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Original Research

Spatial Distribution of Air Pollution and Its Relationship with Meteorological Factors: A Case Study of 31 Provincial Capitals in China

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Abstract

Analyzing the spatial distribution of meteorological factors and air pollutants and its correlation is of great importance for urban air pollution prevention. This study explored the spatial distribution of meteorological factors and air pollutants, analyzed the correlation between meteorological factors and air pollutants, and revealed the main meteorological factors that influence the air pollutants in 31 provincial capitals of China during 2010-2020. The results show that the spatial distribution characteristics of air pollutants and the days of air quality equal to or above grade II in 31 provincial capitals of China during 2010-2020 vary obviously. The days of air quality equal to or above grade II are negatively correlated with the annual average concentration of NO_2 and annual average concentration of PM_{10} during 2010-2020 and annual average concentration of SO_2 during 2010 to 2018. The temperature, precipitation, and relative humidity are the main meteorological factors affecting the air quality in different seasons in 31 provincial capitals of China during 2010-2020. The findings will provide a scientific basis for atmospheric environment control and urban air quality forecast.

Keywords: air pollutant, meteorological factors, air quality, correlation analysis

Introduction

With the rapid growth of China's economy, the acceleration of urbanization, and the rapid growth of urban population, the problem of urban air pollution has become increasingly prominent, which restricted the sustainable development of society and seriously threatened human health [1-3]. The air pollutants affecting urban air quality mainly included SO_2, NO_2, PM_{10}, CO, O_3, and $PM_{2.5}$ [4-5]. The concentration of air pollutants was mainly affected by pollution source emission, meteorological factors, landform, and pollutant characteristics [1]. When the pollution source, landform, and pollutant characteristics were relatively stable, the concentration of air pollutants was mainly affected by meteorological factors [1]. A number of studies also had found positive or negative correlations between the concentrations of air pollutants

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and meteorological factors [6-8]. Therefore, it has important significance to analyze spatial distribution of air pollution, reveal correlation between air pollutants and meteorological factors and identify the main meteorological factors influencing the urban air quality.

Many scholars had paid attention on the spatial patterns or spatial-temporal distribution of air pollution [5, 8-14]. Hu et al. [5] studied the spatial-temporal changes in air pollution, including SO_2, NO_2, O_3, CO, PM_{10}, and $PM_{2.5}$, from 2006 to 2019 in the Pearl River Delta. Zhou et al. [8] analyzed the concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3, and air quality index in 368 cities of China during 2015-2018. Xiao et al.[9] presented the satellite-based monthly $PM_{2.5}$ concentrations from 2000 to 2018 with a 1-km resolution and complete spatial-temporal coverage to analyze the spatial pattern of $PM_{2.5}$ pollution in China.

A lot of scholars also have conducted extensive research on the correlation between the concentrations of air pollutants and meteorological factors [5-7, 15-18]. Zhang et al. [15] analyzed the mass concentration characteristics of air pollutants and change characteristics of air quality in Shenyang from 2014 to 2019 and the effect of meteorological factors on the mass concentration of atmospheric pollutants PM_{10}, $PM_{2.5}$, and O_3. Ulpiani et al. [17] studied the intercorrelation between the meteorological factors and pollutant concentrations in Sydney, Australia, and showed that strong correlation exists between temperature and NO_2, and relative humidity and $PM_{2.5}$. Barzeghar et al. [18] explored the relationships between air pollutants and meteorological factors using Spearman's rank correlation test and demonstrated that NO_2, NO, SO_2, and CO have a obvious correlation with meteorological factors.

Moreover, some scholars had analyzed the relation between the meteorological factors and air quality [19-21]. Dutta et al. [19] analyzed the correlation between the meteorological parameters and the air-quality index developed by four major pollutants including $PM_{10,}$ $PM_{2.5}$, NO_2, and SO_2. Zhu et al. [20] used the Granger causality test to analyze the intrinsic dynamic relationship between meteorological factors and Air Quality Index in the areas of Zhongshan, Shilin, and Yangmingshan of Taipei City in 2018. Some other scholars had studied the correlation between the air pollutants and air quality [22-24]. Zhang et al. [23] used generalized additive models to derive LUR models of air pollutants including $PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3 and air quality index in Beijing by considering the potential nonlinear relationship between predictor variables.

