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TEMPORAL PATTERNS, SPATIAL REALITIES: UNVEILING THE COMPLEX TAPESTRY OF AIR QUALITY IN CHINA

Zheng Ming Li
School of Geography and Tourism, Huizhou University, Huizhou, Guangdong, 516007, China

Abstract: Rapid urban expansion, surging vehicular traffic, and industrial growth have led to recurrent air pollution episodes, compelling regions to adopt measures to mitigate these challenges. However, the amelioration of air quality is a gradual process, inducing diverse shifts in regional air quality trends. Moreover, the response of industrial structures and meteorological conditions varies across different regions, leading to distinct air quality patterns. Despite extensive efforts to curb air pollution, several cities grapple with persistently poor air quality, and in some cases, witness further deterioration. This underscores the imperative for comprehensive studies on regions experiencing shifts in air quality, facilitating the formulation or refinement of targeted air quality control strategies and developmental blueprints.

Keywords: Urban expansion, air pollution, industrial development, regional air quality, pollution abatement strategies.

1. Introduction

Continuous urban expansion, growing number of motor vehicles and industrial development contribute to frequent air pollution incidents, forcing many regions to alleviate air pollution problems by means of adjusting industrial structure and implementing a wide range of air pollution abatement strategies[1].Nevertheless, the improvement in air quality is a slow accumulation process, which changes to various extents the change trends of regional air quality[2]. Additionally, the industrial structures and meteorological conditions in different regions respond differently to the air quality[3], and the types and changes of air quality in different regions also vary[4]. Although a number of cities implement a wide range of air pollution abatement strategies, their air quality remains highly polluted, and even tends to deteriorate[5]. It is therefore very necessary to conduct a study on the regions whose air quality changes in order to formulate or adjust the regional air quality control measures and development plans.

Against the backdrop of increasingly grave historical environmental problems and gradually improved environmental awareness, the types and change trends of urban air quality are capturing more attention from policy makers and scientific researchers[6]. São Paulo, the Klang Valley, most cities in Europe, Beijing and other cities hope to find an appropriate way to improve air quality through probing into the change trends of air quality[7-10]. Sicard et al.[7] analyzed the trends in urban air pollution from a global perspective, and concluded that analyzing the historical air quality could be used to evaluate success or failure of the past or current air pollution abatement strategies. Wen et al.[8] studied the changes of air quality in Beijing from 2014 to 2018 in order to evaluate the effects of clean air actions. They demonstrated that the actions were effective for air quality improvement, but Beijing was still in an urgent need to introduce other air pollution abatement strategies to mitigate its harmfulness. Nonetheless, the current research into the change trends of air quality is mainly based on state (province) and city, while the research on the national scale does not receive enough attention, which adversely affects the formulation of national macro-policy.

In order to explore and evaluate the change trends of air quality, many methods for different purposes have been proposed and widely used. The most popular methods include the seasonal Kendall slope estimator[11], seasonal-trend decomposition procedure[12], wavelet analysis[13] and numerical simulation model[14]. Because the air quality is affected by seasonality, meteorological conditions[15], and many pollution projects (such as SO_2, NO_2), these determine non-normal distribution characteristics of the air quality. Therefore, parametric methods (e.g., linear regression) are inadequate to evaluate its temporal trends. Besides, high-dimensional air quality pollution items cannot integrate and intuitively evaluate the air quality situation. To overcome this shortcoming, air pollution index (API), air quality index (AQI) and air quality health index (AQHI) reduce the high-dimensional air pollution items to one-dimensional items so as to reflect the air quality, which also facilitates the study on changes in air quality[16].

The research into overall exploration of changes in air quality primarily concentrates on the following aspects[7,17]: (i) Changes in challenges faced by air quality; (ii) Comparative study on changes in air quality of different metropolitan areas; (iii) Study on temporal and spatial changes in the regional air quality; (iv) Changes in the air pollutant sources. Tons of studies have shown that the challenges faced by urban air quality are increasing, such as increase in air pollution sources, diminished air selfpurification capacity and more complex meteorological conditions caused by climate changes[18]. Regional and temporal differences cause the changes in air quality to have different performance characteristics[19]. Although a host of studies have analyzed the changes in air quality in different regions and time scales, most of them focus on a certain city. The time scales are mostly analyzed on a yearly basis or on four seasons. However, studies on nations (regions) with different meteorological conditions cannot conduct targeted analyses, which to some extent separate some meteorological conditions. Additionally, most of the current research into change trends of air quality concentrates more on qualitative analysis, but less on qualitative and quantitative analysis.

In view of the above analyses, this study took China as an example and carried out the following research: (i) to qualitatively and quantitatively evaluate the spatial and temporal change trends of the overall air quality; (ii) to explore the change trends of air quality under different dry and wet meteorological conditions (e.g., annual scale, dry season and rainy season); (iii) to propose classification criteria for air quality types based on historical API values and reveal the characteristics of different air quality types; (iv) to analyze the distribution characteristics of different air quality types under different temporal and spatial conditions. It is hoped that the research results will provide theoretical support for comprehensive air control in dry and wet meteorological conditions.

