Air Primary Pollutant During 2015-2019 Over 19 Chinese Urban Agglomerations: Spatiotemporal Distribution And Emission Source Impacts

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Abstract

The "comparative attitude" of urban agglomerations (UAs) involves multidimensional perspectives such as infrastructure, ecological protection, and air pollution. Based on monitoring station data, comparative studies of multispatial, multitime scale and multiemission pollution sources of air quality on 19 urban agglomerations (UAs) during the 13th Five-Year Plan period in China were explored by mathematical statistics. The comparison results are all visualized and show that clean air days gradually increased and occurred mainly in summer, especially in South and Southwest China. $PM_{2.5}$, PM_{10} and O_3 were still the main primary pollutants. $PM_{2.5}$ is mainly concentrated in December, January and February, and PM_{10} is mainly concentrated in October-November and March-April. The O_3 pollution in the Pearl River Delta and Beibu Gulf UA located in the south is mainly concentrated from August to November, which is different from others from May to September. Second, the hourly O_3 concentration rates were significantly higher than the particulate matter (PM) pollution rates from 2015 to 2019. Diurnal trends in O_3 concentration in all directions also showed a single peak, with the largest increments that appeared between 13:00 and 16:00, while the spatial distribution of this peak was significantly regional, earlier in the east but later in the west. Third, this analysis indicated that the annual average air quality index (AQI) showed a gradually decreasing trend outward, taking the Central Plains UA as the center. Furthermore, the total amount of $PM_{2.5}$ pollution caused by anthropogenic sources is approximately 2.5 times that of PM_{10} , and industries are the main sources of $PM_{2.5}$, PM_{10} and VOCs (volatile organic compounds). VOCs and NO_x increased in half of the urban agglomerations, which are the reasons for the increase in ozone pollution. The outcomes of this study will provide targeted insights on pollution prevention in urban agglomerations in the future.

1 Introduction

In global ecological protection and urban development, air pollution has become a crucial issue affecting human health and the environment, along with climate change, which has attracted increasing attention from scholars and government administrators¹⁻³. The number of air pollutants has grown from dozens to hundreds now. Major phenomena, such as acid rain, ozone holes, and urban heat islands, continuously challenge the airways of urban dwellers and sustainable urban development^{4,5}. After decades of efforts by developed countries in Europe and America, sulfur pollution and soot pollution in urban air have basically been solved, and the environmental air quality has been greatly improved. However, the contribution of NO_x to environmental acidification is growing as the tropospheric ozone problem is aggravated by the emission of nitrogen oxides (NO_x) and volatile organic compounds (VOCs)⁶. In recent decades, the enormous emissions of airborne particulate pollution have become the primary cause of climate change and air pollution in China⁷. Air pollution has gradually changed from a local problem to a regional problem and may be either emitted directly (primary pollutants) or formed in the atmosphere⁸. Major metropolises have invested large human and financial resources to control particulate pollution,

but the effect is still unsatisfactory. CO, NO_x, hydrocarbons and photochemical smog pollution remained serious.

Urban agglomeration is a crucial phenomenon at the urban scale and form in the process of globalization. In 1957, geographer Gottmann published his academic essay "Megalopolis or the Urbanization of the Northeastern Seaboard" and used the Greek term "megalopolis" to describe the BosWash corridor⁹. Gottmann pointed out that the future direction of urbanization is to develop and form megacities gradually integrated with nearby areas. Gottmann is considered a major contributor to urban agglomeration research. In 1983,¹⁰ introduced Gottmann's works on "Metropolis" in the Chinese context and formally established the theme and background of the study of urban agglomerations in China. In different stages of socioeconomic and human development, scholars use different terms to describe this urban landscape phenomenon, such as urban clusters¹¹, metropolitan chain areas¹², urban agglomerations¹³, metropolitan interlocking regions¹⁴ and conurbations¹⁵. Despite the inconsistency in terminology, this extensive, multicentered, multicity urban landscape has been well recognized. Urban agglomerations (UAs) in China are dynamic regions with immense potential for regional development, which play a vital role in global competition and the international division of labor⁷. Obviously, UAs are air high-pollution focal points, which gather many industries, transportation and residents, and the mechanisms of environmental pollution are more complicated¹⁶. Source contributions to PM_{2.5} indicate that coal¹⁷, biomass burning¹⁸, transport¹⁹ and industry²⁰ are the main sources.

