

# Spatial-temporal Analysis of Daily Air Quality Index in the Yangtze River Delta Region of China During 2014 and 2016

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**Abstract:** Urban air pollution is a prominent problem related to the urban development in China, especially in the densely populated urban agglomerations. Therefore, scientific examination of regional variation of air quality and its dominant factors is of great importance to regional environmental management. In contrast to traditional air pollution researches which only concentrate on a single year or a single pollutant, this paper analyses spatiotemporal patterns and determinants of air quality in disparate regions based on the air quality index (AQI) of the Yangtze River Delta region (YRD) of China from 2014 to 2016. Results show that the annual average value of the AQI in the YRD region decreases from 2014 to 2016 and exhibit a basic characteristic of ‘higher in winter, lower in summer and slightly high in spring and autumn’. The attainment rate of the AQI shows an apparently spatial stratified heterogeneity, Hefei metropolitan area and Nanjing metropolitan area keeping the worst air quality. The frequency of air pollution occurring in large regions was gradually decreasing during the study period. Drawing from entropy method analysis, industrialization and urbanization represented by per capita GDP and total energy consumption were the most important factors. Furthermore, population agglomeration is a factor that cannot be ignored especially in some mega-cities. Limited to data collection, more research is needed to gain insight into the spatiotemporal pattern and influence mechanism in the future.

**Keywords:** air quality index (AQI); spatial-temporal evolution; contributing factors; Yangtze River Delta (YRD)

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## 1 Introduction

Since 2015, the Yangtze River Delta (YRD) region has experienced severe urban air pollution, especially in its most developed areas. These areas include southern Jiangsu Province, northern Zhejiang Province, and Shanghai municipality, where visibility is often reduced to only 1–3 km (Hu et al., 2014). As one of the most developed regions in China, controlling urban air pollution is imperative in the process of building world-class urban agglomerations. Sustained exposure to urban air pollution of high levels has significant negative effects

including reduced atmospheric visibility (Kan et al., 2012), endangered human health (Correia et al., 2013) and affected climate change through changes in insolation balance (Ebenstein et al., 2013). Recent studies also indicate that the spatial extent of urban air pollution in the YRD region is no longer limited to several cities but has expanded to a regional scale (Zhang et al., 2018). This trend highlights the need for large-scale urban air pollution monitoring program to determine its spatial-temporal variation and to design effective control strategies.

Over the past decades, studies of urban air pollution in the YRD region either focused on spatial and/or tem-

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poral variations of a single air pollutant or pollution index, such as levels of SO<sub>2</sub>, PM<sub>10</sub>, NO<sub>2</sub>, CO, O<sub>3</sub>, and the air pollution index (API) (Boichu et al., 2015; Dijkema et al., 2016; Tartakovsky et al., 2016; Lu et al., 2017). From June 2000, Chinese government regularly published the API index of the major cities. Because of a lack of data for particulate matter smaller than 2.5 µm (PM<sub>2.5</sub>), the government proposed to use the air quality index (AQI) instead of the API. The availability of AQI data released by 120 Chinese cities also provides reliable data source for air pollution analyses. Recent studies on urban air pollution discussed air pollution at different scales, varying from a national scale (Lin and Wang, 2016) or an urban agglomeration scale (Buchholz et al., 2010) to a city scale (Ozcan, 2012; Dimakopoulou et al., 2017). The relative abundance of monitoring sites in the most developed regions of China such as the Yangtze River Delta and the Pearl River Delta, where continuous data sets were available, made these places the focus of pollution studies (Fu et al., 2016; Chen et al., 2017). In addition, the impact factors of urban air pollution were another research focus. Besides population density, there were other factors affecting the formation of urban air pollution. Many previous studies have been biased towards natural factors. However, given the variation in research site location and study period, the impacts of natural factors on air pollution were still unclear and sometimes contradictory (Dominick et al., 2012; Ding et al., 2016). Exploring the relationship between urban air quality and economic development based on environmental Kuznets curves was another research focuses. Now there were many studies centering on urbanization (Han et al., 2014), traffic (Patton et al., 2014), energy structure (Ma and Zhang, 2014), population distribution, and industrial

development (Zhao et al., 2012).

To better understand the changing process and influencing factors of air quality in the YRD region, we illustrated the spatiotemporal evolution and pattern of urban AQI throughout the YRD region based on datasets from 2014 to 2016, and explored the influence of relevant factors. Compared with previous literatures, the accuracy of AQI collection in our research was significantly improved, which helps to bring out more accurate and reliable results. In addition, the spatial autocorrelation model was used to quantify the correlation of air pollution in the same metropolitan area and explored possible areas of atmospheric pollution spreading. Therefore, this research is expected to contribute not only to a more accurate understanding of the current urban air pollution within the YRD region, but also to the formulation of different air pollution prevention and control measures at the metropolitan level.

## 2 Materials and Methods

### 2.1 Study area

The geographical scope of this study covers the area addressed in ‘The Development Plan of the Yangtze River Delta’ (National Development and Reform Commission of China, 2016). It includes 26 cities located in Shanghai Municipality, Jiangsu, Zhejiang and Anhui provinces. In 2016, its land area, gross domestic product (GDP), and total population of this broad area were 211 700 km<sup>2</sup>, 14.45 trillion yuan (RMB), and 150 million people, respectively. These values accounted for about 2.2%, 19.4%, and 11.0% to China as a whole. To facilitate a regional comparison, these 26 cities of the YRD region are subdivided into eight regions, according to their location and economic status (Table 1).

