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Spatiotemporal impact of major events on air quality based on spatial differences-in-differences model: big data analysis from China

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Abstract

In an attempt to investigate the impact of major events on urban air quality in terms of the extent, duration and spatial scope, data on the daily air quality index and the concentrations of individual pollutants are collected in 140 cities of China from January 2, 2015, to November 28, 2017. Based on a spatial differences-in-differences, the impact of major events, such as political conferences, sporting events at the national level, on urban air quality in the dimensions of time and space are explored. It is concluded that major events not only affected the air quality of the host city, but also exercised influence on the air quality of the surrounding areas. Recommendations for mitigating the impact of major events on urban air quality have been proposed, such as establish regional atmospheric environment management system and formulate regional unified standards for pollutant discharge, industrial access and law enforcement.

Keywords Urban air quality · Propensity score matching · Spatial differences-in-differences · Major events

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1 Introduction

According to the latest evaluation of WHO (2018), 90% of the world's population currently lives in areas where $PM_{2.5}$ levels exceed WHO limits (an average of 10ug/m^3 per year). In developed countries and regions such as North America, Europe, the haze-related problems are well controlled, but haze still poses a serious threat in undeveloped regions such as in East Asia, South Asia and Africa (Rafaj et al. 2018).

In China, with the global warming and increasing calm weather days in recent decades, the frequent occurrence of haze has attracted wide attention of the government and all sectors of the society. The effective prevention and control of air pollution and the guarantee of air quality are closely related to the image of the state and government, as well as the health of the people (Matus et al. 2012). When faced with major political conferences or events, governments at all levels take various measures to control air pollution. For example, during the 2008 Beijing Olympic Games, the Ministry of Environmental Protection laid down *Measures for Air Quality Guarantee in Beijing for the 29th Olympic Games*, and the General Office of Hebei Provincial Government formulated *the Emergency Measures for Air Pollution Control under Extremely Adverse Meteorological Conditions* during the Olympic Games in the Hebei Province. These efforts were meant to ensure that the atmospheric environment quality during the Olympic Games met acceptable standards to ensure the normal progress of the competition. In addition, Beijing and its surrounding provinces implemented a series of temporary control measures for air pollution, including strengthening motor vehicle management, suspending part of a construction site operation, enhanced road cleaning, shutting down and limiting production of key pollution enterprises (Song et al. 2019, 2020). Other measure taken included the reduction in the discharge of organic exhaust and implementing emergency measures for pollution control under extreme adverse weather conditions. These measures achieved remarkable results. For example, from July 20 to September 20 in 2008, the total emission of air pollutants in Beijing dropped by 34.98%, the best level in 14 years after 1995 (Chen et al. 2013). The momentary "political blue sky" also appeared during the APEC meetings, the 70th anniversary parade of anti-fascist victory, the Nanjing Youth Olympic Games and the Hangzhou G20 Summit. While it seems a common practice to conduct temporary air quality control during major events (Shi et al. 2016; Wu et al. 2018, 2019a, b, c), little is known about the real impact of these major events on the quality of air in these cities and the surrounding towns. This study therefore seeks to address the following questions how much impact do major events have on urban air quality? How long does the impact last? What are the spatial characteristics of the impact?

Very limited studies on the impact of major events on air quality have been carried using quantitative methods. In this regard, this paper adopts a quantitative approach by using data on the daily air quality index (AQI) and the concentration of individual pollutants constituting air quality indices of 140 cities from 2015 to 2017, to analyze the impact of major events on air quality in China. The data included details on major competitions, important conferences and urban air quality from two dimensions of time and space. The data were analyzed using a spatial differences-in-differences (DID).

The rest of this paper is arranged as follows: The second part deals with the literature review, followed by the data and empirical strategy, indicators and sources of data. The fourth section covers the empirical analysis, followed by the conclusion.

2 Literature review

Some cities, both at home and abroad, endeavor to take temporary control measures to ensure air quality during major events, such as the Busan Asian Games in 2002, Delhi Federal Games in 2010, Beijing Olympic Games in 2008, and Beijing APEC Conference in 2014. Several authors have conducted thorough analyses and reported improvements in urban air quality during major events (Wang et al. 2012; Lee et al. 2005; Wang and Xie 2009; Beig et al. 2013; Liu et al. 2016; Huang et al. 2015; Zhao et al. 2016; He et al. 2016; Jia and Chen 2019; Li et al. 2019a, b). For example, Lee et al. (2005) investigated the significant concentration decrease in PM_{10}, CO, NO_2 and SO_2 in 13 air stations during the 24th Asian Games in Busan, Korea in 2002. Beig et al. (2013) found that Delhi adopted a series of measures, such as vehicle and traffic control, factory relocation and power plant emission reduction when the 2010 Commonwealth Games was held in India.

In addition, Wang and Xie (2009) evaluated the effect of environmental quality improvement by reducing traffic emissions during the 2008 Beijing Olympic Games. Based on the analysis of "Parade Blue" and "APEC Blue", Liu et al. (2016) found that the concentration of NO_2 decreased by 43% in the military parade, compared with the normal level, while a decrease of 21% in concentration of NO_2 was reported during the APEC conference. Huang et al. (2015) analyzed the regional emission control effects and found the "APEC Blue" phenomenon in China. Zhao et al. (2016) made a comparison between the air pollutant concentration data in Beijing from August 1, 2015, to September 18, 2015, and the monitoring data of the same period in 2014. Based on the comparison of NO_2 concentration in Hangzhou during and before the G20 Summit, Zhao et al. (2017) made a conclusion that the concentration of NO_2 decreased significantly during the G20 Summit. Ngo et al. (2019) gave an interesting research about the effects of transboundary air pollution following major events in China on air quality in the USA.

Toward the end of 2019, COVID-19 as a major event, has had a huge impact on industrial production and human life. Many scholars have studied the impact of COVID-19 on air pollution emissions. For example, He et al. (2020) analyzed the short-term impact of China's lockdown measures on urban air governance during COVID-19. Fan et al. (2020) studied the impact of China's prevention and control measures on air pollution during COVID-19. Bera et al. (2020) studied the impact of the COVID-19 blockade on air pollution in Kolkata (India). Other studies include Dutheil et al. (2020), Bogdan (2020), Li et al. (2020), etc. However, these studies only focused on the impact of a single event not multiple events on air pollution. Based on the above considerations, this paper explores a number of events, and their impact on air pollution to supplement previous studies.

Despite the findings from available literature on urban air quality, this paper holds that the existing studies (e.g., list of some of the studies—Lee et al. 2005; Wang and Xie 2009; Beig et al. 2013; Liu et al. 2016; Huang et al. 2015; Zhao et al. 2016; Ngo et al. 2019; Wu et al. 2019a, b, c, 2020) did not exclude the influence of seasonal trend, year difference and regional effect on urban air quality. In addition, existing studies did not assess the effect of major events on urban air quality, and also failed to reveal continuous changes and associated spatial characteristics before and after the major events. In order to address these shortfalls, this study posits spatial differences-in-differences to provide a better estimation of the impact of major events on urban air quality. In this regard, the present study adopts the spatial DID models to investigate spatio-temporal impact of major events on urban air quality as new contribution to the current literature.

