

Characterization of Air Pollution in Urban Areas of Yangtze River Delta, China

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Abstract: The hallmark of development in the Yangtze River Delta (YRD) of East China has been sprawling urbanization. However, air pollution is a significant problem in these urban areas. In this paper, we investigated and analyzed the air pollution index (API) in four cities (Shanghai, Nanjing, Hangzhou and Ningbo) in the YRD from 2001 to 2012. We attempted to empirically examine the relationship between meteorological factors and air quality in the urban areas of the YRD. According to the monitoring data, the API in Shanghai, Nanjing, Hangzhou slightly declined and that in Ningbo increased over the study period. We analyzed the inter-annual, seasonal, and monthly variations of API, from which we found that the air quality had different temporal changes in the four cities. It was indicated that air quality was poor in winter and spring and best in summer. Furthermore, different weather conditions affected air quality level. The wind direction was considered as an important and influential factor to air pollution, which has an impact on the accumulating or cleaning processes of pollutants. The air quality was influenced by the different wind directions that varied with seasons and cities.

Keywords: air pollution index (API); urban area; meteorological factor; environmental decision; Yangtze River Delta; China

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1 Introduction

Concern about global warming and urban air pollution has become central issue in China, and much research over recent years has focused on urban air pollution. It is generally accepted that urban air pollution impacts human health and well-being and environment, especially in developing countries, for example China. A World Bank study reported that 16 of the world's 20 most air-polluted cities are located in China (López *et al.*, 2000). The increase in energy consumption due to the growth of the urban population exacerbates air pollution and follows urbanization in metropolitan regions

(Harlan and Ruddell, 2011). The air pollution index (API) is a reference index that is frequently used by many developed countries and regions throughout the world to report the ambient air pollution levels (Yu *et al.*, 2011). In June 2000, three major pollutants, including PM₁₀, SO₂, and NO₂, were included in the daily API reports in China, and the pollutants PM_{2.5}, O₃ and CO were added in 2012.

Previous studies have focused on the assessment of urban air quality (Gurjar *et al.*, 2008; Özden *et al.*, 2008). In these studies, a large quantity of temporal and spatial data were interpreted by international and domestic academics (Clark *et al.*, 2011; Dominick *et al.*,

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2012; Nalley *et al.*, 2013; Li *et al.*, 2014; Tian *et al.*, 2014; Zhang *et al.*, 2015). In recent years, researchers have analyzed and forecasted API using different models. Jiang *et al.* (2016) estimated nitrogen oxide emissions at city scale in China using a nightlight remote sensing model. They found that the fossil fuel derived NO_x emissions presented a significant linear correlation with the Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) nighttime stable light data. Wang *et al.* (2012) developed an urban air quality forecasting system using the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) and a regional haze forecasting system based on the Regional Atmospheric Environment Modeling System (RegAEMS) to forecast urban air quality and regional haze in the Yangtze River Delta (YRD) of China. In general, the synoptic patterns and anthropogenic emission densities were found to be the causes of air pollution episodes (Ji *et al.*, 2012). Consequently, statistical studies using meteorological data and air pollution monitoring data have confirmed that meteorological conditions affect atmospheric pollution in numerous ways (Akyüz and Çabuk, 2009; Unal *et al.*, 2011; Tian *et al.*, 2014; Gong *et al.*, 2015; Wang *et al.*, 2015; Mishra *et al.*, 2016).

In China, air pollution displays different characteristics in different regions and periods. Many Chinese researchers have focused on air pollution and its influence on heavy polluted areas, such as the Beijing-Tianjin-Hebei region (Zhao *et al.*, 2013; Tang *et al.*, 2014), the Pearl River Delta (Li J *et al.*, 2014; Li L *et al.*, 2014) and the YRD (Fu *et al.*, 2013; Liao *et al.*, 2014). A number of studies have focused on air pollution in China. The influence of air pollution on the YRD has increased over the past decade. Existing air pollution studies in the YRD region have focused on the high concentrations of aerosol particles (Wang, 2004; Chan and Yao, 2008). During a haze episode, the extremely low visibility in the YRD region was investigated as a function of PM_{2.5} concentrations at several meteorological sites (Che *et al.*, 2009; Huang *et al.*, 2011; Jia, 2011; Xiao *et al.*, 2011). However, previous studies concentrated on a specific city or the YRD region as a whole, and few studies have focused on comparisons between cities (Deng *et al.*, 2011; Wang *et al.*, 2012; Fu *et al.*, 2013; Song *et al.*, 2015; Wang *et al.*, 2015).

In this study, we analyzed API records from 2001 to

2012 in Nanjing, Shanghai, Hangzhou, and Ningbo cities in the YRD of East China, which all had a burst of urban expansion over the past two decades. In addition, the emission levels of various air pollutants have accelerated due to the expansion in the urban population, rapid economic growth, and increased industrial production, transportation and traffic infrastructure in the four cities. However, meteorological factors are more important dynamic variables to effectively interpret the changes in the API time series. Therefore, the correlation between API and its meteorological causes was examined in this paper.