**Table 1** Subdivision of the Yangtze River Delta (YRD) region of China in this study

Region name	Municipality/Province	Cities included
Shanghai	Shanghai	Shanghai
Hangzhou metropolitan area	Zhejiang	Hangzhou, Jiaxing, Shaoxing, Huzhou, Jinhua
Ningbo metropolitan area	Zhejiang	Ningbo, Taizhou, Zhoushan
Nanjing metropolitan area	Jiangsu	Nanjing, Yangzhou, Zhenjiang
Sunan metropolitan area	Jiangsu	Suzhou, Wuxi, Changzhou
Tongtaiyan metropolitan area	Jiangsu	Nantong, Taizhou, Yancheng
Hefei metropolitan area	Anhui	Hefei, Chuzhou, Ma'anshan, Wuhu, Tongling
Wannan region	Anhui	Anqing, Chizhou, Xuancheng

Notes: This subdivision mainly reflects defined metropolitan areas, with some additional considerations. First, Shanghai municipality, as the core of the YRD, needs to be singled out. Second, although Jinhua does not belong to Hangzhou metropolitan area or Ningbo metropolitan area, we decided to incorporate it into the Hangzhou metropolitan area given its traffic links with Hangzhou and Ningbo. Last, the name for the Tongtaiyan metropolitan area originates from the ‘13th Five-Year’ for Jiangsu Province.

## 2.2 Data sources

In January 2013, the Ministry of Environmental Protection in China started publishing real-time hourly concentrations of SO<sub>2</sub>, NO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, CO, and O<sub>3</sub>, which were used to calculate the AQI. Data presented in this study were obtained from this website (<http://www.tianqihoubao.com/aqi/>) for the period from 1 January 2014 to 31 December 2016. Given the subtropical monsoon climate in the YRD region, the seasons are defined as spring (March to May), summer (June to September), autumn (October to November), and winter (December to February). Data on social and economic development are from the annual ‘Urban Statistical Yearbook of China’ (State Statistical Bureau, 2015–2017), ‘Urban Construction Statistical Yearbook of China’ (Ministry of Housing and Urban-Rural Construction, 2015–2017) and the Statistical Yearbooks of Shanghai Municipality (Shanghai Bureau of Statistics, 2015–2017), Statistical Yearbooks of Jiangsu Province (Jiangsu Bureau of Statistics, 2015–2017), Statistical Yearbooks of Zhejiang Province (Zhejiang Bureau of Statistics, 2015–2017) and Anhui Province (Anhui Bureau of Statistics, 2015–2017).

## 2.3 Statistical analysis

In this study, data are analyzed to determine their spatial patterns, interpolated to assess spatial distributions over the whole region, while factors influencing their distributions are determined using the entropy method, as described below.

### (1) Moran’s *I* index

Geographical entities or attributes may be clustered, randomly or regularly distributed (Tobler, 1970). Often, correlation between entities decreases with increasing distance, which is called spatial auto-correlation (Moran 1948). In the field of air pollution, spatial analysis has been successfully applied at multiple scales, in studies of important cities (Wong et al., 2001), provinces (Lin et al., 2012), and key areas (Karar et al., 2006). Here, we use spatial auto-correlation to evaluate the spatial-temporal evolution of the AQI and to identify hotspots. Its common statistical measure is the Global Moran’s *I* index, defined as:

$$\text{Moran's } I = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\left( \sum_{i=1}^n \sum_{j=1}^n w_{ij} \right) \sum_{i=1}^n (x_i - \bar{x})^2}, (i \neq j) \quad (1)$$

where  $x_i$  and  $x_j$  are the values for the AQI at city  $i$  and city  $j$ ,  $n$  is the number of cities,  $w_{ij}$  is a space-related weight and  $\bar{x}$  is average value of AQI per month. The value range of Moran’s *I* is  $[-1, 1]$ . In this case, negative values infer a negative correlation, while positive ones indicate a positive correlation, and values close to zero infer a random distribution. We also used a standardized *Z* statistic to test whether there was spatial autocorrelation. This *Z* statistic is calculated, as follows:

$$Z_I = \frac{I - E[I]}{\sqrt{\text{Var}[I]}} \quad (2)$$

$$E_I = -\frac{1}{n-1} \quad (3)$$

$$\text{Var}_I = E[I^2] - E[I]^2 \quad (4)$$

where  $[I]$  is a spatial matrix consisting of several Moran’s *I* indices,  $E[I]$  and  $\text{Var}[I]$  are their theoretical expectations and theoretical variances, respectively. 95% confidence level is used, a significant spatial autocorrelation is indicated when  $Z_I$  is great than 1.96.

### (2) Spatial interpolation

To model spatial-temporal characteristics of PM<sub>2.5</sub> in China (Wang et al., 2015), an ordinary kriging method (OKM) is used to simulate spatial distributions of air pollutants. Because existing monitoring sites do not adequately cover the YRD region, we used an OKM to calculate spatial-temporal characteristics of the AQI.

### (3) Entropy method

The entropy method reflects the utility value of the index of information entropy. Its weight has higher credibility than weights derived using a hierarchical process or expert scoring method, making it suitable for comprehensive evaluation of multiple indicators. Steps involved in the entropy method are outlined elsewhere (Qiao, 2004). Consistent with previous air quality studies of cities in the YRD (Ding et al., 2016; Jassim and Coskuner, 2017), we select 15 indicators, ranging from natural variables, population density, economic status, urban status, and level of environmental regulation to investigate the main factors influencing the AQI in various cities of the YRD region (Table 2).

