Study on Temporal and Spatial Evolution Characteristics of Air Quality in Urban Agglomerations in Northwestern China

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Abstract: This paper analyzes the air quality monitoring data of Qingyang, Tianshui and Pingliang in northwestern China in 2015 by time series analysis. The research results are as follows: (1) the concentrations of $PM_{2.5}$, PM_{10} and SO_2 in the three cities began to decline in March, reached a minimum in September before rising gradually; (2) concentrations of $PM_{2.5}$, PM_{10} and SO_2 in the three cities were low in summer and autumn, but high in winter and spring; (3) the coefficient of correlation among $PM_{2.5}$, PM_{10} and SO_2 in the three cities was greater than 0.589, indicating a strong correlation.

1 Introduction

China has experienced rapid industrialization and urbanization with the development of technology and economy since the reform and opening-up. The advancement of industrialization and urbanization is accompanied by huge consumption of resources and severe damages to the environment. The extensive development model with high energy consumption and low efficiency has further aggravated the destruction of the ecological environment and caused a series of environmental problems [1]. Air pollution will not only cause serious economic losses [2], but also reduce atmospheric visibility [3]. The particulate matter in the air can induce respiratory diseases [4] and cardiovascular and cerebrovascular diseases [5], having a significant impact on human health. According to statistics, about 6.1 million people died of air pollution-related diseases [6] in 2016.

The monitoring and characteristic analysis of air quality have become the current research hotspots of Chinese and foreign scholars in recent years. Mu et al. [7] studied a nationwide large-scale smog incident in China in January 2013 and estimated that the incident caused about RMB 23 billion direct economic losses to traffic and health based on the publicly reported data. Liao et al. [8] studied the variation trend of air pollutant concentration in Shenzhen from 2006 to 2016. The results showed that concentrations of SO_2, PM_{10} and NO_2 in Shenzhen presented an overall downward trend from 2006 to 2016 and that the air quality had improved significantly year by year but there was still a big gap from air quality standards of developed countries. Existing studies mostly focus on municipalities directly under the central government such as Beijing, Shanghai and Tianjin and capital cities in central and eastern China. Related studies in northwestern China also focus on provincial capital cities. The overall research on the air quality in small underdeveloped urban agglomerations has not been reported yet.

Qingyang, Pingliang and Tianshui are located in northwestern China, the climate is the warm temperate zone, continental monsoon climate. This study analyzes and evaluates the air quality status of the three cities in 2015 and analyzes the correlation of cities and pollutants with the multiple regression method with a view to provide data support for air pollution prevention and control decision-making and comprehensive cross-regional management in third- and fourth-tier cities in under-developed regions in northwestern China.

2 Data and method

2.1 Data source

The air quality data of Qingyang, Pingliang and Tianshui in 2015 came from the China Air Quality Online Monitoring and Analysis Platform (https://www.aqistudy.cn/). The air quality monitoring data included average concentrations of $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2 and O_3, etc.

2.2 Evaluation criteria

The evaluation criteria used in this study are from the *Ambient Air Quality Standard* (BG3095-2012)[9] .

2.3 Research method

The analysis was mainly conducted with the time series analysis method and the multiple regression method in statistics, and the data was processed preliminarily based on Excel 2007. The variation trend of $PM_{2.5}$, PM_{10}, SO_2,

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NO_2 and O_3 concentrations in each city was analyzed with the software Origin, and the correlation of pollutants and cities with the software SPSS. Seasons were divided by the combination of astronomical seasons and climatic seasons.

3 results and analysis

3.1 Variation characteristics of monthly average mass concentrations of pollutants

Figure 1 shows variation curves of the monthly average $PM_{2.5}$ data of the three cities in Gansu Province in 2015. According to the figure, the $PM_{2.5}$ concentration in all the three cities was low in the middle and high on both sides, and had a small peak in July. The $PM_{2.5}$ concentration in Pingliang was slightly higher than that in the other two cities, with a maximum of 83 μg/m^3 and a minimum of 24 μg/m^3.
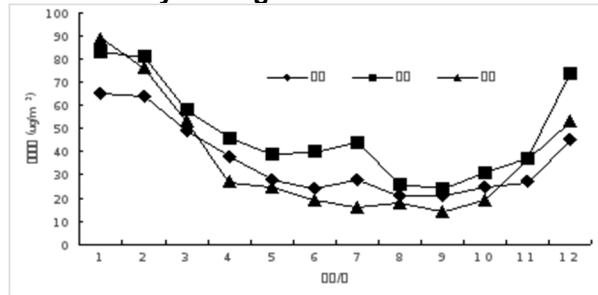

Figure 1. Variation curves of the monthly average mass concentrations of $PM_{2.5}$ in the three cities in 2015