2 Data and Methods

2.1 Study area and site distribution

The YRD is an alluvial plain situated west of the area where the Yangtze River drains out to the Yellow Sea. The YRD is the economic center of China and the world's most advanced manufacturing base. Furthermore, it is an important international gateway in the Asia-Pacific region and is targeted by the central government. It is the first region of China to become a world-class urban agglomeration area. The YRD includes Shanghai City, parts of Jiangsu Province and Zhejiang Province and has an area of 210 700 km². In this study, four major cities in the YRD (Nanjing, Shanghai, Hangzhou, and Ningbo) were selected as sample cities based on their location and fast urbanization processes. The locations of the four cities are shown in Fig. 1.

2.2 Ambient air quality data

According to the promulgated ambient air quality standards from the Ministry of Environmental Protection of the People's Republic of China in 2012, the API has six pollutants including SO₂, NO₂, PM₁₀, PM_{2.5}, O₃, and CO. The daily API values from 2001 to 2012 for the sample cities were downloaded from the data center of the Ministry of Environmental Protection of the People's Republic of China (<http://datacenter.mep.gov.cn/>). The API calculation equation is as follows:

$$API_i = (API_U - API_L) / (C_U - C_L) \times (C_i - C_L) + API_L \quad (1)$$

$$API = \max(API_i) \quad (2)$$

where API_i is the daily index value of pollutant *i* (i.e.,

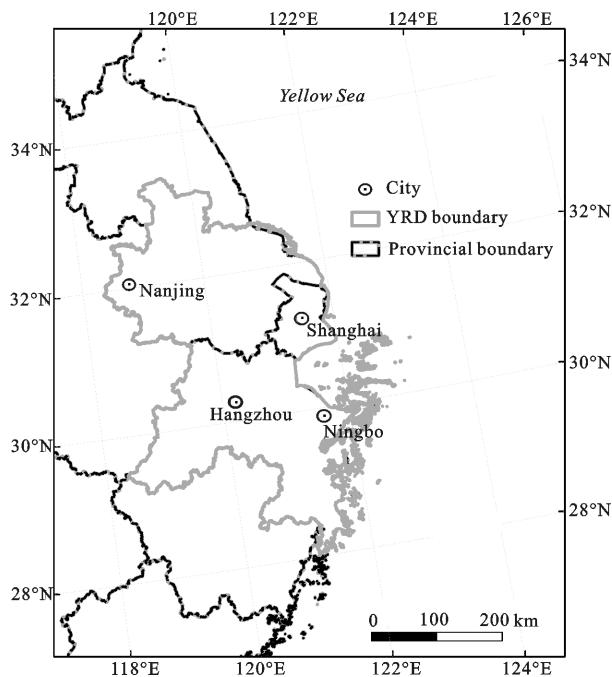


Fig. 1 Location of sample cities in Yangtze River Delta (YRD)

SO_2 , NO_2 , PM_{10} , O_3 , CO , and $\text{PM}_{2.5}$) in a city; API_U and API_L are the API values at the upper and lower limits of an API category, respectively; C_i is the observed concentration of pollutant i ; C_U and C_L represent the breakpoint concentrations of pollutant i at the upper and lower limits of an API category listed in Table 1 (GB3095-2012). As described by Equ. (2), the maximum API_i value of all contaminants is taken as the API of a city and the pollutant responsible for the highest index value is defined as the ‘primary pollutant’ under the condition that the API is greater than 50. In addition, we calculated the monthly API for the four cities from January 2001 to December 2012 to analyze their variable trends.

2.3 Meteorological data

Daily meteorological data for the sample cities from January 2001 to December 2012 were obtained from the National Meteorological Information Center (<http://data.cma.cn/>), for the same period as the air quality data. The meteorological data included temperature, relative humidity, wind speed, and wind direction.

2.4 Statistical analysis

Seasonal-Trend Decomposition Procedure Based on Loess (STL) and Morlet wavelet analysis methods were applied to analyze the time series variations. STL is a

filtering procedure used with the application of loess smoothing models for decomposing a time series into the additive components of the variation (Cleveland and Cleveland, 1990). In this study, we used the STL method over other decomposition techniques due to its applicability to a large amount of time series data (Theodosiou, 2011). The applicability to large data sets is why this method has been widely used in meteorology, environmental science, ecology and other fields (García-Mozo *et al.*, 2014; Masiol *et al.*, 2014). There are some distortions produced by the components of the API time series, which impede the understanding of their long-term changes. Therefore, the STL method was applied to analyze the temporal trends of the monthly API time series.

2.5 Matrix trajectory analysis

To effectively reduce air pollution, the characteristics of the air pollution episodes should be identified, and the causes of these episodes must be understood. We used the web version of the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) model, which is available on the National Oceanic and Atmospheric Administration (NOAA)’s Air Resources Laboratory website (Stein *et al.*, 2016), to calculate matrix trajectories of pollutants. The 48-h backward trajectories were calculated using the HYSPLIT model (<http://www.arl.noaa.gov/HYSPLIT.php>) for 24-h intervals terminating at 0:00 Coordinated Universal Time (UTC) (matrix points 30°N , 31°N , 32°N by 118°E , 119°E , 120°E , 121°E , 122°E) for each day from October 29 to November 9, 2012, at a height of 500 m.