2. Materials and methods

2.1. Study area

China is located in eastern Asia and western Pacific. It covers an area of about 9,600,000 km², across nearly 50° of latitude and 5,500 km between north and south and 62° of longitude and 5,200km between east and west (Figure 1). The land is high in the west and low in the east and distributed in three-level ladders, descends from the west to the east. The terrestrial height greatly differs. Also, the terrain is complicated, including mountains, plateaus, hills, basins, plains, deserts and other terrains. Due to the wide geographical span of China, it has tropical monsoon climate, subtropical monsoon climate, temperate monsoon climate, temperate continental climate, plateau climate and other climates. These different climates are responsible for obvious spatial and temporal differences in rainfall and temperature in China. The temporal and spatial distribution of annual precipitation is non-uniform, and is characterized by decrease from southeast coast to northwest inland and more precipitation in rainy season than in dry season. Yet, the durations of rainy season and dry season differ from place to place (Table 1). Besides, temperature also shows great temporal and spatial differences. In winter, temperature is generally low, and the south is hot while the north is cold. Also, there are great temperature differences between the north and the south. In summer, the majority of areas across the country are hot (except the Qinghai-Tibet Plateau), and there is no significant temperature difference in the north and the south. Different natural and resource conditions give rise to extremely imbalanced regional economic development. Specifically, the economic development level of the northwest regions lags behind that of other regions, and that of the inland generally falls behind that of the coastal regions. The difference in development levels between the south and the north is relatively minor. Light industry is the major industry in the south. By contrast, heavy industry is the main industry in the north. This paper selected 86 main cities in China. In accordance with the cities' geographical locations, China is divided into South China, Central China, North China, Northwest China, Southwest China and Northeast China. The specific city distribution and their respective regions are shown in Figure 1.

Table 1: The selected main cities in China.

Subregions	The number and name of the main cities	Rainy season
South China	1 Beihai, 2 Nanning, 3 Guangzhou, 4 Liuzhou, 5 Guilin, 6 Shantou, 7 Haikou, 8 Shenzhen, 9 Zhanjiang, 10 Zhuhai, 11 Shaoguan	Apr. to Sep.
Northeast China	12 Haerbin, 13 Dalian, 14 Fushun, 15 Shenyang, 16 Mudanjiang, 17 Changchun, 18 Anshan, 19 Qiqihaer	Jul. to Aug.
North China	20 Beijing, 21 Huhehaote, 22 Datong, 23 Tianjin, 24 Taiyuan, 25 Shijiazhuang, 26 Qinhuangdao, 27 Chifeng, 28 Changzhi, 29 Yangquan	Jul. to Sep.
Southwest China	30 Nanchong, 31 Deyang, 32 Chengdu, 33 Lasa, 34 Kunming, 35 Qujing, 36 Luzhou, 37 Yuxi, 38 Mianyang, 39 Zigong, 40 Guiyang, 41 Chongqing	Jul. to Aug.
Northwest China	43 Wulumuqi, 45 Kelamayi, 46 Lanzhou, 53 Baoji, 69 Weinan, 73 Shizuishan, 79 Xining, 80 Xi'an, 83 Yinchuan	Jun. to Sep.
Central China	54 Changde, 55 Pingdingshan, 56 Kaifeng, 57 Zhangjiajie, 62 Wuhan, 78	Jun. to Sep.

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	Jingzhou, 82 Zhengzhou, 85 Changsha	
East China	42 Shanghai, 44 Jiujiang, 47 Nanjing, 48 Nanchang, 49 Nantong, 50 Xiamen, 51 Hefei, 52 Ningbo, 58 Yangzhou, 59 Rizhao, 60 Hangzhou, 61 Zaozhuang, 63 Quanzhou， 64 Taian, 65 Ji'nan, 66 Jining, 67 Zibo,68 Wenzhou, 70 Huzhou, 71 Weifang, 72 Yantai, 74 Fuzhou, 75 Shaoxing, 76 Wuhu, 77 Suzhou, 81 Lianyungang, 84 Zhenjiang, 86 Qingdao	Jun. to Sep.

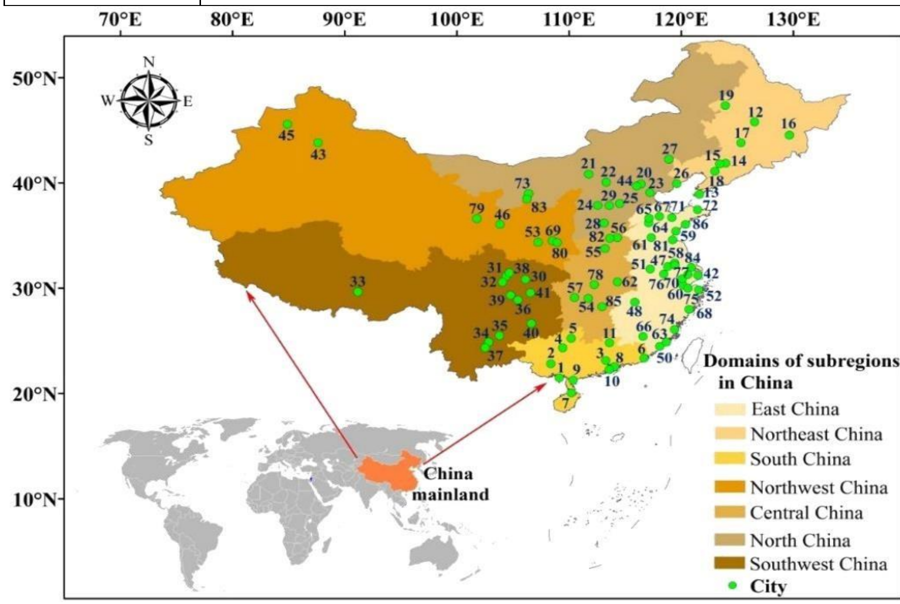

Figure 1: The main cities location and domains of subregions in China.

2.2. Data sources and processing

In this study, 86 main cities in China were selected based on the daily report by the Ministry of Environmental Protection of the People's Republic of China. Particularly, three key air pollutants were collected in each city, including sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter with aerodynamic diameter less than or equal to 10 mm (PM_{10}). The length of monitoring sequence in the 86 cities varied from 8 years to 13 years. The shortest time sequence was conducted by Nanchong and Zigong (Jan. 1, 2006 to Dec. 31, 2013), while the longest time sequence by Shantou, Zhanjiang and Yantai (Jun. 5, 2000 to Dec. 31, 2013).