Figure 2 shows variation curves of the monthly average PM_{10} data of the three cities in Gansu Province in 2015. According to the figure, the PM_{10} concentration in Pingliang was the highest among the three cities, with a maximum of 149 μg/m^3 and a minimum of 49 μg/m^3.
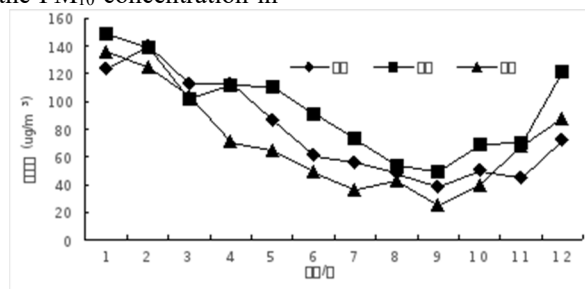

Figure 2. Variation curves of the monthly average mass concentrations of PM_{10} in the three cities in 2015

Figure 3 shows variation curves of the monthly average SO_2 data of the three cities in 2015. According to the figure, the variation curves of SO_2 concentrations in the three cities were all U-shaped; the SO_2 concentrations were low and well consistent, ranging from 5 to 16 μg/m^3 from April to October, and increased significantly in other months. From November to March, the SO_2 concentration in Pingliang was the lowest among the three cities, ranging from 27 to 45 μg/m^3.
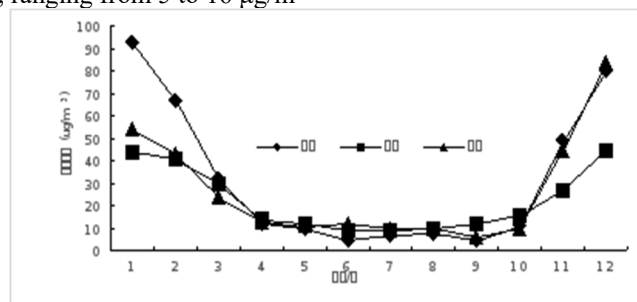

Figure 3. Variation curves of the monthly average mass concentrations of SO_2 in the three cities in 2015

Figure 4 shows variation curves of the monthly average NO_2 data of the three cities in Gansu Province in 2015. The annual average concentrations of NO_2 in Qingyang, Pingliang and Tianshui were 20.42, 44.33, and 33.8 μg/m^3 respectively. NO_2 concentrations in Pingliang and Qingyang had small variations, but the concentration in Pingliang was much higher than that in Qingyang. The concentration of NO_2 in Qingyang was the lowest, ranging from 12 to 95 μg/m^3. That in Tianshui had the greatest variation.
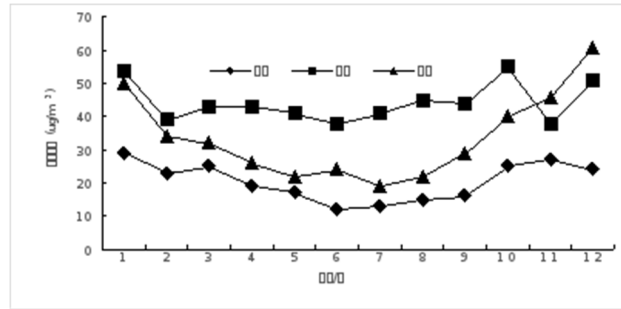
Figure 4. Variation curves of the monthly average mass concentrations of NO_2 in the three cities in 2015

Figure 5 shows variation curves of the monthly average mass concentrations of O_3 in the three cities in eastern Gansu Province in 2015. Variation curves of O_3 were completely different from those of other pollutants, showing an inverted "U" shape. The O_3 concentrations in the cities were the lowest in November, ranging from 37 to 38 $\mu g/m^3$, and high from April to July. The highest O_3 concentration in Qingyang was 134 $\mu g/m^3$.
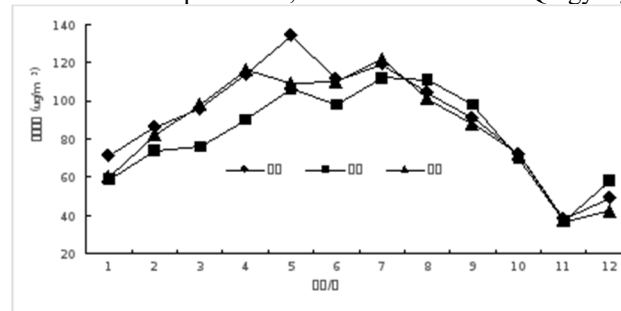

Figure 5. Variation curves of the monthly average mass concentrations of O_3 in the three cities in 2015

In summary, the concentrations of $PM_{2.5}$, PM_{10} and SO_2 in the three cities in eastern Gansu showed a downward trend from March, fell to the lowest level in September and then increased gradually, among which the SO_2 concentration remained at a low level from April to October and increased sharply thereafter. The NO_2 concentrations in the three cities were slightly higher in November and December. The variation of their O_3 concentrations was different from that of other pollutants, showing an inverted "U" shape.