3 Data and empirical strategy

3.1 Variable and data

3.1.1 The air quality level

Air pollutants mainly include particulate matter, nitrogen oxides, carbon monoxide, sulfur dioxide, etc. (Li et al., 2019a, b). In the present study, the daily average air quality index (AQI) and the concentration data of fine particulate matter ($PM_{2.5}$), inhalable particulate matter (PM_{10}), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2) and ozone (O_3), are selected to measure the air pollution quality level.

3.1.2 Control variable

In an attempt to exclude the influence of other factors (apart from major events) on air quality indicators, weather factors are added as control variables X_{it} in this paper. Weather variables mainly include the highest temperature (highest_t), lowest temperature (lowest_t), rainfall, density of snow and wind grade, etc., to control the impact of weather changes on haze level.

3.1.3 Sample selection

The major events in this paper are defined as international or national sporting events and important political conferences in China. The major events considered were from January 2, 2015, to November 28, 2017 (as shown in Table 1).

The sample include 28 cities involved in these activities (9 host cities and 19 co-host cities). Based on the panel data of 140 cities over a span of 1094 days, 28 cities involved in major events (treatment group) were identified together with 112 control cities (control group) around them (as shown in Table 2 and Fig. 1).

3.1.4 Data collection

In this paper, the daily AQI and the daily mean value of individual pollutant concentration are used as the object of analysis. AQI data were downloaded from the Environmental Protection Data Center of the People's Republic of China (http://datacenter.mee.gov.cn/websjzx/queryIndex.vm), and the individual pollutant concentration data were obtained from the national real-time publishing platform of urban air quality of China Environmental Monitoring Station (http://106.37.208.233:20035/). In order to ensure the slight fluctuation of the city-fixed effects in the short term, the time span of the samples was not too long. Besides, due to the missing data, the final time span of samples is from January 2, 2015, to November 28, 2017.

In addition, meteorological data such as rainfall, temperature and wind grade are derived from the historical weather data of the cities provided by "2345 Weather Network." Specific indicators include the highest temperature (highest_t), lowest

Table 1 Major events during January 2, 2015, and November 28, 2017

Major event	Start date	End date	Host cities
The first youth movement of the people's Republic of China	October 18, 2015	October 27, 2015	Fuzhou
the Fifth Plenary Session of the 18th Communist Party of China (CPC) National Congress	October 26, 2015	October 29, 2015	Beijing
Fourth Meeting of China-Central and Eastern European Leaders	November 24, 2015	November 25, 2015	Suzhou
Fourteenth Meeting of the Council of Heads of Government of the Shanghai Cooperation Organization (SCO) Member States	December 14, 2015	December 15, 2015	Zhengzhou
Third Session of the Twelfth Chinese People's Political Consultative Conference (CPPCC) National Committee	March 3, 2015	March 13, 2015	Beijing
Third Session of the Twelfth National People's Congress	March 5, 2015	March 15, 2015	Beijing
Beijing International Association Of Athletics Federations (IAAF) World Track and Field Championship	August 22, 2015	August 30, 2015	Beijing
The 70th Anniversary Parade of the Victory of the War of Resistance Against Japan	September 3, 2015	September 3, 2015	Beijing
Boao Forum for Asia (BFA)	March 22, 2016	March 25, 2016	Haikou
Fourth Session of the Twelfth Chinese People's Political Consultative Conference (CPPCC) National Committee	March 3, 2016	March 14, 2016	Beijing
Fourth Session of the Twelfth National People's Congress	March 5, 2016	March 14, 2016	Beijing
Group of Twenty (G20) summit	September 4, 2016	September 5, 2016	Hangzhou
The Standing Committee of the Political Bureau of the Central Committee of the Communist Party of China (CPC)	January 10, 2017	January 10, 2017	Beijing
The Nineteenth National People's Congress of the Communist Party of China	October 18, 2017	October 24, 2017	Beijing
Five Sessions of the Twelfth Chinese People's Political Consultative Conference (CPPCC) National Committee	March 3, 2017	March 13, 2017	Beijing
Fifth Session of the Twelfth National People's Congress	March 5, 2017	March 15, 2017	Beijing
International Cooperation Summit Forum	May 14, 2017	May 15, 2017	Beijing
BRICS(Brazil, Russia, India, China, South Africa) Games	June 17, 2017	June 21, 2017	Guangzhou
Thirteenth National Games of the People's Republic of China	August 27, 2017	September 8, 2017	Tianjin
General Assembly of International Standards Organization	September 12, 2017	September 14, 2017	Beijing
BRICS(Brazil, Russia, India, China, South Africa) Summit	September 3, 2017	September 5, 2017	Xiamen
Thirteenth Hangzhou National Student Games	September 4, 2017	September 8, 2017	Hangzhou

temperature (lowest_t), rainfall, density of snow, wind grade, etc. In terms of the wind grade, this paper adopts the mean treatment, such as 3.5 wind grade instead of 3–4 grade.

3.2 Empirical strategy

During the major event of a city, other cities without such events become the control group. In this regard, a double difference is shown between the occurrence and non-occurrence periods in the same city, as well as the host and non-host cities in the same period, which lays the foundation of the idea of spatial differences-in-differences.

Specifically speaking, the model is established as follows:

$$\begin{aligned} y_{\mathrm{it}} =& \beta_0 + \rho \mathrm{Wy}_{\mathrm{it}} + \beta_1 \mathrm{event}_i \mathrm{dt}_{\mathrm{it1}} + \beta_2 \mathrm{event}_i \mathrm{dt}_{\mathrm{it2}} \\ &+ \beta_3 \mathrm{event}_i \mathrm{dt}_{\mathrm{it3}} + \beta_4 \mathrm{distance}_{\mathrm{ij}} \mathrm{dt}_t + \lambda X_{\mathrm{it}} + \mu_i + v_t + \varepsilon_{\mathrm{it}} \end{aligned} \tag{1}$$

where subscript i represents the ith city, subscript t represents the date (year, month, day) of the data, $\varepsilon_{\mathrm{it}}$ represents the stochastic disturbance, and Y_{it} represents the air quality level of the ith city at the time t. W represents the spatial weight matrix (please see explanation of W in Part of "3.2.1 Establishment of spatial weight matrix"). Event$_i$ denotes the cities involved in the major event. If $\mathrm{event}_i = 1$, the ith city is the one involved in the major event, otherwise $\mathrm{event}_i = 0$, owing to the different time of each major event. In order to investigate the duration of the impact of major events on urban air quality, the values of "1–5 days after events" and "6–10 days after events" were added to $\mathrm{dt}_{\mathrm{it}}$. Given the occurrence of major events in the ith city at the time t, $\mathrm{dt}_{\mathrm{it1}} = 1$, otherwise 0; at the time t after 1–5 days of the major event in the ith city, $\mathrm{dt}_{\mathrm{it2}} = 1$, otherwise 0; at the time t after 6–10 days of the major event in the ith city, $\mathrm{dt}_{\mathrm{it3}} = 1$, otherwise 0. Besides, β_1, β_2 and β_3 are used to analyze the duration of the impact of the major events on urban air quality.

