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Article

# Spatio-temporal Differences and Driving Forces of Air Quality in Chinese Cities

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**Abstract:** Deterioration of city air quality is the serious problem in the process of rapid urbanization and economic development in China. Taking 74 cities that have implemented the new Ambient Air Quality Standards (GB3095-2012) since 2013 as examples, using statistical and ArcGIS spatial analysis method, the multi-scale temporal and spatial variations characteristics and the impact of social and economic factors on urban air quality variations, are analyzed in this paper. The main research conclusions are as follows:(1) Air quality in Chinese cities shows very significant seasonal variations, with higher air quality in summer and autumn, and lower air quality in spring and winter; (2) Seen from a daily pollution perspective, air pollution is very serious and will tend to be more serious in the future; (3) Seen from an hourly variation perspective, urban air quality is time coupled with social production and urban living; (4) The overall spatial pattern of urban air quality is high in the east and north and low in the west and south, but with an obvious trend towards regional integration. (5) Cities in different regions have different factors that cause air quality variations. In general, urbanization level and energy consumption per GDP are the common factors.

**Key words:** city air quality; spatio-temporal characteristics; driving forces; China

## 1 Introduction

China has gradually moved into a period of rapid economic growth and urbanization since the *Reform and Opening-up* of the late 1970s. From 1978 to 2012, China's GDP increased from 364.5 billion Yuan to 51894.2 billion Yuan, with an average annual growth rate of 9.98%. The urbanization level also increased from 17.9% in 1978 to 52.6% in 2012, at an average annual growth of 0.96%. These changes no doubt led to the quick accumulation of material wealth and also the significant improvement to livelihoods that has been observed. However, at the same time, severe environmental problems, especially air pollution, have appeared in many urban areas, and their complexity (for example dust-haze and photochemical smog) is becoming increasingly serious. In the autumn and winter of 2011, severe haze appeared continuously in eastern and central China for the first time, and at that time urban air pollution and air quality began to gain attention from all sectors of society.

The relationship between environmental pressures and economic growth has been a heated research topic for a long time. Before the 1970s, *Silent Spring* and other studies suggested that economic growth was leading to the deterioration of the environment (Rachel, 2000). However afterwards, it is argued that technological progress promotes energy conservation in the process of economic development. Some studies have verified the positive correlation between economic development and environmental quality improvement (Panayotou, 1993; Dinda, 2004). Is economic growth the solution to solve environment problems or the cause of environmental issues? Discussion on this issue led to the study on Environmental Kuznets Curve theory (Grossman, *et al*., 1991; Arrow, *et al*., 1995).

City is regarded as the focus in discussing the relationship between economic development and environmental

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pressure. City is the pilot area of regional development, but it is also the relatively sharp contradiction area between the economic development and environmental protection. Western scholars analyzed the influence of population growth and traffic flow on urban environment, in which urban air quality change was regarded as important research object (Sarrat, *et al*., 2006; Tai, *et al*., 2010; Patton, *et al*., 2014). Along with the rapid economic development and the deterioration of urban air quality, Chinese scholars began to analyze the trend and pattern of air quality change (Li, *et al*., 2011; Wang, *et al*., 2011; Wu, *et al*., 2011; Zhao, *et al*., 2011). It is a pity that these studies were lack of comparison of air quality of different parts of the city. They focused on the factors, such as weather conditions (Zhang, *et al*., 2011; Li, *et al*., 2012), industrial emissions (Wu, *et al*., 2015; Bo, *et al*., 2015), vehicle exhaust (Guo, *et al*., 2014), etc. Moreover, they ignored that the influence direction and intensity of economy and society on air quality are different due to the different development levels in different regions., These issues are to be addressed in this study.

## 2 Research method and data sources

### 2.1 Research method

Analysis of the temporal and spatial variations in air quality in 74 cities that have implemented the new *Ambient Air Quality Standards* (GB3095-2012) since 2013 was carried out through statistical analysis and ArcGIS spatial analysis. The data set contained the monthly, daily and 24-hourly air quality index (AQI) statistics from January to December 2013. Urban air quality is affected by various factors, including a series of natural environmental factors such as weather and climate, rainfall, landform, coastal or inland location, and also a set of human factors such as regional economic development, urbanization, industrialization, and energy consumption. To study the impact of social and economic development on urban air quality, the following factors were selected based on existing theoretical and empirical research: GDP per capita ($X_{1}$); the share of secondary industry in GDP ($X_2$); the share of R&D expenditure in GDP ($X_3$); the share of environmental protection investment in GDP ($X_4$); energy consumption per GDP ($X_5$); the share of non-agricultural population in total urban population($X_6$); the share of the built-up area in the city area ($X_7$); the share of the service industry in GDP ($X_8$); natural gas consumption per capita ($X_9$); liquefied petroleum gas consumption per capita ($X_{10}$); and the level of private car ownership per capita ($X_{11}$). The above-mentioned indicators are selected for following reasons: firstly, the importance of the indicators are proved by the previous studies (Wu, *et al*., 2015; Bo, *et al*., 2015; Guo, *et al*., 2015); secondly the combination of 11 indicators can fully reflect the level of the regional economic and social development; the third is an objective reason——other indicators are not statistically available in China now. Theoretically, there is a non-linear relationship between economic development, urbanization and the ecological environment(Pasche,2002; Huang, et al., 2003). Therefore, SPSS18.0 software and the quadratic curve-fitting method are used to study the impact of economic development and urbanization on air environmental quality. The following mathematical relation model of air environment quality and social and economic factors is established:

