Global NEST Journal, Vol 26, No 10, 05848

Spatial-temporal variations and attribution analysis of SO_2 concentration in Beijing-Tianjin-Hebei regions from 2013 to 2022

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Received: 23/02/2024, Accepted: 25/05/2024, Available online: 28/10/2024

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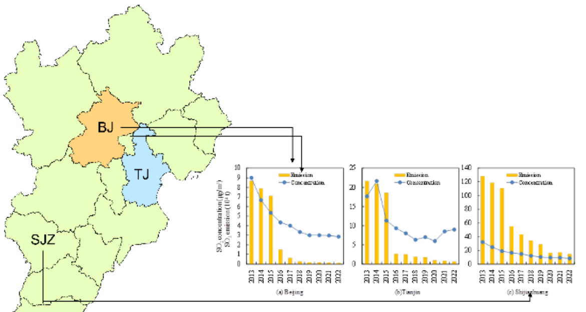
https://doi.org/10.30955/gnj.05848

Graphical abstract



The annual averaged concentration and emissions of SO_2 in three cities from 2013 to 2022

Abstract

Based on the monitoring data of air pollutants in Beijing-Tianjin-Hebei regions from 2013 to 2022, the spatial-temporal distribution of SO_2 concentration and main influencing factors were analyzed through multi-methods of Daniel trend test, KZ filtering and WRF/CMAQ model simulations. From 2013 to 2022, the annual averaged concentrations of SO_2 in Beijing, Tianjin and Hebei regions were in significant downward trends, all passing the Daniel trend test (α=0.01). The annual averaged concentration of SO_2 in Beijing, Tianjin and Hebei regions decreased from 26.6~114.3$\mu g \cdot m^{-3}$ in 2013 to 3.0~11.0$\mu g \cdot m^{-3}$ in 2022, with the decline rates fluctuating from 2.62~11.81$\mu g/(m^3 \cdot yr)$. The average annual concentration of SO_2 in Tangshan city decreased the most, reaching 92.3% while it changed to be the smallest, about 78.2% in Chengde City. The reduction of coal consumption in the Beijing-Tianjin-Hebei regions significantly reduced the atmospheric SO_2 emissions and directly reduced the regional averaged concentrations of SO_2. Meteorological factors were generally conducive to the diffusion of SO_2 concentration during 2013~2022, and meteorological factors contributed approximately 0.4% to 5.5% in the 13 cities of the Jingjinji regions, while the contribution of anthropogenic emission reduction ranged from 94.5% to 99.6%. The inter-annual variation of meteorological factors during the summer periods from 2013 to 2022 was overall not conducive to the dispersion of SO_2 concentrations, with the contribution ranging from -52.6% to -1.0% in 13 cities. During the summer season from June to August, under easterly and southerly winds, the SO_2 concentration in Beijing was approximately twice as high as that under northerly and westerly winds. The contribution of southwest regional transport channel to the SO_2 concentration in Beijing was 33.5%, while it increased to 38.9% in the southeast regional transport channel. Therefore, enhancing the management and control of air pollutants in the surrounding areas of Beijing will be beneficial for further reducing air pollutant levels in Beijing and achieving the air quality improvement targets set for the 14th Five-Year Plan period.

Key words: SO_2; Temporal and spatial distribution; Beijing; Trend; WRF/CMAQ; Regional transport; Cooperative control

1. Introduction

Sulfur dioxide in the atmosphere primarily originates from coal-fired emissions (Wang *et al.* 2017). High concentration of SO_2 and the sulfuric acid mist and secondary aerosols formed by the transformation of SO_2 gas particles pose great hazards to ecosystems and human health (Qian *et al.* 2021). Among the six atmospheric pollutants, SO_2 is a significant air pollutant in China to be decreased and be controlled first (China's Ministry of Environmental Protection,2022). Since 2000, China has implemented strict SO_2 emission control measures. Especially since 2013, the implementation of the Air Pollution Prevention and Control Action Plan, the Three Year Action Plan to Win the Blue Sky Defense War and Deepening the Battle of Pollution Prevention and Control Plan have significantly accelerated air pollution control, reduced SO_2 emissions, and achieved significant improvement in air quality (China State Council,2013; China State Council,2018; China State Council,2021). However, due to variations in functional positioning and industrial structure, the relative intensity of air pollution reduction measures and the changes in SO2 concentration differ significantly among various regions and cities (Wei *et al.* 2023).