Although many studies explored the influence of meteorological factors on air quality from different contexts, a deep understanding on the correlation between meteorological factors and air pollutants in different months and the identification of main meteorological factors that influenced the air quality in large regions with many cities and different meteorological factors is still lacking. Here, we analyzed the spatial distribution of meteorological factors and air pollutants and the correlation between meteorological factors and air pollutants in 31 provincial capitals of China from 2010-2020. We revealed the main meteorological factors influencing the air quality in 31 provincial capitals of China from 2010-2020. The aims of this study are as follows: (a) to show the spatial distribution characteristics of meteorological factors and air pollutants in 31 provincial capitals of China from 2010-2020; (b) to analyze the correlation between the meteorological factors and air pollutants in 31 provincial capitals of China from 2010-2020; and (c) to identify the main meteorological factors influencing the air quality in 31 provincial capitals of China from 2010-2020.

Material and Methods

The data of meteorological factors, including average air pressure, average temperature, extreme maximum temperature, extreme minimum temperature, precipitation, sunshine duration, and relative humidity, in 31 provincial capitals of China during 2010-2020 were collected from China Meteorological Yearbook 2011-2021. The statistical data of the annual average concentration of SO_2, annual average concentration of NO_2, and annual average concentration of PM_{10} during 2010-2020 were collected from China Statistical Yearbook 2011-2021. The vector maps of China's administrative regions were obtained from the geospatial data cloud (www.gscloud.cn). The Pearson correlation analysis was analyzed on IBM SPSS Statistics Version 25. The spatial distribution characteristics of air quality in 31 provincial capitals in China was analyzed on ArcGIS Software Version 10.6.

Pearson Correlation Coefficient

The Pearson Correlation Coefficient model is a statistical indicator used to quantitatively describe the correlation between variables [25]. This paper used the Pearson Correlation Coefficient model to analyze the correlation between the air pollutants and air quality, and the meteorological factors and air pollutants in 31 provincial capitals of China during 2010-2020. The Pearson Correlation Coefficient model can be calculated as follows [19, 25-26]:

$$R = \left| \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \right|$$

where R is value of Pearson Correlation Coefficient; x_i and y_i are different values of the factor $\bar{x}$ and $\bar{y}$

respectively; $\bar{x}$ and $\bar{y}$ are the average value of factor x and y respectively; n is the number of factor value.

Results

Spatial Distribution Characteristics of the Annual Average Concentration of Air Pollutants in 31 Provincial Capitals of China during 2010-2020

The spatial distribution characteristics of the annual average concentration of air pollutants in 31 provincial capitals of China during 2010-2020 were obtained on ArcGIS Software Version 10.6 and graded in accordance with the ambient air quality standards [27]. The results are shown in Fig. 1. The spatial distribution characteristics of the annual average concentration of air pollutants in 31 provincial capitals of China varied obviously. As shown in Fig. 1a), the annual average concentration of SO_2 in all provincial capitals of China during 2010-2020 belonged to the first-class and second-class concentration limit. The highest annual average concentration of SO_2 during 2010-2020 was observed in Taiyuan (54.73 μg/m^3), followed by Shenyang (51.09 μg/m^3). The lowest annual average concentration of SO_2 during 2010-2020 was found in Haikou (5.91 μg/m^3). As shown in Fig. 1b), the annual average concentration of NO_2 during 2010-2020 of about half of the provincial capitals of China was under 40 μg/m^3 and belonged to the first-class concentration limit. However, the 17 provincial capitals in China occupying 54.84% exceeded 40 μg/m^3 and belonged to the second-class concentration limit. The highest annual average concentration of NO_2 during 2010-2020 was observed in Lanzhou and Taiyuan (54.27 μg/m^3), followed by Chengdu (50.91 μg/m^3). The lowest annual average concentration of NO_2 during 2010-2020 was found in Haikou (14.82 μg/m^3). As shown in Fig. 1c), the annual average concentration of PM_{10} during 2010-2020 in most provincial capitals of China exceeded 70 μg/m^3. The annual average concentration of PM_{10} during 2010-2020 in Haikou was under 40 μg/m^3 and belonged to the first-class concentration limit. The annual average concentration of PM_{10} during 2010-2020 in Lhasa, Fuzhou, Guangzhou, Kunming, Shanghai, Guiyang and Changsha were under 70 μg/m^3 and belonged to the first-class and second-class concentration limit. The highest annual average concentration of PM_{10} during 2010-2020 was observed in Shijiazhuang (147.36 μg/m^3), followed by Jinan (130.73 μg/m^3). The lowest annual average concentration of PM_{10} during 2010-2020 was found in Haikou (37.82 μg/m^3).