$$Y=\alpha_0+\alpha_1 X+\alpha_2 X^2+\varepsilon \tag{1}$$

where: $Y$ is the dependent variable and represents AQI; $X$ is an independent variable and represents the indexes $X_1,\ldots,X_{11}$ mentioned above; $\alpha_0$, $\alpha_1$, $\alpha_2$, $\alpha_3$ are parameters of the model; and $\varepsilon$ is stochastic error.

### 2.2 Data sources

The comprehensive AQI data used in this study include monthly AQIs from January to December 2013, and the daily AQIs and 24-hourly AQIs for each day of October, November and December 2013. The monthly AQIs of the 74 cities were obtained from the *Monthly Report of 74 Cities' Air Quality Situation* from January to December 2013, published by the China National Environment Monitoring Center, while the daily and 24-hourly AQI statistics were obtained from the Sina Microblog account *Ranks of Chinese Cities in Air Pollution*. Population data for each of the cities were derived from the statistics of counties and cities in the Sixth National Population Census of 2010. The data on built-up areas, city areas, GDP per capita, share of the secondary industry in GDP, share of tertiary industry in GDP, city natural gas consumption, liquefied petroleum gas consumption, and the level of civil car ownership in 2011 were obtained from the *China Urban Construction Statistics Yearbook 2011* and the *China City Statistics Yearbook 2012*. The total amount of environmental protection investment is from the *China City Statistical Yearbook in 2007*; R&D inputs were derived from the *Main Data Bulletin on the Second National Scientific Research and Development (R&D) Resources Inventory* of all provinces (municipalities and autonomous regions) in 2009; and consumption per GDP was obtained from the statistical yearbooks of all provinces (municipalities and autonomous regions) published in 2012.

### 2.3 Research scope

As noted above, this study covered the 74 cities that have implemented the new *Ambient Air Quality Standards* (GB3095-2012) regulations since 2013. These include $PM_{2.5}$, CO, and $O_3$ in the evaluation of air quality, and are of great significance in making clear the current air quality situation, and the key requirements for controlling air pollution in China. An important feature of air pollution is that it can spread from one region to another and from one city to another. Therefore, the air quality of one city may be influenced by its neighboring cities. Based on this, China is divided into seven regions according to the characteristics of regional social and economic integration and air quality variation. These are the Circum-Bohai Sea Region, Yangtze River Delta Region, the Pearl River Delta Region, the Northeast China Region, the Central China Region, the Northwest China Region, and the Southwest Region.

## 3 Temporal and spatial variations of urban air quality in China

### 3.1 Significant seasonal variations in air quality

From January to December 2013, the air quality indexes of the 74 cities all showed a similar trend: rapid decline - slow decline in volatility - steady rise. Affected by seriously poor air quality in 2012 and a wide range of heavy fog weather in January 2013, the air quality indexes of all cities were extremely high (between 4 and 28, with Xingtai the highest at 27.7). In February 2013, rapid improvements in air quality made AQI fall quickly to between 2 and 10 in all cities. Then from March to July, volatility in the AQI fell slowly. From August 2013, AQI levels began to rise steadily, and by December had reached the second highest level of the period (with January the highest)(Fig. 1).

There is also significant seasonal variation in air quality. Air quality indexes are high in spring and winter, low in summer and autumn. This seasonal variation is closely related to the climatic variations found in China. The country has a very typical monsoon climate with significant changes in the prevailing wind direction in winter and summer, and the associated rainfall also has significant seasonal variation as a result of these changes in the prevailing wind patterns. In winter and spring, the atmosphere is steady in structure with little rainfall, which in turn prevents pollutants from spreading. However, the sand and dust weather in the spring in northern cities, along with coal-fired heating in the winter, can increase the amount of pollutants in the atmosphere. In the summer, the air is constantly moving. Frequent cross-ventilation brings a lot of rainfall, which makes it very easy for pollutants to sink and spread, but effectively decreases the concentration of air pollutants. However, air pollution patterns are gradually shifting from those caused by extreme weather and winter heating to comprehensive pollution patterns