The Beijing Tianjin Hebei Urban Agglomeration is China's "capital economic circle"(National Bureau of Statistics,2022). The significant decrease in SO_2 concentration in the Beijing, Tianjin, and Hebei regions has been the most notable achievement in air pollution control in China in recent years; Furthermore, it has also been the primary driving force behind the substantial reduction in regional particulate matter concentration (Guo *et al.* 2014; Zhang *et al.* 2021). Taking Beijing, the capital city of China, as an example, with the continuous implementation of local coal-fired boiler elimination, coal-fired and gas-fired boiler renovation, "coal to gas" and "coal to electricity" projects in Beijing, the SO_2 concentration in Beijing has decreased to single digit levels in recent years (Miao *et al.* 2020; National Bureau of Statistics,2022).

Research on changes in SO_2 concentration in the Beijing, Tianjin and Hebei regions is of great significance for scientifically and effectively exploring the next stage of air pollution control measures in China. Additionally, SO_2 can be utilized as a tracer to analyze the impact of regional pollution transport on air quality in Beijing. Especially during the heating season, the coal consumption in Beijing and surrounding areas increases exponentially compared to the non-heating periods, and sudden increase in SO_2 concentration and regional air pollution transport belt under easterly and southerly winds poses a significant challenge to the air quality standards in Beijing (Hao *et al.* 2007; Huang *et al.* 2009; Yang *et al.* 2017). In order to further improve the air quality in the Beijing, Tianjin and Hebei regions, explore the ideas for air pollution control during the 14th Five Year Plan period, and coordinate the air pollution control work such as "treating winter diseases in summer" and "combining peace and war", this study comprehensively analyzed the spatio-temporal variations and main influencing factors of SO_2 concentration in Beijing and surrounding cities from 2013 to 2022 by multiple methods such as statistical analysis, meteorological filtering, and numerical simulation.

2. Materials and methods

2.1. Instruments and observations

The Beijing, Tianjin and Hebei regions includes 13 cities such as Beijing, Tianjin, and Shijiazhuang city, with a total regional area of 183400 km^2 and a population of 110 million, accounting for approximately 10% of the country's GDP (National Bureau of Statistics,2022). The SO_2 monitoring data of various cities in the region is downloaded from the Air Quality Release Platform of the China Environmental Monitoring Station (https://air.cnemc.cn:18007/) and the historical dataset of air quality in China (https://quotsoft.net/air/). There are 11 monitoring stations in Beijing, 15 monitoring stations in Tianjin, and 53 monitoring stations in Hebei Province. The arithmetic mean of all national control assessment points in each city represents the pollution level of the city. Based on the pulsed fluorescence technology, the 43i SO_2 analyzer (Thermo Scientific™ 43i) were applied to monitor the SO_2 concentration. The meteorological data applied in the study was downloaded from the China Meteorological Data Sharing Network (http://cdc.cma.gov.cn/) and the statistical data on coal consumption in various regions was sourced from the National Statistical Yearbook (http://www.stats.gov.cn/tjsj/ndsj/).

2.2. Daniel Trend Test

In order to analyze the trends of air pollutant concentration, the Daniel trend test was applied in this study. It is also called Spearman's rank correlation coefficient test. Spearman's rank correlation coefficient, named after Charles Spearman, is usually represented by Charles Spearman and applied to test and evaluate the correlation between two groups of variables (Daniel *et al.*1990). Spearman coefficient is applicable to continuous and discrete ordinal variables, which is defined as Pearson correlation coefficient between sorting variables. The Daniel trend test is a commonly method for quantitative analysis of specific time series data, which is mainly applied for single factor small sample test (Spearman, 1904).

The spearman's rank correlation coefficient is a non parametric (independent of distribution) rank statistical parameter. The main principle states that if there are two variables X and Y, and Rx and Ry are their respective ranks, then the correlation coefficient between the two variables is calculated by equation 2.1.

$$\mathrm{r}_R = \frac{\sum R_X R_Y - \frac{\sum R_X \sum R_Y}{N}}{\sqrt{\sum R_X{}^2 - \frac{(\sum R_X)^2}{N}} \times \sqrt{\sum R_Y{}^2 - \frac{(\sum R_Y)^2}{N}}} \tag{2.1}$$

When Rx and Ry do not have the same level, the formula is simplified as follows:

$$r_s = 1 - \left(6\sum_{i=1}^{n}(x_i - y_i)^2\right) / \left(n^3 - n\right) \tag{2.2}$$

In the formula 2.1 and 2.2, r_s presents Spearman rank correlation coefficient; X_i presents sequence number of concentrations arranged from small to large; Y_i presents sequence number of concentration value arranged in chronological order; N presents the study period. According to the calculated rank correlation coefficient r_s, take its absolute value, and compare it with the critical value of r_s to determine the trends, that is, if $|r_s| \geq WP$ and Rs is positive, the data shows a significant upward trend; when $|r_s| \geq WP$ and r_s is negative, the data shows a significant downward trend.