Distance$_{\mathrm{ij}}$ is a grouping variable, representing the distance of the jth city from where the major event takes place (in ith city) at the time t. dt_t denotes whether a major event occurs within the time t. Accordingly, the coefficient β_4 is the estimation of the impact of spatial scope of each major event on urban air quality and the difference of its impact on different cities.

A set of control variables X_{it} is added to exclude the influence of other factors on air quality indicators. μ_i refers to the regional dummy variable, which reflects the city-fixed effects that will not change in a short time. v_t represents a set of time-fixed effects used to control the effects of seasonal factors and human working hours on air quality. Seasonal factors mainly include dummy variables of the year, month in the year and the week in the year, and the effects of human working hours on air pollution include the dummy variables of the day in a week.

3.2.1 Establishment of spatial weight matrix

Geographical location and distance are important factors that need to be considered. For the sake of comparison, adjacent weight matrix and inverse distance weight matrix are selected, and their definitions are as follows:

Set w_{ij} as the distance between region i and region j, and

Table 2 A list of cities involved in events and corresponding control cities

Cities involved in events (Treatment group)	Beijing, Changzhou, Foshan, Fuzhou, Guangzhou, Haikou, Hangzhou, Huzhou, Jinan, Jiaxing, Nanjing, Nantong, Ningbo, Quanzhou, Sanya, Xiamen, Shanghai, Suzhou, Taizhou, Tianjin, Wuzi, Wuhan, Xian, Zhenjiang, Zhengzhou, Zhongshan, Shenzhen, Shaoxing
Control cities (Control group)	Shijiazhuang, Zhangjiakou, Handan, Langfang, Baoding, Cangzhou, Xingtai, Chengde, Hengshui, Qinhuangdao, Tangshan, Xinxiang, Kaifeng, Jiaozuo, Hebi, Xuchang, Luoyang, Pingdingshan, Anyang, Puyang, Sanmenxia, Nanyang, Shangqiu, Xinyang, Zhoukou, Zhumadian, Luohe, Yancheng, Huaian, Suqian, Xuzhou, Lianyungang, Yangzhou, Nanping, Zhangzhou, Putian, Sanming, Longyan, Ningde, Wenzhou, Jinhua, Taizhou, Lishui, Zhoushan, Quzhou, Weinan, Tongchuan, Shangluo, Baoji, Ankang, Hanzhong, Yanan, Yulin, Taian, Liaocheng, Zibo, Dezhou, Binzhou, Qingdao, Weihai, Yantai, Dongying, Weifang, Zhizhao, Heze, Linyi, Zaozhuang, Jining, Xiaogan, Suizhou, Huangshi, Xianning, Jingzhou, Xiangyang, Yichang, Shiyan, Jingmen, Ezhou, Huanggang, Huizhou, Dongguan, Zhuhai, Jiangmen, Zhaoqing, Qingyuan, Shantou, Chaozhou, Jieyang, Shanwei, Zhanjiang, Maoming, Yangjiang, Shaoguan, Yunfu, Meizhou, Heyuann, Datong, Shuozhou, Taiyuan, Yangquan, Changzhi, Jincheng, Linfen, Suzhou, Bengbu, Chuzhou, Maanshan, Wuhu, Xuancheng, Huangshan, Qingyang, Changsha

$$w_{\mathrm{ij}} = \begin{cases} 1\ , & \text{Region } a \text{ is adjacent to region } b \\ 0\ , & \text{Region } a \text{ is not adjacent to region } b \end{cases} \tag{2}$$

Therefore, $W = \begin{bmatrix} w_{11} & \cdots & w_{1n} \\ \vdots & \vdots & \vdots \\ w_{n1} & \cdots & w_{nn} \end{bmatrix}$ is the adjacent weight matrix of n cities, and the main diagonal elements are all 0 (the distance between the same city is 0).

Define: $w_{ij} = \frac{1}{d_{ij}} d_{ij}$ is defined as geographical distance.

$W_d = \begin{bmatrix} w_{11} & \cdots & w_{1n} \\ \vdots & \vdots & \vdots \\ w_{n1} & \cdots & w_{nn} \end{bmatrix}$ is the inverse distance weight matrix, in which the main diagonal elements are also 0.

The rows of the spatial weight matrix need to be standardized. Each element in the matrix (denoted as $\tilde{w}_{ij}$) is divided by the sum of the elements in its row. Ensure that the sum of the elements in each row is 1, and the formula is:

$$w'_{\mathrm{ij}} \equiv \frac{\tilde{w}_{\mathrm{ij}}}{\sum_{j} \tilde{w}_{\mathrm{ij}}} \tag{3}$$