2.3. Data analysis

Daily pollution datasets of 86 cities in China were calculated by API method, i.e., the highdimensional pollution items were reduced one-dimensional values. And daily API values of each year were divided into seasonal (rainy season and dry season) and annual scale in each city. In order to analyze air quality change trends, seasonal Kendall and Sen's slope estimator statistical tests were used, and the change trends in different time scales were calculated in this study. Based on the historical API and its impact on human health, the principles for classifying the air types were defined.

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2.3.1. Air pollution index

Air pollution index (API) is an air quality evaluation method which reduces the high-dimensional pollutants (e.g., SO_2, NO_2, and PM_{10}) to one-dimensional conceptual index to characterize the air quality. This method was extensively used to evaluate urban air quality[20]. API values range from 0 to 500. The smaller the API values are, the better the air quality of the region is. The air and environment quality decreases with the increase of the API values. Due to the differences in pollution items monitored by different cities in China, this paper selected for calculation the important cities which monitored SO_2, NO_2 and PM_{10} for at least 8 years of monitoring time sequence. The Ministry of Environmental Protection of the People's Republic of China divided the concentration of different pollutants into 7 levels (Level 0, 1, 2, ..., 6). Each level is assigned a corresponding constant V_n (n = 0,1,2,...,6) to reflect the concentration of each evaluation item (Table 2). As the evaluation items are high-dimensional data, they cannot intuitively reflect the overall air situation. As a result, this paper adopted the API index method to conduct dimension reduction calculation of the monitored items and the calculation method is described as follows.

Table 2: The maximum permissible pollutant concentration ($\mu g \cdot m^{-3}$) corresponding to API values.

Evaluation item	The maximum permissible pollutant concentration versus API values						
	Level 0 (L_0=0)	Level 1 (L_1=50)	Level 2 (L_2=100)	Level 3 (L_3=200)	Level 4 (L_4=300)	Level 5 (L_5=400)	Level 6 (L_6=500)
SO_2	0	≤50	≤150	≤800	≤1600	≤2100	≤2620
NO_2	0	≤80	≤120	≤280	≤565	≤750	≤940
PM_{10}	0	≤50	≤150	≤350	≤420	≤500	≤600

(1) Calculate the API value of each monitored evaluation item

The API values (I_i) of the corresponding pollutants were calculated based on the daily average concentration C_i of the i (i=1,2,3) evaluation item monitored by each city. The formula is as follows:

$$I_i = \begin{cases} \dfrac{(V_{i,n+1} + V_{i,n})}{(C_{i,n} + C_{i,n+1})}(C_{i,n} - C_{i,n}) + V_{i,n} \\ 500, if\, C_i\ exceed\ the\ level\ 6\ maximum\ premissible\ concentration \end{cases} \quad (1)$$

In the formula, $V_{i,n}$ and $V_{i,n+1}$ were the corresponding API values of n and n+1 levels of the i evaluation item. $C_{i,n}$ and $C_{i,n+1}$ were the maximum permissible pollutant concentrations of the i measured pollutant concentration most approaching to C_i, where $C_{i,n} < C_i < C_{i,n+1}$.

(2) Calculate the regional comprehensive API values

Based on the calculated API values (I_i) of pollutants, the maximum value is taken as the API value as follows

$$API = \max(I_1, I_2, I_3) \quad (2)$$

Different API values reflect the regional air quality. If API is less than 50, air quality is considered clean. In case of 50 <API ≤ 100, air quality is considered clean or good and will not harm human health. In case of 100＜API≤150, air quality is low-level pollution; in case of 150＜API≤200, air quality is midlevel

pollution; in case of API＞200, air quality is high pollution and is significantly detrimental to human health. **2.3.2. Trend test**

Among non-parametric data treatment methods, the seasonal Kendall testing method was one of the most popular patterns for analyzing change characteristics in different areas, and it had some advantages over parametric methods[21]. As analytical method for monotony trend, MKT had been widely used for researching on environmental change trend. It did not need to take into account the distribution characteristics of the data, and was applicable to the data analysis of side leakage values. It conducted a statistical significance trend test by calculating MKT test statistic and variance. The actual measured values were not used and replaced by the relative magnitude of the data. However, this method reflects the changing trends without quantitatively description. To compensate for this limitation, Sen's slope estimator statistical test was proposed, which was always applied with MKT method at the same time. So the MKT and Sen's slope estimator statistical tests were used to qualitatively and quantitatively analyze the API variety characteristics.

During the trend test, the test results are considered to be highly significant when the significance level α ($\alpha \le 0.01$). They are considered to be significant when $0.01 < \alpha \le 0.1$, and to be no trend when the significance level is greater than 0.1. Changes in air quality (improvement or deterioration) are determined based on the Sen's slope. In this paper, if the Sen's slope is positive, this indicates the air quality deteriorates, but if it is negative, this suggests that the air quality is improved.

2.3.3. Classification principles of air quality

Different cities were classified based on the impact of different API values on the human body and the ecological environment, the historical values of API of these cities and the following principles. (1) Poor-quality type. (I) API> 100 is greater than 20%; (II) Mean value of API is greater than 85. If a city meets any of the above conditions, it is considered to this type. (2) Slight-pollution type. (I) Mean value of API ranges between 50 and 70 and the proportion of API> 200 is greater than 1%; (II) Mean value of API ranges between 70 and 85. If a city meets any of the above conditions, it is considered to this type. (3)Saltatory-quality type. The mean value of API is less than 70, and the proportion of API> 200 ranges between 0 and 1%. (4) Acceptable-quality type. The mean value of API ranges between 50 and 70, and is not greater than 200. (5) Ideal-quality type. (I) The mean value of API is less than 50 without API＞200; (II) The proportion of API＞100 is 0. If a city meets any of the above conditions, it is considered to this type.

3. Results and discussion

3.1. The API spatial variety characteristics during the different seasonal scales

Trend calculation of the API values of 86 main cities in China was carried out based on MKT method, which showed that the overall air quality was improved (Table 3 and Figure 2). In general, the number of cities with improved air quality (or even highly significant ascending) exceeds that of cities with deteriorated or no significantly changed air quality. The proportion of cities with no significant changes in air quality outnumbers that of cities with deteriorated air quality. More specifically, the numbers of cities with improved air quality in annual scale, rainy season and dry season account for 62.8%, 48.8% and 57%, respectively, of the total cities.

