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Characterization of the Air Quality Index for Wuhu and Bengbu Cities, China

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ABSTRACT

From 2015–2017, the atmospheric PM_{10}, SO_2, NO_2, CO, and O_3 in Wuhu and Bengbu were investigated in this study. In addition, the AQI values and seasonal variations in six AQI classes and corresponding primary pollutants were also studied. In Wuhu, the daily AQI ranged from 23 to 298 in 2015, from 33 to 290 in 2016, and from 34 to 278 in 2017, and the corresponding mean values were 81, 80 and 90, respectively. In Bengbu, the daily AQI ranged from 23 to 288 in 2015, from 32 to 286 in 2016, and from 27 to 500 in 2017, and the corresponding mean values were 88, 89 and 97, respectively. During the three-year study, in Wuhu, the mean proportion of levels with Grade I, II, III, IV, V and VI were 9.33%, 69.3%, 18.3%, 3.00%, 0% and 0% in spring; were 35.0%, 55.0%, 7.00%, 3.00%, 0% and 0% in summer; were 13.6%, 65.0%, 18.0%, 3.33%, 0% and 0% in fall, and were 5.33%, 48.7%, 30.7%, 9.67%, 5.67% and 0% in winter. In Bengbu, the mean proportion of levels with Grade I, II, III, IV, V and VI were 3.00%, 64.0%, 30.3%, 2.67%, 0.333% and 0.333% in spring; were 19.3%, 68.7%, 11.3%, 0.667%, 0% and 0% in summer; were 20.7%, 56.3%, 17.3%, 4.67%, 1.00% and 0% in fall, and were 9.67%, 36.7%, 31.0%, 32.0%, 5.67% and 0% in winter. Generally, the air quality in the two cities were in the following order: summer > fall > spring > winter. AQI ranged between 101–150, where in Wuhu, the primary air pollutants were $PM_{2.5}$ and NO_2 in 2015; were $PM_{2.5}$, NO_2 and O_3 in 2016, and were $PM_{2.5}$, PM_{10}, NO_2 and O_3 in 2017. In Bengbu, $PM_{2.5}$, PM_{10} and O_3 were the primary air pollutants during the three years. When AQIs ranged between 151 and 200, in Wuhu, the primary air pollutant was $PM_{2.5}$ in 2015; were $PM_{2.5}$ and PM_{10} in 2016, and were $PM_{2.5}$, PM_{10}, and O_3 in 2017. In Bengbu, the primary air pollutant was $PM_{2.5}$ in 2015 and 2016 and comprised $PM_{2.5}$ and O_3 in 2017. When AQIs were between 201 and 300, in Wuhu, $PM_{2.5}$ was the primary air pollutant in 2015–2017. In Bengbu, the primary air pollutant was $PM_{2.5}$ in 2015 and 2016 and comprised $PM_{2.5}$ and PM_{10} in 2017. When the AQI ranged between 301–500, which did not occur in Wuhu from 2015–2017 or in Bengbu during 2015–2016, $PM_{2.5}$ was as the primary air pollutant in Bengbu in 2017. When the AQI can be analyzed in more detail, the control strategies for air pollution will be more precise.

Keywords: AQI; PM_{10}; $PM_{2.5}$; SO_2; NO_x; CO; O_3.

INTRODUCTION

Over past decades, along with the acceleration of economic growth and urbanization, air quality has been influenced directly or indirectly by industrial activities, biomass burning, and vehicle exhaust, which emit large amount of pollutants into the atmosphere (Liu *et al.*, 2012; Liu and Wang, 2014; Li *et al.*, 2017a), as well as meteorological factors (Zhang *et al.*, 2009; Zhang and Cao, 2015; Shen *et al.*, 2017). Large numbers of cities currently suffer from severe air quality degradation (Ran *et al.*, 2011; Tang *et al.*, 2012; Li *et al.*, 2012b; Li *et al.*, 2014).

Lots of previous studies have demonstrated clearly that air pollution poses a high risk to human health (Pope and Dochery, 2006; Cao *et al.*, 2012; Heal *et al.*, 2012; Pope and Dochery, 2013; Jin *et al.*, 2017). Related studies have found that there is a positive correlation between the number of deaths caused by respiratory diseases and atmospheric particulate matter (PM) and that $PM_{2.5}$ present greater harm than PM_{10} (Brook *et al.*, 2013; Deng *et al.*, 2013a, b). Sulfur dioxide in the atmosphere can stimulate the human respiratory tract and injure the cardiovascular system and

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liver. In particular, children and old people are more sensitive to this type of air pollutant (Lovati *et al.*, 1996). Atmospheric nitrogen dioxide can affect the functioning of the human respiratory system and significantly reduce the lung function indicators in humans (Chen *et al.*, 2011). Ozone can easily enter the deep part of the respiratory tract, causing an increase in airway inflammation, aggravating asthma, and decreasing lung function (Yang *et al.*, 2012). Human will exhibit symptoms including headaches, dizziness, and even nausea if they inhale carbon monoxide because atmospheric carbon monoxide can easily induce oxidative stress and inflammatory reactions. Atmospheric carbon monoxide not only destroys the neurological function of the heart but also affects the central nervous system and even causes suffocation to the point of death (Yang *et al.*, 2012). Previous studies have revealed that from 2010–2012, the number of premature deaths was caused by global air pollution increased from 0.22 million to 3.7 million. Therefore, the huge burden of air pollution (Chen *et al.*, 2013; Brauer *et al.*, 2016) and the frequent occurrence of severe air pollution events has triggered growing world-wide public awareness (Wang *et al.*, 2015a, b).