## 3 Results and Discussion

### 3.1 Temporal variation characteristics of AQI in the YRD region

Fig. 1 shows the monthly AQI values over the entire

**Table 2** The comprehensive evaluation system used to assess changes in the air quality index (AQI) of each city in the Yangtze River Delta region

Content	Indicators	Unit
Natural condition	Annual average temperature	°C
	Annual average rainfall	mm
	Annual average wind speed	m/s
Population size	Population density	person/km <sup>2</sup>
	Resident population	10000 persons
	Proportion of urban population	%
Economic development	Per capita GDP	10000 yuan (RMB)
	Industrial added value accounted for GDP	%
	R&D expenditure accounted for GDP	%
Social civilization	Total energy consumption	10000 ton of standard coal
	The number of public vehicles	10000 cars
	The number of college students per 10000 students	person/10000 persons
Environmental regulation	Environmental investment accounted for GDP	%
	Proportion of built-up area accounted for total administrative area	%
	Green coverage rate of built-up area	%

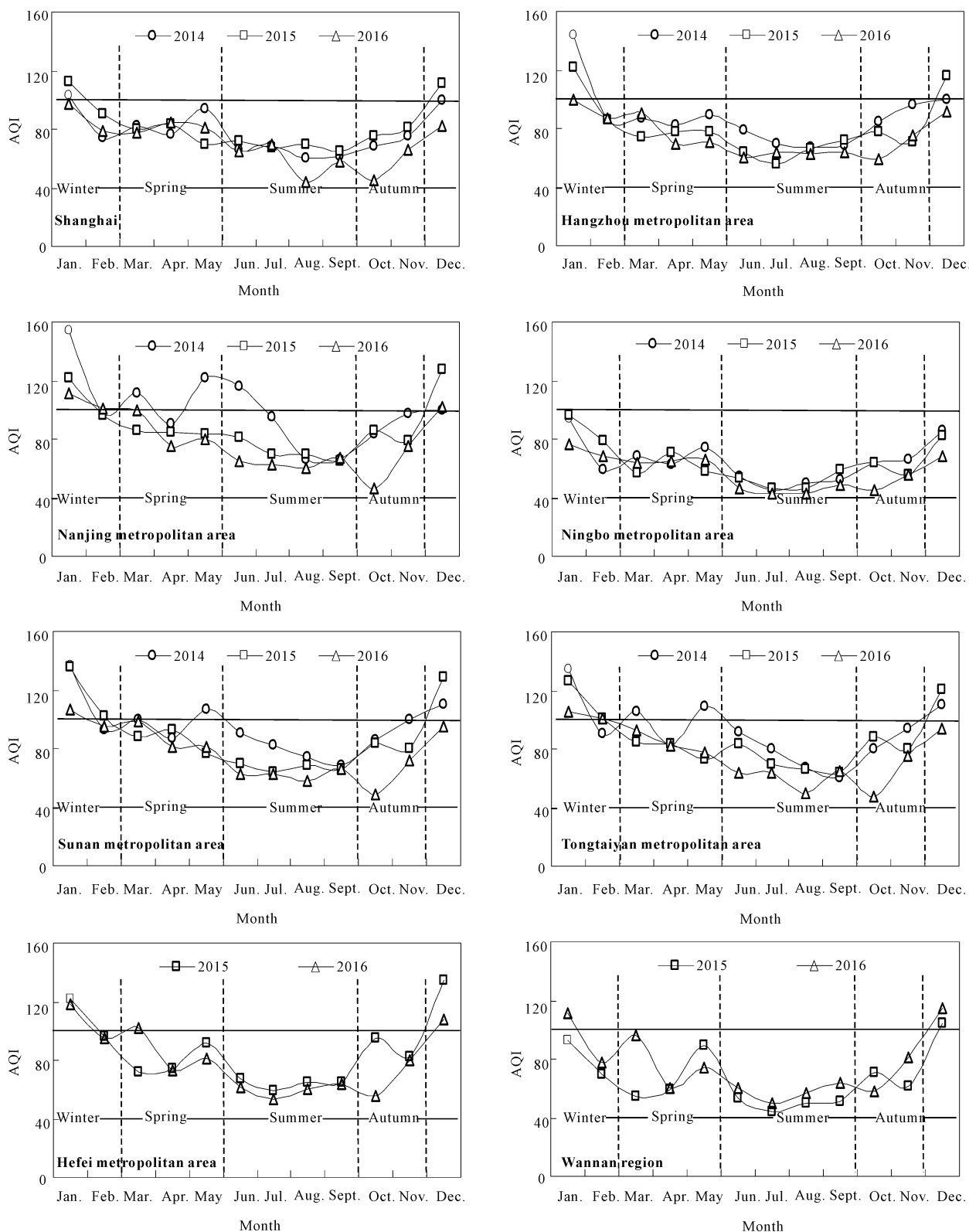
Notes: Because of lacking data for some cities in Anhui Province, including Hefei, Chuzhou, Ma'anshan, Wuhu, Tongling, Anqing, Chizhou and Xuancheng, we used data for 2015 and 2016 in this region. And GDP in the above table is gross domestic product.

study period (2014–2016) for all eight regions just as Table 1 shows. For most metropolitan areas, the AQI curve of 2016 is significantly lower than that of 2014, which suggests that air quality of most cities has improved significantly during the study period, except for Anqing and Chizhou from Anhui province. This indicates that air pollution control measures, including desulfurization and denigration of electric power outputs, elimination of small coal-fired boilers, and prohibition of straw burning, have achieved remarkable results. Some cities like Nanjing (Jiangsu Province), Zhenjiang (Jiangsu Province), Jinhua (Zhejiang Province) and Hefei (Anhui Province) show > 20% reduction in AQI values over the study period. However, top 10 cities with the highest annual average AQI belong to Hefei and Nanjing metropolitan area, suggesting that greater efforts should be made to remediate atmospheric environments in these areas.