2.3. Kolmogorov-Zurbenko filter method

To filter out the influence of meteorological factors, it is necessary to further adjust and reconstruct the observation sequence of atmospheric pollutants' concentration. The KZ filter is a statistical method based on iterative moving average algorithm to remove high-frequency changes in original data proposed by RAO *et al.* (1994). The KZ filtering method can further decompose the original series data of air pollutants into long-term components, seasonal components, and short-term components, which are independent of each other (Zurbenko *et al.* 1996). The study first established a multiple linear relationship between the short-term and baseline components of SO_2 concentration and meteorological factors, and then obtained the total residual. Subsequently, the authors applied the KZ filtering to the total residual to obtain the long-term component and added it to the long-term component of the original SO_2 time-series data to obtain a reconstructed sequence data after filtering out meteorological factors. The specific method and operation were shown in **Figure 1.**

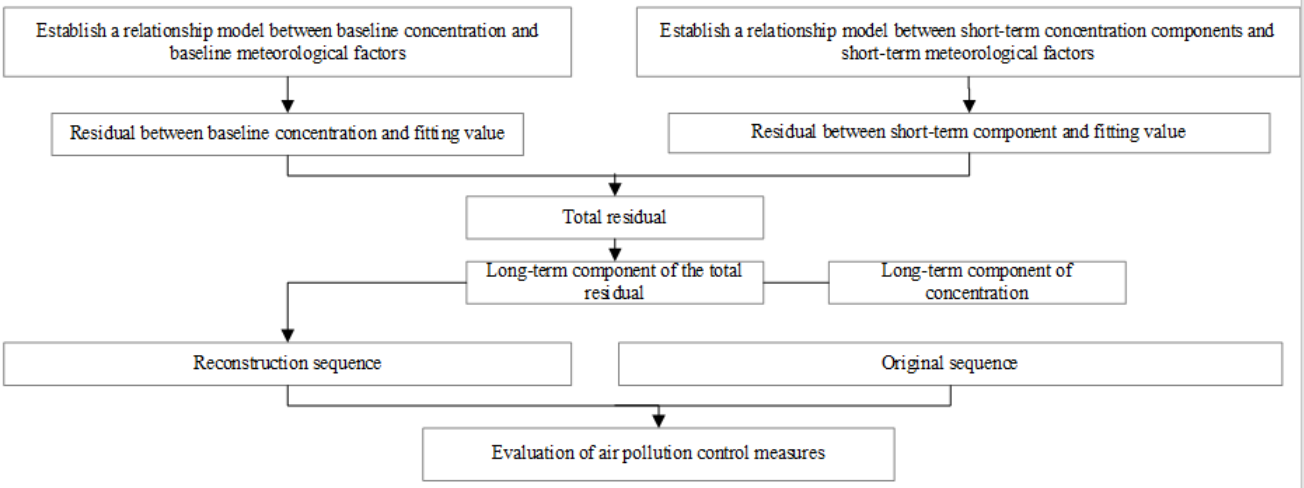


Figure 1. The KZ filtering technology method in this study

Table 1. Comparisons between measured and simulated SO_2 and $PM_{2.5}$ concentrations in 2017

Contaminant	City	Observed	Simulated	R	Standardized mean deviation	Root mean square error
$PM_{2.5}$	Beijing	58.0	57.2	0.73	0.1	24.9
	Tianjin	62.0	60.8	0.62	0.9	60.6
	Shijiazhuang	65.0	64.9	0.67	1.0	70.2
SO_2	Beijing	4.0	5.8	0.71	1.3	25.8
	Tianjin	8.0	9.7	0.64	7.2	67.8
	Shijiazhuang	19.0	21.3	0.65	8.7	87.4

2.4. WRF/CMAQ Model settings

The research selected the WRF/CMAQ Air Quality Simulation System to study the spatio-temporal variations and source apportionment of SO_2 in the Jingjinji regions. This model is a commonly and widely applied for the air quality numerical simulations (CEMPD, 2014; MMMD, 2014). The spatial resolution of the CMAQ simulation area in the study was 9km×9km, covering the Jingjinji regions and its surrounding areas. Due to the fact that the publicly available China regional scale list on the MEIC website (http://www.meicmodel.org/) is from 2017, the study used the year 2017 as the baseline scenario. The study employed CMAQ-ISAM (Integrated Source Apportionment Method) to calculate the local and regional contributions of atmospheric pollutant emissions in various regions within the simulated grids.