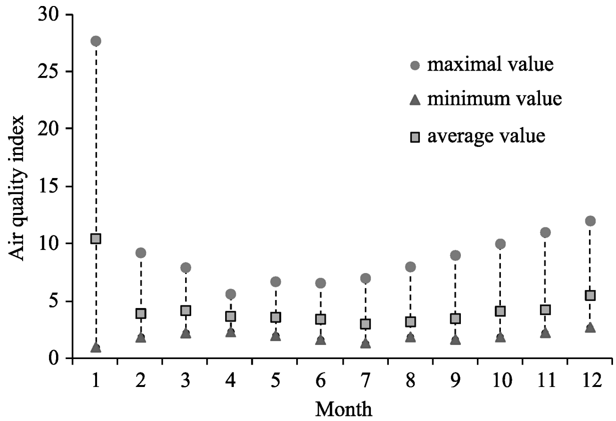


Fig.1 The monthly change of city air quality index from January to December in 2013

that are mainly caused by emissions from factories and automobiles. Thus the seasonal variation feature of air quality patterns is fading.

### 3.2 Urban air pollution was severe and will tend to be more severe in the future

Monthly air quality variations in the 74 cities in October and December, when pollution is comparatively more serious, are now analyzed. First, the daily AQIs of the 74 cities and their different regions in October and December were obtained by adding up the 24-hourly air quality indices and averaging these data. Then the number of days where city air quality indices were higher than 100 in different regions (Table 1), and the number of cities with different pollution days (Table 2), were calculated. According to the *Ambient Air Quality Index (AQI) Technical Regulations (Trial)* (HJ633-2012), AQIs are grouped into six levels: 0<AQI<5, the air quality is best; 51< AQI<100, the air quality is good; 101<AQI<150, the air quality is characterized by mild pollution; 151<AQI<200, the air quality is characterized as middle-level pollution; 201<AQI<300, air pollution is severe; AQI>300, air pollution is extremely severe. It can be seen from Figure 1 that the air quality in all regions was mainly at the mild and middle pollution levels during

Table 1 The number of days when city AQIs higher than 100 in October and December in 2013 unit: day

| Region | October | | | | December | | | |
|---|---|---|---|---|---|---|---|---|
| | Mild pollution | Middle-level pollution | Severe and extremely severe pollution | Total | Mild pollution | Middle-level pollution | Severe and extremely severe pollution | Total |
| Circum-Bohai Sea region | 9 | 9 | 2 | 20 | 4 | 5 | 12 | 21 |
| Yangtze River Delta region | 7 | 0 | 0 | 7 | 8 | 7 | 12 | 27 |
| Pearl River Delta region | 13 | 0 | 0 | 13 | 17 | 6 | 0 | 23 |
| Northeast region | 5 | 5 | 3 | 13 | 11 | 7 | 5 | 23 |
| Central region | 14 | 9 | 4 | 27 | 8 | 8 | 13 | 29 |
| Northwest region | 9 | 0 | 0 | 9 | 17 | 6 | 2 | 25 |
| Southwest region | 7 | 0 | 0 | 7 | 20 | 3 | 0 | 23 |

Table 2 The number of cities with different pollution days in October and December in 2013 unit: number; %

| Region | October | | | | | | December | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pollution days<10 | | Pollution days between 10~20 | | Pollution days>20 | | Pollution days<10 | | Pollution days between 10~20 | | Pollution days>20 | |
| | City number | Percentage | City number | Percentage | City number | Percentage | City number | Percentage | City number | Percentage | City number | Percentage |
| Circum-Bohai Sea region | 3 | 20 | 7 | 47 | 5 | 33 | 2 | 13 | 3 | 20 | 10 | 67 |
| Yangtze River Delta region | 17 | 68 | 8 | 32 | 0 | 0 | 0 | 0 | 2 | 8 | 23 | 92 |
| Pearl River Delta region | 2 | 22 | 5 | 56 | 2 | 22 | 0 | 0 | 1 | 11 | 8 | 89 |
| Northeast region | 1 | 25 | 3 | 75 | 0 | 0 | 1 | 25 | 0 | 0 | 3 | 75 |
| Central region | 0 | 0 | 1 | 17 | 5 | 83 | 0 | 0 | 0 | 0 | 6 | 100 |
| Northwest region | 3 | 50 | 2 | 33 | 1 | 17 | 0 | 0 | 4 | 67 | 2 | 33 |
| Southwest region | 3 | 50 | 1 | 17 | 2 | 33 | 0 | 0 | 2 | 33 | 4 | 67 |

October 2013, but with only the Central region, the Northeast region, and the Circum-Bohai Sea region having fewer than 5 days of severe pollution. The Circum- Bohai Sea region and Central region had more than 20 pollution days during this period; the Pearl River region and the Northeast region had 10 to 20 pollution days; and the Yangtze River Delta region, the Northwest region, and the Southwest region each had fewer than 10 pollution days. During December 2013, there were mild, middle-level and severe pollution days in all regions, with severe pollution days in the cities of the Circum-Bohai Sea region, the Yangtze River Delta region, the Central region, the Northeast region, and the Northwest region. In all regions, pollution occurred on more than 20 days. Thus it can be seen that urban air pollution in China was severe from October to December 2013, and will likely be more severe in the future. The regions can be ranked according to the degree of pollution; from high to low are the Circum-Bohai Sea region, the Yangtze River Delta region, the Central region, the Northeast region, the Northwest region, the Pearl River Delta region, and the Southwest region.