Only three air pollutants, SO₂, NO₂ and PM₁₀, were monitored, and the air pollution index (API) was calculated by the China National Environmental Monitoring Centre before 2013. Then, China promulgated the Ambient Air Quality Standard (GB3095-2012), adding three indicators, PM_{2.5}, CO, and O₃, for air quality evaluation. The air quality index (AQI) was used to evaluate the air quality, which makes the air quality evaluation more accurate and strict. At present, China's air quality evaluation indicators are mainly PM_{2.5}, PM₁₀, SO₂, NO₂, CO and ozone. However, in terms of identifying regions with similar air pollution behaviors and locating emission sources, few studies have comprehensively considered the spatiotemporal comparison of primary pollutants among UAs and detailed emission sources. For many countries, without this comprehensive assessment, it is impossible to understand the synergies and interrelationships between energy-related urban sprawl and air pollution. Previously published studies on spatiotemporal variations in PM_{2.5} and O₃ have mainly focused on a specific region in China (Beijing-Tianjin-Hebei, Yangtze River Delta, or Pearl River Delta) and shorter observation times, ignoring UAs with weak economic development, such as northwest and central China^{21–23}. Few studies have compared the changes in pollutant concentrations and primary pollutants in multiple UAs. As China has entered the 14th Five-Year Plan period, it is necessary to review and summarize the air quality situation of China's key UAs in the 13th Five-Year Plan and study the impact of anthropogenic emission sources generated in urban construction on air pollution. This is a research highlight of this paper. Given these facts and based on air quality monitoring data, this study aims to answer the following questions: (1) Is the primary pollutants in UAs changed during China's 13th Five-Year Plan period? What are the differences between

the primary pollutants in the 19 urban agglomerations? (2) How do the concentrations of primary pollutants fluctuate over the timescales of years, months and hours? (3) What is the dissimilarity of the contribution of atmospheric pollutants produced by anthropogenic sources at the urban agglomeration scale?

This paper is organized as follows. In the first stage, we described the study area and the datasets used in the study. Then, we will present the spatial-temporal variation characteristics of primary pollutants based on urban agglomeration and anthropogenic source emissions. Finally, we summarized key research findings and drew conclusions.

2 Study Area And Methods

2.1 China's urban agglomerations

Due to the compound and regional features of air pollution, UAs are the main unit of joint prevention and control of air pollution. Urban agglomeration development planning in China can be divided into world-class, national and regional levels. The 19 selected Chinese UAs from south to north and from west to the east are Beibu Gulf, Pearl River Delta, Central Yunan, Central Guizhou, Chengdu-Chongqing, Triangle of Central China, Central Plains, West Side of the Straits, Yangtze River Delta, Shandong Peninsula, Tianshan North-Slope, Lanzhou-Xining, Guanzhong Plain, Ningxia Yanhuang, Hohhot-Baotou-Ordos-Yulin, Tianyuan-Jinzhong, Beijing-Tianjin-Hebei, Mid-southern Liaoning and Harbin-Chang urban agglomeration. Nineteen urban agglomeration locations and names are annotated with colors and numbers in Figure 1. Moreover, for convenience of expression, Table 1 briefly lists the basic indicators of the 19 UAs in China.