In view of statistical data results, on the whole, the trend of annual concentration of SO_2, NO_2, and PM_{10} in most of 31 provincial capitals of China were gradually decreased from 2010 to 2020. However, the annual concentration of SO_2, NO_2, and PM_{10} in many provincial capitals of China including Shijiazhuang, Taiyuan, Shenyang, Jinan, Zhengzhou and Yinchuan in 2013 were obviously higher than the other years. The days of air quality equal to or above grade II in these cities in 2013 were obviously fewer than the other years. From 2010 to 2020, the annual concentration of SO_2, NO_2, and PM_{10} decreased most were 80 μg/m^3 in Urumqi, 28 μg/m^3 in Beijing and 79 μg/m^3 in Lanzhou respectively. Meanwhile, the annual concentration of SO_2, NO_2, and PM_{10} decreased least were 0 μg/m^3 in Lhasa, -25 μg/m^3 in Taiyuan and -3 μg/m^3 in Shijiazhuang and Hohhot respectively. The days of air quality equal to or above grade II increased most was 89 in Lanzhou and decreased most was 114 in Shijiazhuang.

Correlation Analysis Results between Air Pollutants and the Days of Air Quality Equal to or above Grade II in 31 Provincial Capitals of China during 2010-2020

As shown in Fig. 1d), the spatial distribution characteristics of the average days of air quality equal to or above grade II in 31 provincial capitals of China during 2010-2020 had obvious difference. Fig. 1d) showed that most of the provincial capitals in China, including Lhasa, Fuzhou, Guiyang, Kunming, Nanning, Haikou, Guangzhou, and Nanchang, had long average days of air quality equal to or above grade II during 2010-2020. Shijiazhuang, Zhengzhou, Jinan, Taiyuan, and Xi'an had short average days of air quality equal to or above grade II during 2010-2020. The longest average days of air quality equal to or above grade II during 2010-2020 were observed in Kunming (357.18), followed by Haikou (355). The shortest average days of air quality equal to or above grade II during 2010-2020 were found in Shijiazhuang (194.55).

As shown in Table 1, the days of air quality equal to or above grade II during 2010-2020 had significant negative correlation with concentration of NO_2, and PM_{10}. The highest correlation was observed between annual average concentration of PM_{10} and the days of air quality equal to or above grade II in 2012 (-0.904), followed by the correlation between annual average concentration of PM_{10} and the days of air quality equal to or above grade II (-0.902).

As shown in Table 1, the days of air quality equal to or above grade II in 31 provincial capitals of China during 2010-2020 were mainly affected by the annual average concentration of NO_2, and annual average concentration of PM_{10}. However, the annual average concentration of SO_2 did not influence continuously the days of air quality equal to or above grade II in 31 provincial capitals of China during 2010-2020.

Correlation Analysis Results between the Meteorological Factors and Air Pollutants in 31 Provincial Capitals of China

As shown in Tables 2 to 8, the annual average concentration of SO_2 was correlated with air

Table 1. Correlation analysis results between air pollutants and the days of air quality equal to or above grade II in 31 provincial capitals of China during 2010-2020.

Air pollutants \ Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Annual average concentration of SO_2 (μg/m^3)	-0.519**	-0.467**	-0.504**	-0.656**	-0.526**	-0.460**	-0.417*	-0.506**	-0.444*	-0.234	-0.334
Annual average concentration of NO_2 (μg/m^3)	-0.447*	-0.358*	-0.497**	-0.746**	-0.685**	-0.795**	-0.840**	-0.840**	-0.819**	-0.733**	-0.663**
Annual average concentration of PM_{10} (μg/m^3)	-0.902**	-0.901**	-0.904**	-0.856**	-0.882**	-0.869**	-0.861**	-0.906**	-0.893**	-0.876**	-0.895**

**. Significant correlation at 0.01 level (bilateral),*. Significant correlation at 0.05 level (bilateral).

temperature, extreme maximum temperature, extreme minimum temperature, precipitation, sunshine duration, and relative humidity in different months and degrees in 31 provincial capitals of China during 2010-2020. The air temperature, extreme minimum temperature and precipitation were obviously correlated with the SO_2 concentration from January to December in 31 provincial capitals of China during 2010-2020. The extreme maximum temperature, sunshine duration, and relative humidity were correlated with the SO_2 concentration from October to March, from February to June, and from January to June, respectively.

Tables 2 to 8 indicated that the annual average concentration of NO_2 was not particularly affected by meteorological factors and only correlated with air pressure from January to April and from September to December, extreme maximum temperature in January, February, June, July, August and December, air temperature in February and precipitation in October. The annual average concentration of PM_{10} was correlated with precipitation from January to December in 31 provincial capitals of China during 2010-2020, temperature including air temperature, extreme maximum temperature and extreme minimum temperature in cold season, sunshine duration from March to May, relative humidity from January to July.