It can be seen from Figure 2 that most cities in the seven regions had fewer than 20 pollution days in October. The proportions of cities with fewer than 20 pollution days in the Circum-Bohai Sea region, the Yangtze River Delta region, the Pearl River Delta region, the Northeast region, the Central region, the Northwest region, and the Southwest region were respectively 67%, 100%, 78%, 100%, 17%, 83%, and 67%. When it came to December, however, there were many more cities with more than 20 pollution days in all the regions. The proportions of cities with more than 20 pollution days in the Circum-Bohai Sea region, the Yangtze River Delta region, the Pearl River Delta region, the Northeast region, the Central region, the Northwest region, and the Southwest region were 67%, 92%, 89%, 75%, 100%, 33%, and 67%, respectively. Measured by days of pollution, the levels of air pollution and the number of days of polluted air in the cities both increased from October to December 2013, which means that urban air pollution was very serious at this time, and that pollution in winter lasted longer, spread more widely, and was heavier than in autumn, as measured by daily variations.

### 3.3 Hourly variations show time coupling between urban air quality and social production and living activities

October 2, 2013 was chosen randomly to allow analysis of the 24-hour variations in AQIs of the cities in the various regions (Fig.2). It can be seen that the AQIs of cities in the Circum-Bohai Sea region over the 24 hours recorded a rapid rise after falling slowly in volatility. From 24:00 to 06:00 AQIs fell slowly, then reached the highest AQI of the day at 07:00, and then again fell slowly after 09:00, reaching the lowest AQI of the day at 15:00. From 16:00 to 21:00 the AQI levels increased, especially between 18:00 and 21:00, but after 21:00 again fell slowly. The 24-hour AQIs of cities in the Yangtze River Delta area also fell in volatility. From 24:00 to 08:00, these grew steadily and reached the highest AQI of the day at 08:00. Between 09:00 and 11:00 they fell quickly, but from 12:00 to 13:00 grew quickly. From 14:00 to 19:00 they fell, but between 19:00 and 21:00 grew slowly, while from 21:00 to 23:00 they decreased slowly. The AQI of cities in the Pearl River Delta region rose slowly, then fell slowly and then recovered smoothly. From 24:00 to 08:00 they rose slowly, reaching the highest level of the day at 08:00; from 09:00 to 16:00 they fell in volatility, from 17:00 to 22:00 the pollution levels grew quickly, and after 23:00 they fell back a little. As for the Central region, city AQIs kept falling steadily and slowly from 24:00 to 14:00 and from 14:00 to 22:00, and grew a little with two peaks at 16:00 and 21:00, but fell back after 23:00. The AQI of the Northwest region cities generally increased in volatility over

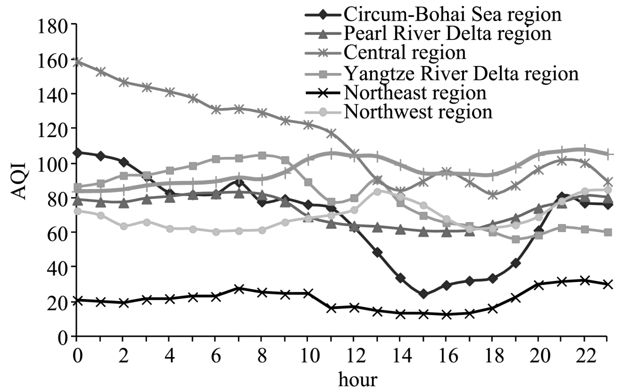


Fig.2 The 24-hour variations in AQIs of the cities in the various regions in October 2, 2013