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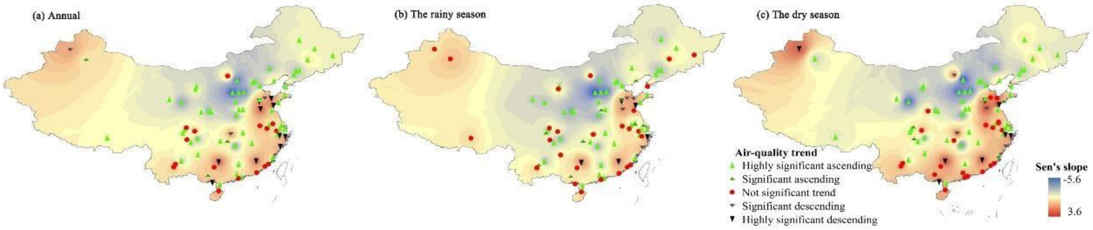

Figure 2: Change trend of the spatial air-quality in different time scales.

The change trends of air quality have obvious spatial and temporal change characteristics. From the perspective of deterioration in air quality, Southwest China and Northeast China show no deterioration in air quality in varied time scales. The air-quality trend is consistent with the targets of energy conservation and emissions reduction in this areas during the 11th and 12th Five-Year plan, and lots of studies also showed that the concentration of NO_x, SO_2 and particulate matter displayed a decrease trend in these areas[22]. Except the above-mentioned areas, other areas show deterioration in urban air quality in different time scales, and have the characteristic that the number of cities with deteriorated air quality in the dry season and annual scale exceed that in the rainy season. The area with the greatest proportion of cities with deteriorated air quality is East China. The numbers of cities with deteriorated air quality in East China represent 33.3%, 29.6%and 25.9%, respectively, of the total cities in East China in annual scale, rainy season and dry season. The main reason for this phenomenon is that East China has been under significant urbanization and industrial development with the increasing population density. What's worse, haze clouds often form over this area, and a great many aerosol particles and their precursors are emitted in this area. By contrast, the proportions of cities with deteriorated air quality in other areas and in different time scales are less than 20%. In respect of improvement in air quality, the proportion of cities with improved air quality is roughly the same in China in different time scales, but different areas demonstrate different characteristics. The proportion of cities with improved air quality is less than 50% in East China and South China, while greater than 50% in other areas in different time scales. Especially in North China and Central China, that of cities with improved air quality is more than 75% in different scales. This demonstrates that air pollution control has made positive progress in these areas, and the SO_2 and PM_{10} emissions have decreased in the past years. The proportion of cities with improved air quality in annual scale and dry season is greater than that in rainy season in Northeast China, Southwest China and Northwest China. That of cities with improved air quality in dry season is less than that in rainy season and annual scale in Central China and South China. Particularly, that of cities with improved air quality in dry season is only 18.2% in South China. It might be because there is more potential to improve air quality in dry season or poor air quality areas. Overall, the air quality of most cities in Northeast China, North China, Northwest China, Central China and East China changes significantly, while the areas with no significant changes in air quality in different time scales are mainly concentrated in Southwest and South China.

Table 3: Changes in air quality in different space and time scales.

Area	Time scale	HSD (P)	SD (P)	NST (P)	SA (P)	HSA (P)
China	Annual scale	10 (11.6%)	3 (3.5%)	16 (18.6%)	3 (3.5%)	54 (62.8%)

	Rainy season	5 (5.8%)	4 (4.7%)	26 (30.2%)	9 (10.5%)	42 (48.8%)
	Dry season	8 (9.3%)	4 (4.7%)	21 (24.4%)	4 (4.7%)	49 (57%)
South China	Annual scale	2 (18.2%)	0 (0%)	4 (36.4%)	1 (9.1%)	4 (36.4%)
	Rainy season	1 (9.1%)	0 (0%)	5 (45.5%)	1 (9.1%)	4 (36.4%)
	Dry season	2 (18.2%)	0 (0%)	7 (63.6%)	0 (0%)	2 (18.2%)
Northeast China	Annual scale	0 (0%)	0 (0%)	0 (0%)	0 (0%)	8 (100%)
	Rainy season	0 (0%)	0 (0%)	3 (37.5%)	0 (0%)	5 (62.5%)
	Dry season	0 (0%)	0 (0%)	0 (0%)	0 (0%)	8 (100%)
North China	Annual scale	0 (0%)	0 (0%)	1 (10%)	0 (0%)	9 (90%)
	Rainy season	0 (0%)	0 (0%)	1 (10%)	1 (10%)	8 (80%)
	Dry season	0 (0%)	1 (10%)	0 (0%)	0 (0%)	9 (90%)
Southwest China	Annual scale	0 (0%)	0 (0%)	5 (41.7%)	0 (0%)	7 (58.3%)
	Rainy season	0 (0%)	0 (0%)	6 (50%)	2 (16.7%)	4 (33.3%)
	Dry season	0 (0%)	0 (0%)	3 (25%)	2 (16.7%)	7 (58.3%)
Northwest China	Annual scale	0 (0%)	1 (11.1%)	0 (0%)	1 (11.1%)	7 (77.8%)
	Rainy season	0 (0%)	0 (0%)	3 (33.3%)	0 (0%)	6 (66.7%)
	Dry season	1 (11.1%)	0 (0%)	1 (11.1%)	0 (0%)	7 (77.8%)
Central China	Annual scale	0 (0%)	1 (12.5%)	0 (0%)	1 (12.5%)	6 (75%)
	Rainy season	0 (0%)	0 (0%)	1 (12.5%)	2 (25%)	5 (62.5%)
	Dry season	0 (0%)	1 (12.5%)	1 (12.5%)	0 (0%)	6 (75%)
East China	Annual scale	8 (29.6%)	1 (3.7%)	6 (22.2%)	0 (0%)	12 (44.4%)
	Rainy season	4 (14.8%)	4 (14.8%)	7 (25.9%)	3 (11.1%)	9 (33.3%)
	Dry season	5 (18.5%)	2 (7.4%)	9 (33.3%)	2 (7.4%)	9 (33.3%)

Note: HSD, SD, NST, SA and HSA represent that the air quality showed the trend of highly significant descending, significant descending, not significant trend, significant ascending and highly significant ascending, respectively. (P) means the number of cities with different trends account for the total number of according regional cities.