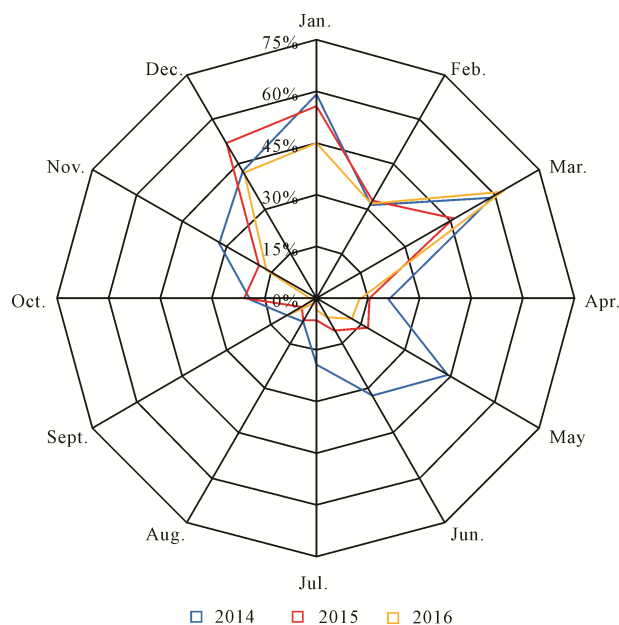
Seasonal changes of AQI are characterized by high values in winter, lowest in summer, and intermediate in spring and autumn. These changes reflect seasonal differences in economic activities, social life, and meteorological conditions. The YRD region is one of the China's most important manufacturing centers, with

massive annual emissions of air pollutants from steel, petrochemical, and power generation enterprises. High emissions are compounded by stable winter meteorological conditions, leading to high levels of pollution in winter. Typically, low rainfall and low wind speeds in winter are not conducive to diffusion of pollutants, which has become an important natural factor for serious pollution in winter. In summer, meteorological conditions that favor diffusion makes air pollution levels lower; while in spring and autumn, air pollution is exacerbated by straw burning, producing intermediate levels of pollution.

Fig. 2 shows the proportion of pollution days per month based on the AQIs of 26 cities from 2014 to 2016. During the study period, air quality in the YRD region improves, especially in May and June, with the proportion of pollution days per month decreasing from 44.1% and 32.5% in 2014 to 11.7% and 5.9% in 2016, respectively. The proportion of pollution days with exceeding pollution standard (AQI = 100) varies for each season, with average frequencies of 28%, 4%, 9% and 40% for spring, summer, autumn and winter, respectively. January and March have the worst levels of air quality.



**Fig. 1** Monthly variation in air quality index (AQI) values for the Yangtze River Delta region of China from 2014 to 2016. Central black line in all panels defines the limit of good air quality. Given the lack of data for several cities in the Wannan region and Hefei metropolitan area of Anhui Province in 2014, only data for 2015 and 2016 are shown in this part. And the cities included in each metropolitan area are shown in Table 1. According to China's Environmental Protection Standard HJ633-2012, a value of AQI higher than 100 indicates a polluted state.



**Fig. 2** Percentage of air quality index (AQI) values over the HJ633-2012 pollution standard (AQI = 100) in different months in the Yangtze River Delta region of China from 2014 to 2016

### 3.2 Spatial variation characteristics of AQI in the YRD region

According to China's Environmental Protection Standard (HJ633-2012), AQI is divided into six intervals (0–50, 51–100, 101–150, 151–200, 201–300, and > 300), which corresponds to six levels of air quality (excellent, good, mild pollution, moderate pollution, severe pollution, and serious pollution). Calculate the proportion of different pollution levels in different regions from 2014 to 2016 and draw them on eight doughnut charts (Fig. 3). Two spatial characteristics of air pollution can be reached. First, although air quality improves from 2014 to 2016, regional differences remain significant. Second, the areal extent of air pollution is greatest in winter and almost every region is in mild or moderate pollution.