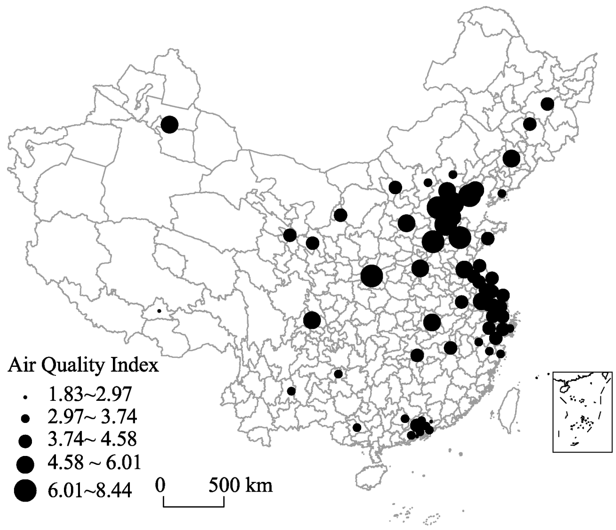


Fig.3 Spatial pattern of air quality index in Chinese 74 cities in 2013

24 hours. From 24:00 to 06:00 they fell slowly, from 07:00 to 13:00 they rose steadily, from 14:00 to 16:00 they fell quickly, and from 17:00 to 23:00 they kept growing. In the Southwest region, city AQIs rose slowly in volatility. From 24:00 to 06:00 they grew slowly, and from 07:00 to 11:00 they grew quickly in volatility, with AQIs at 07:00 increasing and reaching a peak at 11:00. From 12:00 to 16:00 they fell slowly in volatility, while from 17:00 to 22:00 they grew quickly, and after 23:00 fell back.

It can be seen from these data that the AQI of most cities increased between 06:00 and 08:00 in the morning and between 17:00 and 19:00 in the afternoon. The two periods are urban rush hours. The variation in AQI thus is time coupled with motor vehicles' travel and exhaust emissions. This pattern can be further divided into two periods between 08:00 and 17:00. From 08:00 to 13:00 some regions such as the Southwest region, the Yangtze River Delta region, and the Northwest region showed increases in AQI, while the AQIs of the Circum-Bohai Sea region, the Pearl Delta region, and the Northeast region fell after 1–3 hours of being rather high. From 13:00 to 17:00 the AQI in all regions decreased. Apart from the impact of climate, weather, landform and other natural factors, the AQI variation is thus time coupled with urban social production and life activities, and is influenced by automobile emissions and production.

### 3.4 The overall spatial pattern of urban air quality: high in eastern and northern areas, low in western and southern areas, and a clear trend in regional integration

In 2013, the overall spatial pattern of urban air quality nationwide was high in the eastern and northern areas, and low in the western and southern areas. The average AQI of the Circum-Bohai Sea region was the highest, followed by the Northwest region, the Central region, the Northeast region, the Yangtze River Delta region, the Southwest region, and the Pearl River Delta region. The AQI fell gradually from the coastal regions to the inland regions, and shifted from high to low from the north to the south (Fig.3). It can be seen that inside the more seriously polluted eastern coastal regions, the cities near the oceans had lower AQIs than those far away. For example, Tianjin had a lower AQI than Beijing and Shijiazhuang; Shanghai had a lower AQI than Nanjing and Hangzhou, and Zhuhai and Shenzhen had lower AQIs than Guangzhou. This shows that being near the ocean has a great impact on urban air quality. Meanwhile, it can be seen from the spatial distribution of AQI that the areas with high AQIs have neighbors with high AQIs, and areas with low AQIs have neighbors with low AQIs. The high AQI areas are centralized in the Circum-Bohai Sea Region, the Central China Region, the Northeast China Region, and the Yangtze River Delta Region, while the low AQI areas are centralized in the Pearl River Delta Region and the Southwest China Region. This pattern shows that urban air pollution tends to integrate regionally. Urban air quality is not only affected by the natural atmospheric environment, but also by the emission of air pollutants, transport, and other factors in the neighboring regions, thus united prevention and control of air pollution will be increasingly important in the future (Wang *et al*., 2005).

## 4 Social and economic driving factors behind China's cityair quality

Section 2 detailed the sources of the air quality statistics for the 74 cities in 2013, and those for the urban social and economic statistics data comparison data of 2011. In this study of the socioeconomic driving forces behind China's urban air quality, urban AQIs were taken as the dependent variable, and GDP per capita ($X_1$); the share of secondary industry in GDP ($X_2$); the share of R&D expenditure in GDP ($X_3$); the share of environmental protection investment in GDP ($X_4$); energy consumption per GDP ($X_5$); the share of non-agricultural population in total urban population($X_6$); the share of the built-up area in the city area ($X_7$); the share of the service industry in GDP ($X_8$); natural gas consumption per capita ($X_9$); liquefied petroleum gas consumption per capita ($X_{10}$); and the level of private car ownership per capita ($X_{11}$), were taken as independent variables. According to Formula (1), a quadratic regression model of AQI and the socioeconomic factors in the cities of China's different regions can be used to analyze the drivers behind urban air quality variations in these regions (Table 3). However, because there are too many indices, only the significant ones at the 10% level and 5% level are listed in Table 3.