The air pressure only influenced the annual average concentration of NO_2. The air temperature, extreme maximum temperature and extreme minimum temperature mainly affected the annual average concentration of SO_2 and the annual average concentration of PM_{10} in cold season. The extreme minimum temperature affected the annual average concentration of NO_2 in cold and hot seasons. The precipitation affected the annual average concentration of SO_2 and the annual average concentration of PM_{10} all year round. The sunshine duration just influenced the annual average concentration of SO_2 and the annual average concentration of PM_{10} in spring or early summer. The relative humidity influenced the annual average concentration of SO_2 and the annual average concentration of PM_{10} lasting about half a year or above.

On the basis of the above results, the temperature including air temperature, extreme maximum temperature, and extreme minimum temperature, precipitation, and relative humidity were identified as the main meteorological factors influencing the air quality in 31 provincial capitals of China during 2010-2020.

Discussion

In this study, we showed the spatial distribution characteristics of air pollutants and the days of air quality equal to or above grade II and revealed the correlation between the meteorological factors and air pollutants and main meteorological factors influencing

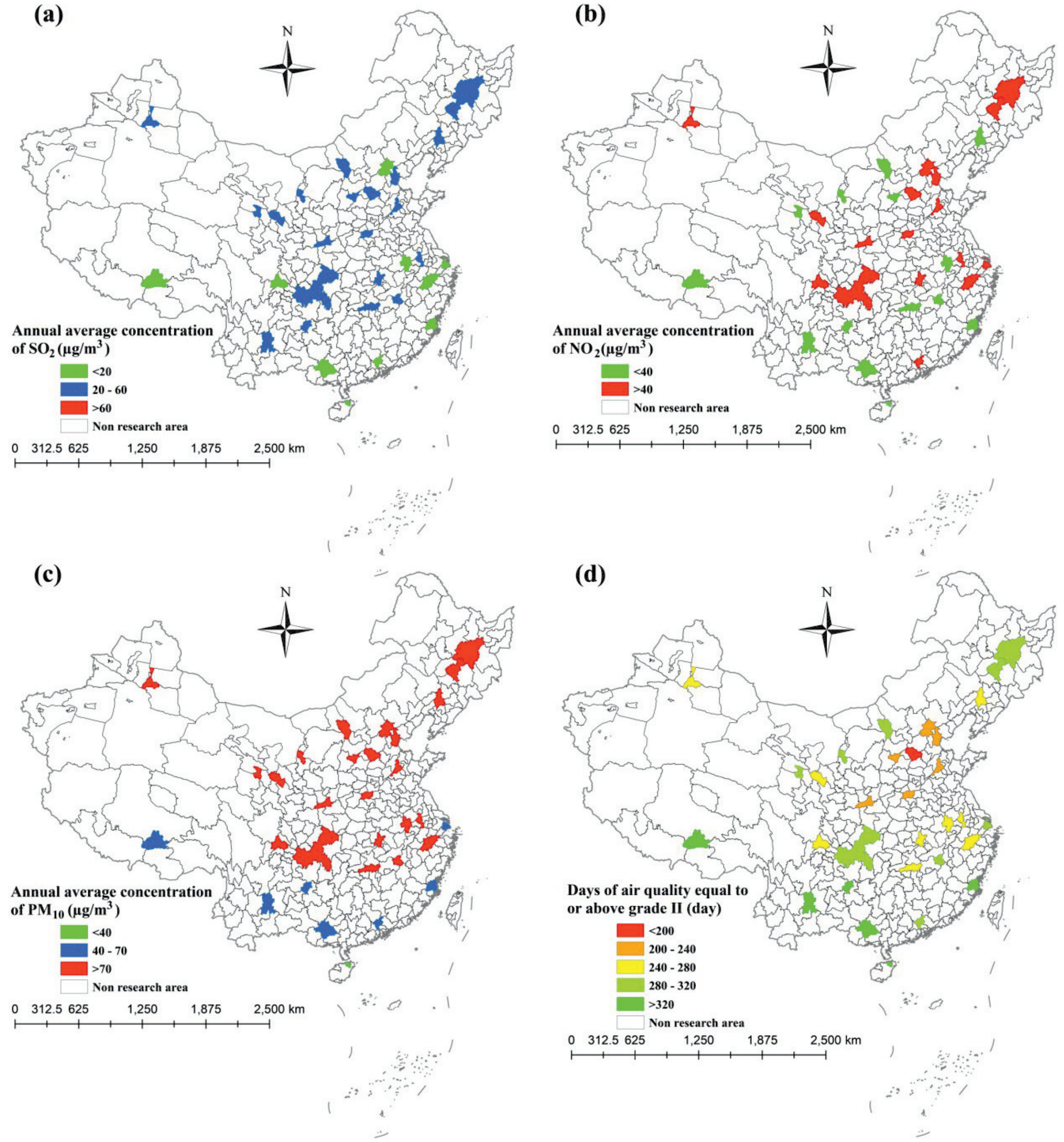

Fig. 1 Spatial distribution characteristics of annual average concentration of air pollutants and the days of air quality equal to or above grade II in 31 provincial capitals of China during 2010-2020.

the air pollutants in 31 provincial capitals of China during 2010-2020.