The Air Quality Index (AQI) is a typical indicator to estimate environmental air quality, which can inform the public to take proper health protection measures and provide the government with guidance to formulate corresponding pollution regulations. According to the World Health Organization (WHO), the AQI value is determined by six criteria for the concentration of pollutants, including sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), fine particulate matter ($PM_{2.5}$), and coarse particulate matter (PM_{10}). When the AQI value is used to reflect the air quality, better air quality is associated with a lower AQI. The largest contributor to air quality degradation among the six air pollutants is defined as the daily "primary pollutant," which determines the Air Quality Index for that day (She *et al.*, 2017).

Since September 2013, China began to implement the Air Pollution Prevention and Control Action Plan, which is viewed as an unprecedentedly stringent air pollution regulation (Sheenhan *et al.*, 2014; Shi *et al.*, 2016; Li *et al.*, 2017c), and the air quality has gradually improved (Xie *et al.*, 2016). However, air pollution has spatial and temporal variation characteristics, so China is experimenting with various air pollution control policies, some of which were reflected in pollution control programs for the APEC Meeting and the Victory-day Parade in Beijing. Li *et al.* (2017d) show that the regulations resulted in short-term, substantial improvements in air quality, where the AQI decreased by 35.9% during the APEC Meeting period, and the daily average concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO reduced by 41.3%, 48.2%, 56.5%, 38.9%, and 35.5%, respectively; the AQI was lowered by 37.4% during the Victory-day Parade period, and the daily average concentrations of $PM_{2.5}$, PM_{10}, O_3, SO_2, NO_2, and CO were reduced by 55.8%, 50.1%, 27.2%, 35.9%, 39.9%, and 28.8%, respectively. Moreover, the information about heavily polluted days also arouse heated discussion and debates among the general public. Based on this situation, this study focused on the air pollution characteristics in Wuhu and Bengbu through the AQI values, in the hope of offering a useful basis by which to formulate and experiment with tighter air pollution control strategies for local governments.

This research discusses the six criteria pollutants, including $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3 ($PM_{2.5}$ was discussed in our previous study by Wang *et al.* (2018)). In addition, as for the section on the Air Quality Index (AQI) analyses, the variations in the six AQI classes for four seasons and the corresponding primary pollutants are further discussed. The objective of this study is providing essential information and a better understanding of the air pollution characteristics in both Wuhu and Bengbu, so as to propose better suggestions for the control of atmospheric pollutants.

METHODS

Two cities, Wuhu (31°33′N, 118°38′E) (south of the Huai River) and Bengbu (32°93′N, 117°34′E) (north of the Huai River) located in Anhui province, China, which are located across the basins of the Yangtze River and the Huai River, were selected and evaluated in this study. The main climate features in both Wuhu and Bengbu include being cold and dry in the winter and warm and humid in the summer. Over recent decades, these two cities underwent economic development with the total GDP rising to more than 0.13 and 0.26 trillion RMB in Wuhu and Bengbu, respectively. It was argued in a previous study that the increasing population and urbanization and rapid economic growth has been equaled with air quality deterioration (Che *et al.*, 2009). Wang *et al.* (2018) showed that the annual average $PM_{2.5}$ concentration in both Wuhu (53.0 μg m^{-3}, 2015–2017) and Bengbu (61.4 μg m^{-3}, 2015–2017) have exceeded the limitation of the World Health organizational air quality standards (10 μg m^{-3}) to characterize and gain more insight into the air pollution issue is of great importance for the protection of human health.

This study obtained data for three years from January 2015 to December 2017 in both Wuhu and Bengbu cities. The PM mass concentration (including daily $PM_{2.5}$ and PM_{10}) and gaseous pollutants (including daily SO_2, NO_2, CO, and 8 hr-averaged O_3) were obtained from the China air quality online monitoring and analysis platform (http://www.aqistudy.cn/).

Air Quality Index (AQI)

The sub-AQI of the six criteria pollutants were first calculated with the observation concentrations, as shown in Eq. (1) (Shen *et al.*, 2017; She *et al.*, 2017). The overall AQI represents the maximum of the sub-AQI of all pollutants, where when the AQI is higher than 50, the highest sub-AQI contributor is defined as the primary pollutant on that day, as shown in Eq. (2) (Shen *et al.*, 2017; She *et al.*, 2017):

$$IAQI_P = \frac{I_{high} - I_{low}}{C_{high} - C_{low}}\left(C_P - C_{low}\right) + I_{low} \quad (1)$$

$$AQI = \max(I_1, I_2, \ldots, I_n) \quad (2)$$

$IAQI_p$: the air quality sub index for air pollutant p;
C_P: the concentration of pollutant p;
C_{low}: the concentration breakpoint that is $\leq C_P$;
C_{high}: the concentration breakpoint that is $\geq C_P$;
I_{low}: the index breakpoint corresponding to C_{low};
I_{high}: the index breakpoint corresponding to C_{high}.

The six criteria air pollutants have acute effects on human health. The daily AQIs were calculated by the 24-hour average concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, and the daily average 8-hour maximum concentration of O_3. From the United States Environmental Protection Agency (US EPA) AQI , the ranges of AQI values related to air quality can be classified into six classes: Grade I: 0–50 (Good, Green); Grade II: 51–100 (Moderate, Yellow); Grade III: 101–150 (Unhealthy for Sensitive Groups; Orange); Grade IV: 151–200 (Unhealthy; Red); Grade V: 201–300 (Very unhealthy; Purple), and Grade VI: 300–500 (Hazardous; Maroon) (Hu *et al*., 2015; Lanzafame *et al*., 2015; She *et al*., 2017; Zhao *et al*., 2018).