It can be seen from Table 3 that different regions have different urban air quality factors. AQI variations in the Circum-Bohai Sea Region are significantly concerned with energy consumption per GDP, urbanization level, the share of the built-up area in a city and the number of private cars per capita. The higher the energy consumption per GDP, the higher the level of AQI, but the higher the level of urbanization, the lower the level of AQI, which means that urban population growth in the Circum-Bohai Sea Region is improving urban air quality. However, the larger the built-up area in a city, the higher the level of AQI, and this means that rapid urban expansion mainly for industry in the Circum-Bohai Sea Region has a very significant negative impact on air quality. In this region, however, the fact that AQI fell after growing in line with the growth of private car ownership per capita means that the growth in the number of private cars per capita does not absolutely cause urban air quality deterioration.

In the Yangtzi River Delta Region, AQI variations are obviously concerned with the share of R&D expenditure in GDP, energy consumption per GDP, urbanization level and natural gas consumption per capita. The larger the share of R&D expenditure in GDP, the higher the level of AQI, which means that the R&D input does not efficiently reduce the impact of production and urban living on the air quality environment through technological advancement. The higher the energy consumption per GDP, the higher the level of AQI showing that increases in energy consumption from economic growth have led to urban air quality deterioration. The higher the urbanization level, the higher the level of AQI, which shows that the growth in urban population is one reason for the urban air quality deterioration in the Yangtze River Delta Region. There is an inverted u-shaped curve relationship between natural gas consumption per capita and AQI and most cities are on the left of the fitted curve, meaning that AQI grows along with rising natural gas consumption per capita. This shows that the growing use of clean energy represented by natural gas has resulted in no obvious improvement in air quality.

In the Pearl River Delta Region, only GDP per capita is closely related to AQI variations, with almost all cities on the left of the curve. This means that the higher the energy consumption per GDP, the higher the level of AQI, showing that urban air quality is closely related to energy consumption by economic activities in the Pearl River Delta Region. Analyses of the social and economic factors and urban air

Table 3 The drivers behind urban air quality variations in the various regions in 2013

| Region | Independent variable | $R^2$ | $F$ | $Sig$ | $\alpha_0$ | $\alpha_1$ | $\alpha_2$ |
|---|---|---|---|---|---|---|---|
| Circum-Bohai Sea region | $X_5$ | 0.206 | 1.703 | 0.095* | 5.030 | 0.179 | 0.513 |
| | $X_6$ | 0.278 | 2.312 | 0.081* | 5.804 | 0.056 | –0.001 |
| | $X_7$ | 0.489 | 5.741 | 0.018** | 6.972 | –0.186 | 0.004 |
| | $X_{11}$ | 0.539 | 6.250 | 0.016** | –4.306 | 86.502 | –163.805 |
| Yangtze River Delta region | $X_3$ | 0.201 | 2.640 | 0.095* | 3.188 | 1.082 | –0.283 |
| | $X_5$ | 0.350 | 5.665 | 0.011** | 0.606 | 7.358 | –3.607 |
| | $X_6$ | 0.287 | 4.226 | 0.029** | 2.784 | 0.038 | 0.000 |
| | $X_9$ | 0.303 | 4.352 | 0.027** | 3.336 | 0.004 | $–3.93E^{–6}$ |
| Pearl River Delta region | $X_5$ | 0.585 | 4.227 | 0.072* | –5.465 | 28.858 | –22.952 |
| Central region | $X_3$ | 0.989 | 88.533 | 0.011** | 17.547 | –19.050 | 6.778 |
| | $X_5$ | 0.785 | 3.657 | 0.085* | –59.099 | 175.061 | –188.134 |
| | $X_6$ | 0.539 | 1.170 | 0.061* | 12.071 | –0.206 | 0.001 |
| Northwest region | $X_3$ | 0.850 | 8.514 | 0.058* | 5.056 | –1.215 | 0.338 |
| | $X_5$ | 0.490 | 1.441 | 0.064* | 6.888 | –2.350 | 0.507 |
| | $X_6$ | 0.847 | 8.299 | 0.060* | 18.849 | –0.307 | 0.002 |
| | $X_{10}$ | 0.903 | 13.915 | 0.030** | 3.757 | 12.679 | –15.395 |
| Southwest region | $X_3$ | 0.716 | 3.783 | 0.021** | 3.096 | –0.589 | 1.114 |
| | $X_6$ | 0.320 | 0.705 | 0.061* | 0.551 | 0.117 | –0.001 |
| | $X_{10}$ | 0.767 | 4.937 | 0.012** | 3.245 | 0.830 | 3.857 |

Note: * represents significant at 10% level, **represents significant at 5% level quality in the Northeast Region all failed the 10% significance test, and are therefore not listed in the Figure. In the Central Region, AQI variation is closely related to the share of R&D expenditure in GDP, energy consumption per GDP and urbanization level. While the share of R&D expenditure in GDP increases, AQI grows after falling.AQI increases as energy consumption per unit of GDP grows, which shows that energy consumption for productive activities has greatly led to air quality deterioration.AQI falls when the urbanization level rise, which shows that urbanization greatly contributes to improvements in air quality.