The spatial distribution characteristics of air pollutants in 31 provincial capitals of China exhibited obvious differences, which were consistent with the previous studies conducted by Wang et al. [28]. Previous studies also pointed that the spatial distribution of urban air pollutants was uneven [2, 5, 8-10]. The meteorological conditions, geographical situation, and emission of pollution source influenced the concentration of air pollutants [1, 5, 29]. Some studies have demonstrated that the concentrations of air pollutants were positively or negatively correlated with meteorological factors [6-8]. Our results revealed the correlation between the meteorological factors and air pollutants in 31 provincial capitals of China. Previous studies demonstrated that the concentrations of air pollutants and meteorological factors were correlated in Beijing [30], western China [2], Shenyang [15], the Pearl River Delta [5], and Sydney [16].

The air pollutants, including SO_2, NO_2, and PM_{10}, were selected in this study. The air pollutants such as SO_2, NO_2, PM_{10}, CO, O_3, and $PM_{2.5}$ were commonly measured and widely adopted in many studies to analyzed the air quality [2, 5, 14, 23]. The air pressure, air temperature, extreme maximum temperature,

Table 2. The average correlation analysis results between air pollutants and air pressure in 31 provincial capitals of China during 2010-2020.

Air pollutants \ Month	1	2	3	4	5	6	7	8	9	10	11	12
Annual average concentration of SO_2 (μg/m^3)	0.004	0.002	-0.003	-0.006	-0.008	-0.007	-0.009	0.001	0.006	0.007	0.004	0.003
Annual average concentration of NO_2 (μg/m^3)	0.364*	0.362*	0.358*	0.355*	0.354	0.351	0.347	0.354	0.361*	0.364*	0.363*	0.365*
Annual average concentration of PM_{10} (μg/m^3)	0.092	0.089	0.083	0.079	0.077	0.075	0.071	0.082	0.090	0.093	0.091	0.093

**. Significant correlation at 0.01 level (bilateral),*. Significant correlation at 0.05 level (bilateral).

Table 3. The average correlation analysis results between air pollutants and air temperature in 31 provincial capitals of China during 2010-2020.

Air pollutants \ Month	1	2	3	4	5	6	7	8	9	10	11	12
Annual average concentration of SO_2 (μg/m^3)	-0.642**	-0.626**	-0.551**	-0.494**	-0.337	-0.209	-0.145	-0.284	-0.499**	-0.586**	-0.624**	-0.641**
Annual average concentration of NO_2 (μg/m^3)	-0.335	-0.362*	-0.290	-0.163	-0.025	0.131	0.238	0.215	-0.049	-0.196	-0.284	-0.323
Annual average concentration of PM_{10} (μg/m^3)	-0.546**	-0.547**	-0.458**	-0.367*	-0.226	-0.042	-0.004	-0.106	-0.364*	-0.476**	-0.539**	-0.542**

**. Significant correlation at 0.01 level (bilateral),*. Significant correlation at 0.05 level (bilateral).

Table 4. The average correlation analysis results between air pollutants and extreme maximum temperature in 31 provincial capitals of China during 2010-2020.

Air pollutants \ Month	1	2	3	4	5	6	7	8	9	10	11	12
Annual average concentration of SO_2 (μg/m^3)	-0.635**	-0.588**	-0.456**	-0.232	-0.118	0.057	0.010	-0.105	-0.325	-0.466**	-0.599**	-0.653**
Annual average concentration of NO_2 (μg/m^3)	-0.367*	-0.405*	-0.198	0.039	0.244	0.393*	0.443*	0.405*	0.189	-0.078	-0.249	-0.361*
Annual average concentration of PM_{10} (μg/m^3)	-0.565**	-0.552**	-0.301	-0.065	-0.099	0.323	0.300	0.172	-0.119	-0.344	-0.519**	-0.571**

**. Significant correlation at 0.01 level (bilateral),*. Significant correlation at 0.05 level (bilateral).

Table 5. The average correlation analysis results between air pollutants and extreme minimum temperature in 31 provincial capitals of China during 2010-2020.