RESULTS AND DISCUSSION

PM_{10} Concentration

Atmospheric particulate matter (PM) carries acids and toxic species such as polycyclic aromatic hydrocarbons and heavy metals, which are presently recognized as affecting visibility and human health (Song *et al*., 2008; Tao *et al*., 2009; Matus *et al*., 2012; Sun *et al*., 2014; Liang *et al*., 2016). Increasing PM_{10} pollution plays a crucial role in severe haze and degradation of air quality. For the period 2015-2017, the monthly average PM_{10} concentration in the ambient air of Wuhu and Bengbu are shown in Tables 2(a), 2 (b) and 2(c), respectively.

For Wuhu, in 2015, the monthly average PM_{10} concentration was in the range of 50–151 μg m^{-3}, and with an average of 85 μg m^{-3}; while in 2016, it was 39–125 μg m^{-3}, with an average of 78 μg m^{-3}; and the level in 2017 was in the range of 48–111 μg m^{-3}, with an average of 83 μg m^{-3}. Generally, based on the annual average values, the highest PM_{10} concentration occurred in 2015 and was reduced by approximately 9.0% by 2016; but from 2016 to 2017, the PM_{10} concentration increased by approximately 6.0%. As a whole, over the three years under examination, the PM_{10} concentration ranged between 39 and 151 μg m^{-3}, with an average of 82 μg m^{-3}. The above results also indicate that the PM_{10} concentration in Wuhu was 4.1 times higher than

Table 1(a). Monthly average atmospheric PM_{10} concentrations in Wuhu and Bengbu in 2015.

Month	Wuhu			Bengbu		
	Range (μg m^{-3})	Mean (μg m^{-3})	RSD (%)	Range (μg m^{-3})	Mean (μg m^{-3})	RSD (%)
Jan.	33.0–228	126	40.7	33.0–211	105	37.2
Feb.	22.0–175	84.5	48.0	24.0–192	96.1	48.9
Mar.	23.0–164	62.8	41.3	29.0–124	76.9	32.6
Apr.	37.0–109	68.4	29.3	44.0–165	89.8	38.6
May	44.0–166	88.3	38.8	64.0–159	100	18.4
June	27.0–107	63.6	36.2	20.0–182	77.8	54.7
July	30.0–105	50.3	38.0	25.0–135	63.9	34.3
Aug.	25.0–101	56.5	33.8	20.0–137	74.2	34.4
Sep.	34.0–97.0	66.9	25.2	24.0–140	77.1	31.3
Oct.	37.0–215	110	38.4	27.0–233	119	37.6
Nov.	26.0–146	87.7	36.7	22.0–202	100	49.4
Dec.	81.0–305	151	41.2	41.0–278	113	46.3
Annual	22.0–305	84.7	37.3	20.0–278	91.1	38.6

Table 1(b). Monthly average atmospheric PM_{10} concentrations in Wuhu and Bengbu in 2016.

Month	Wuhu			Bengbu		
	Range (μg m^{-3})	Mean (μg m^{-3})	RSD (%)	Range (μg m^{-3})	Mean (μg m^{-3})	RSD (%)
Jan.	42.0–297	125	47.6	49.0–263	127	44.3
Feb.	34.0–139	79.2	36.8	26.0–165	102	36.6
Mar.	25.0–155	84.6	35.8	33.0–190	98.5	39.0
Apr.	30.0–131	66.9	41.5	27.0–176	104	36.6
May	35.0–262	87.2	45.0	39.0–180	81.4	33.3
June	24.0–153	61.1	50.5	29.0–119	65.6	31.2
July	24.0–66.0	43.3	31.6	20.0–100	61.2	31.2
Aug.	25.0–76.0	38.7	26.5	30.0–135	58.6	35.4
Sep.	20.0–106	58.4	42.5	26.0–134	83.8	35.2
Oct.	26.0–120	67.2	33.8	28.0–119	65.5	37.5
Nov.	49.0–205	109	40.2	38.0–258	110	42.6
Dec.	22.0–215	116	44.7	39.0–245	144	42.6
Annual	20.0–297	78.0	39.7	20.0–263	91.8	37.1

Table 1(c). Monthly average atmospheric PM_{10} concentrations in Wuhu and Bengbu in 2017.

Month	Wuhu			Bengbu		
	Range (μg m^{-3})	Mean (μg m^{-3})	RSD (%)	Range (μg m^{-3})	Mean (μg m^{-3})	RSD (%)
Jan.	31.0–196	91.8	45.5	38.0–239	124	42.7
Feb.	45.0–154	95.3	30.6	57.0–173	124	23.4
Mar.	60.0–173	104	27.9	40.0–186	114	30.3
Apr.	45.0–169	110	26.6	53.0–154	113	21.6
May	34.0–265	99.2	47.6	62.0–614	127	85.8
June	26.0–161	61.7	47.6	40.0–165	91.6	29.2
July	17.0–111	56.6	43.9	26.0–101	64.6	28.5
Aug.	22.0–77.0	47.9	34.0	24.0–104	54.8	32.5
Sep.	25.0–96.0	56.8	35.6	19.0–136	61.2	42.9
Oct.	16.0–133	66.9	46.9	22.0–194	76.8	57.4
Nov.	35.0–154	96.9	32.9	57.0–192	121	32.8
Dec.	42.0–201	111	32.2	53.0–283	144	40.3
Annual	16.0–265	83.3	37.6	19.0–283	101.4	39.0

the WHO air quality regulated standard (20 μg m^{-3}). Therefore, in order to carry out sustainable development and improve air quality, more efficient control strategies of PM_{10} concentration are needed.