3.2 Correlations between air pollutants in different cities

Correlation analysis refers to the analysis of two or more related variable elements to measure their correlation.

Table 1 shows the results of Spearman correlation analysis of different pollutants in the same city for the three cities in 2015.

Table 1. Spearman correlation coefficients of pollutants in the three cities in 2015

City	Pollutants	$PM_{2.5}$	PM_{10}	SO_2	NO_2	O_3
Qingyang	$PM_{2.5}$	1				
	PM_{10}	.882**	1			
	SO_2	.814**	.589*	1		
	NO_2	.569	.289	.839**	1	
	O_3	-.207	.102	-.648*	-.739**	1
Pingliang	$PM_{2.5}$	1				
	PM_{10}	.937**	1			
	SO_2	.628*	.618*	1		
	NO_2	-.004	-.018	.351	1	
	O_3	-.396	-.389	-.844**	-.192	1
Tianshui	$PM_{2.5}$	1				
	PM_{10}	.979**	1			
	SO_2	.915**	.887**	1		
	NO_2	.685*	.567	.713**	1	
	O_3	-.523	-.385	-.556	-.907**	1

**. At the level of 0.01 (two-tailed), indicating significant correlation. *. At the level of 0.05 (two-tailed), indicating significant correlation.

Table 1 indicates a strong positive correlation among $PM_{2.5}$, PM_{10} and SO_2 in the three cities with a coefficient of correlation between 0.589 and 0.979, a positive correlation between NO_2 and $PM_{2.5}$, PM_{10} and SO_2 in Qingyang and Pingliang and a negative correlation between the same in Pingliang, and a strong negative correlation between O_3 and NO_2 in Qingyang and Tianshui. The reason is that O_3 in the air near the ground in urban

areas is generated by a series of photochemical reactions of its precursor NOx [10]:

$$NO_2 + hv \rightarrow NO + O \qquad (1)$$
$$O_2 + O \rightarrow O_3 \qquad (2)$$
$$O_3 + NO \rightarrow N_2 + O_2 \qquad (3)$$
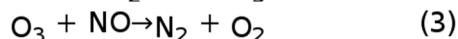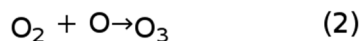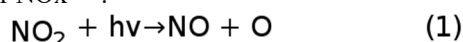
In the real environment, the more oxidizing free radical present will react with NO, leading to the termination of the zero-cycle reaction in formulas 1 to 3 and thereby the accumulation of O_3 concentration [25] as shown in formulas (4) and (5).

$$OH + VOC_S \rightarrow RO_2 + CH_2O \qquad (4)$$
$$O_2 + NO \rightarrow NO_2 + PAN \qquad (5)$$
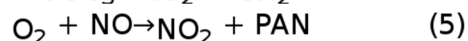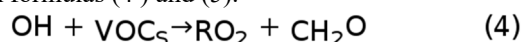
The reactions above show that the most fundamental cause of O_3 generation is the photolysis of NO_2 . Therefore, NO_2, as one of the precursors of O_3, shows a good negative correlation with the concentration. However, O_3 and NO_2 had a weak correlation in Pingliang due to the high level of the NO_2 concentration throughout the year in combination with the influence of volatile organic compounds (VOCS) and other pollutants produced by the chemical industry and other industries [11].

Table 2 shows the results of further analysis of the Spearman correlation of the same pollutant among different cities. Except for the correlation coefficients of NO_2 between Pingliang and Qingyang and between Pingliang and Tianshui, the others were close to or greater than 0.8, indicating a strong correlation. According to Figure 5, the NO_2 concentration in Pingliang remained at a high level throughout the year, resulting in the correlation coefficients of NO_2 between Qingyang and Pingliang and between Pingliang and Tianshui ranging from 0.3 to 0.4. Studies have shown that the contribution rate of motor vehicles to NO_2 is about 60% [12]. Pingliang as an important coal-producing area in Gansu Province, it had an annual output of raw coal of 21.3556 million tons in 2015 . Except for mining and processing, the tail gas emission caused by the transportation of a large amount of raw coal was much higher compared to the other two cities, which is also an important reason for this phenomenon.