Air pollutants \ Month	1	2	3	4	5	6	7	8	9	10	11	12
Annual average concentration of SO_2 (μg/m^3)	-0.635**	-0.631**	-0.578**	-0.604**	-0.524**	-0.432*	-0.358*	-0.481**	-0.606**	-0.608**	-0.632**	-0.629**
Annual average concentration of NO_2 (μg/m^3)	-0.303	-0.299	-0.272	-0.256	-0.139	-0.018	0.062	0.020	-0.162	-0.219	-0.301	-0.288
Annual average concentration of PM_{10} (μg/m^3)	-0.505**	-0.490**	-0.454*	-0.467**	-0.392*	-0.301	-0.233	-0.320	-0.440*	-0.480**	-0.514**	-0.486**

**. Significant correlation at 0.01 level (bilateral),*. Significant correlation at 0.05 level (bilateral).

Table 6. The average correlation analysis results between air pollutants and precipitation in 31 provincial capitals of China during 2010-2020.

Air pollutants \ Month	1	2	3	4	5	6	7	8	9	10	11	12
Annual average concentration of SO_2 (μg/m^3)	-0.527**	-0.412*	-0.432*	-0.466**	-0.483**	-0.560**	-0.533**	-0.418*	-0.616**	-0.452*	-0.461**	-0.473**
Annual average concentration of NO_2 (μg/m^3)	-0.101	0.037	-0.047	-0.062	-0.225	-0.218	-0.186	-0.208	-0.292	-0.498**	-0.173	-0.139
Annual average concentration of PM_{10} (μg/m^3)	-0.544**	-0.371*	-0.443*	-0.455*	-0.591**	-0.643**	-0.465**	-0.459**	-0.624**	-0.528**	-0.458**	-0.522**

**. Significant correlation at 0.01 level (bilateral),*. Significant correlation at 0.05 level (bilateral).

Table 7. The average correlation analysis results between air pollutants and sunshine duration in 31 provincial capitals of China during 2010-2020.

Air pollutants \ Month	1	2	3	4	5	6	7	8	9	10	11	12
Annual average concentration of SO_2 (μg/m^3)	0.331	0.387*	0.504**	0.531**	0.529**	0.463**	0.196	0.138	0.282	0.270	0.243	0.300
Annual average concentration of NO_2 (μg/m^3)	-0.049	-0.068	0.058	0.107	0.021	-0.034	-0.061	-0.027	-0.090	-0.130	-0.118	-0.015
Annual average concentration of PM_{10} (μg/m^3)	0.171	0.200	0.389*	0.450*	0.410*	0.352	0.066	0.045	0.087	0.070	0.104	0.215

**. Significant correlation at 0.01 level (bilateral),*. Significant correlation at 0.05 level (bilateral).

Table 8. The average correlation analysis results between air pollutants and relative humidity in 31 provincial capitals of China during 2010-2020.

Air pollutants \ Month	1	2	3	4	5	6	7	8	9	10	11	12
Annual average concentration of SO_2 (μg/m^3)	-0.369*	-0.420*	-0.525**	-0.578**	-0.590**	-0.534**	-0.336	-0.206	-0.302	-0.301	-0.329	-0.307
Annual average concentration of NO_2 (μg/m^3)	-0.018	0.022	-0.085	-0.156	-0.198	-0.172	-0.162	-0.135	-0.133	-0.010	0.084	0.027
Annual average concentration of PM_{10} (μg/m^3)	-0.377*	-0.358*	-0.490**	-0.502**	-0.550**	-0.571**	-0.396*	-0.286	-0.328	-0.258	-0.258	-0.326

**. Significant correlation at 0.01 level (bilateral),*. Significant correlation at 0.05 level (bilateral).

extreme minimum temperature, precipitation, sunshine duration, and relative humidity were chosen as meteorological factors to analyze the correlation between the meteorological factors and air pollutants. Temperature, sunshine duration, precipitation, and relative humidity were also adopted as meteorological factors to analyze their relationship with air pollution in previous studies [5]. Some studies selected temperature, relative humidity, wind speed, wind direction, and its standard deviation to analyze the meteorological factors influencing the NO_2, O_3, PM_{10}, and $PM_{2.5}$ concentrations [12]. Barzeghar et al. [18] used solar radiation, temperature, wind speed, relative humidity, and precipitation to analyze the effect of meteorological factors on air pollutants. The above studies indicated that different meteorological factors had obvious effect on different air pollutants in different degrees and season. Our results further proved this phenomenon.