In Bengbu, the monthly average PM_{10} concentration in 2015 was between 64 and 119 μg m^{-3}, with an average of 91 μg m^{-3} and that in 2016 ranged from 59 to 144 μg m^{-3}, with an average of 92 μg m^{-3}; during 2017, it ranged from 55 to 144 μg m^{-3}, with an average of 101 μg m^{-3}. On the contrary, the annual average PM_{10} concentration rose slowly during the three years, increasing by approximately 1.09% from 2015 to 2016, and approximately 8.91% from 2016 to 2017. This may be attributed to the poor control of industrial activity and the increasing number of vehicles (Han *et al*., 2005; Tang *et al*., 2005; Huang *et al*., 2010). As a whole, the PM_{10} concentration for these three years ranged between 55 to 144 μg m^{-3}, with an average of 95 μg m^{-3}, so the PM_{10} concentration was higher than that in Wuhu, which was 4.8 times higher than the WHO air quality regulated standard (20 μg m^{-3}), and the increasing tendency for increases in PM_{10} should be of concern and improved.

With regard to seasonal variations, in Wuhu, in 2015, the average PM_{10} concentrations in spring, summer, fall, and winter were 73, 57, 88 and 120 μg m^{-3}, respectively, and those in 2016 were 80, 48, 78, and 107 μg m^{-3}, respectively. Those in 2017 were 104, 56, 74 and 99 μg m^{-3}, respectively. On a three-year basis, the average PM_{10} concentration in winter (109 μg m^{-3}) was approximately 2.0 orders of magnitude higher than that in summer (54 μg m^{-3}). For Bengbu, during 2015, the average PM_{10} concentrations in spring, summer, fall and winter were 88, 72, 99 and 105 μg m^{-3}, respectively, and those in 2016 were 94, 62, 87 and 124 μg m^{-3}, respectively. Those in 2017 were 118, 71, 86 and 131 μg m^{-3}, respectively. This indicates that the PM_{10} concentrations varied from season to season, and that, generally, the highest values always occurred in winter and the lowest in summer, while the values for spring were very similar with those in fall and were both at intermediate levels. On the three-year basis, the average PM_{10} concentration in winter (120 μg m^{-3}) was approximately 1.8 orders of magnitude higher than that in summer (68 μg m^{-3}).

Previous studies reported that the main source of coarse particles (PM_{10}) is natural processes such as dust storms and re-suspension of local soil, and anthropogenic processing is another important source, such as road dust and various industrial processes (Querol *et al*., 2004; Xu *et al*., 2017). In winter, a temperature inversion with a low ground temperature can hinder the dispersion of pollutants (Tang *et al*., 2017; Xing *et al*., 2017; Wang *et al*., 2018), and polluted air caused by heating activities blowing from northern China (Shang *et al*., 2018) can elevate the atmospheric PM_{10} levels in both Wuhu and Bengbu. During summer, higher temperatures with both violent vertical transport of air current and stronger rainfall scavenging can reduce the PM_{10} concentration significantly.

Traffic and power plants produce largely primary and secondary anthropogenic combustion products, which are a crucial source of fine particles ($PM_{2.5}$). Since the diverse sources of fine and coarse particles and different physic-chemical properties reveal different particle pollution characteristics, the $PM_{2.5}/PM_{10}$ ratio can be used to determine underlying atmospheric processes and thus evaluate the status of air quality (Speranza *et al*., 2014; Blanco-Becerra *et al*., 2015; Xu *et al*., 2017; Wang *et al*., 2018). Speranza *et al*. (2014) and Wang *et al*. (2018) found that the $PM_{2.5}/PM_{10}$ ratio shows apparent seasonal variations, where the value in cold seasons is higher than that in warm seasons. Akinlade *et al*. (2015) also found that the $PM_{2.5}/PM_{10}$ ratio was higher in the wet season and lower in the dry season as a consequence of the significant contribution of dust re-suspension to PM_{10}. It has also been found that due to re-suspended coarse road dust, traffic hours correspond with the minimum $PM_{2.5}/PM_{10}$ ratio (Querol *et al*., 2001; Evagelopoulos *et al*., 2006). This demonstrates that controlling dust is an important way to reduce PM_{10} concentrations and improve air quality.

SO_2 Concentration

Atmospheric sulfur dioxide (SO_2) reacts with hydroxyl (OH) and other oxidizing agents and converts into sulfate particles and sulfuric acid in the troposphere. It is a key

precursor of acid rain that presents a hazard to forests and fresh water ecosystems (Ferrari and Salisbury, 1999). Thus, SO_2 as one of the criteria pollutants can affect air quality and regional climate (Aneja *et al.*, 2001; Khattak *et al.*, 2013). The monthly average SO_2 concentrations in Wuhu and Bengbu from 2015-2017 are provided in Figs. 1(a), 1(b) and 1(c), respectively.

The monthly SO_2 concentration in Wuhu ranged between 4.20 and 9.45 ppb, with an average of 6.80 ppb in 2015; it ranged between 5.25 and 10.9 ppb, with an average of

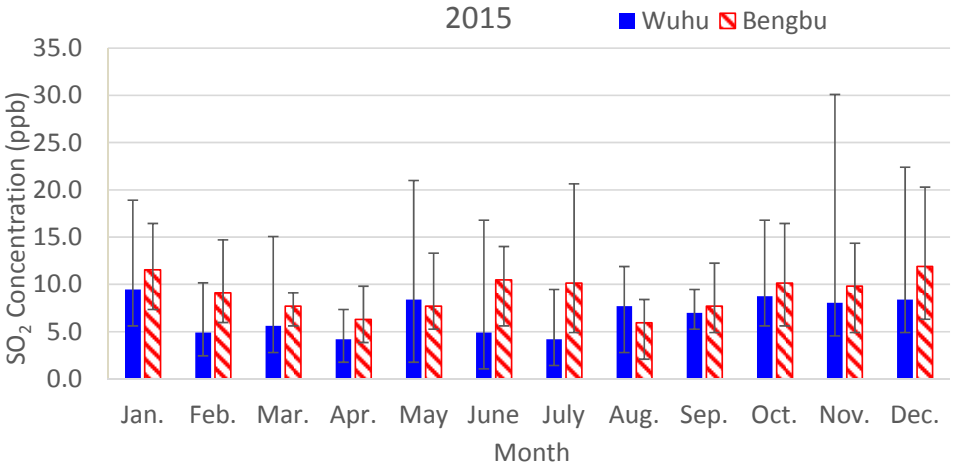

Fig. 1 (a). Monthly average atmospheric SO_2 concentrations in Wuhu and Bengbu in 2015.