Table 1
Basic indicators of UAs in China

Urban Agglomeration (Abbreviation)	Core cities	Level	Functions of UAs	Stations number	Key cities
Beijing-Tianjin-Hebei(BTH) ^N	Beijing,Tianjin	National	China's political and cultural center	79	13
Taiyuan-Jinzhong(TJ) ^N	Taiyuan	Local	The most dynamic economic belt in central Shanxi province	12	2
Hothot-Baotou-Ordos-Yulin(HBOY) ^N	Hothot, Ordos	Local	National High-end Energy and Chemical Industry Base	23	4
Ningxia Yanhuang(NY) ^N	Yinchuan	Local	Concentrating 90% of the urban population of Ningxia and spreading along the Yellow River	16	4
Shangdong Peninsular(SP) ^E	Qingdao	Regional	The economic center of the Yellow River basin	89	14
Yangtze River Delta(YRD) ^E	Shanghai, Hangzhou	National	The leader of the Yangtze River Economic Belt	170	27
West Side of the Straits(WSS) ^E	Xiamen, Wenzhou	Regional	New comprehensive corridor for opening to the outside world along the southeast coast	88	19
Central Plain(CP) ^C	Zhengzhou	Regional	The most densely populated one with rapid industrialization and urbanization	110	28
Triangle of Central China(TCC) ^C	Wuhan	National	An essential part of the Yangtze River economic belt and a key area to promote new urbanization	138	31
Pearl River Delta(PRD) ^S	Guangzhou, Shenzhen	National	China Open and Innovation Pilot Zone	72	15
Beibu Gulf (BG) ^S	Zhanjiang	Regional	Chinese most growing coastal economic belt	41	15
Harbin-Changchun (HC) ^{NE}	Harbin, Changchun	Regional	Core competitiveness and essential influence in Northeast China	55	11

Note: N□E□C□S□NE□SW□NW correspond to North□East□Central□South□Northeast□Southeast□Northwest.

Urban Agglomeration (Abbreviation)	Core cities	Level	Functions of UAs	Stations number	Key cities
Mid-southern Liaoning (MSL) ^{NE}	Dalian, Shenyang	Regional	A region of earlier industrial development and a high level of urbanization	57	9
Central Guizhou (CG) ^{SW}	Guiyang	Local	Pilot demonstration area of new urbanization with mountainous characteristics	23	6
Central Yunnan (CY) ^{SW}	Kunming	Local	China's southwest economic growth pole	17	5
Chengdu-Chongqing(CC) ^{SW}	Chengdu, Chongqing	National	China's largest economy closest to Southeast and South Asia	88	16
Guanzhong Plain(GP) ^{NW}	Xi'an	Regional	The second largest urban agglomeration in the western region	51	10
Lanzhou-Xining(LX) ^{NW}	Lanzhou, Xining	Local	A major area for national security and ecological security	19	9
Tianshan North-Slope(TNS) ^{NW}	Urumqi	Regional	Chinese westernmost urban agglomeration and the core area of the Silk Road Economic Belt	13	10
Note: N□E□C□S□NE□SW□NW correspond to North□East□Central□South□Northeast□Southeast□Northwest.					

2.2 Data sources and statistical analyses

City daily monitoring data were derived from China's National Environmental Monitoring Centre. It is well known that 2020 is the year for China to fight the COVID-19 pandemic with all their strengths²⁴. Home isolation was adopted to reduce mobility, and social and economic development stagnated. Meanwhile, anthropogenic activities such as transportation and industry are directly proportional to air pollution. Therefore, the study period was conducted from January 1, 2015, to December 31, 2019, avoiding the impact of the COVID-19 epidemic. The air quality index (AQI) is a quantitative description of air quality data, which can denote the short-term air quality status and trends in a city²⁵. The overall AQI represents the maximum of the sub-AQI of all pollutants, where when the AQI is higher than 50, the highest sub-AQI contributor is defined as the primary pollutant on that day²⁶. The calculation of the AQI and primary pollutants is as follows:

$$IAQI_P = \frac{IAQI_{Hi} - IAQI_{Lo}}{BP_{Hi} - BP_{Lo}} \times (C_P - BP_{Lo}) + IAQI_{Lo} \quad (1)$$

$$AQI = \text{Max}\{IAQI_1, IAQI_2, \dots, IAQI_p, \dots, IAQI_n\} \quad (2)$$

where $IAQI_p$ is the air quality subindex of pollutant item P . C_p is the concentration value of P . BP_{HI} and BP_{LO} are the high and low values of the pollutant concentration limit, respectively, similar to C_p . $IAQI_{HI}$ and $IAQI_{LO}$ are air quality subindexes corresponding to BP_{HI} and BP_{LO} . After calculating the air quality subindex of various pollutants, the maximum value is the air quality index (AQI). Primary pollutants are the largest corresponding pollutant items of $IAQI_p$.