Table 2. Spearman correlation coefficient of the same pollutant among different cities in 2015

Pollutants	City	Qingyang	Pingliang	Tianshui
PM$_{2.5}$	Qingyang	1		
	Pingliang	.944**	1	
	Tianshui	.873**	.828**	1
PM$_{10}$	Qingyang	1		
	Pingliang	.918**	1	
	Tianshui	.827**	.867**	1
SO$_2$	Qingyang	1		
	Pingliang	.935**	1	
	Tianshui	.878**	.795**	1
NO$_2$	Qingyang	1		
	Pingliang	.347	1	
	Tianshui	.835**	.361	1
O$_3$	Qingyang	1		
	Pingliang	.886**	1	
	Tianshui	.958**	.869**	1

**.At the level of 0.01 (two-tailed), indicating significant correlation.

4 Discussion

4.1 Time series analysis of air quality

PM$_{2.5}$ and PM$_{10}$ concentrations in all the three cities were low in summer and autumn and high in winter and spring. The concentration of SO$_2$ showed a typical "U" shape, remained at a low level from April to October and increased significantly in other months. That of O$_3$ showed an inverted "U" shape with the characteristic of being "high in spring and summer and low in autumn and winter". This agrees with the research results of Wang et al. [13] on urban air quality in the Fenwei Plain. These variation characteristics are related to the combined effect of pollutant emissions, meteorological conditions, and photochemical reactions. In summer, there are fewer combustion sources and pollution emissions, strong vertical diffusion of the atmosphere, more precipitation and strong scavenging action, which can lower the concentration of pollutants. A large amount of pollutants from central heating and the emission of fossil fuel combustion coupled with unfavorable diffusion conditions during the heating period in winter (mid-November to mid-March of the following year) in comparison with other seasons result in a high concentration of pollutants . NO$_2$ mainly comes from automobile exhaust, power plants and industrial activities, among which automobile exhaust is the main emission source [14]. Huating Coal Field in Pingliang is the largest coalfield in Gansu Province. The transportation and deep processing of coal produce a large amount of NO2, resulting in a high NO$_2$ concentration throughout the year in Pingliang.

4.2 Correlation analysis and reasons

There was a strong positive correlation among PM$_{2.5}$, PM$_{10}$ and SO$_2$ in the three cities, with a correlation coefficient between 0.589 and 0.979. Their main pollutants were all particulate matter, which was the same as in other parts of China and was consistent with the research results of scholars such as Sun [15] on northern cities. As a coal resource-based city, Pingliang was faced with a large amount of NO$_2$ from the mining, processing and transportation of raw coal.

According to the analysis of the correlation among

different cities for the same pollutant, the other coefficients were close to or greater than 0.8, indicating a strong correlation, except for the correlation coefficient of NO_2 between Pingliang and Qingyang and between Pingliang and Tianshui. The three cities, all located in Gansu Province in northwestern China, have similar geographical environment and climate, city scale and level of social and economic development which result in their strong correlation.

4.3 Advantages and limitations

This paper studies the characteristics and correlation of air quality, monthly average mass concentrations of pollutants and AQI in small urban agglomerations in northwestern China, explores their underlying variation features and regional synergic relationship and discusses the variation mechanism. In addition, it conducts a multi-scale analysis on the evolution of each pollutant in time series and provides more research results.

However, it only analyzes the evolution characteristics of the three cities in 2015 and lacks research on large-scale evolution rules. Moreover, urban air quality is also affected by meteorological factors, population, economic development and other factors, which will be studied in future work.

5 Conclusion

In summary, this paper makes the following conclusions:

1) The concentrations of $PM_{2.5}$, PM_{10} and SO_2 in the three cities showed a downward trend from March, fell to the lowest level in September and then increased gradually, among which the SO_2 concentration remained at a low level from April to October and increased sharply thereafter. The NO_2 concentration in Pingliang was 2.17 times that of Qingyang and 1.31 times that of Tianshui. The variation of their O_3 concentrations was different from that of other pollutants, showing an inverted "U" shape.

2) In the three cities, particulate matter had a higher over-limit ratio. The over-limit ratio of PM_{10} in Qingyang was slightly higher than that of $PM_{2.5}$, and the ratio of fine particulate matter in Pingliang and Tianshui was higher than that of coarse particulate matter. SO_2 and NO_2 concentrations had a low over-limit ratio and exceeded the standard only in a few months of the year. The concentration of O_3 did not exceed the standard.

3) According to the analysis of the Spearman correlation among different pollutants in the three cities, the correlation coefficient of $PM_{2.5}$, PM_{10} and SO_2 was between 0.589 and 0.979, indicating a strong correlation. According to the analysis of the Spearman correlation among different cities for the same pollutant, the other correlation coefficients except for NO_2 were all high.

These findings can help in better understanding the evolution characteristics of air quality in small urban agglomerations in northwestern China and provide a reference for the application of policies. $PM_{2.5}$ and PM_{10} concentrations in Pingliang were slightly higher than those in the other two cities due to the exhaust gas produced by coal processing, production and transportation. Qingyang,

which is also positioned as an energy base, should learn from Pingliang, accelerate industrial upgrading and improve scientific and technological innovation capabilities to avoid deterioration of air quality due to energy mining, transportation and production.

Acknowledgment：

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