Temporal-spatial Distribution Characteristics of Air Pollutants in the Pearl River Delta Region, China

Tao Jiang\textsuperscript{1,2}, Zhaoyang Liu\textsuperscript{3}, Jianping Wu\textsuperscript{2,*}, Wenpeng Zhao\textsuperscript{1} and Xunjiang Zhu\textsuperscript{1}

\textsuperscript{1}College of Computer Science and Technology, National University of Defense Technology, Changsha, Hunan, 410073, China; \\
\textsuperscript{2}College of Meteorology and Oceanography, National University of Defense Technology, Changsha, Hunan, 410073, China; \\
\textsuperscript{3}Department of Atmospheric and Oceanic Sciences, Fudan University, Shanghai 200433, China

*Corresponding author

Abstract. Studying the influences of meteorological factors on air pollutants (including SO\textsubscript{2}, NO\textsubscript{2}, O\textsubscript{3} and PM\textsubscript{10}) and quantifying the relationships between them should enable further investigation on the variation of air pollutants in a region, especially their temporal-spatial distribution characteristics. We combined observed air pollutants data from ground-based monitoring sub-stations and relevant meteorological data in the Pearl River Delta region to investigate relationships between air pollutants and various meteorological factors, and then established regression models for each sub-station through principal component regression (PCR). According to these regression equations, the seasonal average temporal-spatial distribution of air pollutants is determined by inversion of the distance priority principle, and it provides strong support for the study of the spatial distribution and temporal variation of air pollutants in this region. Our conclusions are as follows: Different air pollutants have different spatial distribution characteristics with significant seasonal changes, and the concentration of each air pollutant in winter was higher than that in summer; PM\textsubscript{10} levels in this region were higher than SO\textsubscript{2}, NO\textsubscript{2} and O\textsubscript{3}.

1. Introduction
The Pearl River Delta region (PRD) in southeastern China is a typical example of China's economically prosperous urban agglomerations, including the cities of Guangzhou, Shenzhen, Zhuhai, Dongguan, Zhongshan, Foshan, Jiangmen, Huizhou and Zhaoqing, as well as the special administrative regions of Hong Kong and Macau [1]. In the past decade or so, the rapid economic development and increased industrialization in the PRD has led to a significant increase in emissions of various atmospheric pollutants in the region [2]. The unique meteorological conditions and increasing anthropogenic emission sources have markedly increased air pollutant levels in central cities [3] causing widespread societal concern. The commonly used urban pollution research methods (solar photometer observation, regional air monitoring network) are real-time monitoring of air pollutants through ground monitoring sub-stations and analysing long-term concentration changes and their influencing factors, to obtain the temporal variation of air pollutants in a certain region [4]. For example, Liao et al. used air monitoring network observational data in the PRD from 2006 to 2012 to study air pollutants change and found that their concentration had been decreasing annually [5]. Wu et al. studied the characteristics of ash weather in the PRD since the 1980s and found that it was more serious in Guangzhou and Shenzhen [6], and often occurs in the spring, autumn and winter seasons. Presently, China has established an air monitoring
network in the PRD which has many, evenly distributed observation sub-stations, providing an important data source for studying the air pollution situation. However, it is difficult to directly rely on the observational data from the ground monitoring sub-stations to solely reflect pollutants spatial distribution within an area.

With the development of reanalysis data procedures, its spatial and temporal resolution continues to increase. The European Centre for Medium-Range Weather Forecast (ECMWF) upgraded ERA-interim to ERA5 with a spatial resolution of $0.1^\circ \times 0.1^\circ$, which allowed the possibility of studying the spatial distribution of air pollutants in a small area in combination with reanalysis data. Additionally, meteorological factors are the key drivers affecting the quality of the atmospheric environment as they have a huge impact on pollutants accumulation, diffusion and transport, and are also of great significance for pollution control. Recently, some scholars have conducted research on the influence of meteorological factors such as air pressure, temperature, precipitation, humidity, wind, and solar radiation on air pollutants, including mainly SO$_2$, NO$_2$, O$_3$, and PM$_{10}$ [7]. For example, Yu et al. found that NO$_2$ concentration was negatively correlated with daily minimum relative humidity and daily minimum temperature, and that PM$_{10}$ concentration was negatively correlated with daily average relative humidity and wind speed, and positively correlated with daily air pressure difference [8].