In the Northwest Region, AQI is closely related to the share of R&D expenditure in GDP, energy consumption per unit of GDP, urbanization level and liquefied petroleum gas consumption per capita. However, when the share of R&D expenditure in GDP in this region grew, and energy consumption per GDP decreased, AQI grew after falling. Along with urbanization, AQI decreases, which shows that increases in urban population and urbanization have had a positive effect on air quality improvement in the Northwest Region. Here, the liquefied petroleum gas consumption per capita is in a second linear fitting relationship with AQI, but most cities are on the left of the curve, meaning that AQI grows along with that of liquefied petroleum gas consumption per capita. This shows that consumption of liquefied petroleum gas and other resources has a negative impact on air quality. Finally, In the Southwestern Region, AQI variation is also closely related to the share of R&D expenditure in GDP, urbanization level and liquefied petroleum gas consumption per capita. When the share of R&D expenditure in GDP increases, AQI levels grow, and also grow when liquefied petroleum gas consumption per capita increases. But the urbanization level rises, AQI levels fall.

In general, in the eastern coastal regions including the Circum-Bohai Sea Region, the Yangtze River Delta Region, the Pearl River Delta Region and other regions with highly developed economies and high urbanization levels, economic development has no clear influence on urban air quality, and the theoretical inverted u-shaped curve relationship between these variables is not obvious. However, economic growth patterns with high energy consumption have clear negative impacts on urban air quality, while scientific and technological progress along with innovation inputs do not contribute significantly to emission reduction and air quality improvement. In different regions, urbanization factors have been shown to have different influences on air quality variations. In the Circum-Bohai Sea Region, urban population increase has had a positive effect on air quality variations, while urban space expansion has had a negative effect. Within the Yangtze River Delta Region urban population increase has exacerbated air quality deterioration, while other urbanization-related factors have not had an obvious influence on air quality. Generally speaking, the influence of economic development on air quality is larger than the influence of urbanization development in eastern coastal areas, while it is the opposite in the western regions. The development of urbanization has efficiently improved urban air quality, while increased energy consumption and low efficiency brought about by the extensive economic development mode have had clear negative impacts on urban air quality.

## 5 Conclusions and discussion

(1) Air quality in Chinese cities shows very significant seasonal variations, with higher air quality in summer and autumn, and lower air quality in spring and winter. Seen from a daily pollution perspective, air pollution is very serious and will tend to be more serious in the future; seen from an hourly variation perspective, urban air quality is time coupled with social production and urban living. Finally, the overall spatial pattern of urban air quality is high in the east and north and low in the west and south, but with an obvious trend towards regional integration.

(2) Cities in different regions have different factors that cause air quality variations. In general, urbanization level and energy consumption per GDP are the common factors. In the eastern coastal regions, urbanization has obvious negative impacts on air quality, and the energy consumption fueling the extensive economic development mode also has a negative influence on air quality. In the western regions, urbanization has effectively improved the urban air environment, while the high energy consumption and low efficiency of economic development has obvious negative impacts on air quality.

(3) In the future, the eastern coastal regions need to speed up the transformation and upgrading of industrial structure, and should shift from resource-dependent to a scientific and technical innovation-driven economic development mode. Meanwhile, energy structures should become green and diversified, energy consumption should be controlled rationally, energy efficiency should be increased, and emissions should be reduced. As for urbanization, city scale should be strictly controlled, and land should be used intensively, within a low-carbon path of urbanization. As for the western regions, new-type urbanization should be adopted to accommodate people in the cities according to the bearing capacity of the natural environment. In these areas dependence on fossil energy for economic development should be lowered, and higher standards should be set to create a “High Carbon” Industry. Ecological agriculture and industries with ecological benefits should be developed rapidly.

This study has identified the temporal and spatial features and social and economic driving factors of air quality in Chinese cities. The 74 cities that have implemented the new *Ambient Air Quality Standards* since 2013 were used as examples. As a result of the limited sample, this research is only a preliminary study of the relationship between urban air quality and social and economic factors. The prefecture-level cities on the National Air Quality Real-time Publishing Platform have increased from 74 to 161 since 2014. The author will continue studying air quality variation in Chinese cities using these data, and will carry out further in-depth studies of the relationship between urban air quality in China and social and economic development.

## References

Arrow K, Bolin B, Costanza R, *et al*. 1995. Economic growth, carrying capacity, and the environment. *Ecological Economics*, 15(1): 89–90.