2.6 Spearman rank correlation analysis

For the consideration of abnormally distributed API values, we used the Spearman’s rank correlation coefficient from spatial perspectives to analyze the relationships between the API and the same periods’ meteorological data from the sample cities.

3 Results and Discussion

3.1 Temporal variation of API

The original monthly API data were decomposed into seasonal, long-term trend, and remainder components (Fig. 2). Overall, the monthly APIs of the four cities

Table 1 The air pollution index (API) ranges and corresponding air quality levels in accordance with national standard GB3095-2012 of China

API category	Air quality level	Air quality	Health implication
0–50	I	Excellent	No health implication
51–100	II	Good	No health implication
101–150	III ₁	Lightly polluted	Slight irritations may occur, individuals with breathing or heart problems should reduce outdoor exercise
151–200	III ₂	Lightly polluted	Ditto
201–250	IV ₁	Moderately polluted	Healthy people will be noticeably affected. People with breathing or heart problems will experience reduced endurance in activities. These individuals and elders should remain indoors and restrict activities
251–300	IV ₂	Moderately polluted	Ditto
>300	V	Severely polluted	Healthy people will experience reduced endurance in activities. There may be strong irritations and symptoms and may trigger other illnesses. Elders and the sick should remain indoors and avoid exercise. Healthy individuals should avoid outdoor activities

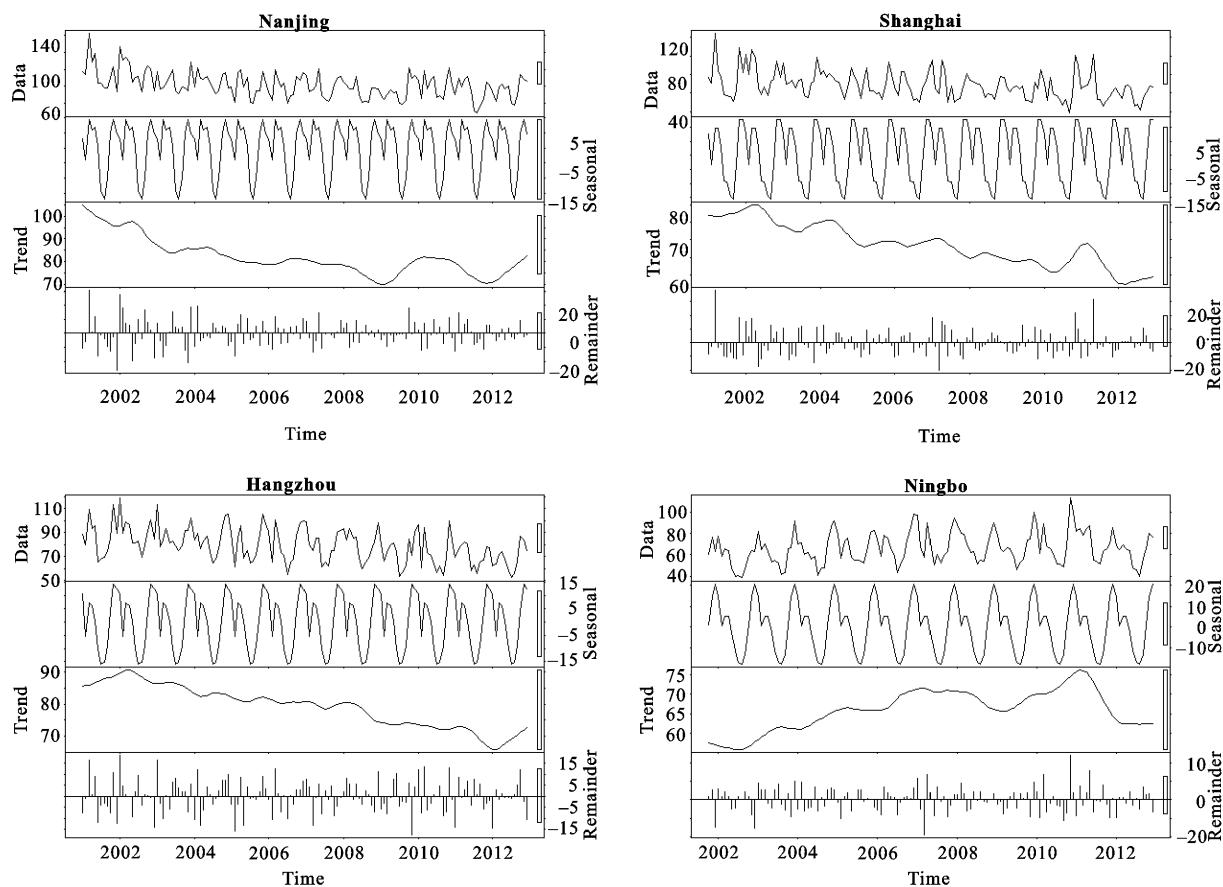


Fig. 2 Decomposition plots of average monthly air pollution index (API) data in four cities from 2001 to 2012