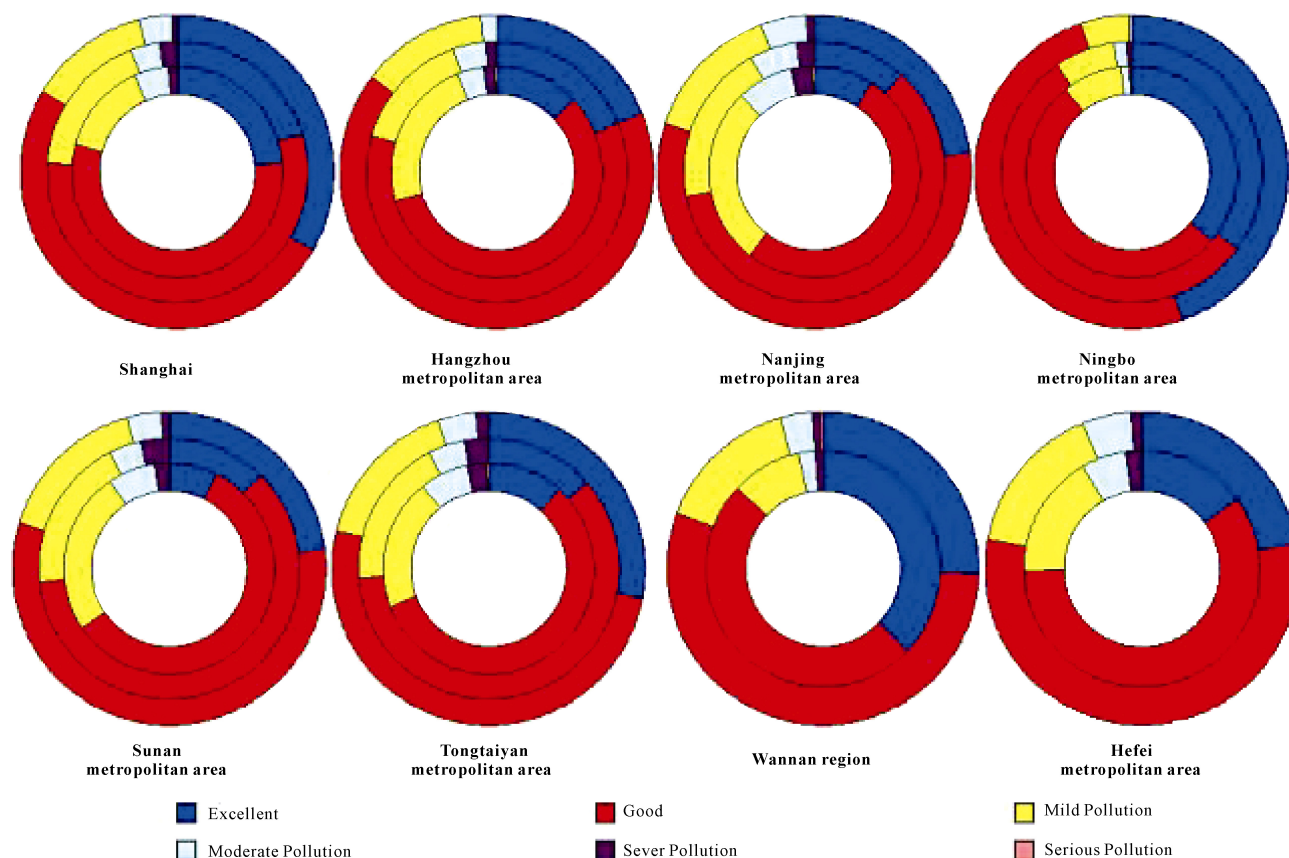
The proportions of pollution days of eight regions in 2016 are (sorting from high to low): Hefei metropolitan area (22.0%), Tongtaiyan metropolitan area (21.2%), Sunan metropolitan area (20.4%), Nanjing metropolitan area (20.0%), Wannan region (19.1%), Shanghai municipality (16.4%), Hangzhou metropolitan area (14.8%), and Ningbo metropolitan area (5.4%), respectively. Obviously, most of metropolitan areas along the Yangtze River account for a relatively high proportion of pollution days at various levels, which are the most polluted

areas in the YRD region. In addition, it is particularly important to note that the Wannan region of Anhui Province is the only area where the proportion of polluted days rises (by about 6%), which is related to a sharp increase in the number of mildly polluted days, with a contribution rate of 88.5%.

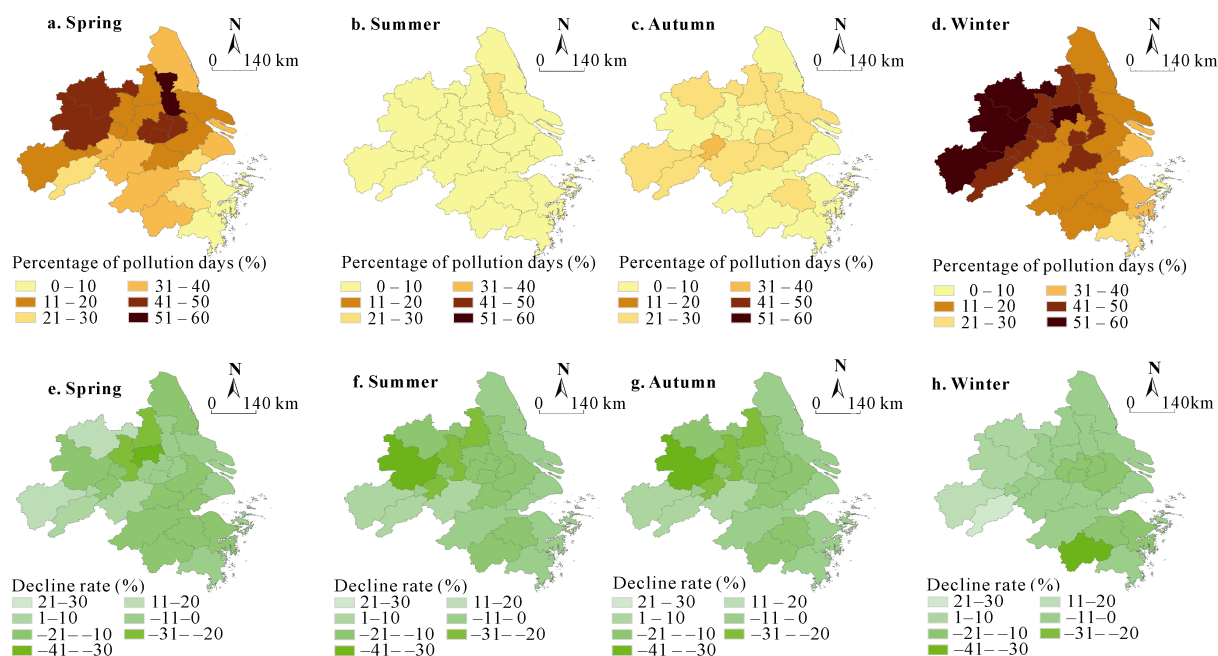
Of course, spatial variation of air pollution is also seasonal (Fig. 4). Cities which AQI exceeds the pollution limits of 40% or more are mainly distributed towards the northwest of the YRD region in winter. In fact, only Zhoushan (Zhejiang Province) and Taizhou (Zhejiang Province) have lower rates (less than 20%). In spring, many cities are over the pollution standard and excess rate is often greater than 30%. These cities are mainly located along the Yangtze River, especially in Taizhou (Jiangsu Province), where the ratio reaches 52.2%. Summer and autumn are the two seasons with the lower levels of air pollution. The AQI values for Zhoushan, Ningbo and Taizhou (all in Zhejiang Province) in summer typically reach an 'excellent' level, while other cities exceeds the pollution standard less than 10%. In 2016, the over-standard rate in most cities is lower than that in 2014, especially Nanjing (Jiangsu Province), Hefei (Anhui Province), and Jinhua (Zhejiang Province) which adds at least 72 non-polluted days. However, it is important to note that the pollution in the southern Anhui Province has increased the overall level of air pollution throughout the YRD region.