2.3 Illustration of spatiotemporal variations in sector emissions

The emission source inventory used in the experiment is from the MEIC (Multi-resolution Emission Inventory for China) 2017 version developed by Tsinghua University, with a spatial resolution of $0.5^\circ \times 0.5^\circ$ (<http://meicmodel.org>). MEIC is a bottom-up emission inventory model based on a cloud computing platform that covers dozens of major air pollutants and greenhouse gases. The emission data are divided into five sectors: industry, power, civil, transportation and agriculture. Annual grid emission inventories of 0.25° , 0.5° and 1.0° spatial resolutions are provided. Currently, MEIC data are widely used by more than 100 research institutions and business units to forecast air quality and plan air pollution standards^{27,28}.

Herein, in our research, two mathematical statistical methods, including the average industrial emission of pollutants (IEP) and growth rate, were used to evaluate spatiotemporal variations in IEP in 19 urban agglomerations. The formulas of these indexes are specified as follows:

$$AI_{x,j} = \frac{1}{n} \sum_i^n IEP_{i,j} \quad (3)$$

$$GI_{x,j} = \frac{AI_{x,j}^{2017} - AI_{x,j}^{2015}}{AI_{x,j}^{2015}} \times 100\% \quad (4)$$

where $AI_{x,j}$ is the average industrial emission of j pollutants in country x , $IEP_{i,j}$ is the estimated IEP of pixel i of j pollutants, and $GI_{x,j}$ stands for the growth rate of IEP of j pollutants. To further explore the spatial and temporal variations in urban agglomerations, the spatial changes in the industrial emissions of pollutants at the urban agglomeration scale were calculated by averaging the AI value in the inner city.

3 Results And Discussion

3.1 Daily change in primary pollutant over China urban agglomerations in 2015-2019

To elucidate the change trend of primary pollutants under the 13th Five-Year Plan, we calculated the daily primary pollutants in 2015 and 2019 based on formula (1) and formula (2). Such diurnal comparisons

can reduce the effects of seasonal weather to some extent. From the 19 UAs (224 prefecture-level cities), the heat diagram of the daily change transfer matrix of primary pollutants from 2015 to 2019 is shown in Figure 2, including six primary pollutants and clean day conditions.

From the sum of the diagonal numbers, 37% of the primary pollutants had no shift during the 13th Five-Year Plan period. $PM_{2.5}$, PM_{10} and O_3 were the main primary pollutants, especially $PM_{2.5}$. More primary pollutants were diverted to ozone pollution, indicating that the proportion of O_3 as the primary pollutant is gradually increasing. In addition, the proportion of clean air has increased significantly, which shows that pollution control has been effectively reflected during the 13th Five-Year Plan period. However, the proportion of NO_2 before and after metastasis was approximately the same, with approximately 5% NO_2 pollution. This may imply that the governance of NO_2 pollution was rendered nonsignificant. It is noteworthy that ozone pollution in China has become an increasingly prominent task in recent years. Similar to Xiao's ¹⁶ research on ozone pollution, they argue that present-day ozone levels in major Chinese cities are comparable to or even higher than the 1980 levels in the United States. Taken together, ozone and $PM_{2.5}$ have become the top two air pollution pollutants in China.