Taking the WRF-CMAQ benchmark scenario simulation verification results in 2017 as an example (**Table 1**), the ratio of the simulated $PM_{2.5}$ and SO_2 values to the measured values was between 0.5 and 2.0, indicating a consistent fluctuation pattern on all time scales. The range of correlation coefficients between simulated and measured values of $PM_{2.5}$ and SO_2 was 0.62~0.79, 0.64~0.71, respectively. The range of standardized average deviation was 0.1~1.0, 1.3~8.7, and the range of root mean square error was 24.9~70.2, 25.8~87.4, separately. Overall, the simulated SO_2 concentration in various cities was relatively higher, while the $PM_{2.5}$ concentration was slightly lower. Much of the variation and discrepancy was primarily attributed to the uncertainty of regional emission inventories; overall, the simulated $PM_{2.5}$ and SO_2 values in Beijing, Tianjin, and Shijiazhuang cities aligned well with the measured values.

3. Results and Discussions

3.1. Spatio-temporal distribution of SO_2 concentration

As shown in **Figure 2**, from 2013 to 2022, the annual averaged concentration of SO_2 in all cities in the Jingjinji regions presented significant downward trends, from 26.6~114.3μg·m^{-3} in 2013 decreases to 3.0~11.0μg·m^{-3} in 2022. The cumulative decrease in SO_2 concentration in Tangshan was the largest, reaching 92.3% while it changed to be the smallest in Chengde, reaching 78.2% during 2013~2022. Except for Handan and Hengshui cities, the SO_2 concentrations in other 11 cities were all at the single digit levels, with the lowest annual averaged SO_2 concentration at 3.0μg·m^{-3} in Beijing in 2022. The decrease trends of SO_2 annual averaged concentration in 13 cities from 2013 to 2022 all passed the Daniel trend tests (α=0.01) with the highest declining rate of 11.81μg/(m^3·yr) in Tangshan city and the smallest descent rate of 2.62μg/(m^3·yr) in Beijing city.

Table 2. Daniel trend tests of SO_2 concentration in 13 cities from 2013 to 2022

Cities	Annual comparison				Summer comparison			
	rs	Wp(α=0.01)	k	Trend	rs	Wp(α=0.01)	k	Trend
Baoding	-1.000	0.834	-6.79	Significant decrease	-0.976	0.834	-1.75	Significant decrease
Beijing	-1.000	0.834	-2.62	Significant decrease	-1.131	0.834	-0.68	Significant decrease
Cangzhou	-1.000	0.834	-4.97	Significant decrease	-0.976	0.834	-1.70	Significant decrease
Chengde	-0.976	0.834	-3.39	Significant decrease	-1.083	0.834	-1.84	Significant decrease
Handan	-1.000	0.834	-9.50	Significant decrease	-0.952	0.834	-5.45	Significant decrease
Hengshui	-1.000	0.834	-6.38	Significant decrease	-0.976	0.834	-2.07	Significant decrease
Langfang	-1.000	0.834	-4.33	Significant decrease	-1.155	0.834	-1.04	Significant decrease
Qinhuangdao	-1.000	0.834	-5.92	Significant decrease	-1.000	0.834	-2.84	Significant decrease
Shijiazhuang	-1.000	0.834	-10.96	Significant decrease	-0.929	0.834	-3.51	Significant decrease
Tangshan	-1.000	0.834	-11.81	Significant decrease	-0.976	0.834	-7.80	Significant decrease
Tianjin	-1.000	0.834	-5.55	Significant decrease	-0.952	0.834	-1.16	Significant decrease
Xingtai	-1.000	0.834	-11.69	Significant decrease	-0.976	0.834	-4.94	Significant decrease
Zhangjiakou	-0.976	0.834	-5.50	Significant decrease	-0.988	0.834	-2.54	Significant decrease

Compared to the annual averaged concentrations, the overall SO_2 concentrations during the summer periods were at a lower level throughout the year. As shown in **Table 2**, from 2013 to 2022, the averaged concentration of SO_2 during summer seasons in 13 cities also presented significant downward trends, from 9.0~75.7μg·m^{-3} in 2013 decreases to 3.0~9.7μg·m^{-3} in 2022. The cumulative decrease in SO_2 concentration in Tangshan was the largest, reaching 91.3% while it changed to be the smallest in Tianjin, reaching 55.9% during 2013~2022. Similarly, the decrease trends of SO_2 concentration during summer seasons in 13 cities from 2013 to 2022 all passed the Daniel trend tests (α=0.01) with the highest declining rate of 7.80μg/(m^3·yr) in Tangshan and the smallest speed of 0.68μg/(m^3·yr) in Beijing. Compared to the whole year, the decrease rate of SO_2 concentrations in summer was relatively lower, which was mainly related to the low coal consumption in summer.