Our results showed that the temperature, precipitation, and relative humidity were the main meteorological factors influencing the air quality in 31 provincial capitals of China during 2010-2020. These results were consistent with the results obtained by Hu et al. [5]. Hu et al. [5] demonstrated that air pollutants were correlated with relative humidity, precipitation, and temperature. The results in this study can provide better understanding of the spatial distribution characteristics of air pollutants and their relationship with meteorological factors in different seasons in different cities. They may also serve as reference for the atmospheric environment control and air quality forecast in cities.

This study has some limitations. This study only analyzed the spatial distribution of meteorological factors and air pollutants and the correlation between meteorological factors and air pollutants in 31 provincial capitals of China during 2010-2020 at the month level. Smaller level of studies should be conducted in the future to obtain more reliable results. This study only selected 31 provincial capitals in China. More cities should be considered in the future to improve the accuracy of research results. More meteorological factors, such as wind speed, wind direction, and water vapor, should be considered in future research.

Conclusions

This study revealed the spatial distribution characteristics of air pollutants and the days of air quality equal to or above grade II in 31 provincial capitals of China during 2010-2020. The obvious differences are observed in the spatial distribution characteristics of air pollutants and the days of air quality equal to or above grade II in 31 provincial capitals of China during 2010-2020. The correlation analysis results between the air pollutants and the days of air quality equal to or above grade II in 31 provincial capitals of China during 2010-2020 demonstrated that the days of air quality equal to or above grade II were negatively correlated with the annual average concentration of SO_2, NO_2, and PM_{10}. The results also revealed the main meteorological factors including air temperature, extreme maximum temperature, extreme minimum temperature, precipitation, and relative humidity were the main meteorological factors influencing the air quality in 31 provincial capitals of China during 2010-2020.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. LI X.H., LI W.W., XU D.Q. Relationship between meteorological factors and air quality in Xi'an city. J Environ Hyg. **7** (3), 203, **2017**.
2. YANG J.H., JI Z.M., KANG S.C., ZHANG Q.G., CHEN X.T., LEE S.Y. Spatiotemporal variations of air pollutants in western China and their relationship to meteorological factors and emission source. Environ Pollut. **254**, 112952, **2019**.
3. ZHANG L.C., TIAN X., ZHAO Y.H., LIU L.L., LI Z.W., TAO L.X., WANG X.N., GUO X.H., LUO Y.X. Application of nonlinear land use regression models for ambient air pollutants and air quality index. Atmos Pollut Res. **12**, 101186, **2021**.
4. ROMERO Y., DIAZ C., MELDRUM I., VELASQUEZ R.A., NOEL J. Temporal and spatial analysis of traffic – related pollutant under the influence of the seasonality and meteorological variables over an urban city in Peru. Heliyon, **6**, e04029, **2020**.
5. HU M.M., WANG Y.F., WANG S., JIAO M.Y., HUANG G.H., XIA B.C. Spatial-temporal heterogeneity of air pollution and its relationship with meteorological factors in the pearl river delta, China. Atmos Environ. **254**, 118415, **2021**.
6. LI C., LIU J., WANG Y.M. Influences of meteorological factors on air quality of Xi'an city. J Arid Land Res Environ. **31** (3), 83, **2017**.
7. HADDAD K., VIZAKOS N. Air quality pollutants and their relationship with meteorological variables in four suburbs of Greater Sydney, Australia. Air Qual Atmos Hlth. **14**, 55, **2021**.
8. ZHOU X.T., STREZOV V., JIANG Y.J., KAN T., EVANS,T. Temporal and spatial variations of air pollution across China from 2015 to 2018. J Environ Sci. **112**, 161, **2022**.
9. XIAO Q.Y., GENG G.N., LIANG F.C., WANG X., LV, Z., LEI Y., HUANG X.M., ZHANG Q., LIU,Y., HE, K.B. Changes in spatial patterns of $PM_{2.5}$ pollution in China