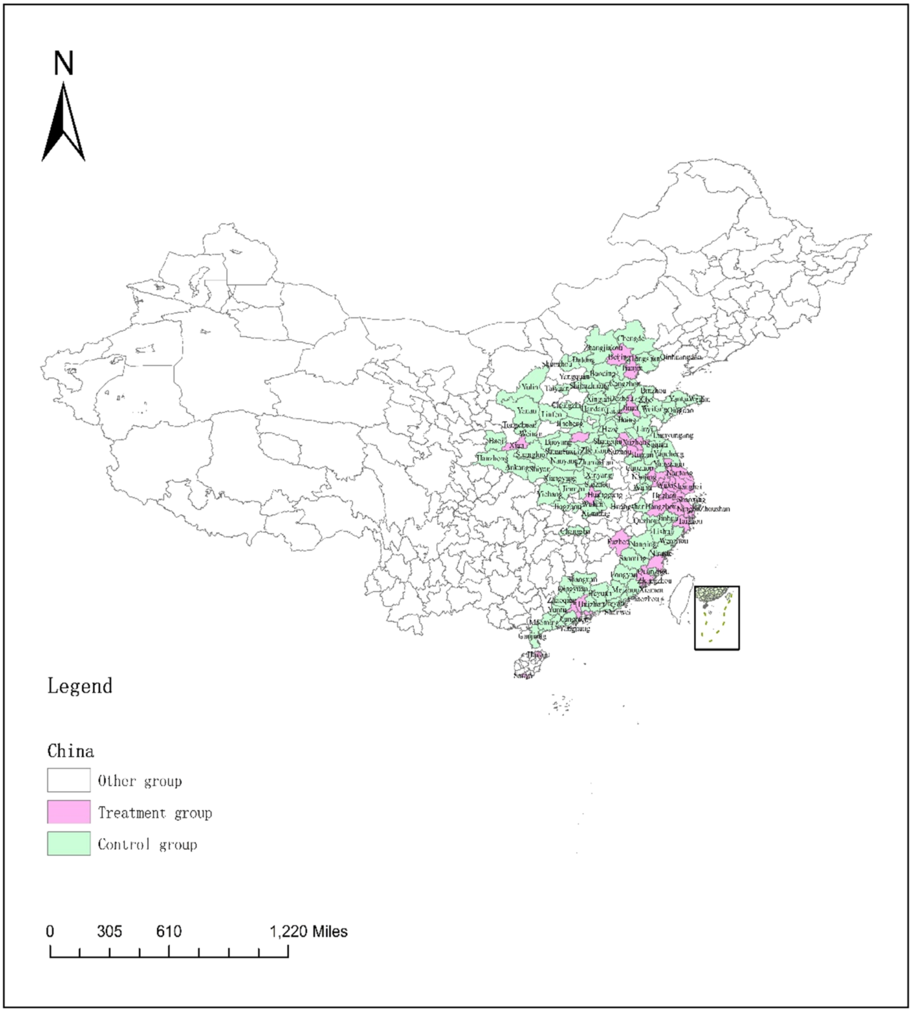

Fig. 1 Location of the cities in treatment group and control group

3.2.2 The selection of control group

The impact assessment in this paper is mainly based on cities where major events occurred during the period under review. In this sense, cities with major events are defined as treatment groups, and the ones around which no major event takes place are defined as control groups. A double difference is made between the two groups of cities.

3.2.3 Robustness test

In order to further prove the robustness of the estimated results, the methods adopted are as follows:

1. Transform window. Samples of 20, 30 and 40 days before and after major events are retained. The retained similar results account for the robustness of results.
2. Using different controls. Different cities are selected as the control group to investigate the consistency of the findings.
3. Placebo test. Under the condition of fictitious event time, the change of regressive results from significant to insignificant verifies the robustness of the previous conclusion.

4 Empirical analysis

4.1 Exploratory analysis

The daily air quality data of the 28 cities involved in the events are divided into two parts according to $dt_{it} = 1$ or 0, that is to say, whether the major events take place in the ith city at the time t. Descriptive statistics are made for the main variables, and longitudinal comparison is made with the sample data of the 28 cities. The average and maximum concentrations of AQI and individual pollutant during major events were found to be lower than those during non-major events (Table 3). Among them, the average AQI of the 28 activities involved in the urban major events is 64.346, which is 10.3 lower than that without major events, decreasing by about 16.01%. Besides, the maximum AQI during major events is 331, much lower than that without major events. From the perspective of individual pollutant, the average concentration of fine particulate matter ($PM_{2.5}$), inhalable particulate matter (PM_{10}), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2) and ozone (O_3) in the 28 cities was lower than those during non-major events. Therefore, based on preliminary judgment, the air quality during major events is better than that during non-major events.

The samples with major events are divided into two parts. One part includes the samples of cities involved in the major events, and the other involves the ones without major events for a horizontal comparison. The average AQI of the cities involved was 66.74, which is much lower than that of the cities without major events (Table 4). In terms of individual pollutant, the mean concentration values of fine particulate matter ($PM_{2.5}$), inhalable particulate matter (PM_{10}), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2) and ozone (O_3) in the cities with major events are lower than those without major events. On this basis, it can be preliminarily demonstrated that the occurrence of major events can improve the urban air quality.

Table 5 presents the mean values of air quality indicators and control variables in the 28 cities during major events, 1–5 days before and after major events, as well as 6–10 days before and after major events. It can be seen that except ozone, AQI and the average values of five other single pollutants show a sudden increase within 1–5 days after the end of major events and then decrease slowly within 6–10 days. This indicates that local governments may improve air pollution quality by adopting temporary measures in advance (e.g., 7 days). However, after major events, the air quality index rebounds significantly, even higher than before. In this regard, it can be speculated that the temporary control has no long-term benefits for air quality. Therefore, the statistically significant difference needs to be further analyzed by establishing a model.

The whole sample of 140 cities is classified by month to calculate the monthly mean of seven air quality indicators. Figure 2 shows the trend of the average air quality in the cities from January to December. For ease of observation, the carbon monoxide concentration is magnified 100 times. As Fig. 2 indicates, there are obvious seasonal characteristics in air quality. The AQI and most single pollutant concentration data in winter are higher than those in summer, while ozone concentration presents an opposite trend. In this sense, in order to eliminate the impact of other factors (excluding major events) on air quality, it is necessary to make some seasonal adjustments of air quality indicators, which accounts for the consideration of seasonal factors in the regression equation.

To illustrate the impact of major events on air quality, the event "the Fifth Plenary Session of the 18th Communist Party of China (CPC) National Congress" which took place in Beijing in October 26–29, 2015, was chosen as a case. In order to reflect the comprehensive effect of air pollution, the daily data of AQI are selected. To make a comparison before and after the event, the data of 10 days before and after the meeting were selected. To carry out the comparison between cities, Baoding in Hebei province, which is close to Beijing, was selected as the comparison sample Fig. (3).

From the date comparison, AQI gradually decreases before the event and AQI is the lowest point in the event. After the event, AQI gradually rose. This shows that in order to hold the meeting, the government carried out air quality control, such as restricting the production of highly polluting factories, which gradually improved the air quality. But after the meeting, factories resumed production and air pollution rebounded in retaliation.

In terms of urban comparison, the daily air pollution data of Beijing and Baoding have followed roughly the same trend. But in the days and days after the meeting, Beijing's air quality was significantly better than Baoding's. Interestingly, by November 2, 2015, the level of air pollution in Beijing had surpassed that in Baoding, and the trend of retaliatory rebound is obvious.

The above is a statistical descriptive analysis. Did the event have a significant impact on air quality? Whether there is a statistically significant difference between the cities where the event occurred and the surrounding city requires further quantitative analysis.

4.2 Time persistence analysis of the impacts of major events on urban air quality

4.2.1 Empirical analysis based on DID

In this paper, the 28 cities involved in hosting major events from January 2, 2015, to November 28, 2017, were selected as the treatment group, and the 112 prefecture-level cities participating in major events in the very province and adjacent provinces were taken as initial control cities. This constitutes a double difference between the occurrence and non-occurrence periods in the same city, as well as between the cities with and without major cities. On this basis, a spatial differences-in-differences model could be established directly. Regression based on Model 2 with AQI as the interpreted variable shows the remarkable effect of the model as a whole. An elaborate examination is made into the existence of intergroup heteroscedasticity, intergroup synchronous correlation and intra-group autocorrelation in the perturbation test of regression model. It is found that there are intergroup heteroscedasticity and intergroup synchronous correlation, but no intra-group autocorrelation. Therefore, the clustered standard error is used in the regression results in this paper. The regression coefficients of each variable are summarized in Table 6.