3.2 Monthly distribution of primary pollutants over China's urban agglomerations in 2019

To further explore the spatiotemporal distribution of the primary pollutants across the UAs, we obtained the most primary pollutants per month by dividing the number of days with the most pollutants by the number of cities in each urban agglomeration from the 2019 data. In Figure 3, the urban agglomeration location is plotted on the abscissa, and the monthly variance of the primary pollutant is plotted on the ordinate. As shown in Figure 3, $PM_{2.5}$ appears as dark green, PM_{10} appears as light green, O_3 appears as orange, NO_2 appears as yellow, and clean days appear as dark blue. The main pollutants in the 19 UAs are $PM_{2.5}$, PM_{10} and O_3 . NO_2 , as the primary pollutant, only appeared in the HBOY urban agglomeration in January. CO and SO_2 did not become major pollutants. Clean days (where $AQI < 50$) occur mainly in South and Southwest China during summer. As the primary pollutant, $PM_{2.5}$ is mainly concentrated in December, January and February, that is, it occurs in winter. As the primary pollutant, PM_{10} is mainly concentrated in October-November and March-April, that is, autumn and spring. As the primary pollutant, O_3 is mainly concentrated from May to September, that is, summer.

From the perspective of UAs, monthly primary pollutants in different UAs are different. The O_3 pollution in the PRD and BG, as representatives of UAs in southern China, is mainly concentrated from August to November. In addition to human factors, this may be associated with lower latitudes, higher temperatures and stronger solar radiation. The northern, northwestern, northeastern, central and eastern UAs have similar monthly primary pollutant distributions, with $PM_{2.5}$, PM_{10} and O_3 pollution distributed in the 12 months of 2019. Nearsurface O_3 is mainly produced by the complex photochemical reactions between nitrogen oxides, volatile organic compounds, carbon monoxide, methane and other precursors. O_3 is a

major pollutant in most UAs from May to September, which may be the result of the comprehensive action of anthropogenic factors and meteorological conditions.

3.3 Annual patterns of PM_{2.5}, PM₁₀ and O₃ concentrations over China’s urban agglomerations in 2015–2019

As shown in Figure 4, unary linear regression was used to extract the time variation trend of PM_{2.5}, PM₁₀ and O₃ concentrations in each urban agglomeration. The slope value depicted a decreasing trend in the annual mean PM_{2.5} and PM₁₀ during 2015–2019, suggesting that the emissions of particulate matter were effectively controlled.

In terms of urban agglomerations, the average annual PM_{2.5} and PM₁₀ concentrations significantly decreased, mostly in Harbin-Changjiang (HC) and mid-southern Liaoning (MSL) in the northeast, while there was little difference in annual ozone concentration. In contrast, the annual mean ozone pollution displayed the greatest enhancement, while PM_{2.5} and PM₁₀ showed a minimal decrease in the Taiyuan-Jinzhong (TJ) urban agglomeration in northern China. At the same time, by checking the annual average AQI in 2019, we showed that the Central Plains urban agglomeration has the highest annual average AQI, and the particulate matter pollution and ozone are both high, suggesting that the control effect is not obvious in the central region. We found that the annual average AQI showed a gradually decreasing trend outward, taking the CP urban agglomeration as the center. In addition, the UAs in the southern and southwestern regions showed both good annual average AQI and low fine particulate pollution while high ozone concentration pollution. The average annual AQI, fine particulate matter and ozone pollution in the TNS are also at a high level in 19 UAs. This is consistent with the level of the monthly primary pollutants mentioned above.

The World Health Organization (WHO) published new Global Air Quality Guidelines (AQGs), which recommend new air quality levels on 22 September 2021. As shown in Table 2 and Figure 5, almost half of the UAs have reached the second-level national standards of China and the first-stage interim target of the World Health Organization.

Table 2
Recommended AQG levels and interim targets

Pollutants	Averaging time	GB3095-2012		AQG 2021				AQG
		Level-1	Level-2	IT-1	IT-2	IT-3	IT-4	
PM _{2.5} (µg/m ³)	Annual	15	35	35	25	15	10	5
PM ₁₀ (µg/m ³)	Annual	40	70	70	50	30	20	10