As shown in Table 3, there is a significant positive auto-correlation in the YRD region, where areas with high AQI are adjacent to each other, and likewise for areas with low AQI. Consistent with this pattern, values of Moran's  $I$  in Table 3 are greater than zero (except for October 2016). Typically, both Moran's  $I$  and  $Z$  values for corresponding months in 2015 and 2016 are lower, suggesting that air pollution has been eased following implementation of control measures in each city. In polluted seasons, especially winter and spring, both Moran's  $I$  and  $Z$  values from February to April showed a marked rise, indicating that the strength and range of expansion of air pollution in geographical space is most obvious.

To analyze the characteristics of air pollution during the peak pollution period, we select the AQI values for winter of 2016 and use the OKM method to interpolate values at a greater scale (Fig. 5). Clearly, the severity of air pollution increases gradually from the southeast



**Fig. 3** Different air quality levels at regional scale from 2014 to 2016. The inner, middle and outer circles depict results for 2014, 2015 and 2016, respectively. Because of the lack of data for 2014, the Wannan region and Hefei metropolitan area have only two circles, representing 2015 and 2016, respectively.

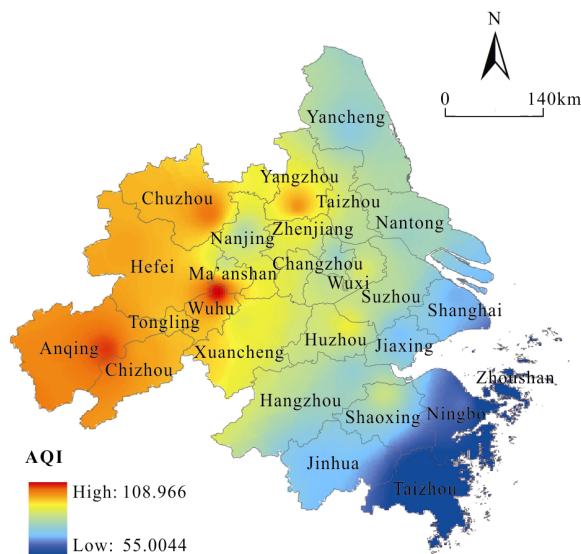


**Fig. 4** Percentage of pollution days in different seasons and decline rate of pollution days in each season compared with 2014 in the Yangtze River Delta of China. Spring (March to May), summer (June to September), autumn (October to November), and winter (December to February)



**Table 3** Spatial autocorrelation of air quality index (AQI) values in 26 cities of the Yangtze River Delta region

Index	Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Moran's <i>I</i>	2015	0.33	0.20	0.43	0.52	0.35	0.53	0.50	0.29	0.38	0.39	0.31	0.29
	2016	0.41	0.28	0.34	0.38	0.24	0.30	0.39	0.07	0.12	−0.03	0.07	0.27
Z score	2015	2.57	1.67	3.27	3.98	2.77	3.92	3.80	2.28	3.02	3.01	2.49	2.39
	2016	3.24	2.21	2.63	2.86	1.89	2.37	2.93	0.79	1.10	0.08	0.79	2.17

**Fig. 5** Spatial distribution of the air quality index (AQI) in winter for the Yangtze River Delta region in 2016

coast to northwest inland areas. The Hefei metropolitan area, Wannan region, and Nanjing metropolitan area form high-value areas (clustering), while Shanghai and Ningbo metropolitan area form low-value areas. This auto-correlation shows that more joint governance must be enforced on air pollution control strategies in the YRD region in order to have a better governance effectiveness.