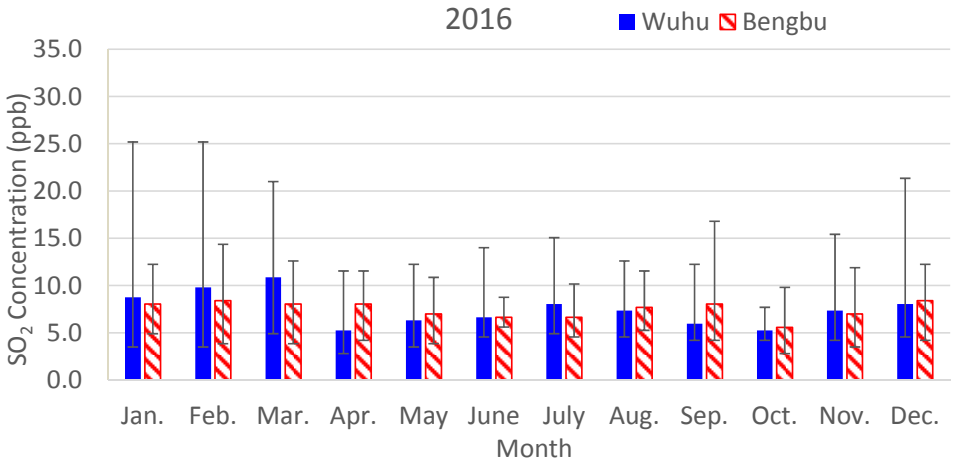

Fig. 1 (b). Monthly Average Atmospheric SO_2 Concentrations in Wuhu and Bengbu in 2016.

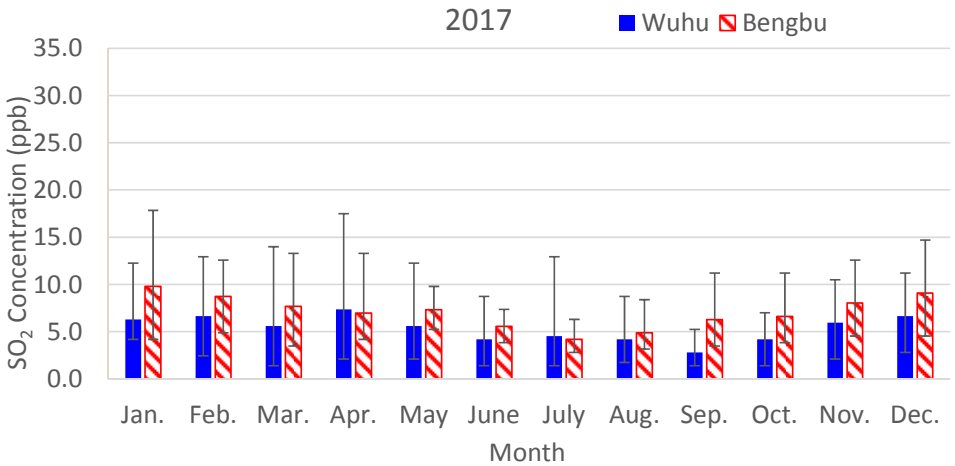

Fig. 1 (c). Monthly average atmospheric SO_2 concentrations in Wuhu and Bengbu in 2017.

7.47 ppb in 2016, and it ranged between 2.80 and 7.35 ppb, with an average of 5.34 ppb in 2017. The annual average SO_2 concentration increased by approximately 8.97% from 2015 to 2016 but reduced by approximately 28.5% from 2016 to 2017. In the case of Bengbu, the monthly concentration of SO_2 was in the range of 5.95-11.9 ppb and with an average of 9.04 ppb in 2015; of 5.60-8.40 ppb, with an average of 7.47 ppb in 2016 and was 4.20-9.80 ppb, with an average of 7.12 ppb in 2017. By comparing the mean concentrations, SO_2 concentrations were shown to have decreased slowly during the three-year period, reducing by approximately 17.4% from 2015 to 2016, and by 4.69% from 2016 to 2017. The fluctuation in the average SO_2 concentrations in the three-year period was 2.80–10.9 ppb in Wuhu and 4.20–11.9 ppb in Bengbu, for which the corresponding mean values were 6.54 and 7.88 ppb, respectively. The results indicated that the SO_2 concentration in Wuhu was slightly lower than WHO air quality regulated standard of 7.00 ppb, but that of Bengbu were slightly higher than the WHO standard.

SO_2 results from anthropogenic activities, like fossil fuel combustion, metal smelting, and the burning of biomass (Kettle and Andreae, 2000; Halmer *et al*., 2002; Vijay *et al*., 2004; Dentener *et al*., 2006; Lee *et al*., 2008) and the combustion of coal are common major sources in China (Kurokawa *et al*., 2013; Kato *et al*., 2016). Another crucial emitted source of SO_2 is natural processes, such as volcanic activity, oxidation in the soil, and the oxidation of hydrogen sulfide. Previous studies have indicated that volcanic eruptions are sporadic primary contributors (Andres and Kasdnoc, 1998; Halmer *et al*., 2002; Kato *et al*., 2016). The natural sources of SO_2 were found to significantly limited by the absence of volcanic activity in both Wuhu and Bengbu.