Bo X, Wang G, Wen R, *et al.* 2015. Air pollution effect of the thermal power plants in Beijing-Tianjin-Hebei region. *China Environmental Science*, 35(2):364-373. (in Chinese)

Dinda S. 2004. Environmental Kuznets Curve Hypothesis: A Survey. *Ecological Economics*, 49(4):431-455.

Grossman G M, Krueger A B. 1991. Environmental Impacts of a North American Free Trade Agreement. Social Science Electronic Publishing, 8(2): 223-250.

Guo Y H, Wang Z F, Kang H, *et al*. 2014. Impact of automobile vehicles exhaust emissions on metropolitan air quality: Analysis study on the air pollution change before and after the Spring Festival in Urumqi City, China. *Acta Scientiae Circumstantiae*, 34(5): 1109-1117. (in Chinese)

Huang J C, Fang C L. 2003. Analysis of coupling mechanism and rules between urbanization and eco-environment. *Geographical Research*, 22(2): 211-220. (in Chinese)

Li W J, Zhang S H, Gao Q X, *et al*. 2012. Relationship between temporal-spatial distribution pattern of air pollution index and meteorological elements in Beijing, Tianjin and Shijiazhuang. *Resources Science*, 34(8): 1392-1400. (in Chinese)

Li X Y, Ding X M, Gao H, *et al*. 2011. Characteristics of air pollution index in typical cities of North China. *Journal of Arid Land Resources & Environment*, 25(3): 96-101. (in Chinese)

Panayotou T. 1993. Empirical tests and policy analysis of environmental degradation at different stages of economic development. *Iio Working Papers*.

Pasche M. 2002. Technical progress, structural change, and the environmental Kuznets curve. *Ecological Economics*, 42(3):381-389.

Patton A P, Perkins J, Zamore W, *et al*. 2014. Spatial and temporal differences in traffic-related air pollution in three urban neighborhoods near an interstate highway. *Atmospheric Environment*, 99:309–321.

Rachel Carson. 2000. Silent Spring. London: Penguin Classics.

Sarrat C, Lemonsu A, Masson V, *et al*. 2006. Impact of urban heat island on regional atmospheric pollution. *Atmospheric Environment*, 40(10): 1743–1758.

Tai A P K, Mickley L J, Jacob D J. 2010. Correlations between fine particulate matter (PM2.5) and meteorological variables in the United States: Implications for the sensitivity of PM2.5 to climate change. *Atmospheric Environment*, 44(32):3976-3984.

Wang H P, Zhang B, Liu Z H, *et al.*. 2011. Wave letanalysis of air pollution index changes in Lanzhou during the last decade. *Acta Scientiae Circumstantiae*, 31(5): 1070-1076. (in Chinese)

Wang S L, Zhang Y H, Zhong L J, *et al*. 2005. Interaction of urban air pollution among cities in Zhujiang Delta. *China Environmental Science*, 25(2):133-137. (in Chinese)

Wu Y, Ji D S, Song T, *et al*. 2011. Characteristics of atmospheric pollutants in Beijing, Zhuozhou, Baoding and Shijiazhuang during the period of summer and autumn. *Environmental Science*, 32(9): 2741- 2749. (in Chinese)

Wu Q, Li J, Zhu Z C, *et al*. 2015. Effect of the process of industrial development in Inner Mongolia on the regional air environmental quality. *Environmental Engineering*, 33(9): 134-138. (in Chinese)

Zhang R W, Fan S J. 2011. Study of the influence of wind field on air quality over the Pearl River Delta. *Acta Scientiarum Naturalium Universitatis Sunyatseni*, 50(6):130-134. (in Chinese)

Zhao X J, Zhang X L, Xu X F, *et al.* 2009. Seasonal and diurnal variations of ambient PM 2.5 concentration in urban and rural environments in Beijing. *Atmospheric Environment*, 43(18): 2893-2900.

## 中国城市空气质量变化的时空特征及其经济社会因素解析

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**摘　要：**城市空气质量恶化是我国在快速城市化和工业化进程中亟待解决的难题。本文以第一阶段实施新空气质量标准的74个城市为例，通过比较2013年各区域城市每日和每时的空气质量指数变化，总结空气质量变化的时空特征，并借助SPSS18.0软件，采用相关分析中的二次曲线拟合法探讨工业化和城市化对空气质量的影响趋势。结论认为中国城市空气质量季节性变化特征显著，空气质量春冬差，夏秋好；从污染天数看，城市空气污染形势严峻且有加重态势；从小时变化看，城市空气质量与社会生产生活活动表现出一定的时间耦合性；城市空气质量总体空间格局表现为东高西低、北高南低，且区域一体化态势明显。不同区域城市空气质量的影响因素差异明显，总体来看，单位GDP能耗、城市化水平等是影响全国城市空气质量变化的共同因素。

**关键词：**空气质量指数；时空演化；城市化；工业化；驱动力