### 3.3 Correlations between air quality and various influencing factors

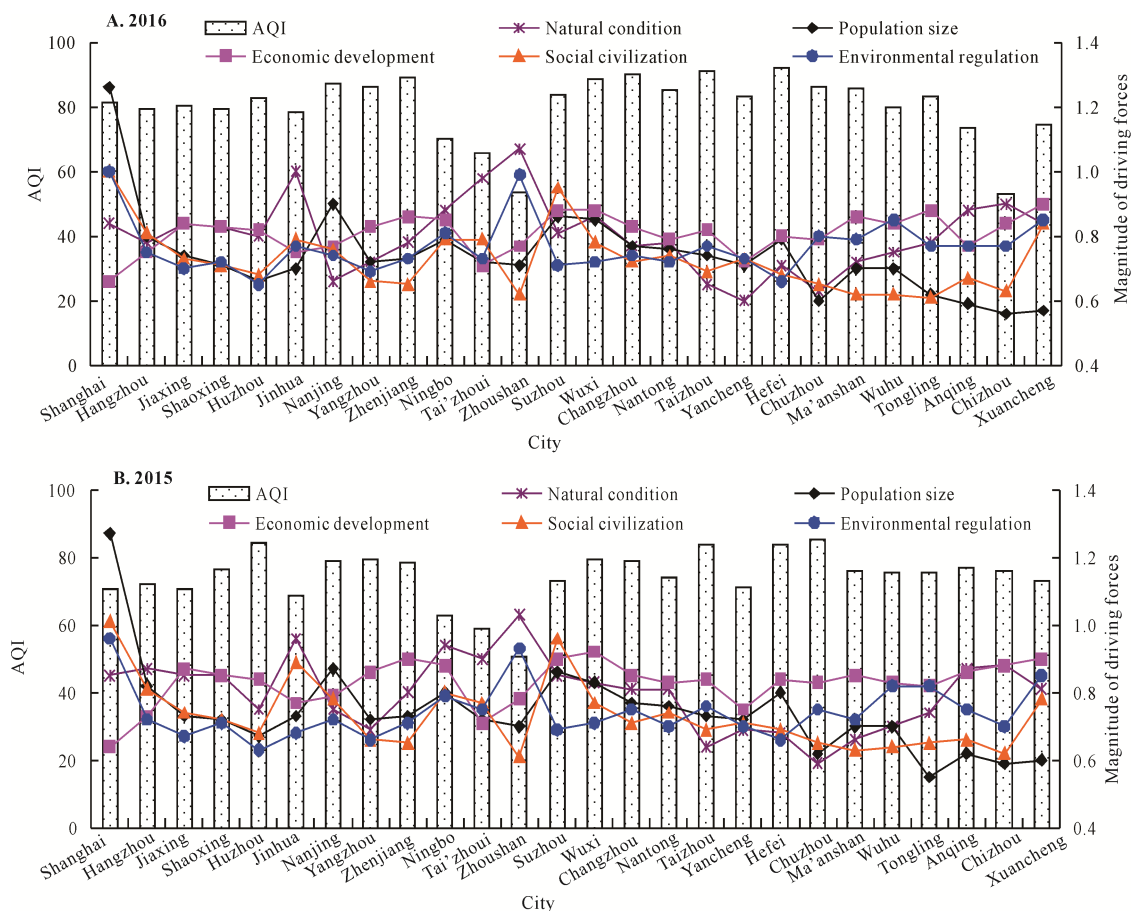
This study reveals that various factors contribute to air pollution in different cities (Fig. 6). Most cities in the YRD are industrial cities, including Jiaxing (Zhejiang Province), Shaoxing (Zhejiang Province), Zhenjiang (Jiangsu Province), Yangzhou (Jiangsu Province) and Ma'ansha (Anhui Province); these cities are heavily affected by their industrial exhaust emission. In our study, high population density is also correlated with high pollution levels, despite several studies suggesting that population density has no significant impact on air quality in China (George et al., 2017). Because high popula-

tion density is often associated with higher numbers of cars, urban constructions, and higher urban sewage levels. Although environmental regulations have lowered air pollution levels, their impact on the AQI is not sufficient to counter impacts related to rapid urbanization and economic development. Levels of social civilization, represented by the number of private vehicles in use, appears to be another factor correlated with air pollution in the cities like Jinhua and Suzhou, which have over 1.5 and 3.0 million cars, respectively. It is particularly important to note that under the premise of a similar regional climate and geography in the YRD region, some local natural factors play a critical role in specific cities. For instance, the land and sea breeze system operating all year round helps dissipate atmospheric pollutants in Zhoushan, Ningbo, and Taizhou of Zhejiang Province. In contrast, Chizhou (Anhui Province) and Anqing (Anhui Province) in the southwest of the YRD region experience buildup of pollutants related to stable air currents around Dabie Mountain (in the west of Anhui Province).

The atmospheric pollutant discharge data for the YRD region (Table 4) and some reports on urban pollution sources suggest that the main sources of air pollution in this area are coal-fired power plants, vehicles exhaust, industrial emissions, and dust emissions. Because there are quite a few industrial enterprises producing thermoelectricity and building materials within urban areas and their surroundings, in addition to the growing number of cars in most urban clusters, there are substantial emissions of coal-fired dust, industrial dust, road dust and other primary pollution particles, as well as sulfur dioxide, nitrogen oxides, carbon monoxide and other gaseous pollutants that can be converted into secondary pollution particles.

The planetary boundary layer is also known to affect meteorological factors in this area. In our study, we conclude that an inversion layer produced through advection and radiation makes the regional atmospheric structure more stable, resulting in reduced dissipation of





**Fig. 6** Driving forces of air quality disparity in different cities in the YRD region from 2015 to 2016. Left ordinate represents AQI value and right ordinate represents the magnitude of different driving forces

air pollution. This phenomenon mainly occurs in winter and spring, which partly explains why air pollution is more frequent in these seasons. Furthermore, the rapid urbanization in the YRD region has greatly changed its ground surface characteristics, affecting formation of inversion layers and indirectly impacting on air pollution.

To quantify relationships among various factors influencing the AQI, we use AQI data for 2016 for 26 cities of the YRD region as well as data on influential factors to carry out a multivariate regression analysis. Taking the AQI index of each city in 2016 as the dependent variable and assigning five influencing factors as independent variables, a regression analysis is carried out in SPSS. The results are shown in Table 5. First, the variance expansion factor for each variable is less than 3 (much less than the critical value of 10), which indicates that the model does not have multiple collinearity. Second, the adjusted  $R^2$  in the regression model is 0.659,

indicating that the fitting degree of the model is relatively good. Finally, economic development and social civilization fails to pass the 95% confidence interval significance test, in contrast to the other three factors. All three other factors show a significant correlation with changes in urban air quality. Natural variables and environmental regulations have obvious negative effects on AQI. In this case, higher levels of rain or wind and stricter environmental control measures inhibit the increases in AQI. In contrast, increasing population size facilitates an increase in AQI. Our regression analysis shows that when rain/wind, environmental control and population size increase by 1%, the AQI index increases by  $-0.573\%$ ,  $-0.324\%$  and  $0.468\%$ , respectively.