To further study the influence of meteorological factors on air pollutants and quantify their inter-relationships, we analyzed air pollutants variation in the target area, as reflected in its spatial and temporal distribution characteristics. Then, air pollutants data from the ground monitoring sub-stations and the reanalysis data of relevant meteorological factors in the PRD were chosen to analyze the relationships between them, and establish a regression model for each sub-station through principal component regression [9]. Using the regression equations, the seasonal average temporal-spatial distribution of air pollutants in the PRD was obtained by inversion of the distance priority principle, and then the temporal-spatial distribution characteristics of this region are further analyzed.

2. Regression Models of Air Pollutants Based on the Reanalysis Data

2.1. Data Introduction

The air pollutants data was extracted from the monitoring report of the air monitoring network of the PRD issued by the Guangdong Provincial Department of Ecology and Environment. The monthly average values of SO$_2$, NO$_2$, O$_3$, and PM$_{10}$ in each study sub-station from 2007 to 2010 were selected for 48 months. The Pearl River Delta Air Monitoring Network consists of 16 automatic air quality monitoring sub-stations. Because of missing data due to instrument maintenance and engineering upgrades, we excluded the five sub-stations in Jinguowan, Liwan, Tamen, Tung Chung and Gion, and only included air pollutants observational data from the 11 remaining sub-stations.

The meteorological factor data was derived from the ERA5 in ECMWF. The spatial resolution is $0.1^\circ \times 0.1^\circ$, the time interval is hourly, and the initial data at step 0 was selected. Meteorological factors obtained directly include hourly wind speed (u, v component), hourly surface pressure, hourly temperature, and hourly dew point temperature, as well as monthly precipitation. The daily minimum pressure, daily minimum temperature, daily maximum pressure, daily maximum temperature, daily average pressure, daily average wind speed, daily average temperature, and daily average relative humidity were obtained from the surface pressure and temperature, respectively. Additionally, relative humidity was obtained using the temperature and dew point temperature.

2.2. Establishment of Regression Model

There is a strong correlation between air pollutants and meteorological factors. Air pollutants show obvious regular changes with meteorological factors such as wind, temperature, humidity and pressure, which is of great significance for the study of inversion and the derivation of long-term relationships between them. To quantify the correlation between air pollutants and meteorological factors, we selected air pollutants data (including SO$_2$, NO$_2$, O$_3$, PM$_{10}$ in units of mg/m$^3$) and meteorological factors (monthly average of the daily minimum pressure, daily minimum temperature, daily maximum pressure, daily maximum temperature, daily average wind speed, daily average temperature, and daily average relative humidity as well as monthly precipitation) for 48 months from 2007 to 2010.
Taking the concentration of air pollutants as the independent variable and each meteorological factor as the dependent variable, we used principal component regression to carry out multiple linear regression analysis of their relationships. In the process of establishing multiple regression, the following two factors need to be considered. Firstly, if there are multiple collinearity problems between meteorological elements, then some factors may need to be eliminated in the stepwise regression. Therefore, to ensure that all factors are incorporated into the regression equations, in the case of multiple regression, principal component analysis of meteorological factors is initially conducted, followed by the selection of principal component factors with a large cumulative contribution rate, and finally a regression model between air pollutants and meteorological factors is established by PCR. The basic steps are: (1) transforming the independent variables into a set of linear uncorrelated standard variables (principal components), and ensuring there is a linear relationship between each principal component and the original independent variables; (2) sorting the principal components according to their contributions, and each time introducing a principal component that contributes a relatively large amount; (3) stopping the introduction of new principal components when their contribution ratio is less than 5%; (4) ensuring that the imported principal component is returned as an independent variable, and the regression equations are obtained; (5) ensuring the regression equations of the original variable are retained according to the linear relationship between the principal component and the original independent variable. Secondly, the geographical location of each sub-station is different, so the regression equations established for one sub-station are not fully applicable to other sub-stations. To avoid errors caused by geographical difference, this section establishes a regression model that incorporates variations in each sub-station, to obtain regression equations of air pollutants for all 11 sub-stations. Based on these equations, each sub-station is inverted separately, and the regression inversion values of air pollutants at each sub-station are compared with actual observations as shown in Figure 1. There are 528 samples in total, and each 48 samples represent a sub-station.