The observed coefficients during the major events are significantly negative, and the value of AQI is obviously lower than that of other periods at a significant level of 5% among the four models (Table 6). The model presents a better fitting effect with the

Table 3 Non-event period and event period for 28 cities involved in the events

Variable	Units	Non-event period			Event period			Difference		
		Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
AQI	Index number	74.65	500	11	64.346	331	15	10.30	169.00	−4.00
$PM_{2.5}$	μg/m^3	47.68	606	2.55	37.45	228	6.52	10.23	378.00	−3.97
PM_{10}	μg/m^3	78.96	838	6.67	61.86	365	15.73	17.10	473.00	−9.06
SO_2	μg/m^3	16.64	175	1.57	12.34	89	2.47	4.30	86.00	−0.90
NO_2	μg/m^3	38.52	161	3.36	33.87	87	7.45	4.65	74.00	−4.09
CO	μg/m^3	0.93	9	0	0.92	3	0	0.01	6.00	0.00
O_3	μg/m^3	112.45	363	2.25	106.85	270	31	5.60	93.00	−28.75
Highest_t	°C	22.96	41	−10.84	23.34	35	4.51			
Lowest_t	°C	15.47	31	−15.27	15.76	27	−4.84			
Rainfall	Dummy variable	0.39	1	0	0.33	1	0			
Density of snow	Dummy variable	0.01	1	0	0	0	0			
Wind grade	Ordinal number	3.1	11.5	1.7	2.99	6	2			

Table 4 The cities involved and cities not involved at event period

Variables	Cities involved			Cities not involved			Difference		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
AQI	66.74	423	16	81.12	500	10.01	−14.38	−77.00	5.99
$PM_{2.5}$	37.92	316	6.71	49.86	537	3.02	−11.94	−221.00	3.69
PM_{10}	64.83	398	16	88.15	675	5.05	−23.32	−277.00	10.95
SO_2	12.96	112	2.5	22.19	551	1.11	−9.23	−439.00	1.39
NO_2	34.18	110	7.12	34.72	144	2.13	−0.54	−34.00	4.99
CO	1.012	4	0	1.15	13	0	−0.14	−9.00	0.00
O_3	106.72	264	29.5	114.56	407	2.02	−7.84	−143.00	27.48
Highest_t	23.17	35	2.5	21.22	38	−8.6			
Lowest_t	15.36	27	−5.85	12.56	29	−22.5			
Rainfall	0.41	1	0	0.32	1	0			
Density of snow	0	0	0	0.02	1	0			
Wind grade	2.97	5.5	1.52	2.98	10	2.2			

Table 5 The mean values of main variables in 28 cities involved during different periods

Variables	6–10 days before	1–5 days before	Event period	1–5 days after	6–10 days after
AQI	76.15	76.39	74.61	93.84	82.11
$PM_{2.5}$	45.61	47.35	47.611	60.35	54.04
PM_{10}	74.85	74.15	78.88	91.57	89.72
SO_2	15.05	13.96	16.54	19.08	16.08
NO_2	35.41	36.31	38.44	48.01	43.53
CO	1.01	1.06	0.94	1.06	1.01
O_3	113.42	104.91	112.29	106.52	92.84
Highest_t	23.71	23.11	22.98	21.81	21.53
Lowest_t	16.31	15.92	15.48	13.82	14.31
Rainfall	0.311	0.37	0.41	0.29	0.39
Density of snow	0.021	0.011	0.01	0.01	0.01
Wind grade	3.01	1.01	3.11	2.75	2.92

addition of the city and temporal fixed effects. In terms of the dummy variables with city-fixed effects, the significant coefficient of each region indicates that there are differences in air quality among the regions, and city-fixed effects should be added. However, the coefficients for most years, most months, most weeks of the year and most days of the week are significant with respect to the dummy variables at each time (due to space limitations, the results are not reported), suggesting the existence of time-fixed effects, as well as more addition of dummy variables such as seasons and holidays. Therefore, the double fixed effect model is used for further analysis.

According to the double fixed effect model, the AQI value drops by 8.24% during major events, equivalent to 10% of the average AQI during non-major events. In other words, during the period of major events, AQI decreases by about 10% on average compared with that when events do not occur. After 1–5 days or 6–10 days of the major events, AQI presents

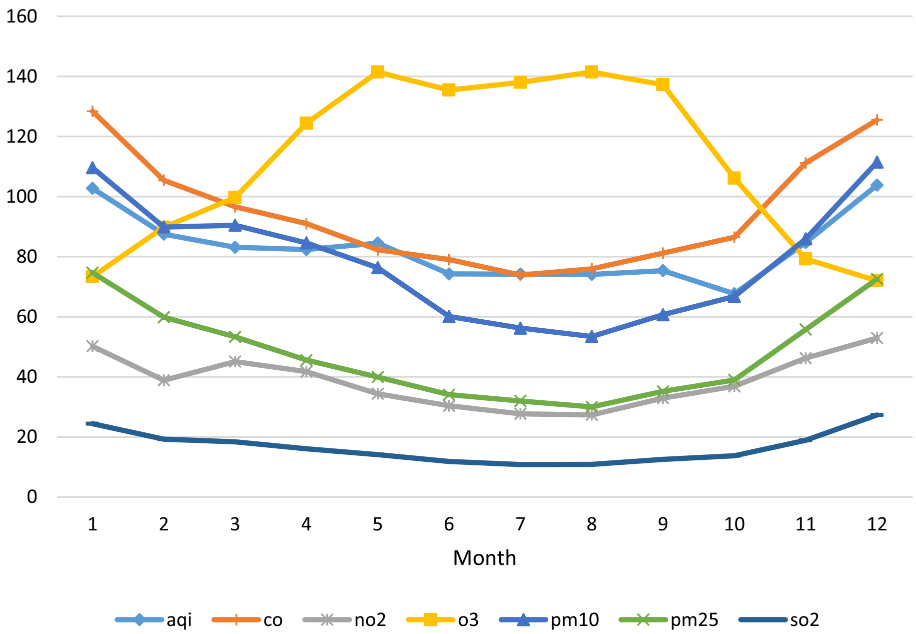

Fig. 2 The trend of the average air quality in cities from January to December. *Notes*: Carbon monoxide concentration has been amplified 100 times to facilitate comparison with other pollutants