With regard to the spatial and temporal distribution of changes in air quality, in annual scale, dry season and rainy season, the areas with greater improvement in air quality are primarily distributed in North China and Northwest China (Figure 2). Besides, the improvement grows less marked from the east, south and west in these two areas, and deterioration in air quality gradually occurs in the east, southeast and south. The city with the greatest improvement in air quality in the annual scale and rainy season is Taiyuan with change slopes of -5.2 and -5.6, respectively. However Datong has the greatest change slope of improvement in air quality in the dry season, namely, -5.31. The areas with deterioration in air quality are East China and South China (Figure 2). The city with the greatest deterioration in air quality in the annual scale, rainy season and dry season is in Rizhao, with changes of 2.83, 2 and 3.71, respectively. The number of cities with improvement change in air quality in the annual scale, rainy season and dry season is 65, 69 and 61, respectively. Among them, the number of cities with an absolute value of greater than 1 is 44, 44 and 52, respectively, in the annual scale, rainy season and dry season, and the change in dry season is the greatest. The number of cities with a change slope of less than -1 in air quality is 36

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in both rainy season and annual scale, while the number reaches 42 in the dry season. The distribution of the number of cities' changes in air quality in different seasons is shown in Figure 3.

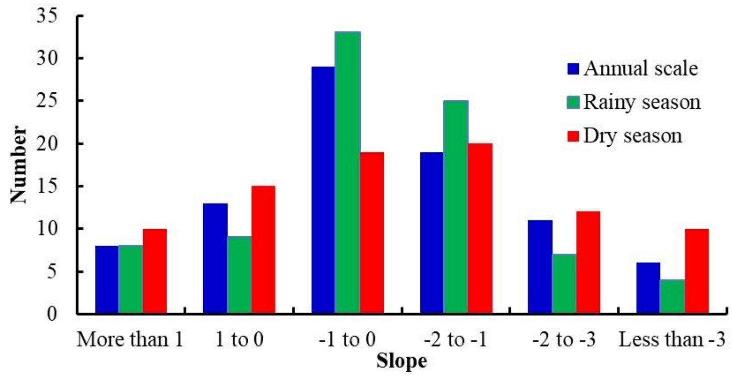

Figure 3: The numbers of the cities with different change slopes in different time scales.

3.2. Characteristics of different air quality types

Based on the change characteristics of historical API values of different cities, the API values and the formulated classification rules (showed in section 2.2.3), the air quality of 86 cities are divided into 5 types, that is, poor-quality type, slight-pollution type, saltatory-quality type, acceptable-quality type and ideal-quality type. Different types of air quality have the following different characteristics.

(1) Poor-quality type (Type I)

The air quality of cities of poor-quality type significantly affect people's normal life and physical health, and the API values of such cities are generally large and often reach 500 with great fluctuations in air quality. Additionally, the air self-purification capacity of such cities is poor. The air pollution sources are not effectively controlled and the pollutant load is high. As a result, in the event of air pollution, no rainfall and intense air movement, the air pollution will last for a relatively long time. Figure 4 shows the changes in air quality of two typical cities of poor-quality type. Since their air quality in rainy season is relatively good, no such cities are shown.

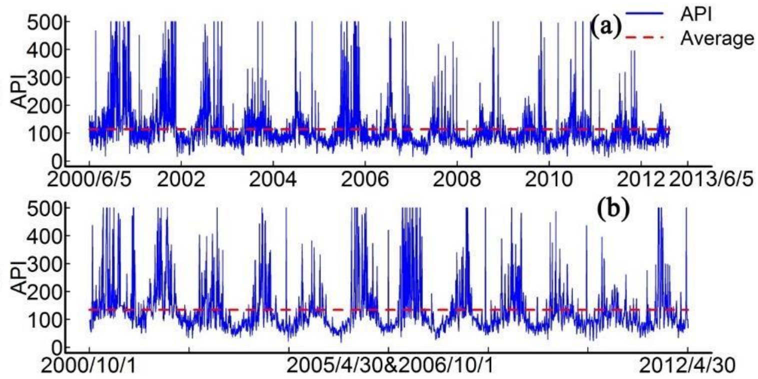

Figure 4: The typical characteristics of poor-quality type. (a) Lanzhou, (b)Wulumuqi.

(2) Slight-pollution type (Type II)

The air quality of cities of slight-pollution type affects people's normal life and health to a certain extent, but the effects are less profound than those of Type I. The API values of these cities mainly range between 50 and 100, but API values often greater than 100 and seldom reach 500. The self-purification

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capacity of such cities is moderate. In case that API is greater than 200, the API values will fall to or below 200 in the short term. The urban pollution sources are adequate, contributing to frequent slight pollution of the air quality. Figure 5 shows the changes in air quality of three typical cities of slightpollution types.

(3) Saltatory-quality type (Type III)

The air quality of cities of saltatory-quality type basically does not affect people's normal life and physical health, but occasional serious pollution will occur. The self-purification capacity of such cities is relatively high. If the air is seriously polluted, the air quality can quickly return to the normal levels. The API values of such cities are less than 70 and their air pollution sources are basically under control. Figure 6 shows the changes in air quality of cities of saltatory-quality type in three different time scales.

