Spatial-temporal characteristics and influencing factors of NO$_2$ and SO$_2$ in the Beijing-Tianjin-Hebei region based on satellite remote sensing

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Abstract. Air is an indispensable natural resource for all human activities. As an essential trace gas in the atmosphere, high NO$_2$ and SO$_2$ will affect the natural environment and human health. Based on the Ozone Monitoring Instrument's data, the temporal and spatial distribution of NO$_2$ and SO$_2$ concentrations in the Beijing-Tianjin-Hebei region from 2005 to 2017 was analyzed. Results showed that, on the annual scale, the concentration increased at first and then decreased. On the monthly scale, both of the two had regular fluctuations with annual cycles. The spatial distribution of pollutants was high in the southeast and low in the northwest. By analyzing the influencing factors of pollutants, it was found that environmental conditions are more the periodic fluctuations and spatial distribution differences of image density, and policy-oriented conditions are the main reason for the concentration trend decline in the later period.

1. Introduction
Air is a necessity for life activities. When the concentration of a particular substance in the atmosphere exceeds the normal level, air pollution is formed, causing adverse effects on the ecological environment, social activities, and human health. China's economic development speed is the world's leading, but the rapid urbanization process puts the ecological environment under tremendous pressure. The rapid increase in coal energy consumption and the continuous expansion of motor vehicle ownership have caused many harmful substances to be discharged into the atmosphere, which seriously affects urban air quality and endangers production and life activities and human health[1-4].

Both NO$_2$ and SO$_2$ are trace gases that are widely present in the atmosphere. NO$_2$ occupies an essential position in tropospheric atmospheric chemistry. Human activities are relatively active in urban areas in which human factors dominate the air's overall NO$_2$ emissions [5-7]. Since volcanic eruptions do not frequently occur in China, emissions from human activities are the primary atmospheric SO$_2$. In recent years, some areas in eastern China have become one of the most polluted areas globally. The
concentrations of air pollutants such as PM2.5, PM10, NO2, and SO2 in many cities have seriously exceeded the standards, far exceeding the World Health Organization's guidance values. Frequent large-scale pollution has made air pollution more and more critical to relevant departments and individuals. Taking the Beijing-Tianjin-Hebei (BTH) region as the research area, this paper analyzes the temporal and spatial distribution of NO2 and SO2 on annual, seasonal, and monthly scales and analyzes its influencing factors. The research results are of great significance to pollution prevention.

2. Study area and data sources
The BTH region (113 ° 27'-119 ° 51'E, 36 ° 02'-42 ° 37'N) were employed to study the present study, and a range includes Beijing, Tianjin, Baoding, Tangshan, Langfang, Shijiazhuang, Qinhuangdao, Zhangjiakou, Chengde, Cangzhou, Hengshui, Xingtai, Handan, a total of 13 cities. The BTH region is China's capital economic circle, China's political and cultural centre, and an important core area of the North China economy. The study area covers an area of about 217,200 square kilometres. In 2019, the regional GDP was about 8.46 trillion yuan, and the total population is about 113 million people, accounting for 2.25%, 8.56%, and 8.08% of the country, respectively. However, as one of China's most dynamic areas, it is also one area with more severe air pollution.

The tropospheric NO2 column concentration data used in this experiment is the monthly average product DOMINO version 2.0 of the tropospheric NO2 vertical column concentration inverted by Koninklijk Nederlands Meteorologisch Instituut (KNMI) based on Ozone Monitoring Instrument (OMI) data, with a spatial resolution of 0.125°×0.125°[8-10]. The SO2 data also comes from OMI data inversion. It is a daily planetary boundary layer (PBL) data product jointly provided by KNMI and Goddard Earth Sciences Data and Information Services Center (GES DISC). Through the preliminary quality screening of the total PBL column data according to the observation angle, altitude, and other conditions, the total SO2 column concentration of the 0.25°×0.25° global grid is obtained. Many existing experimental results have proved that the air quality data obtained through satellite remote sensing inversion has a strong correlation with the ground's measured value.

3. Study area and data sources
The concentration of tropospheric NO2 column is divided into Level-1 (<500), Level- 2 (500-1000), Level-3 (1000-1500), Level-4 (1500-2000), and Level-5 (>2000), and the unit is 10^{13} mole·cm^{-2}. The concentration of PBL SO2 column is divided into Level-1 (<0.35), Level-2 (0.35-0.5), Level-3 (0.5-0.7), Level- 4 (0.7-1.0), and Level-5 (>1.0), and the unit is DU (Dobson Unit). DU refers to the total amount of SO2 in the atmosphere from the vertical atmosphere of 1 square meter on the ground to the boundary layer's height. 1DU is equal to 2.69×10^{16} mole·cm^{-2}.