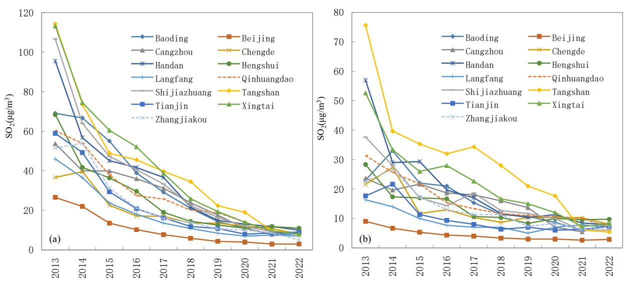


Figure 2. Variation of SO_2 concentration in Beijing, Tianjin and Hebei regions from 2013 to 2022 (a. annual averaged concentration; b. averaged concentration during Summer)

For the spatial distribution of SO_2 concentrations based on the Euclid Distance with weights, the 13 cities in the Jingjinji regions can be grouped into three categories. The concentrations of SO_2 in Beijing, Zhangjiakou, Chengde, Langfang, and Tianjin were relatively low and clustered into the first category. The northern cities of the Jingjinji regions is in a relatively complete natural landscape, a good ecological environment, and low intensity of industrial activities. The impact of human and natural factors on SO_2 concentration in these areas was relatively minimal, with relatively low inter-annual fluctuations. The four cities of Handan, Tangshan, Xingtai, and Shijiazhuang were in relatively heavy SO_2 pollution, and their SO_2 concentrations were clustered into the second category; furthermore, Tangshan and Xingtai were the two high-value centers in the Beijing, Tianjin and Hebei regions, with the highest SO_2 concentration levels. These two cities are mainly concentrated in the southern and eastern parts of the Beijing, Tianjin and Hebei regions, which have a significant proportion of heavy industry and a large amount of coal consumption. The left four cities of Baoding, Cangzhou, Hengshui, and Qinhuangdao were clustered into the third category. In addition, the temporal distribution of SO_2 concentrations could also be divided into three categories: 2013~2014, 2015~2017, and 2018~2022. The gradient of annual averaged SO_2 concentration in 13 cities in 2013 was 87.7μg·m^{-3} and it decreased to 8.0μg·m^{-3} in 2022 while it was 66.7μg·m^{-3} and 6.8μg·m^{-3} during summer seasons in 2013 and 2022 respectively, which revealed the decreasing gradient difference in north to south spatial direction year by year.

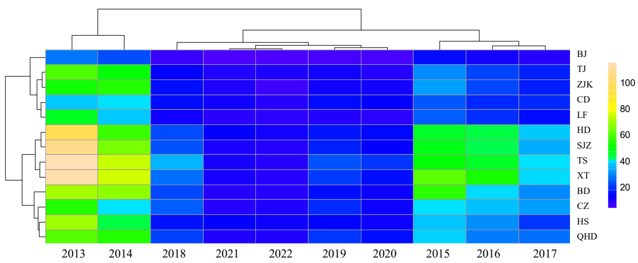


Figure 3. Spatial clustering of SO_2 annual average concentration in the Beijing-Tianjin-Hebei regions (BJ: Beijing, TJ: Tianjin, ZJK: Zhangjiakou, CD: Chengde, LF: Langfang, Hd: Hangdan, SJZ: Shijiazhuang, TS: Tangshan, XT: Xingtai, BD: Baoding, CZ: Cangzhou, HS: Hengshui, QHD: Qinhuangdao)

3.2. Impact of meteorological and emission reduction measures

After filtering out meteorological factors through KZ filtering method (as shown in **Table 3**), the decrease rate of annual averaged SO_2 concentration in 13 cities in Jingjinji regions changed from 78.2~92.3% in the original observation sequence to 72.2~92.0% in the reconstructed sequence from 2013 to 2022. Meteorological factors decreased 0.3~8.5% to the accumulated drop of SO_2 concentration in 13 cities while the human efforts to reduce emissions contributed about 94.5~99.6% to the annual decrease in SO_2 concentration during 2013~2022. During summer seasons, the decrease rate of annual averaged SO_2 concentration in 13 cities changed from 55.9~91.3% in the original observation sequence to 72.2~92.2% in the reconstructed sequence. Accordingly, the meteorological factors increased 0.9~28.2% to accumulated drop of SO_2 concentration in 13 cities while the human efforts to reduce emissions contributed about 100% to the decrease in SO_2 concentration. Compared with the whole year, there was no coal-fired heating consumption in the Beijing, Tianjin and Hebei regions during summer seasons, and the diffusion of SO_2 concentration was more susceptible to meteorological conditions such as the East Asian monsoon. Under the dominant southerly wind direction affected by the East Asian monsoon, cities in the northern part of the region were significantly affected by the regional transport which was the unfavorable meteorological conditions for the SO_2 concentration (Bai *et al.* 2022; Huang *et al.* 2020; Shen *et al.* 2021).

