 25 million, and Gross Domestic Product (GDP) of 1.78 trillion RenMinBi (RMB) in 2015 (CSY, 2015). From 2006 to 2011, the GDP growth rate was between 15% and 20% (generally ~15%) per year while it is about 7% after 2011 because of the adjustment of economic policy.

The study region is located in the core area of the middle and western Inner Mongolia, including Hohhut, Baotou, Ordos, Bayannur and Wuhai. Relying on abundant coal and natural gas resources, Hohhut-Baotou-Ordos (H-B-O) agglomeration has become the most dynamic economic circle in Inner Mongolia autonomous region. Hohhut is the capital city; Baotou is the largest city of Inner Mongolia; and Ordos is an emerging prairie city with rich energy resources. As shown in Fig. 1, Hohhut, Baotou and Ordos are situated in the Hetao plain with Yinshan mountain on the northern area, whereas Bayannur and Wuhai are in the ordos plateau. The difference of topography may influence the transport of air pollutants. In this study, we assume that natural contribution is roughly uniform in space (cities) and time while some uncertainties could be introduced. Generally, the anthropogenic

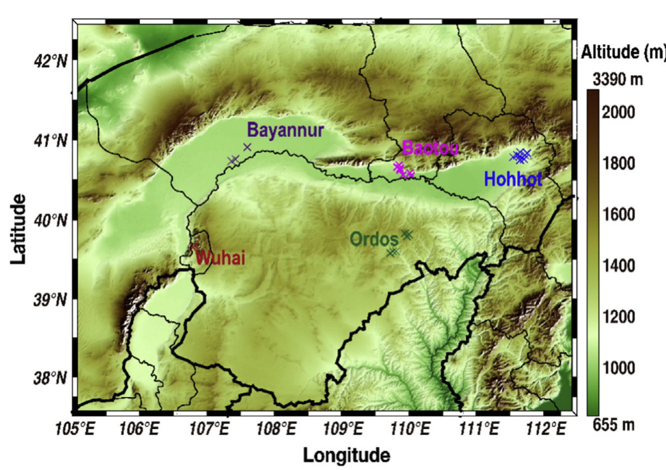

Fig. 1. Topographic map and the site distribution of Inner Mongolia urban.