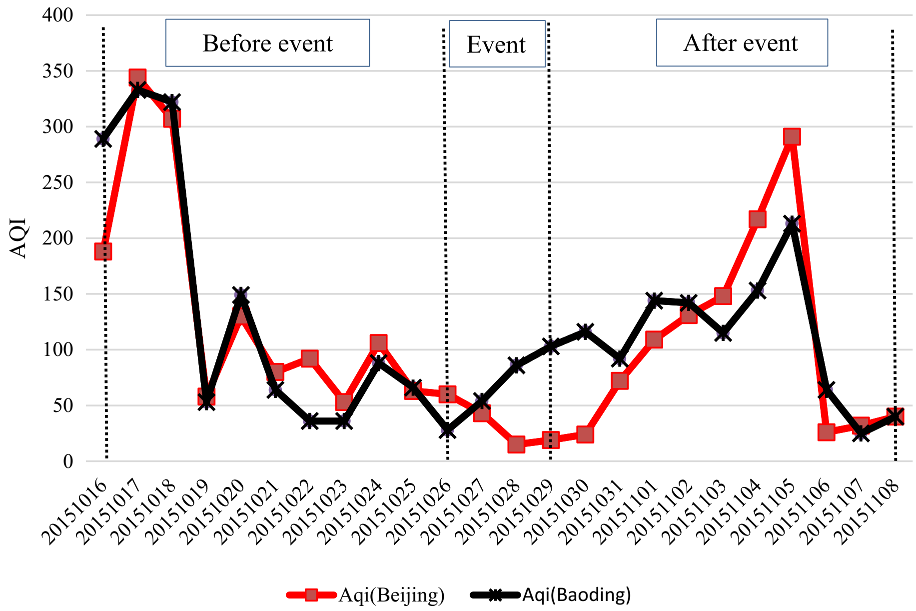

Fig. 3 Comparison of AQI series in Beijing and Baoding

a sharp increase, even much higher than usual. For the weather variables, the significant coefficients display the rationality of the variable addition. Of all the weather factors, wind grade is significantly correlated with air quality, which is also true of rainfall and air quality, but the highest temperature presents a negative correlation with air quality. In fact, considering the higher temperature, less rainfall, and lower wind grade, pollutants, discharged into the atmosphere, are not easy to diffuse, which leads to the poor air quality. In this regard, it can be seen that the conclusions of the study are consistent with common sense.

In order to further explore the specific impact of the major events on individual air pollutants, the spatial differences-in-differences regression is carried out with each individual pollutant concentration as the explained variable in Regression Model 1. The regression results are shown in Table 7.

The long-term impact of major events on individual pollutants revealed very interesting results (Table 7). Despite a concentration decrease in PM_{10} and $PM_{2.5}$, there is a rebound after 1–5 days of the major event, even much higher than in the normal period. However, a slight difference is shown between the normal period and 6–10 days after the major event. Thus, temporary air management had no long-term effect on air improvement, but a retaliatory rebound appears after the end of the temporary measures, then returning to the normal state. Besides, an obvious rebound is shown in SO_2 after the major events. As for NO_2, the concentration decreases significantly in the process of major events and returns to the normal level after events. Another individual pollutant, CO, presents a slight decrease during the major events, but not obvious. Ozone is an exception, since the content is neither an indicator of government performance appraisal nor a public concern. Therefore, ozone is less affected by the major events, but to a larger extent by seasonal factors, and the specific reasons need to be investigated further (Li et al. 2019a, b).

4.2.2 Further investigation into robust test

Due to the short duration of the major events, the period without events had to be appropriately shortened in order to avoid other possible overlooked interference factors. On this basis, the robustness of the results is tested by changing the sample window, and samples of 20, 30 and 40 days before and after the major events are retained, respectively. After changing the different sample windows, the impact of the major events on air quality remains significant in the event-involved cities, and the air quality rebounds after the major events. Moreover, this paper also assesses the robustness of the results with the help of a placebo that artificially sets the time for the major events. Specifically, one month ahead of schedule for the major events, it could be found that the cross-term coefficient was no longer significant, which indicates that the major events indeed contributed to the improvement in urban air quality. At this point, it is reasonable to believe that the above conclusions are robust and valid (Table 8).

4.3 Spatial characteristics of the impacts of major events on urban air quality

4.3.1 Empirical analysis based on spatial DID

With an aim to eliminate the bias of sample selection, the method of spatial DID is adopted for further analysis. During the occurrence of each major event, the cities within 900 km from the host city are treated as the treatment group and the others as the control group. The cities beyond 900 km are searched to match the ones within 900 km. It should be noted

Table 6 Empirical results of AQI based on DID

Variables	Model 1	Model 2	Model 3	Model 4
Event period	−11.76***	−5.85**	−13.96***	−8.24**
	(2.78)	(2.71)	(2.64)	(3.24)
1–5 days after	4.12	7.05**	3.38***	5.51***
	(2.88)	(2.81)	(2.72)	(2.02)
6–10 days after	7.00**	4.85*	5.18***	1.84
	(2.89)	(2.83)	(2.74)	(5.01)
Wind grade	−4.78***	−4.95***	−0.94***	−0.81**
	(0.17)	(0.18)	(0.18)	(0.39)
Rainfall	−5.03***	−3.70***	−2.06***	0.61
	(0.32)	(0.32)	(0.31)	(0.44)
Density of snow	2.21**	5.71***	0.04	5.27**
	(1.17)	(1.16)	(1.1)	(2.07)
Highest_t	1.72***	2.26***	1.30***	2.06***
	(0.05)	(0.05)	(0.05)	(0.16)
Lowest_t	−3.92***	−4.11***	−3.24***	−1.50***
	(0.05)	(0.05)	(0.05)	(0.25)
Time-fixed effects	No	Yes	No	Yes
City-fixed effects	No	No	Yes	Yes
R-square	0.19	0.24	0.29	0.36
Number of observations	17,640	15,120	13,860	13,490

(1) *, ** and *** are significant at 10%, 5% and 1% levels, respectively, with standard errors in parentheses, the same as in the other tables. (2) One of the reasons for the low value of R-square is that PM is affected by many factors, such as energy consumption, industrial structure and economic conditions. Since the focus of this paper is to analyze the impact of major events on PM, these factors are not included

that altogether there were 9 host cities owing to the unfixed location of the major events and the matching process is carried out separately, nine in total. Furthermore, the equilibrium test should be conducted each time, and then, the spatial differences-in-differences method

Table 7 Cross-term coefficient of single atmospheric pollutant

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	O_3
Event period	−9.15**	−8.52**	1.56	−6.61***	−0.01	−15.95***
	(3.53)	(3.73)	(0.88)	(1.60)	(0.06)	(2.05)
1–5 days after	3.59**	3.86***	2.59***	1.00	0.01	-5.00*
	(1.51)	(1.30)	(0.51)	(1.05)	(0.03)	(2.62)
6–10 days after	1.57	6.50	1.57	1.34	−0.01	−20.31***
	(3.90)	(4.46)	(1.04)	(1.15)	(0.01)	(2.29)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
Time-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
City-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
R-square	0.40	0.44	0.46	0.54	0.47	0.45
Number of observations	17,640	17,640	17,640	17,640	17,640	17,640

*, ** and *** are significant at 10%, 5% and 1% levels, respectively

is applied in all successful matched cities. In this paper, the nearest neighbor matching in the caliper scope is used as the matching method, where the caliper is set to 0.01 with one-to-one playback matching. As the equilibrium test shows (Table 9), the standard deviation of almost all variables after matching decreases sharply, and the t-test results do not reject the original hypothesis that there is no systematic difference between the treatment group and the control group, which indicates a favorable result of matching.