![Figure 1. Comparison of regression inversion and actual observed values of air pollutants.](image)

### 3. Temporal-spatial Distribution Characteristics of Air Pollutants

Using the regression equations for the PRD sub-stations obtained in the previous section combined with the reanalysis data, the spatial distribution of air pollutants in this region was inverted. We selected the central area of the PRD for analysis (112°E~115°E, 22°N~24°N), which is mainly in the PRD plain area as it has a more homogeneous terrain and a dense concentration of air quality monitoring sub-stations. Therefore, air pollutants in this area should be less affected by altitude changes and differences in meteorological conditions. Moreover, for the overall monitoring region, variation at the individual
monitoring sub-stations should be more similar. Based on this, the spatial distribution is inferred by the principle of distance priority, that is, the variation in air pollutants at any point in space is reflective of the nearest monitoring sub-station, and therefore, the same regression equation is adopted. The inversion was performed on a seasonally average basis to obtain the temporal-spatial distribution of the PRD. Figures 2, 3, 4, and 5 show the seasonal distribution of SO\textsubscript{2}, NO\textsubscript{2}, O\textsubscript{3}, and PM\textsubscript{10} concentration in the PRD from 2007 to 2010, respectively. Seasonally, air pollutants present the same trend, decreasing from winter to summer, then increasing from summer to winter, with the highest concentration in winter and the lowest concentration in summer. Spatially, there are significant differences in the distribution characteristics of SO\textsubscript{2}, NO\textsubscript{2}, O\textsubscript{3}, and PM\textsubscript{10} concentration. Firstly, PM\textsubscript{10} concentration is higher than that of SO\textsubscript{2}, NO\textsubscript{2}, and O\textsubscript{3}, and its distribution is the most extensive and uniform. It is the most important pollutant in the PRD. Secondly, SO\textsubscript{2} and NO\textsubscript{2} concentration mainly decline from Foshan to the surrounding areas, with central concentration of 0.06mg/m\textsuperscript{3} and above. Foshan is an industry-intensive city with many factories, therefore, there are many emission sources discharging large amounts of SO\textsubscript{2} and NO\textsubscript{2} resulting in a high concentration of these pollutants. Foshan is also located on the west side of the PRD, its terrain is inclined from west to east, and in winter, the weak northwest wind cannot dissipate the air pollutants, while they are easily spread by strong southeast wind in summer. O\textsubscript{3} is not directly discharged from pollution sources, it is formed by photochemical reactions of oxygen, nitrogen oxides and volatile organic compounds under the action of sunlight. Therefore, although ozone precursors are mainly from urban pollution sources, it usually takes several hours for these precursors to form and rise to peaks from emissions to ozone. During this period, ozone and its precursors can be transported downwind of the sources, so ozone concentration in downwind suburbs is often higher than that in the urban area. Because the southerly winds in the PRD are stronger than the northerly winds, O\textsubscript{3} concentration is higher in the downwind northern part of the PRD, and low in its central area.

Then, we calculated the annual average values of these pollutants in the PRD from 2007 to 2010, and the variation trends are shown in figure 6. As can be seen, the concentrations of SO\textsubscript{2}, NO\textsubscript{2}, O\textsubscript{3} change steadily, while the PM\textsubscript{10} concentration decreases significantly.