were high. This situation was mainly caused by the rapid development of economy and the gradual increase of population, which made the energy consumption be increasing daily in the urban areas of the YRD. The monthly APIs in Nanjing, Shanghai and Hangzhou illustrated a fluctuating decrease from 2000 to 2012. However, the monthly API in Ningbo increased prior to 2011, reached a peak in 2011 and then decreased. The

remainder of the time series was composed of the residuals from the seasonal trend and indicated that during winter and spring months, there were greater variances in the four sample cities. These larger variances might be due to short-term air pollution episodes. In general, air quality in the urban areas of the YRD began to improve over the last decade. The main reason for this situation was that a series of laws and regulations were

adopted by the municipal governments to address the serious problem of air pollution. The economy in the YRD has undergone rapid development, and the population has increased quickly. Therefore, the need to improve air quality is more pertinent and remains a critical concern in the eastern coastal China. To improve air quality, the Chinese central government formally promulgated the ‘Air Pollution Action Plan’, which will implement unprecedented control measures. In this plan, the annual average concentration of PM must be reduced by 10% by 2017, and the total energy consumption must be reduced to 65% of China’s total energy consumption of central cities of 2012.

The monthly API patterns (Fig. 3) and seasonal cycles (Fig. 4) were investigated. The monthly API was high in winter (December–February) and spring (March–May). Relatively polluted weather occurred during winter and spring seasons partly due to stable atmospheric stratification that allows pollutants to accumulate near the land surface and reduces the dilution

of pollutants by diffusion. The seasonal API in the four cities showed V-curve trends. The API was relatively low in summer (June–August) because the diffusion conditions were better during this period. To be specific, the air convective mixing was stronger, the wind speed was higher, and the vertical exchange was faster in summer. Moreover, air pollutants, especially PM, may be sharply reduced by wet removal due to increased precipitation during the Meiyu period (i.e., East Asian rainy season, usually from mid-June to early July) (Deng *et al.*, 2011).

3.2 Matrix trajectory analysis of air pollution

The matrix trajectories of 48-h terminated at 0:00 UTC (matrix points 30°N, 31°N, 32°N by 118°E, 119°E, 120°E, 121°E, 122°E) for 24-h intervals from October 29 to November 9, 2012, at the height of 500 m are shown as follows (Fig. 5). Two typical ‘accumulating-to-cleaning’ cycles are shown. The concentration of air pollution declined rapidly, while the origins of the