2000-2018: impact of clean air policies. Environ Int. **141**, 105776, **2020**.
10. ZHAO C.K., SUN Y.,ZHONG Y.P., XU S.H., LIANG Y., LIU S., HE X.D., ZHU J.H., SHIBAMOTO T., HE M. Spatio-temporal analysis of urban air pollutants throughout China during 2014-2019. Air Qual Atmos Hlth. **14**, 1619, **2021**.
11. WEI G.E., ZHANG Z.K., OUYANG X., SHEN Y., JIANG S.N., LIU B.L., HE B.J. Delineating the spatial-temporal variation of air pollution with urbanization in the belt and road initiative area. Environ Impact Asses. **91**, 106646, **2021**.
12. DENG C.X., QIN C.Y., LI Z.W., LI K. Spatiotemporal variations of $PM_{2.5}$ pollution and its dynamic relationships with meteorological conditions in Beijing-Tianjin-Hebei region. Chemosphere, **301**, 134640, **2022**.
13. WU X.H., TIAN Z.Q., KUAI Y., SONG S.F., MARSON S.M. Study on spatial correlation of air pollution and control effect of development plan for the city cluster in the Yangtze River Delta. Socio-Econ Plan Sci. **83**, 101213, **2022**.
14. QI G.Z., CHE J.H., WANG Z.B. Differential effects of urbanization on air pollution:Evidences from six air pollutants in mainland China. Ecolc Indic. **146**, 109924, **2023**.
15. ZHANG C.H., ZHAO T.L., LU Z.Y., WANG D.D., CHEN Y.S., YANG R.W., WANG F. Analysis of change characteristics of air pollutants and meteorological influencing factors in Shenyang. Environ Sci Technol. **43** (S2), 39, **2020**.
16. ULPIANI G., RANZI G., SANTAMOURIS M. Local synergies and antagonisms between meteorological factors and air pollution: a 15-year comprehensive study in the Sydney region. Sci Total Environ. **788**, 147783, **2021**.
17. ULPIANI G., HART M.A., VIRGILIO G.D., MAHARAJ A.M. Urban meteorology and air quality in a rapidly growing city: inter-parameter associations and intra-urban heterogeneity. Sustain Cities Soc. **77**, 103553, **2022**.
18. BARZEGHAR V., HASSANVAND M.S., FARIDI S., ABBASI S., GHOLAMPOUR A. Long-term trends in ambient air pollutants and the effect of meteorological parameters in Tabriz, Iran. Urban Clim. **42**,101119, **2022**.
19. DUTTA S., GHOSH S., DINDA S. Urban air-quality assessment and inferring the association between different factors: a comparative study among Delhi, Kolkata and Chennai Megacity of India. Aerosol Sci Eng. **5** (1), 93, **2021**.
20. ZHU Z.P., QIAO Y.X., LIU Q.Y., LIN C.H., DANG E., FU W.C., WANG G.Y., DONG J.W. The impact of meteorological conditions on air quality index under different urbanization gradients: a case from Taipei. Environ Dev Sustain. **23**, 3994, **2021**.
21. SIGAMANI S., VENKATESAN R. Air quality index prediction with infuence of meteorological parameters using machine learning model for IoT application. Arab J Geosci. **15**, 340, **2022**.
22. DAS B., DURSUN O.O., TORAMAN S. Prediction of air pollutants for air quality using deep learning methods in a metropolitan city. Urban Clim. **46**, 101291, **2022**.
23. ZHANG L.C., TIAN X., ZHAO Y.H., LIU L.L., LI Z.W., TAO L.X., WANG X.N., GUO X.H., LUO Y.X. Application of nonlinear land use regression models for ambient air pollutants and air quality index. Atmos Pollut Res. **12**, 101186, **2021**.
24. KETU S. Spatial Air Quality Index and Air Pollutant Concentration prediction using Linear Regression based Recursive Feature Elimination with Random Forest Regression (RFERF): a case study in India. Nat Hazards, **114**, 2109, **2022**.
25. WANG H., HE R.C., HONG C.S., LEI B., LI X.Y., FENG S.Y., LUO C.W., LIU Y. Analysis for distribution estimation of soil radon concentration and its influencing factors: A case study in decommissioned uranium mill tailings pond. J Rasiat Res Appl Sc, **15**, 100480, **2022**.
26. CHE Y.L., WANG X.R., LV X.Q., LIN H.J. Correlation analysis of traction load sequences based on optimal delay method.Int J Elec Power. **142**, 108356, **2022**.
27. MINISTRY OF ENVIRONMENTAL PROTECTION, GENERAL ADMINISTRATION OF QUALITY SUPERVISION, INSPECTION AND QUARANTINE. Ambient air quality standards (GB 3095-2012), **2012**.
28. WANG Y.G., YING Q., HU J.L., ZHANG H.L. Spatial and temporal variations of six criteria air pollutants in 31 provincial capital cities in china during 2013-2014. Environ Int. **73**, 413, **2014**.
29. CHEN B., SONG Y., KWAN M.P., HUANG B., XU B. How do people in different places experience different levels of air pollution? Using worldwide Chinese as a lens. Environ Pollut. **238**, 874, **2018**.
30. ZHANG Y., GUO Y., LI G., ZHOU J., JIN X., WANG W., PAN X.C. The spatial characteristics of ambient particulate matter and daily mortality in the urban area of Beijing, China. Sci Total Environ. **435**, 14, **2012**.