3.4 Hourly variations in PM_{2.5}□PM₁₀ and O₃

As seen from the above analysis, the spatial distribution of changes and the concentrations of air pollutants shared a location similarity between adjacent UAs. Furthermore, to profile the diurnal changes in pollutant concentrations during the 13th Five-Year Plan, the hourly variations were calculated in seven directions. The results are shown in Fig. 6. From 2015 to 2019, the rates of O_3 concentration in hours significantly increased compared to particulate matter (PM) pollution, which was consistent with the average annual variation trends above. Overall, diurnal trends in O_3 concentration at UAs in all directions also showed a single peak, with the largest increments concentrating between 13:00 and 16:00, due to more frequent heat waves in recent times²⁹ and the fact that higher temperature, lower relative humidity, and stronger solar radiation at 16:00 favor more secondary pollutant production^{8,30}. However, the peak O_3 pollution spatially varied, exhibiting a relatively earlier trend in the southeastern region than in the northwestern region because of the Earth's rotation, making the eastern area receive direct sunlight first. The distance between the whiskers of the box plot in the southern city is the largest compared with the others, indicating that ground-level ozone concentration variations presented great dissimilarity in southern cities.

For PM pollution, there was a significant downward trend in all UAs. $PM_{2.5}$ reduction is more obvious in rush hours (10:00 and 22:00), which reveals the response to aggressive actions by the government to restrict motor vehicles³⁰. In addition, we noticed that the 'coal-to-gas and coal-to-electricity' transformation has substantially improved air pollution, particularly in northern China. It seems clear from these figures that the changing rate of $PM_{2.5}$ in northern regions was significantly higher than that of PM_{10} .

3.5 Sector emission source impacts on primary pollutants

Due to the availability of data, statistics on industry emissions are limited to 2015-2017. The average annual emission value of agricultural sources was too small to provide statistical significance. Fig. 7 only shows the contribution of four sector sources (industry, power, civil and transportation) to pollutants in 19 UAs from 2015 to 2017, where the dotted line represents the average of total emissions. As a result, near-surface ozone pollution is a secondary pollutant produced by the photochemical reaction of a series of precursors under the action of solar radiation. In particular, VOCs and NO_x are important precursors for ozone pollution. Therefore, we explore the emissions of these two important precursors in different urban agglomerations.

Sector pollution sources directly cause increases in $PM_{2.5}$, PM_{10} , nitrogen oxides, volatile organic compounds and other pollutants in the atmosphere. As seen from Figure 7(a), $PM_{2.5}$ is mainly derived from industrial sources, and the main high value areas are TJ, YRD and SP UAs. Meanwhile, in the three UAs, the total contribution of anthropogenic emission sources to particulate pollution declined the fastest, which is largely related to government intervention, industrial transformation and environmental governance. Approximately 50–75% of $PM_{2.5}$ in the northern UAs comes from industrial sources, while $PM_{2.5}$ in the southwestern UAs mainly comes from civil sources. This result is similar to the analysis of

PM_{2.5} sources in BTH in 2013 by Li et al. Regarding PM₁₀, industrial sources have the greatest influence on PM₁₀ in all UAs (Figure 7(b)). There is no significant regional difference in the impact of traffic sources on PM_{2.5} and PM₁₀. The contribution of traffic sources to PM_{2.5} in 19 UAs is 5-7% on average, and PM₁₀ tends to 0. By using the receptor model method,³¹ found that the contribution of gasoline dust to total suspended particulate matter (TSP) in Changzhou was less than 1%, confirming that exhaust gas was not the main contribution source of PM_{2.5}. For the total amount of particulate matter emissions, the total amount of PM_{2.5} pollution caused by anthropogenic emission sources is approximately 2.5 times that of PM₁₀.

Among the 19 urban agglomerations, NO_x and VOCs mainly come from industrial and traffic sources, with less contribution from civil and power sources (Figure 7(c), Figure 7(d)). During the study period, the NO_x emissions of most UAs decreased, but the CY, CG and CC UAs in the southwest, WSS in the eastern and BG urban agglomerations all showed an increasing trend of NO_x. This is mainly concentrated in the increase in industrial sources, which can also be seen from the increase in industrial production in the south. The contribution rate of power sources to VOCs in urban agglomerations is low and can be ignored.