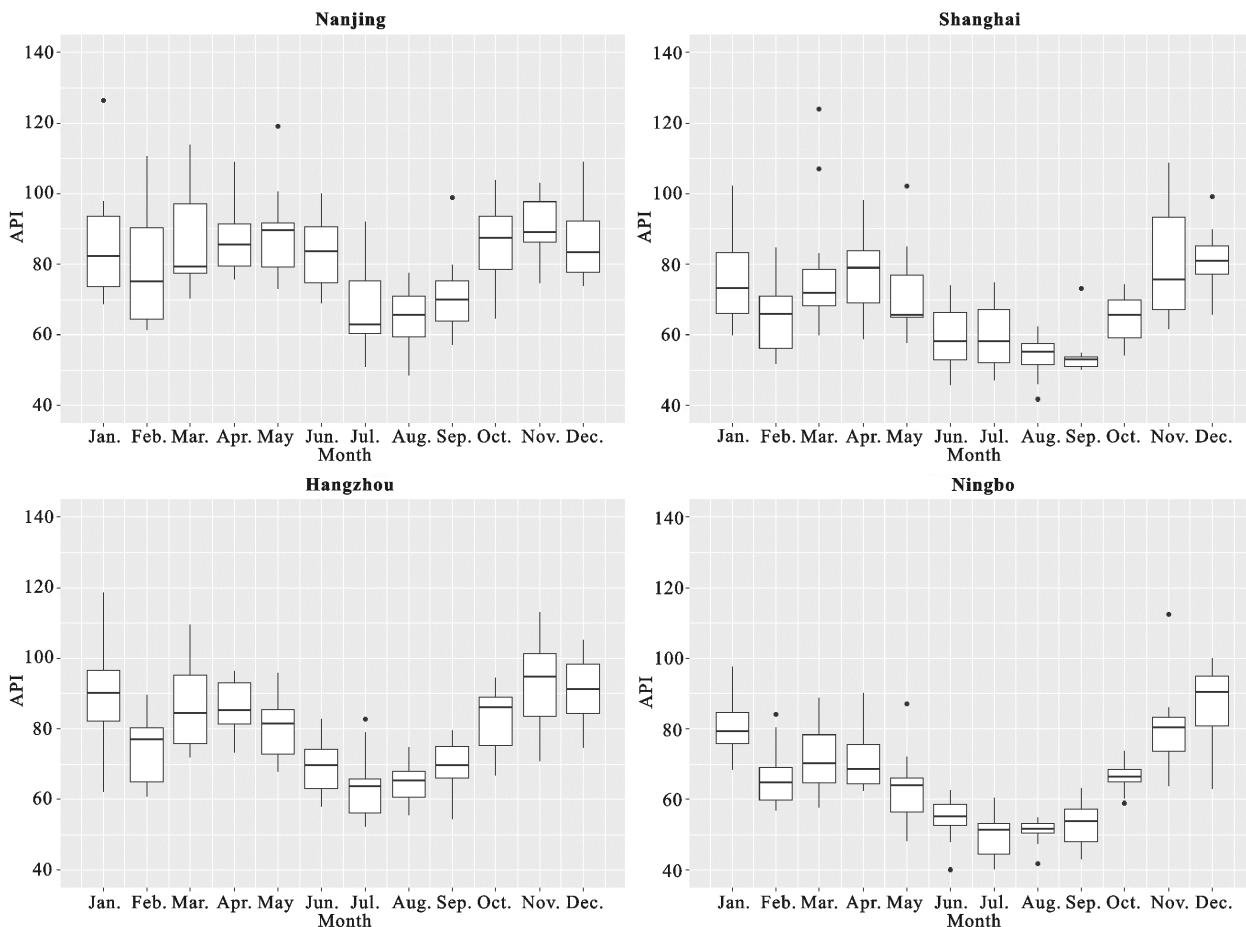


Fig. 3 Monthly mean API and standard deviation in Nanjing, Shanghai, Hangzhou, and Ningbo cities. The block dots are outliers

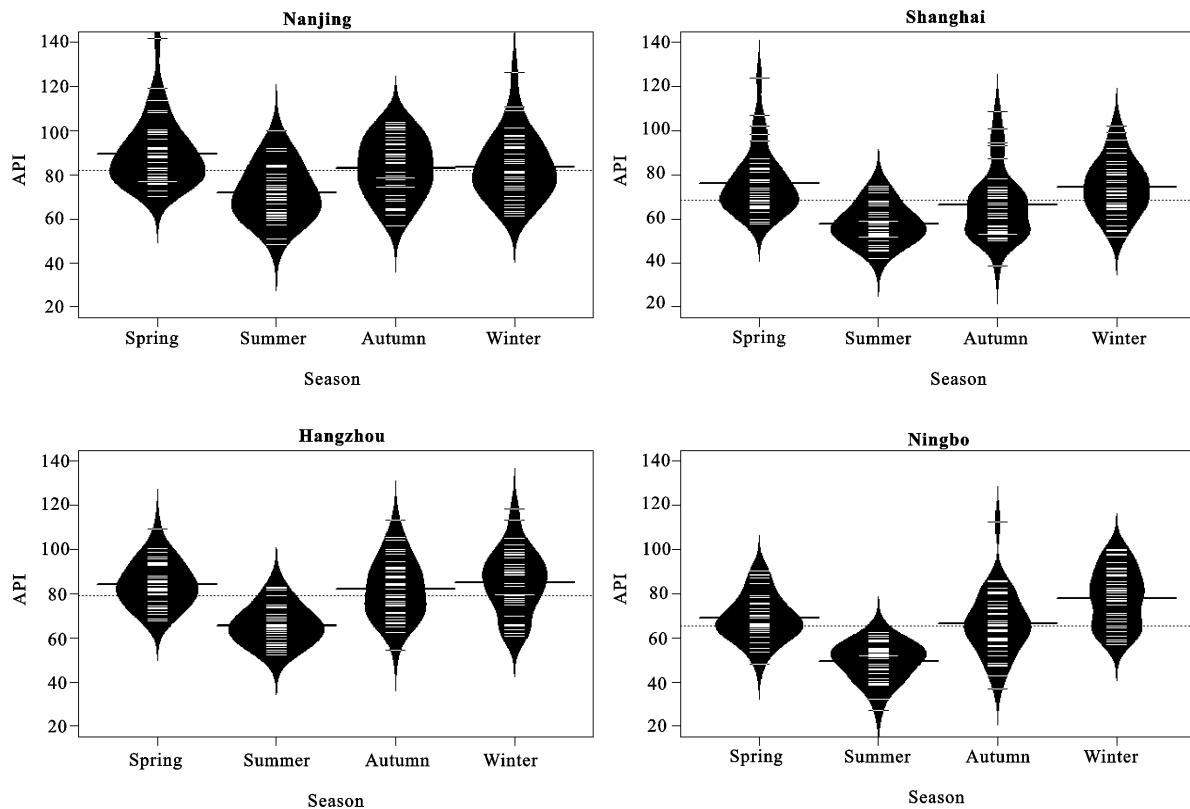


Fig. 4 Mean value, standard deviation and distribution of seasonal air pollution index (API) in Nanjing, Shanghai, Hangzhou, and Ningbo cities

back trajectories changed from northwest and north to northeast and southeast over a series of days, and the air quality improved. The concentration of air pollution increased rapidly, while the origins of the back trajectories changed from northeast and southeast to north and northwest, and the air quality declined.