Correspondingly, the seasonal variations are further discussed. For Wuhu, during 2015, the average SO_2 concentrations were 6.07, 5.60, 7.93, and 7.58 ppb in spring, summer, fall, and winter, respectively, and those in 2016 were 7.47, 7.35, 6.18, and 8.87 ppb, respectively. Those in 2017 were 6.18, 4.32, 4.32, and 6.53 ppb, respectively. As for Bengbu, in 2015, the average SO_2 concentrations were 7.23, 8.87, 9.22, and 10.9 ppb in spring, summer, fall, and winter, respectively, and those in 2016 were 7.70, 7.00, 6.88, and 8.28 ppb, respectively. Those in 2017 were 7.35, 4.90, 7.00, and 9.22 ppb, respectively. The three-year average SO_2 concentrations in spring, summer, fall, and winter were 6.57, 5.76, 6.14, and 7.66 ppb in Wuhu and were 7.43, 6.92, 7.70, and 9.47 ppb in Bengbu. The seasonal levels in Wuhu were lower than those in Bengbu. Wuhu has a subtropical humid monsoon climate with higher air temperatures and stronger rainfall intensity than Bengbu, which enjoys a semi-moist monsoon climate. A higher temperature would be beneficial to the dispersion of pollutants, and stronger levels of rainfall can help in scavenging pollutants.

In general, except for the fact that the SO_2 levels in winter were slightly higher than in the other seasons, there are no clear seasonal cycles in either city. This can be mainly attributed to the fact that Wuhu and Bengbu are located in the middle latitude area of China, the polluted air current with a higher SO_2 concentration from the northern cities of China would slightly increase SO_2 concentration in winter.

NO_2 Concentration

Nitrogen dioxide (NO_2) mainly results from anthropogenic activities, including industrial facilities and traffic emissions (Cheng *et al.*, 2018). NO_2 is involved in complex thermal NO_x formation and is photochemical, reacting with volatile organic compounds that can affect the oxidizing capacity of the atmosphere (Jacob *et al.*, 1999; Seinfeld and Pandis, 2012). It is also an important precursor of ozone and acid rain (Bowman *et al.*, 1994; An *et al.*, 2006; Anttila *et al.*, 2011; Khokhar *et al.*, 2016). Due to increases in the number of vehicles in China, more NO_2 in atmosphere has adversely impacted human health and the ecological environment (Boersma *et al.*, 2009; Sachin *et al.*, 2009). The monthly mean concentration of NO_2 in Wuhu and Bengbu from 2015 to 2017 are shown in Figs 2(a), 2(b) and 2(c), respectively.

As for Wuhu, in 2015, the monthly average NO_2 concentration ranged between 9.30 and 29.7 ppb, and the annual mean value was 18.0 ppb. In 2016, those values ranged between 12.2 and 38.5 ppb, with an annual mean value of 21.9 ppb. In 2017, the values ranged from 15.6 to 32.6 ppb, with an annual mean value of 23.9 ppb. The mean NO_2 concentrations increased slowly during the three-year period, rising by approximately 17.8% from 2015 to 2016 and also increasing by 8.37% from 2016 to 2017. For Bengbu, the monthly concentration of NO_2 ranged between 12.2 and 22.4 ppb, with an average of 16.6 ppb. In 2016, those values ranged between 13.1 and 27.8 ppb, with an average of 18.5 ppb, and in 2017, the values ranged between 11.2 and 30.2 ppb, with an average of 19.5 ppb. The mean NO_2 concentrations increased slowly during the three-year period, rising by approximately 10.3% from 2015 to 2016 and increasing by 5.13% from 2016 to 2017. As a whole, the average concentrations of NO_2 were 9.30–38.5 ppb in Wuhu and 11.2–30.2 ppb in Bengbu during the three-year period, for which the corresponding mean values were 21.4 and 18.0 ppb, respectively. The results indicated that the NO_2 concentrations in Wuhu were slightly higher than those in Bengbu. Official statistics revealed that Wuhu has a larger human population (3.67 million) than Bengbu (3.33 million), and the urbanization rate (63.5%) in the former is also significantly higher than the latter (53.7%) (Anhui Statistical Yearbook 2000–2017). It can thus be inferred that Wuhu has more vehicles. Previous studies have reported that motor vehicles have become the primary source of NO_2 emissions with economic development and rapid urbanization during recent years (Fu *et al.*, 2000; Cheng *et al.*, 2018); thus, a larger amount of nitrogen oxide (NO_x) is being emitted by the vehicles in Wuhu, which results in the higher atmospheric NO_2 concentration as compared to that of Bengbu. It also can be seen that the annual NO_2 levels in Wuhu (21.4 ppb) and Bengbu (18.0 ppb) were near the WHO air quality regulated standard (19.5 ppb), but the highest monthly average values were approximately 2.0 and 1.5 times higher than the WHO air quality regulated standard in Wuhu and Bengbu, respectively.

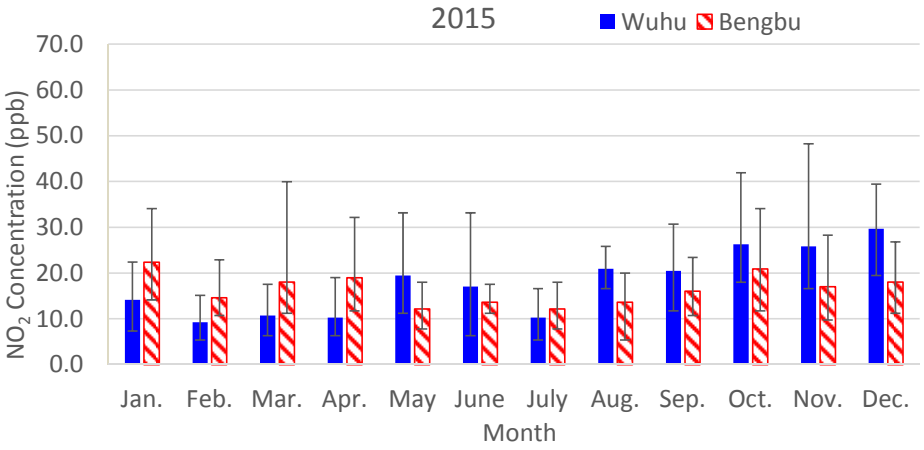

Fig. 2(a). Monthly average atmospheric NO_2 concentrations in Wuhu and Bengbu in 2015.