## 4 Conclusions

Our research analyzes the evolution process and spatio temporal pattern of urban AQI in the YRD region in

**Table 4** Discharge of major pollutants in the Yangtze River Delta region in 2015 and 2016

City	Volume of industrial waste water discharged (10000 t)		Volume of industrial sulphur dioxide emissions (t)		Volume of industrial soot (dust) discharged (t)	
	2015	2016	2015	2016	2015	2016
Shanghai	46900	36599	104900	67376	111400	72782
Nanjing	23216	21624	101021	28639	84128	48592
Wuxi	21993	20935	76092	61633	82859	67638
Changzhou	12977	12178	34420	31683	97999	57542
Suzhou	60506	48437	150010	109594	75406	61777
Nantong	15470	15367	55062	37115	31664	13821
Yancheng	16193	14207	41338	29772	36416	21934
Yangzhou	8871	8233	42415	15193	13917	9092
Zhenjiang	9059	7981	46329	32477	24230	20637
Taizhou	6943	5687	34170	15106	13880	9794
Hangzhou	33807	28382	63814	39499	49176	20414
Ningbo	16098	15760	101980	41928	28128	24009
Jiaxing	21947	19763	67924	27437	20975	10978
Huzhou	8611	8532	40226	28298	28855	19565
Shaoxing	26069	24383	59980	27499	32588	14441
Jinhua	7638	6467	39542	16321	39659	16390
Zhoushan	2202	1439	12379	1925	3050	2066
Tai'zhou	6251	5725	31868	13211	16263	9152
Hefei	5335	5130	40829	9011	85036	11483
Wuhu	4933	3302	38064	31872	39513	37115
Ma'anshan	7695	7558	48713	18947	75916	81449
Tongling	5338	3935	27813	12343	23136	17339
Anqing	4470	4018	14738	8023	24978	11039
Chuzhou	5860	3799	18516	11210	35263	11236
Chizhou	1422	945	17345	5556	13950	15590
Xuancheng	3665	1811	19195	8641	38754	13276

Note: Data source: Statistical Yearbooks for various cities for 2016 and 2017

**Table 5** Estimation of the effects of different factors on the air quality index (AQI) at a city level in the Yangtze River Delta region in 2016

Factor	Unstandardized coefficients		Standardized coefficients	<i>t</i> -test value	Sig.	95% confidence interval for <i>B</i>		Collinearity statistics	
	<i>B</i>	Std. Error	Beta			Lower bound	Upper bound	Tolerance	VIF
Constant	100.380	27.391		3.665	0.002	43.244	157.516		
National condition	-51.840	11.979	-0.573	-4.328	0.000	-76.828	-26.852	0.778	1.285
Population size	34.775	13.604	0.468	2.556	0.019	6.398	63.151	0.408	2.452
Economic development	35.396	22.784	0.206	1.554	0.136	-12.131	82.922	0.777	1.287
Social civilization	-3.851	17.380	-0.037	-0.222	0.827	-40.106	32.404	0.478	2.092
Environmental regulation	-39.510	16.464	-0.324	-2.400	0.026	-73.853	-5.166	0.750	1.333

Notes: *B* is a sample regression coefficient. Std. Error means standard error. Sig. is significance coefficient for short. And VIF means variance expansion factor.

terms of attainment rates, seasonal differentiation, and regional divisions based on a dataset from 2014 to 2016. Furthermore, we centers on different factors which may affect AQI among several metropolitan areas by using the GIS spatial analysis and the entropy method. The main conclusions are as follows:

(1) The annual average value of the AQI in the YRD region decreased from 2014 to 2016, indicating that the air pollution in this area has been obviously improved. Meanwhile, the basic characteristics of 'higher in winter, lower in summer and slightly high in spring and autumn' has not been changed. And heavy pollution weather mainly occurred in December and January.

(2) The attainment rate of the AQI shows an apparently spatial stratified heterogeneity. The air quality of Hefei metropolitan area, Tongtaiyan metropolitan area, Sunan metropolitan area and Nanjing metropolitan area maintained the worst air quality. Ningbo metropolitan area demonstrated a good attainment rate of the average annual air quality and other regions kept mild pollution.

(3) The decrease of Moran's  $I$  index of the AQI from 2014 to 2016 demonstrates a statistically significant decrease of spatial clustering trend, which revealed that the frequency of air pollution occurred in large regions was gradually decreasing. But the news of the continuance of severe pollution in Nanjing metropolitan area and Hefei metropolitan area were reported in different kinds of media.

(4) Per capita GDP and total energy consumption are the most important factors, which is consistent with the results of the analysis of atmospheric pollution sources issued by some cities. Meanwhile, the large concentration of population will inevitably bring a series of negative effects and lead to the aggravation of the environmental pollution. Maybe the limit of research time, the effect of environmental regulation on the AQI is not significant.

In order to optimize air quality in the YRD region, the adjustment of industrial structure, wider use of public transport and integrated environmental control should be further accelerated. In addition, due to data limitation, the paper cannot discuss the long-term change of AQI in the YRD region. However, the spatio-temporal evolution of air quality and its impact mechanism will be studied deeply in the future. We are still working hard to collect more detailed AQI data in order to better understand the changing laws of AQI and its

influencing factors.

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