Table 3. Cumulative decrease of SO_2 original and filtered concentrations at different cities in this study

Period	Parameter/%	BJ	TJ	SJZ	TS	HD	XT	BD	CZ	LF	HS	CD	QHD	ZJK
Annual	Decrease of original sequence	89.5	84.8	92.1	92.3	89.7	87.3	87.7	83.4	84.4	83.9	78.2	81.0	90.3
	Decrease of reconstructed series	89.0	84.0	91.4	92.0	88.2	85.6	87.4	82.8	83.9	81.9	72.2	79.4	81.8
	Decrease of meteorological factors (favorable)	0.5	0.8	0.7	0.3	1.5	1.7	0.3	0.6	0.5	2	6	1.6	8.5
	Contribution of anthropogenic emission reduction measures	96.2	95.7	94.5	97.0	94.8	94.7	95.9	96.1	95.3	94.6	99.6	96.3	97.2
Summer	Decrease of original sequence	66.9	55.9	83.6	91.3	86.1	79.3	71.9	67.7	57.5	65.5	63.1	75.8	74.4
	Decrease of reconstructed series	89.2	84.1	91.5	92.2	88.4	85.8	87.3	82.6	83.9	82.1	72.2	79.9	82.3
	Increase of meteorological factors (unfavorable)	22.3	28.2	7.9	0.9	2.3	6.5	15.4	14.9	26.4	16.6	9.1	4.1	7.9
	Contribution of anthropogenic emission reduction measures	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

(BJ: Beijing, TJ: Tianjin, ZJK: Zhangjiakou, CD: Chengde, LF: Langfang, Hd: Hangdan, SJZ: Shijiazhuang, TS: Tangshan, XT: Xingtai, BD: Baoding, CZ: Cangzhou, HS: Hengshui, QHD: Qinhuangdao)

From 1998 to 2012, Beijing completed sixteen stages of air pollution prevention and control measures (BMBS,2022). Starting from 2013, the Beijing Clean Air Action Plan for 2013~2017 was implemented, systematically carrying out air pollution prevention and control work, with a focus on reducing coal consumption, controlling vehicles and oil consumption, pollution control and emission reduction, and clean dust reduction. Starting from 2016, Beijing implemented the "Comprehensive Action Plan for Autumn and Winter Air Pollution Control in the Beijing Tianjin Hebei and Surrounding Areas". In 2018, the "Three Year Action Plan for Winning the Blue Sky Defense War in Beijing (2018~2020)" was implemented. From 2021 to 2023, Beijing continued to implement the three-year action plan to deepen the battle against air pollution. The total coal consumption in Beijing decreased from 2019 million tons in 2013 to approximately 1 million tons in 2022, with a cumulative reduction of 95.0%. In 2015, the core area was basically free of coal, and the sixth urban area had no coal-fired boilers. In 2017, the plain region achieved coal free transformation, becoming the first region in the country to basically solve the problem of coal pollution. According to National Statistical Yearbook Data, the total coal consumption in Tianjin decreased from 52.78 million tons in 2013 to approximately 37.23 million tons in 2020, with a cumulative decrease of 29.5%. Since 2018, all scattered coal in urban and rural areas in Tianjin was cleared to be zero. The total coal consumption in Hebei Province decreased from 317 million tons in 2013 to approximately 260 million tons in 2020, with a cumulative reduction of 18%. By implementing measures such as coal to gas and coal to electricity projects, the government in Hebei significantly promoted the transformation of new energy, and by the end of 2020, the scattered coal in rural areas of this province's plains was similarly cleared to zero. As a result, the atmospheric SO_2 emissions in Beijing, Tianjin, and Hebei regions decreased significantly from 8.70, 21.68, and 128.5 million tons in 2013 to 0.11, 0.65, and 14.6 million tons in 2022 (**Figure 4**). From the correlation between coal consumption and annual averaged SO_2 concentration in the three regions (**Table 4**), the Pearson correlation coefficients in Beijing, Tianjin, and Hebei provinces in recent years were 0.974**, 0.926**, and 0.980**, respectively. The Pearson correlation coefficients between SO_2 emissions and annual averaged SO_2 concentrations were 0.924**, 0.891**, and 0.939**, respectively. These statistical data indicated that the significant reduction in coal consumption in the Beijing, Tianjin and Hebei regions had led to a significant reduction in atmospheric SO_2 emissions, and then directly reduced the average concentration of SO_2 in the region.