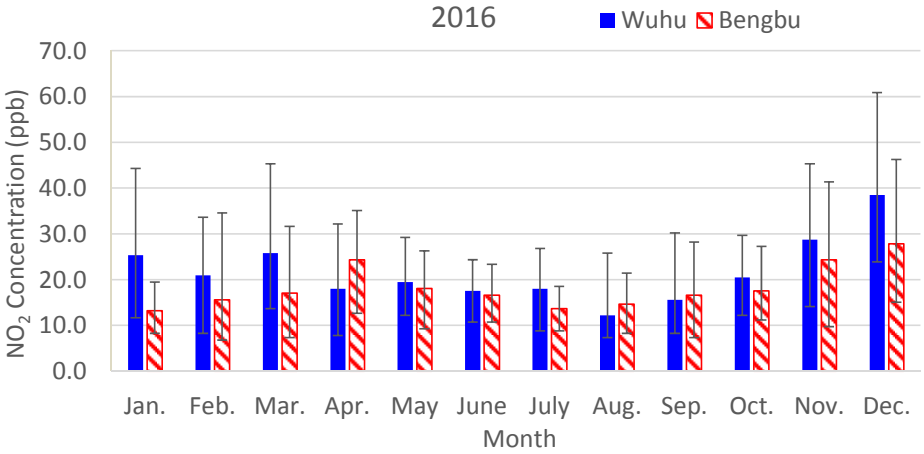

Fig. 2(b). Monthly average atmospheric NO_2 concentrations in Wuhu and Bengbu in 2016.

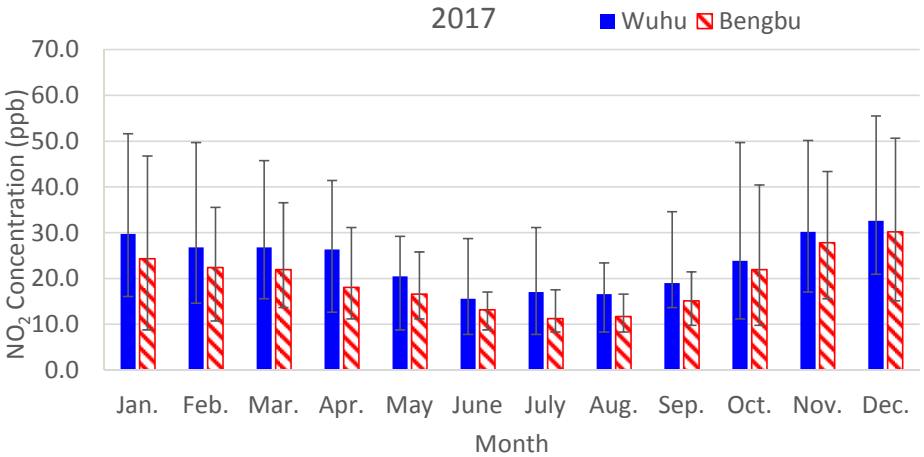

Fig. 2(c). Monthly average atmospheric NO_2 concentrations in Wuhu and Bengbu in 2017.

This means that NO_2 should be considered an important air pollutant. Efficient vehicle emission control measures should be issued to enhance the efforts aimed at improving the air quality, which is consistent with the conclusion that decreasing vehicle NO_x emissions have a crucial effect on decreasing NO_2 in the ambient air (Cheng *et al.*, 2018).

In Wuhu, the seasonal NO_2 concentrations during spring, summer, fall, and winter were 13.6,16.1, 24.4 and 17.5 ppb in 2015 and were 20.9, 16.1, 21.4 and 28.2 ppb in 2016; 24.4, 16.6, 24.4 and 29.7 ppb in 2017, respectively. In Bengbu, the seasonal NO_2 concentrations during spring, summer, fall, and winter were 16.6, 13.1, 18.0, and 18.5 ppb in 2015, were 20.0, 15.1, 19.5, and 19.0 ppb in 2016, and were 19.0, 12.2, 21.4, and 25.8 ppb in 2017, respectively.

Generally, the NO_2 concentrations in fall and winter were higher than the values in spring and summer in both Wuhu and Bengbu, which was similar to the observed NO_2 concentration seasonal variations in urban Beijing (Yang *et al.*, 2015; Cheng *et al.*, 2018). This phenomenon might be related to the various meteorological conditions in different seasons. The two cities have a subtropical monsoon climate with clear distinctions among the four seasons, where especially during fall and winter, the ground meteorological factors are not favorable for the dispersion of air pollutants, which can be mainly characterized as a stable atmosphere with low wind speeds and low rainfall intensity.

The highest monthly mean NO_2 concentration was always observed in winter. In Wuhu, the maximum values of 29.7, 38.5 and 32.6 ppb for 2015, 2016, and 2017 all occurred in December in the three-year period, respectively. In Bengbu, the highest monthly mean NO_2 concentration was observed in January, which was 22.4 ppb for 2015, and the maximum values were 27.8 and 30.2 ppb for 2016 and 2017, respectively, which were both observed in December. In order to control the atmospheric concentration of NO_2 more effectively, numerous emission reduction measures from industrial facilities should be implemented as soon as possible, and restricting vehicle emissions should become the most crucial issue, especially during seasons with unfavorable weather conditions. Based on a previous study, Beijing has obtained significant results from temporary traffic management during air quality assurance periods (Cheng *et al.*, 2018).