From the perspective of time series changes, the contribution rate of anthropogenic emission sources to particulate pollution is decreasing, but for gas pollutants, nearly half of UAs show an increasing trend of VOCs and NO_x. In addition, VOCs high value areas are mainly concentrated in the YRD, PRD, BTH and other state-level urban agglomerations.

4 Conclusions

Other studies conducted on the temporal and spatial variations in air primary pollutants in 19 UAs during the 13th Five-Year Plan are not sufficient. Based on air quality monitoring data and using mathematical statistics and cartography, this paper analyzed the spatiotemporal characteristics of primary pollutants over 19 Chinese UAs. Although we have achieved remarkable results in pollution control during the 13th Five-Year Plan period, PM and O₃ pollution are still serious problems in China. Returning to the question posed at the beginning of this study, it is now possible to state that the main conclusions are as follows:

(1) Generally, from the daily changes of all primary pollutants, 37% of the primary pollutants had no shift during the 13th Five-Year Plan period. PM_{2.5}, PM₁₀ and O₃ were the main primary pollutants, especially PM_{2.5}. The proportion of clean air days has increased significantly. NO₂ pollution was rendered nonsignificant.

(2) From the perspective of monthly distribution of primary pollutants, clean days (where AQI<50) occur mainly in South and Southwest China during summer. As the primary pollutant, PM_{2.5} is primarily concentrated in December, January and February, and PM₁₀ is primarily concentrated in October-November and March-April. The O₃ pollution in the PRD and BG is mainly concentrated from August to

November. The northern, northwestern, northeastern, central and eastern UAs have similar monthly primary pollutant distributions.

(3) In terms of air quality differences in UAs, the annual average AQI showed a gradually decreasing trend outward, taking the Central Plains urban agglomeration as the center. The Central Plains UA has the highest annual average AQI, and the particulate matter pollution and ozone are both high, suggesting that the control effect is not obvious in the central region. The average annual $PM_{2.5}$ and PM_{10} concentrations decreased, most significantly in Harbin-Changjiang (HC) and mid-southern Liaoning (MSL) in the northeast, while there was little difference in annual ozone concentration. In contrast, the annual mean ozone pollution displayed the greatest enhancement, while $PM_{2.5}$ and PM_{10} showed a minimal decrease in Taiyuan-Jinzhong (TJ) UA in northern China.

(4) There were significant differences in the intensity and direction of each sector emission source in nineteen UAs. The total amount of PM discharged from the emission sources of TJ, YRD and SP UAs was much higher than those of others. $PM_{2.5}$ and PM_{10} are mainly derived from industrial sources. The contribution rate of anthropogenic emission sources to particulate pollution is decreasing, but for gas pollutants, nearly half of UAs show an increasing trend of VOCs and NO_x .

Based on the above findings, this paper proposes the following policy recommendations. First, it is necessary to pay more attention to emission reduction efforts in national urban agglomerations. Second, PM and ozone pollution are important pollution types in UAs in China, and they should be coordinated in prevention and control. The government should strengthen regional joint prevention and control and establish a compensation and incentive mechanism for cities with weak economies. Third, different UAs should formulate differentiated PM and O_3 emission reduction strategies according to their own social and economic conditions. Industrial emissions are still an important source of air pollution, and the industrial structure should be optimized based on local resources. We will encourage energy enterprises to develop energy and introduce new energy technologies. We will improve cleaner production technology and build a monitoring platform for urban greening.

Declarations

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Figures

Figure 1

Geographical locations of 19 UAs in China

Figure 2

Transfer change matrix heatmap of primary pollutants from 2015 to 2019

Figure 3

Monthly Calendar of primary pollutants in UAs in 2019

Figure 4

Annual variation trends (slope values) of three major pollutants in each urban agglomeration of China from 2015 to 2019

Figure 5

Numerical distributions of three major pollutant concentrations in urban agglomerations in 2019

Figure 6

Box plots of hourly three major pollutant rates across urban agglomerations.

Figure 7

Average industrial emission of pollutants in 19 UAs