3.1. Annual change analysis
The changing trend of NO2 and SO2 concentration in the study area from 2005 to 2017 is shown in Figure 1. The time change of NO2 concentration can be divided into three stages. The first stage was from 2005 to 2011. The concentration gradually increased during this stage, with an average annual growth rate of about 86×10^{13} mole·cm^{-2}. The large drop in 2008 was directly related to the air-zone joint defence measures adopted to host the Beijing Olympics. The second stage was from 2011 to 2013, and the concentration of these three years has stabilized at about 1350×10^{13} mole·cm^{-2}. The third stage was after 2013. The concentration dropped rapidly at this stage, with an annual decrease of about 98×10^{13} mole·cm^{-2}. The highest and lowest values of NO2 concentration appeared in 2013 and 2005, respectively, and the highest value was 1.6 times the lowest value.

The time change of SO2 concentration can be divided into three stages. The first stage was from 2005 to 2007, showing a steady and rising trend, with an annual increase of about 150×10^{13} mole·cm^{-2}. The second stage from 2007 to 2010 was a steady decline, with an average annual decrease of about 231×10^{13} mole·cm^{-2}. The third stage was after 2011. The concentration continued to show a gradual decline after a rebound in 2011, with an average annual decline of about 150×10^{13} mole·cm^{-2}. The
highest and lowest values of SO₂ concentration appeared in 2007 and 2017, respectively, and the highest value exceeded twice the lowest value.

![Figure 1. Annual change trend of NO₂ and SO₂ concentrations](image)

The spatial distribution of annual mean values of NO₂ and SO₂ concentrations are shown in Figure 2 and Figure 3. The NO₂ concentration showed a trend of high in the southeast and low in the northwest. The Level-4 and Level-5 were concentrated in the main urban areas of cities such as Beijing, Tianjin, Tangshan, and Shijiazhuang, Xingtai, Handan, and other places in southern Hebei Province. Chengde, Zhangjiakou, and other places in the north were mostly in the Level-1 and Level-2. In 2005, high-value areas only appeared in small areas in the Beijing-Tianjin-Tangshan area and southern Hebei Province. At this time, the Level-5 area only accounted for 2%. Over the next few years, the high-value areas gradually expanded and connected into pieces. By 2011, when pollution was the most serious, it almost covered most of the study area's southeast. At this time, the Level-5 range exceeded 22% of the entire study area. After a relatively stable period from 2011 to 2013, high-value areas rapidly contracted after 2014. By 2017, the Level-5 only existed in a tiny area in southern Hebei Province, accounting for 1% of the study area.

![Figure 2. Spatial distribution of annual mean NO₂ concentrations](image)

The SO₂ concentration also showed an overall trend of high in the southeast and low in the northwest. The difference was that there are two main high concentration areas of SO₂, namely Shijiazhuang, Xingtai, Handan in the south of Hebei Province, and Tianjin and Tangshan in the northeast coast. Beijing
was not the center of high SO₂ concentration. In 2005, the Level-4 and Level-5 areas covered most of the southeast plain, and the Level-2 and Level-3 dominated the northwest mountainous areas. By 2007, the high-value area continued to expand, and the Level-5 area reached 56%. From 2008 to 2009, the high-value areas contracted rapidly. Almost all of the eastern area dropped from Level-5 to Level-4, and there was only a Level-5 area in the south. From 2011 to 2012, the high-value areas expanded slightly, forming two high-value areas in southern Hebei Province and Tangshan. At this time, the Level-5 areas accounted for 33% of the entire district. The high-value areas began to shrink rapidly in 2013, and the Level-5 areas disappeared in 2016. In 2017, the Level-4 areas only accounted for 1%. At this time, more than 60% of the area in the entire region was the Level-1 and Level-2.

3.2. Analysis of monthly changes

The monthly average values of NO₂ and SO₂ concentrations from 2005 to 2017 are shown in Figure 4. The results showed that when the annual cycle was used, the monthly average changes of NO₂ and SO₂ concentration showed noticeable periodic changes. The highest value generally occurred in winter, and the lowest value occurred in summer.
in the southeast. July was the lowest monthly average concentration value of $599 \times 10^{13}$ molec·cm$^{-2}$. All the Level-5 disappeared, and the Level-1 and Level-2 covered 85% of the entire area. The highest value was about 3.2 times the monthly average.