Table 4. Correlation statistics between main air pollutants and meteorological, social factors from 2013 to 2022

Correlation coefficient	Wind speed	T	Surface pressure	Relative humidity	Precipitation	SO_2 emissions #	Coal consumption
Beijing	0.460	-0.599	-0.866*	0.808*	0.121	0.924**	0.974**
Tianjin	0.124	-0.380	-0.267	0.661*	-0.117	0.891**	0.926**
Shijiazhuang	0.827*	-0.727	-0.675	0.514	0.206	0.939**	0.980**

*Note: * * and * indicated significant correlation at the 0.01 and 0.05 levels (bilateral) respectively.*
#SO2 emissions and coal consumption data were downloaded from the website (https://data.stats.gov.cn/easyquery.htm?cn).
The coal consumption data was the statistical data up to 2020.

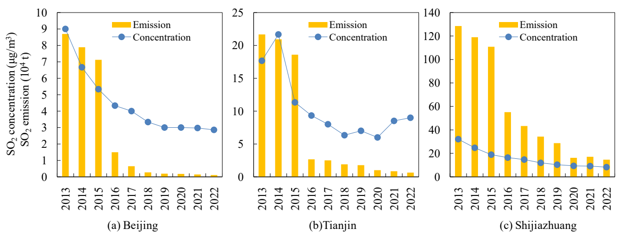


Figure 4. The annual averaged concentration and emissions of SO_2 in three cities from 2013 to 2022

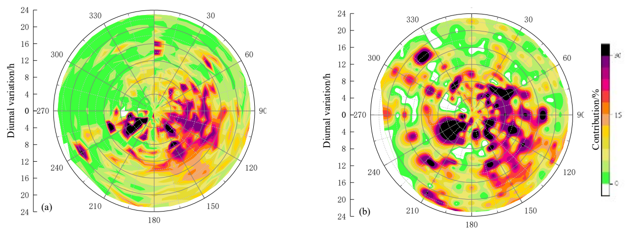


Figure 5. Regional transport contribution of SO_2 to Beijing under different wind directions in 2017 (a. the whole year; b. the summer period)

3.3. Regional transport of SO_2 concentration

In addition to anthropogenic emissions reduction and meteorological impacts, regional transport is also an important factor affecting the distribution of SO_2 concentration in the Beijing, Tianjin and Hebei regions. The simulation results of the WRF-CMAQ benchmark scenario showed that in 2017, the local contributions of SO_2 in Beijing, Tianjin, and Shijiazhuang were 69.0±8.8%,70.9±8.9% and 81.5±4.1%, respectively. In summer, the local contributions of SO_2 in Beijing, Tianjin, and Shijiazhuang were 55.9±8.5%, 62.6±6.1%, and 72.2±3.8%, respectively. Among the three cities, the local contribution of SO_2 was largest in Shijiazhuang city while it was smallest in Beijing city. Compared with the whole year, the contribution of SO_2 regional transport in summer in three cities significantly increased by 10~20%. The concentration of SO_2 in Beijing was mainly affected by the transport of neighboring areas such as Baoding, Tangshan, Langfang, and Tianjin cities. The concentration of SO_2 in Tianjin was mainly affected by the transport of neighboring areas such as Tangshan, Langfang, and Shandong Tianjin cities. The concentration of SO_2 in Shijiazhuang was mainly affected by the transport of neighboring areas such as Henan, Shanxi, Xingtai, and Handan cities in Beijing,Tianjin and Hebei regions.

In 2017, the average frequency of wind directions at ground level in Beijing, from highest to lowest, was southerly, northerly, easterly, and westerly, with values of 32.5%, 30.4%, 29%, and 7.3%, respectively (**Figure 5**). This study further classified Baoding, southern Hebei, and Henan province as southwest regional transport channels, and Langfang, Tianjin, Tangshan, Cangzhou, and Shandong districts as southeast regional transport channels. The numerical simulation results demonstrated that the contribution of the southwest transport channel to the concentration of SO_2 in Beijing during summer was about 33.5%, and the contribution of the southeast transport channel to the concentration of SO_2 in Beijing was about 38.9% in 2017. The higher regional transport contribution was mainly concentrated in the wind direction of 60~150 degrees. Due to the high position of the elevated source exhaust pipe in the Beijing, Tianjin and Hebei regions, the atmospheric pollutants were transported further and led to a larger impact under the influence of higher wind speeds in summer. The results of this study were comparable and reliable compared with other relevant literature on SO_2 regional transport (Lin *et al.* 2019;Tan *et al.* 2020).