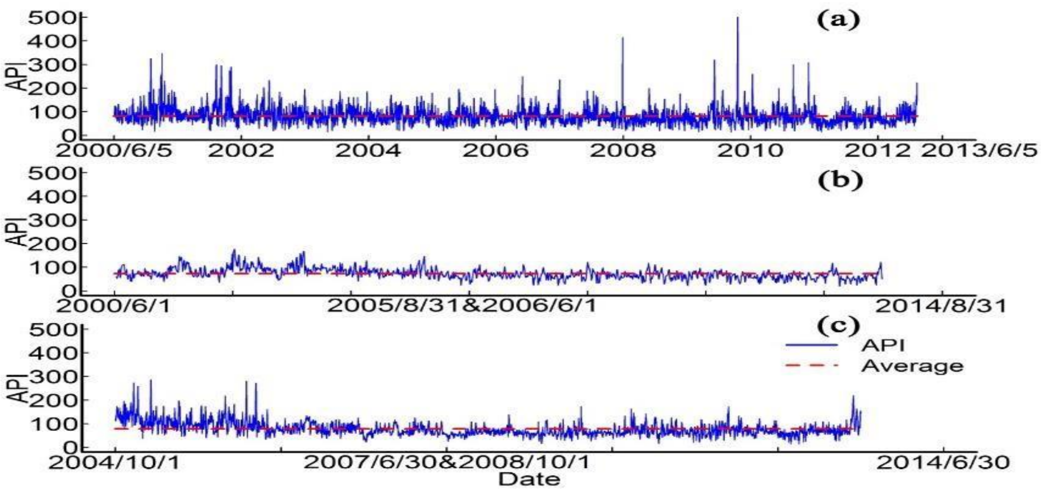

Figure 5: The typical characteristics of slight-pollution type. (a) Nanjing, (b) Chongqing, (c) Yangquan.

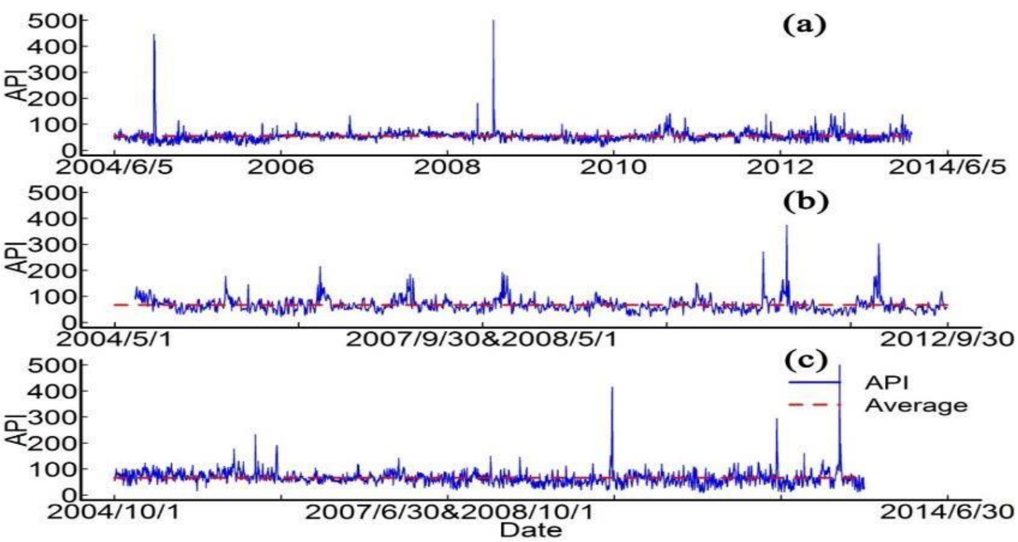

Figure 6: The typical characteristics of Saltatory-quality. (a) Kelamayi, (b) Yangzhou, (c) Deyang.

(4) Acceptable- quality type (Type IV)

The air quality of cities of acceptable-quality type can satisfy human life and health needs most of the time with occasional slight pollution, which however, only affects individual populations. The API values of such cities are less than 100 most of the time, and their mean value ranges from 50 to 70. The air pollution sources are effectively controlled or such cities are geographically advantageous, so the cities will not experience serious air pollution incidents. Figure 7 shows the changes in air quality of cities of acceptable-quality type in three different time scales.

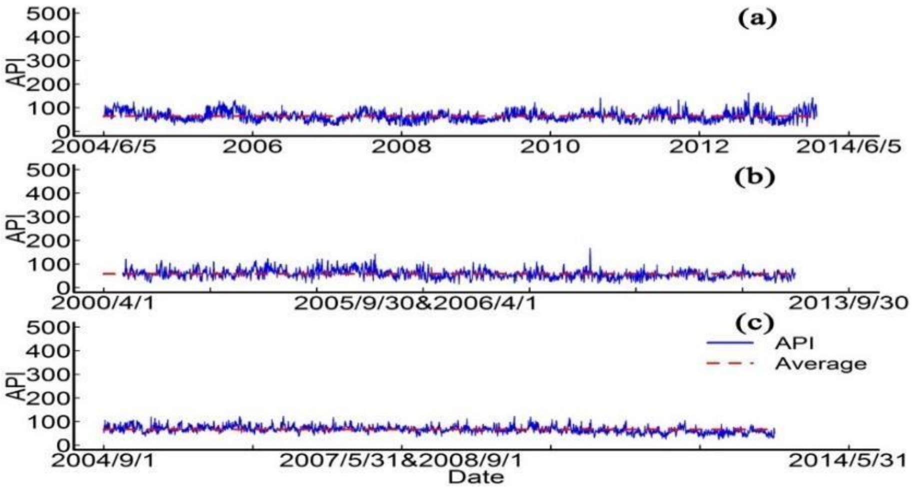

Figure 7: The typical characteristics of acceptable-quality type. (a) Liuzhou, (b) Guangzhou, (c) Qujing.