Large spatial differences existed in the transport patterns as indicated by the 48-h matrix trajectories (Fig. 5). From October 29 to November 2, the origins of the trajectories changed from the northwest and the north to the northeast and the southeast. After several days of clean air, another accumulation process had occurred that the directions of the flows shifted from northeast and southeast to north and northwest in the study area. The origins of the trajectories terminating at $(30^{\circ}\text{N}, 118^{\circ}\text{E})$, $(30^{\circ}\text{N}, 119^{\circ}\text{E})$, $(30^{\circ}\text{N}, 120^{\circ}\text{E})$, $(30^{\circ}\text{N}, 121^{\circ}\text{E})$, $(30^{\circ}\text{N}, 122^{\circ}\text{E})$, $(31^{\circ}\text{N}, 122^{\circ}\text{E})$ and $(32^{\circ}\text{N}, 122^{\circ}\text{E})$ among them shifted markedly. The API details are shown in Table 2. From October 29 to November 2, the origins of the trajectories changed from northwest and north to northeast and southeast, and the API declined in the four cities. However, the air quality improved on November 2 in Nanjing and Shanghai, and there was a

one-day delay in Hangzhou and Ningbo for the first cycle. The delayed effects occurred because the direction of the flow was from north and Hangzhou and Ningbo are located in lower latitudes. The same phenomenon appeared in another accumulation process as well. The air became more humid when the origins of the back trajectories rotated from east to northeast or north (November 6). The higher humidity may result in secondary aerosol formation, such as sulfate and nitrate. Hence, the API of the polluted air was higher in the second cycle (November 7) than the first cycle (November 1 and November 2) and the air quality improved first in Shanghai and Ningbo and then in Nanjing and Hangzhou (with lower longitude than Shanghai and Ningbo) since the flow direction shifted to east.

The fastest flow came from northeast, while the slowest came from north. The accumulation process first occurred in the northern region of the study area, while the cleaning process first occurred in the southern region of the study area. The cleaning processes associated with the low API were created in part by clean air descending from northeast and southeast, whereas the accumulation processes related to the high air pollution

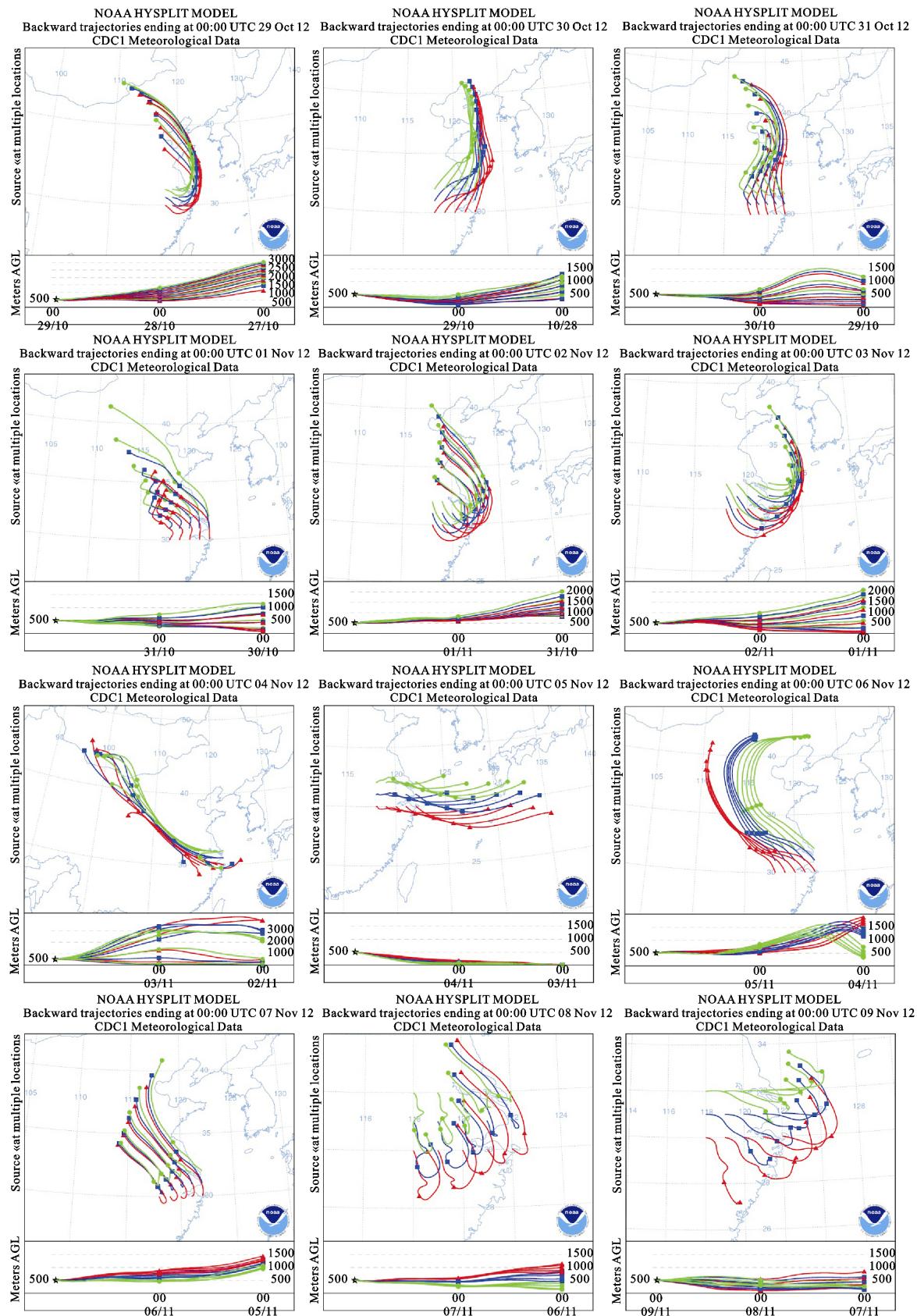


Fig. 5 The 48-h matrix trajectories (matrix points 30°N, 31°N, 32°N by 118°E, 119°E, 120°E, 121°E, 122°E) terminated at 00:00 UTC for 24-h intervals from October 29 to November 9, 2012)