4. Conclusions

China is the third largest emitter of SO_2 in the world, contributing approximately 8% of global anthropogenic SO_2 emissions, second only to India and Russia (Greenpeace Environment Trust,2019). The Beijing, Tianjin and Hebei region is a world-class urban agglomeration centered around the capital city of Beijing. It is a new engine for innovation driven economic growth and a demonstration area for ecological restoration and environmental improvement in China. In 2022, the proportion of Beijing, Tianjin and Hebei regions to the national GDP was 8.3%, and the SO_2 emissions in the Beijing, Tianjin and Hebei regions accounted for 6.3% of the country (National Bureau of Statistics, 2022).

This study analyzed the spatial-temporal distribution of SO_2 concentration and main influencing factors in the Beijing, Tianjin and Hebei regions through multi-methods of statistics, KZ filtering and model simulations. From 2013 to 2022, the annual averaged concentrations of SO_2 in Beijing, Tianjin and Hebei regions were all in obvious downward trends, and all passed the Daniel trend test (α=0.01). The annual averaged concentration of SO_2 in Beijing, Tianjin and Hebei regions decreased from 26.6~114.3$\mu g \cdot m^{-3}$ in 2013 to 3.0~11.0$\mu g \cdot m^{-3}$, with the decline rates fluctuating from2.62~11.81$\mu g/(m^3 \cdot yr)$. The reduction of coal consumption in the Beijing-Tianjin-Hebei regions significantly reduced atmospheric SO_2 emissions and directly reduced the regional average concentration of SO_2. Meteorological factors were generally conducive to the diffusion of SO_2 concentration during 2013~2022, and the meteorological factors contributed about 0.4~5.5% in 13 cities while the contribution of anthropogenic emission reduction changed to 94.5~99.6%. Regional transport is an important factor affecting the distribution of SO_2 concentration in the region. During the summer months from June to August, under easterly and southerly winds, the SO_2 concentration in Beijing was approximately twice as high as that under northerly and westerly winds. The contribution of the southwest transport channel to the SO_2 concentration in Beijing was 33.5%, which increased to 38.9% in the southeast transport channel.

To further enhance regional air quality, it is recommended to continue reducing coal consumption in the Beijing, Tianjin, and Hebei regions, particularly in rural areas, while ensuring energy security. Additionally, it is essential to solidify the progress made in transitioning to cleaner energy sources in flat areas and prevent a resurgence of uncontrolled coal combustion. The government should take emergency measures to reduce heavy air pollution episodes during autumn and winter seasons. During the autumn and winter months, a significant amount of SO_2 emitted from coal combustion in key areas is converted into sulfate under suitable conditions, which can contribute to an increase in particle concentration. Early prediction and forecasting, coupled with the activation of emergency emission reduction measures in advance, can help mitigate the accumulation rate of sulfate. Moreover, enhancing the management and control of air pollutants in the surrounding areas of Beijing can aid in further reducing pollutant levels and achieving air quality improvement targets in the region.

This research has observed that SO_2 concentrations at many sites are below the national environmental air quality standard limits, with some even reaching single-digit levels in the Beijing, Tianjin, and Hebei regions. It is recommended to further optimize the placement of monitoring stations, with a focus on locating SO_2 monitoring stations in urban-rural fringe areas or rural areas, while gradually reducing SO_2 monitoring instruments in urban areas. Against the backdrop of national policies promoting carbon peak and carbon neutrality, reducing coal consumption can not only lower carbon emission intensity but also decrease SO_2 emissions, therefore,strategic planning should prioritize coordinated and regional control of SO_2 and CO_2 concentrations during the 14th Five-Year Plan period.

Acknowledgements

This work was supported by the “Fundamental Research Funds for the Central Universities” (No. 3142023017, 3142021002, 3142023021), the “Hebei Province Higher Education Science and Technology Research Project” (ZC2024016), and the supported by “the Central Government Guides Local Funds for Science and Technology Development” (No. 236Z0307G).

Author Contributions

Bingfen Cheng and Guiqiang Zheng designed the study, performed data analysis and wrote the manuscript. Other coauthors contributed to the research design, proofreading and revision.

Additional Information

Competing Interests

The authors declare no competing interests.

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