(5) Ideal-quality type (Type V)

The air quality of cities of ideal-quality type will not show pollution. The API values of such cities maintain a relatively low and stable level and the mean value of API is less than 50 or all API values are less than 100. Therefore, the human life and health needs can be satisfied. The air pollution sources of such cities are limited and can be effectively controlled or such cities are geographically advantageous. Besides, their remarkable self-purification capacity allows the overall air quality to maintain a good level. Figure 8 shows the changes in air quality of cities of acceptable-quality type in three different time scales.

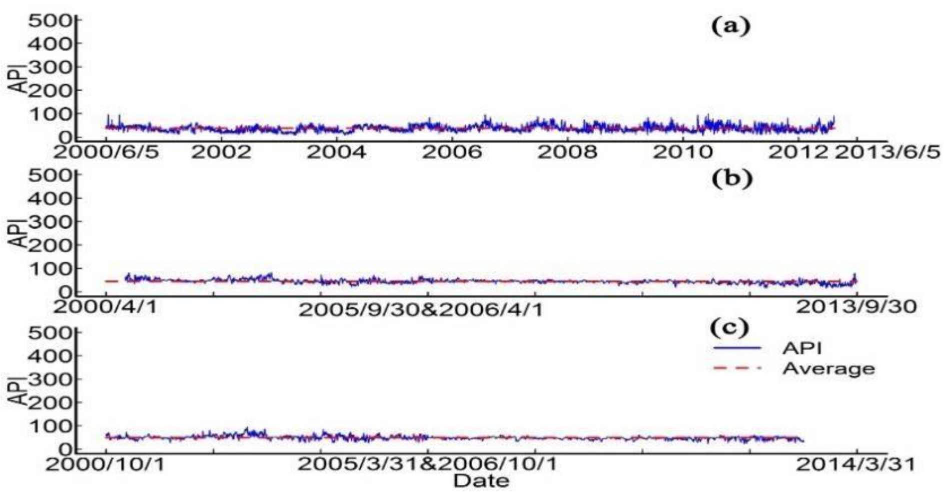

Figure 8: The typical characteristics of ideal-quality type. (a) Haikou, (b) Beihai, (c) Zhanjiang.

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3.3. Spatial and temporal distribution characteristics of different urban types

The urban air quality types have relatively significant differences with the temporal and spatial changes (Table 4 and Figure 9). The air quality of major cities in China is mainly Type II and Type III. Also, the number of cities of Type I is quite large, meaning that the overall air quality maintains a low or intermediate level. Besides, the number of cities shows a declining trend from air quality Type I to Type V in the dry season. To be specific, the number of cities of Type I and Type II is 31 and 25, respectively, while that of cities of Type IV and Type V is only 12 and 2, respectively, whose air quality is quite poor. By contrast, in the rainy season, the overall air quality is relatively good. Specifically, the number of cities of Type IV and Type V is 32 and 15, respectively, without cities of Type I and with the number of cities of Type II declining to 21.

Table 4: The numbers of cities of different air-quality types in different time scales.

Area	Season	Type I	Type II	Type III	Type IV	Type V
China	Annual	15	34	25	7	5
	Rainy season	0	21	18	32	15
	Dry season	31	25	16	12	2
South China	Annual	0	0	3	3	5
	Rainy season	0	0	0	3	8
	Dry season	0	1	2	6	2
Northeast China	Annual	1	4	3	0	0
	Rainy season	0	2	1	3	2
	Dry season	3	2	2	1	0
North China	Annual	4	5	1	0	0
	Rainy season	1	3	0	5	1
	Dry season	6	3	1	0	0
Southwest China	Annual	1	2	5	4	0
	Rainy season	0	2	1	6	3
	Dry season	3	2	3	4	0
Northwest China	Annual	5	3	1	0	0
	Rainy season	0	3	4	2	0
	Dry season	8	0	1	0	0
Central China	Annual	3	3	2	0	0
	Rainy season	0	4	1	3	0
	Dry season	5	3	0	0	0
East China	Annual	1	17	10	0	0
	Rainy season	0	6	11	10	1
	Dry season	6	14	7	1	0

From a spatial point of view, South China has the best air quality, without Type I in selected time scales. Only one city experiences Type II in the dry season, and only 2 and 3 cities fall into Type III in the annual scale and dry season. The overall air quality of Southwest China is moderate. The number of cities with good or poor air quality accounts for half of the total cities in the annual scale and dry season, but the number of cities with improved air quality in the rainy season tends to rise. The cities of poor air quality types (Type I and Type II) in the annual scale and dry season are mainly distributed in the East China, North China, Northwest China, Central China and Northeast China. On the other hand, in the rainy season, the number of cities of Type I and Type II decreases to various degrees. No cities belong to Type IV and Type V in the Northwest China, Central China and North China in the annual scale and dry season, so their air quality is very worrying. The recognized major causes were coal combustion, traffic and industrial emissions for those phenomena.

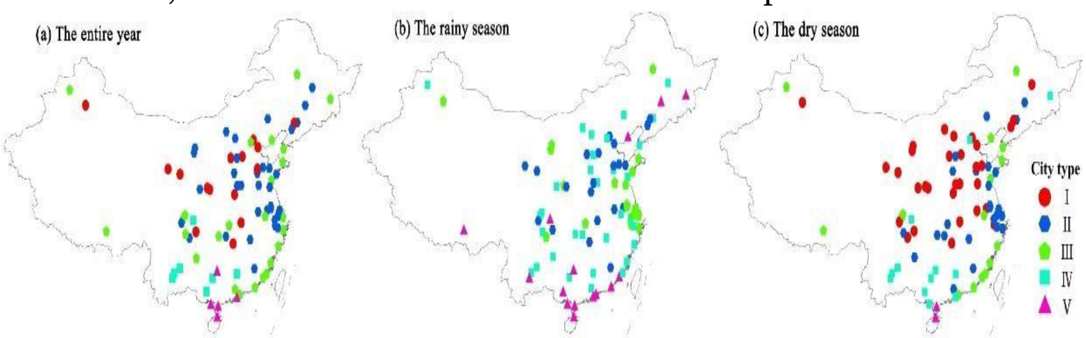

Figure 9: Temporal-spatial distribution characteristics of air-quality types at the different time scales.