After 9 times' matching, 120 cities were successfully matched and the regression results of the DID for the 120 cities, based on Model 3, are shown in Table 10. Combined with AQI and the regression results of individual pollutant concentrations, the major events significantly improved the air quality of cities within 800 km of the event-hosted cities. Moreover, as the distance increases, the improvement gets smaller and it is no longer significant beyond 800 km. The effect of the major events on the concentration of individual pollutants in cities becomes gradually apparent with the distance decreasing from major events, which is consistent with the results of DID, and further verifies the robustness of the results to a large extent.

In addition, owing to the shorter period of the major events than that without their occurrences, the period without events should be appropriately shortened in order to avoid other possible interfering factors. After retaining the samples 30 days before and after the events and conducting the DID analysis of the 120 cities, conclusions can be drawn that the major events significantly improved the air quality of cities within 800 km of the host city, and the improvement in cities within 500 km is relatively remarkable. With regard to individual pollutants such as PM_{10} and $PM_{2.5}$, great improvement is presented in cities within 800 km of the event site, and the concentration of nitrogen oxides in cities within 300 km also improved significantly (Table 11).

4.3.2 Further analysis of robustness

In order to identify whether the impact of major events on urban air quality in different areas is sensitive to the sample window, samples of 20, 30 and 40 days before and after major events are retained, respectively. The regression results were insensitive to the different sample windows (Table 12), and these indicate the robustness of the conclusions drawn.

5 Conclusion

5.1 Research findings

In this study, the daily air quality index (AQI) and the concentration of individual pollutants from January 2, 2015, to March 28, 2017, are empirically investigated. A summary of the research findings is as follows. The air quality of the cities involved in hosting the major events improved significantly during the occurrence, and it is warranted that the improvement is caused by the occurrence of the major events. From the perspective of individual pollutant concentrations, particulate matter exercises the most remarkable impact on the urban air quality, followed by nitrogen oxide, while less obvious impact is shown on the concentrations of carbon monoxide and ozone. After a period of the major events, the AQI value and the concentrations of individual pollutants present a rising trend with varying degrees, exceeding the normal level, which shows that the improvement of air quality

Table 8 Empirical results in different sample windows

Window	AQI	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	O_3
Event period							
20 days	−9.15**	−10.42**	−10.89**	0.46	−6.90***	−0.01	−15.00***
30 days	−9.92**	−11.08**	−11.32**	0.46	−7.36***	−0.04	−14.75**
40 days	−10.40	−11.32**	−11.71**	0.55	−7.24***	−0.04	−14.67***
Before event							
20 days	10.52***	7.56***	7.16**	3.37***	1.88*	0.04	−6.11**
30 days	5.89***	3.71***	4.70***	2.87***	1.03	0.01	−5.00**
40 days	5.81***	3.81**	3.31**	3.03***	1.17	0.02	−4.87**
After event							
20 days	8.68	6.79	13.88**	2.15	2.05**	0.02	−18.00***
30 days	6.41	5.50	3.45**	2.44	2.03	0.01	−16.04***
40 days	5.30	4.73	11.57**	2.27	1.81*	0.02	−16.58***

(1) In "Event period", "20 days, 30 days and 40 days" means that the event period were extended to 20 days, 30 days and 40 days, separately. (2) In "Before", "20 days, 30 days and 40 days" means that 20-day, 30-day and 40-day data prior to the event were collected, separately. (3) The coefficients for "Event period", "Before event" and "After event", come from the econometric analysis with data during "Event period", before "event" and after "event", and by using the formula (1)

*, ** and *** are significant at 10%, 5% and 1% levels, respectively

Table 9 DID applicability test

Variables	Matched or not	Mean		Bias (%)	Bias reduction (%)	*P*-value
		Treatment group	Control group			
wind grade	unmatched	2.9629	2.9326	8.70	−74.8	0.609
	matched	2.9243	2.8713	15.20		0.250
rainfall	unmatched	0.0232	0.0056	197.8	87.3	0.000
	matched	0.0163	0.0140	25.10		0.870
density of snow	unmatched	19.988	24.319	−198.8	94.6	0.000
	matched	21.253	21.021	10.70		0.770
highest_t	unmatched	10.142	16.888	−226.9	95.1	0.000
	matched	12.381	12.048	11.20		0.470
lowest_t	unmatched	0.2564	0.4616	−358.3	96.0	0.000
	matched	0.3279	0.3197	14.20		0.260

*, ** and *** are significant at 10%, 5% and 1% levels, respectively

brought by temporary control exhibits no sustained effect, even at the cost of retaliatory pollution. In this regard, the major events not only affected the air quality of the host city, but also affected the air quality of the surrounding areas. The spatial range of each major event, affecting the urban air quality, is within 800 km around the host city, and the farther away from the host city, the smaller the impact (Guo et al. 2020).

Table 10 Spatial scope of event impact based on spatial DID

AQI	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	O_3
< 100 km						
−12.48***	−10.80***	−13.31**	0.44	−4.63***	−0.09	−16.14***
(3.26)	(4.00)	(5.60)	(0.81)	(1.19)	(−0.09)	(2.68)
100–200 km						
−10.11***	−9.90***	−9.90***	0.87	−2.79***	−0.06	−12.32***
(2.82)	(3.27)	(4.13)	(0.94)	(0.86)	(0.06)	(1.74)
200–300 km						
−10.66***	−9.78***	−13.16***	−2.65**	−3.45***	−0.07**	−9.04***
(2.50)	(2.29)	(2.81)	(1.03)	(0.70)	(0.03)	(2.42)
300–400 km						
−10.32***	−10.69***	−11.06***	−0.22	−0.95	−0.05*	−10.50***
(1.91)	(1.86)	(2.18)	(1.07)	(0.76)	(0.04)	(2.04)
400–500 km						
−7.39***	−7.57***	−6.25***	−1.25	−0.74	−0.06**	−8.20***
(2.58)	(2.35)	(2.56)	(1.08)	(0.71)	(-0.04)	(1.86)
500–600 km						
−4.90***	−4.93***	−2.48	1.08	−0.05	−0.03	0.07
(1.57)	(1.23)	(1.61)	(1.37)	(0.50)	(0.03)	(1.59)
600–700 km						
−6.68**	−7.12***	−5.60*	−2.09	0.04	−0.02	−2.80
(2.70)	(1.90)	(3.22)	(2.19)	(0.68)	(0.03)	(1.89)
700–800 km						
−3.29**	−5.99***	−3.16	−0.62	−0.57	−0.03	1.05
(1.67)	(1.45)	(2.46)	(0.85)	(0.46)	(0.02)	(1.81)
800–900 km						
−0.00	−1.35	1.59	−0.89	0.18	−0.01	−0.25
(1.34)	(1.27)	(1.67)	(0.57)	(0.41)	(0.01)	(2.03)