**Figure 5. Spatial distribution of monthly mean NO$_2$ concentrations**

The monthly average value of SO$_2$ concentration appeared in February and reached $2735 \times 10^{13}$ molec·cm$^{-2}$. The concentration distribution decreased from southeast to northwest. Level-5 covers most areas in the southeast, and there was a small range of Level-1 and Level-2 in the northwest mountainous area; The lowest value was $1426 \times 10^{13}$ molec·cm$^{-2}$ in July, leaving only five high-values in the southern part of Hebei Province, Level-1 and Level-2 in the northwest. The highest value was about 1.92 times the lowest value.

**Figure 6. Spatial distribution of monthly mean SO$_2$ concentrations**

### 4. Analysis of influencing factors

#### 4.1. Environmental conditions

The spatio-temporal variation of pollutant concentration is a complex system driven by multiple influencing factors. The type of land use affects the existence of pollutant concentration distribution. In 2015, the pollutant concentration of each land use type is shown in Table 1. The types of urban land, rural residential areas, and industrial and mining land are positively related to human activities' intensity. Industrial emissions, motor vehicle exhaust emissions, and human life emissions will increase pollutants' concentration [11, 12]. Besides, the built-up area has high building density and high vertical height, and its blocking and friction effect weaken the regional wind, which significantly affects the diffusion of pollutants.
Terrain conditions have a profound impact on the formation and diffusion of pollutants. Statistical analysis found a significant negative correlation between elevation and NO$_2$ and SO$_2$ at each spatial location, and the correlation coefficients were -0.822 and -0.767, respectively. Artificial pollution sources are often distributed in low-altitude areas, and their pollution degree is more significant than that in high-altitude areas. Besides, the blocking of mountains and the sinking of airflow on leeward slopes make it difficult for pollutants to diffuse, increasing the average concentration in low-altitude areas. There are apparent seasonal differences in meteorological conditions such as precipitation, temperature, and humidity in the BTH region, which affects the concentration of pollutants.

On the one hand, due to the relatively dry winter air and low temperature, coal, petroleum, and other fuels have increased significantly compared with non-heating periods, significantly increasing the amount of coal burned. On the other hand, the winter solar radiation weakens, causing the photochemical reaction to take longer. At the same time, the meteorological factors in winter are not conducive to atmospheric diffusion.

### 4.2. Policy-oriented conditions

Natural environmental factors mainly affect the monthly-scale periodic fluctuations and spatial differentiation of pollutants. In contrast, policy-oriented factors affect the inter-annual change trend, which is the main reason for the gradual decline in pollutant concentration in the later study stage. Firstly, with the acceleration of the transformation and upgrading of the industrial structure, the primary and secondary industries' proportions are gradually decreasing, while the tertiary industry is increasing. The tertiary industry's added value accounted for more than 50% for the first time in 2009, and the increase is accelerating. It is essential for ensuring economic growth while reducing pollutant emissions. Secondly, to change energy consumption composition, China has successfully promoted high-quality coal and clean briquette and promoted "coal to gas" and "coal to electricity" projects. Statistics show that China's total energy consumption increases year by year. However, the proportion of coal has dropped rapidly, while the proportion of natural gas, primary power, and other energy sources has risen rapidly. Simultaneously, China's energy consumption per unit of GDP has steadily declined, indicating that energy use in the country's economic activities is gradually decreasing. Thirdly, actively promote energy-saving and new energy vehicles, strengthen oil quality supervision and inspection, and other policies have been implemented one after another. Motor vehicle exhaust emissions are an essential source of air pollutants. Statistics show that while the number of motor vehicles is proliferating, low-emission vehicles are gradually being replaced by high-standard vehicles. The number of new energy vehicles is rapidly increasing.

### 5. Conclusions

Based on the OMI data inversion, the temporal and spatial patterns of NO$_2$ and SO$_2$ concentrations in the BTH region from 2005 to 2017 were analyzed. The conclusions are as follows: (1) The concentrations of NO$_2$ and SO$_2$ both showed a trend of increasing first and then decreasing. (2) The concentrations of NO$_2$ and SO$_2$ had significant periodic fluctuations with annual cycles, and the concentration in winter is significantly higher than that in summer. (3) The spatial distribution of NO$_2$ and SO$_2$ concentrations was generally higher in the southeast and lower northwest. The high-value areas of NO$_2$ are more concentrated in the centres of cities. (4) Many factors were affecting the concentration of image pollutants. Environmental factors such as land use types, topography, and meteorological conditions affected the periodic fluctuations in time and spatial distribution differences. Policy-oriented conditions were the main reason for the improvement of pollution in the later period. Therefore, it is imperative to promote industrial structure transformation reform, energy structure adjustment, and motor vehicle standard supervision from the national level to improve air quality.
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