Table 2 Daily API in Nanjing, Shanghai, Hangzhou, and Ningbo from Oct. 29 to Nov. 9, 2012

Date	Primary pollutant	Nanjing		Shanghai		Hangzhou		Ningbo	
		API	Air quality [*]	API	Air quality [*]	API	Air quality [*]	API	Air quality [*]
2012-10-29	PM _{2.5}	134	Polluted	94	Good	121	Polluted	123	Polluted
2012-10-30	PM _{2.5}	68	Good	40	Good	56	Good	54	Good
2012-10-31	PM _{2.5}	62	Good	47	Good	56	Good	52	Good
2012-11-01	PM _{2.5}	106	Polluted	105	Polluted	88	Good	90	Good
2012-11-02	PM _{2.5}	88	Good	48	Good	125	Polluted	115	Polluted
2012-11-03	PM _{2.5}	69	Good	38	Good	79	Good	70	Good
2012-11-04	PM _{2.5}	73	Good	66	Good	69	Good	56	Good
2012-11-05	PM _{2.5}	72	Good	99	Good	107	Polluted	107	Polluted
2012-11-06	PM _{2.5}	93	Good	88	Good	81	Good	90	Good
2012-11-07	PM _{2.5}	111	Polluted	102	Polluted	111	Polluted	113	Polluted
2012-11-08	PM _{2.5}	142	Polluted	93	Good	144	Polluted	115	Polluted
2012-11-09	PM _{2.5}	138	Polluted	39	Good	157	Polluted	84	Good

Note: * Air quality here just to distinguish between good and bad air quality rather than the levels of Air Pollution Index (API)

concentrations were aided by flows from north and northwest of the YRD, China.

3.3 Relationships between API and meteorological factors

Meteorological conditions affect the accumulation, diffusion, dilution of pollutants and pollutant concentrations even under the same pollutant source conditions. In this study, the Spearman's rank correlation coefficient between API and meteorological factors, including water vapor pressure, relative humidity, surface pressure, air temperature, daily precipitation, wind speed and sunshine duration were analyzed to reveal the relationships between API and meteorological factors (Table 3).

The influences of water vapor pressure, relative humidity, surface pressure, air temperature, daily precipitation, and wind speed on the API were significant in all

cities. However, the impact of sunshine duration was not significant in Hangzhou. In addition, the influence of wind direction on air quality varied significantly with season and city (Fig. 6). There were more air pollution days in winter and spring than in summer and autumn. It is clear that there were more air pollution days in Nanjing when the wind blew from east-southeast and north-northwest in winter, spring and autumn. Thus, we can infer that external pollution sources mainly came from east-southeast and north-northwest in winter in Nanjing. Additionally, the external pollution sources mainly came from west-northwest and north-northeast in winter in Shanghai. Air quality was also obviously affected by the north wind in autumn and winter in Hangzhou. In Ningbo, the air quality was obviously affected by the northwest wind in winter and the east-northeast wind in autumn.

Table 3 Relationships between daily API and meteorological factors in sample cities

City	Index	Type	PRS	TEM	WVP	RHU	PRCP	WS	SD
Nanjing	API	Correlation coefficient	0.091**	-0.080**	-0.137**	-0.186**	-0.164**	-0.139**	0.090**
		Sig.(2-tailed)	0	0	0	0	0	0	0
Shanghai	API	Correlation coefficient	0.150**	-0.204**	-0.241**	-0.172**	-0.138**	-0.156**	0.081**
		Sig.(2-tailed)	0	0	0	0	0	0	0
Hangzhou	API	Correlation coefficient	0.194**	-0.193**	-0.226**	-0.107**	-0.127**	-0.075**	0.011
		Sig.(2-tailed)	0	0	0	0	0	0	0.473
Ningbo	API	Correlation coefficient	0.373**	-0.407**	-0.434**	-0.253**	-0.167**	-0.189**	-0.029**
		Sig.(2-tailed)	0	0	0	0	0	0	0

Notes: ** Correlation is significant at 0.01 level (2-tailed). Sig. is a concomitant probability. PRS—average surface pressure, TEM—average temperature, WVP—average water vapor pressure, RHU—average relative humidity, PRCP—daily precipitation, WS—average wind speed, SD—sunshine duration