*, ** and *** are significant at 10%, 5% and 1% levels, respectively

5.2 Countermeasures and suggestions

China's environmental management system should be innovated systematically based on the experience of developed countries but set within the context of China's in air pollution joint prevention and control measures in recent years, such as during the Beijing Olympic Games, Shanghai World Expo, APEC, etc. On this basis, effective countermeasures should be taken as follows. First of all, a new system of atmospheric environmental management should be established with regional management as the main part and territorial management as the supplement, so as to avoid the "illusion" of governance effectiveness caused by local government "interference" (Yu et al. 2019). Secondly, great attention should be paid to the phenomenon of atmospheric transboundary transmission as a result of meteorological field factors, and a new mechanism of joint prevention and control of atmospheric pollution aimed at improving air quality in different regions should be comprehensively

Table 11 Empirical results in shorter sample window

AQI	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	O_3
< 100 km						
−13.49***	−11.81***	−14.77**	0.35	−5.14***	−0.10	−16.40***
(3.92)	(4.39)	(6.24)	(0.81)	(1.13)	(−0.09)	(2.64)
100–200 km						
−10.64***	−10.23***	−10.55***	0.98	−3.41***	−0.06	−12.63***
(3.39)	(3.46)	(4.40)	(0.90)	(0.86)	(0.06)	(1.90)
200–300 km						
−10.37***	−9.62***	−12.32***	−2.36**	−3.80***	−0.08**	−8.08***
(3.03)	(2.61)	(3.51)	(1.08)	(0.74)	(0.03)	(2.38)
300–400 km						
−12.29***	−11.76***	−12.95***	0.29	−1.40	−0.05*	−10.50***
(2.18)	(2.02)	(2.89)	(1.26)	(0.87)	(0.04)	(1.93)
400–500 km						
−9.20***	−8.87***	−8.29***	−1.53	−0.98	−0.06**	−8.63***
(3.08)	(2.61)	(2.89)	(1.13)	(0.73)	(−0.05)	(1.88)
500–600 km						
−6.27***	−5.91***	−3.82**	0.98	−0.68	−0.03	0.26
(1.62)	(1.27)	(1.52)	(0.75)	(0.50)	(0.03)	(1.59)
600–700 km						
−7.88**	−8.31***	−7.26**	−1.91	0.48	−0.03	−3.38
(2.64)	(1.89)	(3.21)	(2.03)	(0.67)	(0.03)	(2.01)
700–800 km						
−7.88**	−7.05***	−4.42**	−0.54	−0.92	−0.02	1.41
(2.67)	(1.37)	(2.31)	(0.88)	(0.46)	(0.02)	(1.81)
800–900 km						
−0.56	−1.91	1.15	−0.78	0.16	−0.02	−1.23
(1.51)	(1.39)	(1.78)	(0.57)	(0.44)	(0.01)	(2.15)

*, ** and *** are significant at 10%, 5% and 1% levels, respectively

promoted (Xu et al. 2019). In addition, the total amount and proportion of the transboundary transport of atmospheric pollutants should be studied scientifically and reasonably for a further establishment of the regional ecological compensation management system of atmospheric environment. Fourthly, taking big data as the analysis resource, the early warning and emergency warning mechanism should be proposed (Yan et al. 2019). At last, taking China's ongoing current regional economic integrations (such as Beijing-Tianjin-Hebei integration, Yangtze river delta integration, Pearl river delta integration, etc.) as opportunities, regional unified standards for pollutant discharge, industrial access and law enforcement are proposed to be formulated to improve the urban air quality.

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Table 12 Empirical results in different sample windows

window	AQI	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	O_3
< 100 k							
20 days	−12.06***	−10.16***	−13.11**	0.27	−4.42***	−0.04	−17.26***
30 days	−13.49***	−11.81***	−14.77**	0.35	−5.14***	−0.10	−16.40***
40 days	−13.59***	−11.63***	−14.90***	0.40	−4.90***	−0.10	−16.43***
100–200 km							
20 days	−8.72***	−8.11***	−8.69**	1.75	−2.74***	−0.01	−13.16***
30 days	−10.64***	−10.23***	−10.55***	0.98	−3.41***	−0.06	−12.63***
40 days	−10.83***	−10.35***	−10.88***	0.96	−3.21***	−0.06	−12.58***
200–300 km							
20 days	−7.84***	−7.10***	−9.43***	−0.96	−3.59***	−0.03	−8.50***
30 days	−10.37***	−9.62***	−12.32***	−2.36**	−3.80***	−0.08**	−8.08***
40 days	−10.65***	−9.73	−12.93***	−2.44	−3.57***	−0.08	−8.06***
300–400 km							
20 days	−9.46***	−9.23***	−9.97***	2.72	−0.53	−0.00	−11.77***
30 days	−12.29***	−11.76***	−12.95***	0.29	−1.4	−0.05*	−10.50***
40 days	−12.10***	−11.53	−12.82***	0.05	−1.16	−0.06	−10.03***
400–500 km							
20 days	−6.04***	−5.51***	−4.86**	−0.39	−0.46	−0.02	−10.35***
30 days	−9.20***	−8.87***	−8.29***	−1.53	−0.98	−0.06**	−8.63***
40 days	−8.95***	−8.75***	−8.31***	−1.71	−0.91	−0.08	−8.29***
500–600 km							
20 days	−5.01***	−3.87***	−1.76	2.28	−0.70	−0.00	−1.88
30 days	−6.27***	−5.91***	−3.82**	0.98	−0.68	−0.03	0.26
40 days	−6.56***	−6.08***	−4.39***	0.66	−0.53	−0.03	0.08
600–700 km							
20 days	−5.38**	−5.85***	−4.56	0.18	−0.34	0.00	−4.34**
30 days	−7.88**	−8.31***	−7.26**	−1.91	0.48	−0.03	−3.38
40 days	−8.16***	−8.28***	−7.46**	−2.26	−0.40	−0.03	−2.93
700–800 km							
20 days	−2.81**	−4.93***	−2.11	−0.19	−0.99**	0.10	0.75
30 days	−7.88**	−7.05***	−4.42**	−0.54	−0.92	−0.02	1.41
40 days	−4.93***	−7.13	−4.89**	−0.69	−0.85*	−0.02	1.93
800–900 km							
20 days	0.01	−1.05	2.34	−0.54	−0.41	−0.01	−1.12
30 days	−0.56	−1.91	1.15	−0.78	0.16	−0.02	−1.23
40 days	−0.98	−2.13	0.44	−0.89	−0.04	−0.01	−0.97

*, ** and *** are significant at 10%, 5% and 1% levels, respectively

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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