![Figure 2. Seasonal average distribution of SO\textsubscript{2} concentration in the PRD, from 2007 to 2010](image-url)
Figure 3. Seasonal average distribution of NO$_2$ concentration in the PRD, from 2007 to 2010

Figure 4. Seasonal average distribution of O$_3$ concentration in the PRD, from 2007 to 2010
4. Conclusion
The rapid development of industrialization and spread of urbanization in the PRD has led to an increase in urban air pollution sources. The concentration of air pollutants exceeding acceptable standards has caused significant social impacts and become one of the important factors restricting further development of this region. We combined air pollutant data from monitoring sub-stations with reanalysis data of relevant meteorological factors in the PRD to analyze their inter-relationship, and established regression models using principal component regression for each sub-station. Using the obtained regression equations, the seasonal variation of air pollutants in the PRD was studied, and the spatial distribution characteristics of air pollutants in this region were further analyzed by inversion of the distance priority principle. It is found that the concentration of each pollutant has obvious seasonal variation, which is usually higher in winter and lower in summer. What’s more, different air pollutants have different spatial distribution characteristics. SO$_2$ and NO$_2$ concentrations show higher values in the
central area and lower values in the surrounding area while PM$_{10}$ concentration distribution is relatively uniform. Affected by formation process and prevailing wind direction, the high ozone concentration is mainly concentrated in the southern part of the PRD. Considering the sustainable economic development of the PRD, we finally calculated the annual average values of the four pollutants in the entire region from 2007 to 2010. The concentration of PM$_{10}$ decreases significantly, and SO$_2$, NO$_2$, O$_3$ concentrations don’t increase, indicating that the government has some control over pollutant emissions, but more efforts are still needed. In addition, there are still many shortcomings in the regression model based on meteorological elements, and this model can be further optimized to improve the inversion of air pollutants. First, daily average observations or longer-term observations of air pollutants could be used to increase data samples to obtain more accurate regression coefficients. Second, much denser observation sub-stations could be used to reduce the impact of geographical differences. Finally, Appropriate interpolation methods could be used to obtain a more accurate temporal-spatial distribution of air pollutants. We hope that a more reasonable model could be shown in the next step.

Acknowledgments
National Natural Science Foundation of China, Grant/Award Number: 41875121

References
[1] Huang H, Ho K F, Lee S C, et al., (2012) Characteristics of carbonaceous aerosol in PM2.5: Pearl Delta River Region, China[J]. Atmospheric Research, 104-105(none):0-236.
[2] Ko F W S, Tam W, Wong T W, et al., (2007) Temporal relationship between air pollutants and hospital admissions for chronic obstructive pulmonary disease in Hong Kong[J]. Thorax, 62(9):780-785.
[3] Fan, M.; Zhang, S. M.; Chen, L. F.; et al., (2016) Analysis of long-term (2000-2013) spatio-temporal aerosol distribution over Pearl River Delta region in China by using MODIS data. Journal of Remote Sensing. 20(6), 1413-1423.
[4] Chen, W.; Yan, L.; Zhao, H. M., (2015) Seasonal variations of atmospheric pollution and air quality in Beijing. Atmosphere, 6(11), 1753-1770.
[5] Liao, Z. H.; Sun, J. R.; Fan, S. J.; et al., (2015) Characteristics and Impact Factors of Air Pollution in the Pearl River Delta Region from 2006 to 2012, China. Chinese Environmental Science. 35(2).
[6] Wu, M.; Peng, H. P.; Fan, S. J., (2015) Distribution Characteristics of Regional Air Quality in the Pearl River Delta. Environmental Science and Technology. 38(02), 77-82.
[7] Zhang, C. H.; Li, F. S.; Chao, L. M., et al., (2018) Analysis of Air Quality Status and Correlation with Meteorological Factors in Hohhot City. Arid area resources and environment.
[8] Yu, S. Y.; Zhang, W.; Peng, C. Q.; et al., (2008) Study on the Influence of Meteorological Factors in Shenzhen City on Air Pollutants such as SO2. Journal of environment and health. (6).
[9] Jiang, X. H.; Xue, H. R.; Zhang, C. H.; et al., (2016) Study on Influencing Factors of Air Quality in Hohhot City Based on Principal Component Analysis. Safety and environmental engineering. 23(1), 75-79.