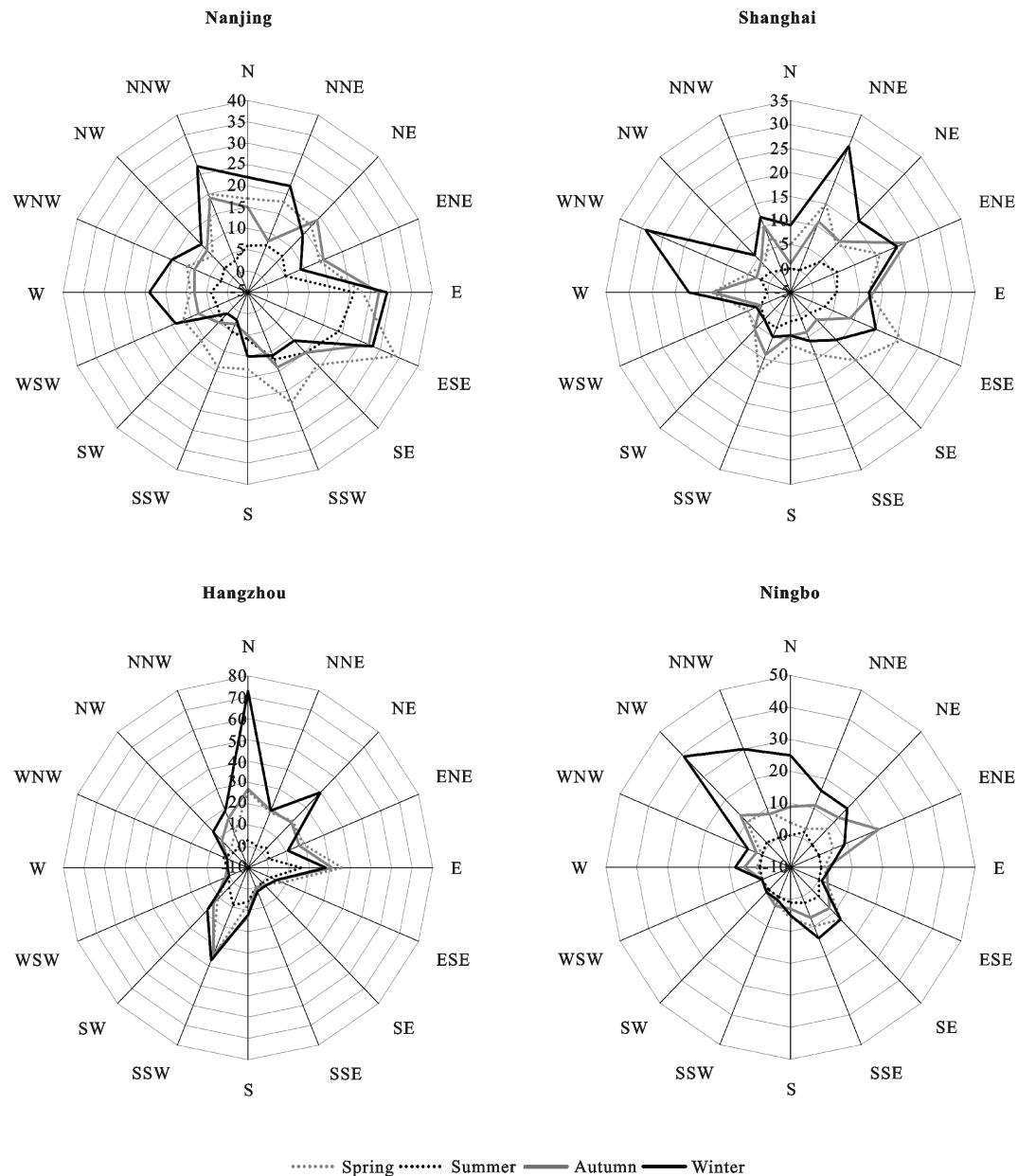


Fig. 6 Air pollution days under different wind direction conditions in sample cities

4 Conclusions

Clear inter-annual, seasonal, and monthly variations of API in Nanjing, Shanghai, Hangzhou, and Ningbo cities in the YRD were revealed by different analysis methods. Moreover, the relationships between daily API and meteorological factors were detected. The following are the study's conclusions:

The APIs in Nanjing, Shanghai and Hangzhou illus-

trated an undulating decrease from 2001 to 2012. However, the API in Ningbo increased prior to 2011, reached a peak in 2011, and then decreased. In general, air quality in the urban areas of the YRD had been improved during the study period.

The air quality was poorest in winter and spring and improved in summer followed by autumn in the YRD. Specifically, air quality was poorest in December and January, followed by March and April and was best in July and August.

The matrix trajectories could reasonably explain the relationship between air pollution and wind direction in the YRD during the study period. To improve air quality, more attention should be paid to the limitation of external pollutants in strong windy weather and the inner emission sources of pollution.

The meteorological factors, including water vapor pressure, relative humidity, surface pressure, air temperature, daily precipitation, sunshine duration and wind speed, all had significant impacts on API in all cities. The air quality was influenced by the different wind directions that varied with the season and city.

One limitation of this study is that 12-year data were used for the analysis, which might obstruct the long-term perspective of the realistic exploration of air quality. In addition, API was an aggregative indicator that cannot adequately explain the specific pollutants, such as SO₂, NO₂ and PM_{2.5}. The interrelations and mechanisms need further investigation and study. Furthermore, the air quality is also affected by pollutant emission and urban landscape patterns, which are beyond the scope of this study. These complex mechanisms still need further professional long-term exploration.

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