3.4. Discussion

As can be observed from the analysis results of air quality in China in different time scales, the overall air quality is improved, but the air quality status is still not optimistic. The air quality of China and its change trends have substantial differences.

(1) Spatial and temporal differences in air quality

The dilution, diffusion and migration of air pollutants in the atmosphere are affected by rainfall, surface temperature, wind speed and other meteorological factors, so different regional climatic conditions lead to marked differences in the air quality of cities[23]. In general, the rainfall in China decreases from the south to the north, so does the rainfall's scouring degree and dissolution capacity of air pollutants. Air flow rate in different areas also varies. The faster the transverse air flow is, the more easily the air pollutants diffuse. Conversely, accumulation of air pollutants is more easily formed. Consequently, the closed circulation formed by air in the basin regions is not conducive to the diffusion of pollutants[24]. Besides, in the absence of rainfall and other scouring effects, it is difficult for the air quality to be improved. Furthermore, as the temperature inversion often occurs in the urban areas, the diffusion of air pollutants is restricted to a certain extent. Additionally, since the dust weather has seriously affected the Northwest China, North China, Northeast China and other regions, these regions are subject to serious air pollution. On the contrary, the southern part of China has a humid subtropical climate and is a coastal area, so its air self-purification capacity is greater. As the increase of the latitude, the climate gradually changes into a temperate sub-humid climate, and the air self-purification capacity diminishes. Therefore, the air quality of the southern part is generally better than that of other areas, and the air quality deteriorates in the north and inland areas.

(2) Temporal and spatial differences in change trends of air quality

The overall improvement in air quality of regions in China results from the following main reasons: (1) Changes in energy consumption structure[25]. At the beginning of the 21st century, the main energy consumption structure in most of the inland areas of China still focused on coal. Moreover, imperfection in desulphurization technology was responsible for generating a considerable number of pollutants such as PM_{10}, SO_2 and NO_2[26]. As a result, the air was polluted to various extents, but the air in the south and east without central heating was less affected. With a collection of policies on regulating the energy consumption structure promulgated around 2005, coal was replaced with such clean energy as natural gas to meet the daily energy needs in most regions. Also, it was stipulated that coal desulfurization should be carried out for power generation, heating and industrial production, and that the exhaust gas produced must be purified. Additionally, wind energy, solar energy and other clean energy were vigorously developed to replace traditional energy, which effectively reduced the emissions of atmospheric pollutants while ensuring the normal use of energy. This initiative has improved the air quality of most cities in the dry season[26]. (2) Adjustment of industrial structure[27]. In 2005, China promulgated relevant provisions to promote industrial restructuring, gradually phased out obsolete equipment and heavily polluting enterprises, or relocated manufacturing industries to other less developed cities. Through the combined effects of control of key pollution sources and various measures of adjusting production capacity structure, the resources and energy consumption are significantly reduced in the process of economic growth, so are the pollutant sources in the regions. (3) Control of construction project fugitive dust[28]. Over the past decade, China's major cities have been constantly expanded and large numbers of urban regions and buildings have been built. Construction and urban bare ground as well as less significance attached to the fugitive dust generated in construction contributed to stagnant air. With the progress of construction projects and continued improvement in relevant systems, the sources of fugitive dust are reduced and controlled through watering and other dust control measures, so that the fugitive dust pollutants in the air are effectively curbed. Hence, the urban air quality deteriorates. Nonetheless, with the continuous improvements in urban infrastructure and green space planning, cities have planted green belts and wind-breaking and sand-fixation vegetation and trees based on local conditions, which play an irreplaceable role in retaining dust, lowering particulate pollutants in the atmosphere and improving urban ecological environment. The change trends of air quality in different regions have different characteristics, which is mainly caused by differences in regional air control measures, economic development and meteorological conditions.

4. Conclusions

This paper analyzed the change trends of air quality in three time scales including annual scale, rainy season and dry season. The following conclusions can be drawn:

(i) The overall air quality in China is improved. The numbers of cities with improved air quality in China account for 62.8%, 48.8% and 57% of the total cities in annual scale, rainy season and dry season. The cities with deteriorated air quality and no significant changes are mainly distributed in East China and South China in the annual scale and dry season, whereas the air quality of most of the other regions is improved. Besides, the regions with deteriorated air quality in the rainy season are mainly distributed in East China and South China, but the spatial distribution of cities with no significant changes in air quality is quite scattered.

(ii) The improvement in air quality is gradually less significant from North China and Northwest China to their surrounding areas, and that in East China and South China is at a minimum. The numbers of cities with an absolute value of greater than 1 are 44, 44 and 52, respectively, in annual scale, rainy season and dry season, and the overall change in dry season is the greatest. The number of cities whose change in improvement in air quality is greater than 1 is 42 in the dry season, and is 36 in both the rainy season and annual scale.

(iii) The main cities in China show sharp differences in different time scales. Cities of Type I and Type II are mainly distributed in East China and North China, those of Type III in East China and those of Type IV and Type V in South China. In the annual scale, the number of cities with overall low or intermediate air quality and Type I and Type II is 49, and the number of cities with Type III is up to 25. The air quality is worse in the dry season, when the number of cities of Type I and Type II is as many as 56 and that of cities of Type III stands at 16. By contrast, the air quality is the best in the rainy season, when Type I never occurs and the number of cities of Type II is only 21. However, the number of cities of Type IV and Type V is as many as 47.

(iv) The regions with more severe air pollution show improved trends in air quality (except some regions in East China), but those with good air quality are no significant changes as a whole and even deteriorates in some cities.

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