CO Concentration

Carbon monoxide (CO) is mainly emitted from fossil fuel combustion and the burning of biomass. These combustion processes also emit NO_x and volatile organic compounds (VOCs). CO is one important air pollutant that has a long lifetime of more than one month and has become a strong indicator of pollution (Kato *et al.*, 2016). The monthly mean concentrations of CO in Wuhu and Bengbu are shown in Tables 2(a), 2(b) and 2(c) from 2015 to 2017, respectively.

In Wuhu, the monthly mean CO concentrations varied from 0.532 to 1.21 ppm in 2015; were between 0.574 and 1.15 ppm in 2016, and ranged between 0.606 and 1.15 ppm in 2017, while the corresponding annual average values were 0.817, 0.852, and 0.826 ppm, respectively. The annual mean concentrations of CO in 2015 increased by about

Table 2(a). Monthly average atmospheric CO concentrations in Wuhu and Bengbu in 2015.

Month	Wuhu			Bengbu		
	Range (ppm)	Mean (ppm)	RSD (%)	Range (ppm)	Mean (ppm)	RSD (%)
Jan.	0.560–1.92	1.21	30.4	0.560–1.76	1.08	26.3
Feb.	0.640–1.60	1.01	23.3	0.800–1.76	1.16	24.2
Mar.	0.560–1.36	0.932	22.3	0.800–1.44	1.06	18.3
Apr.	0.480–1.36	0.976	23.9	0.560–1.20	0.922	15.6
May	0.480–1.12	0.712	23.3	0.480–1.04	0.710	22.1
June	0.400–1.12	0.712	21.6	0.320–0.960	0.574	23.5
July	0.240–0.880	0.532	26.8	0.400–0.800	0.526	19.9
Aug.	0.240–0.960	0.565	32.9	0.240–0.880	0.591	25.6
Sep.	0.400–0.720	0.544	16.6	0.400–1.12	0.608	27.3
Oct.	0.320–1.20	0.674	31.1	0.480–1.28	0.751	24.4
Nov.	0.560–1.44	0.894	31.5	0.480–1.84	0.894	28.8
Dec.	0.480–1.76	1.04	33.6	0.560–1.68	1.11	24.8
Annual	0.240–1.92	0.817	26.4	0.240–1.84	0.832	23.4

Table 2(b). Monthly average atmospheric CO concentrations in Wuhu and Bengbu in 2016.

Month	Wuhu			Bengbu		
	Range (ppm)	Mean (ppm)	RSD (%)	Range (ppm)	Mean (ppm)	RSD (%)
Jan.	0.480–1.44	0.986	26.7	0.400–1.52	0.842	35.5
Feb.	0.560–1.52	1.02	21.9	0.480–1.28	0.800	26.0
Mar.	0.800–1.60	1.15	19.8	0.400–1.28	0.741	32.4
Apr.	0.640–1.60	0.982	19.3	0.400–0.960	0.630	22.3
May	0.400–1.28	0.782	22.4	0.320–0.880	0.539	23.3
June	0.400–0.880	0.574	20.1	0.320–0.720	0.530	18.3
July	0.320–0.880	0.581	31.6	0.320–0.720	0.480	22.4
Aug.	0.320–1.04	0.596	33.4	0.320–0.880	0.537	22.8
Sep.	0.400–0.880	0.664	17.1	0.400–0.880	0.614	19.2
Oct.	0.320–1.04	0.686	24.4	0.320–0.800	0.555	21.4
Nov.	0.480–1.76	1.06	31.4	0.400–1.28	0.734	29.1
Dec.	0.640–1.76	1.15	25.0	0.480–1.60	1.01	26.7
Annual	0.320–1.76	0.852	24.4	0.320–1.60	0.668	25.0

Table 2(c). Monthly average atmospheric CO concentrations in Wuhu and Bengbu in 2017.

Month	Wuhu			Bengbu		
	Range (ppm)	Mean (ppm)	RSD (%)	Range (ppm)	Mean (ppm)	RSD (%)
Jan.	0.720–2.00	1.15	27.4	0.480–1.76	0.973	38.6
Feb.	0.480–1.44	0.889	26.0	0.480–1.20	0.780	20.2
Mar.	0.320–0.960	0.606	26.6	0.480–0.880	0.658	17.1
Apr.	0.400–1.28	0.850	29.9	0.480–0.960	0.678	21.7
May	0.560–1.20	0.813	21.9	0.480–0.720	0.562	13.0
June	0.560–1.20	0.816	24.2	0.320–0.720	0.542	15.9
July	0.560–1.12	0.733	21.8	0.320–0.800	0.465	22.9
Aug.	0.480–1.04	0.756	23.0	0.320–0.720	0.522	18.9
Sep.	0.560–1.12	0.792	16.2	0.400–0.960	0.598	20.4
Oct.	0.400–1.20	0.748	26.8	0.320–1.12	0.594	31.5
Nov.	0.480–1.36	0.864	31.2	0.400–0.960	0.688	21.3
Dec.	0.480–1.68	0.885	31.5	0.400–1.60	0.875	32.5
Annual	0.320–2.00	0.825	25.5	0.320–1.76	0.661	22.8

4.11% compared with those observed in 2016 and decreased by approximately 3.05% from 2016 to 2017. The annual CO concentration has rarely fluctuated in the three years under observation (2015–2017). In Bengbu, the monthly mean CO concentrations varied from 0.526 to 1.16 ppm in 2015, ranged from 0.480 to 1.01 ppm in 2016, and ranged from 0.465 to 0.973 ppm in 2017, while the corresponding annual average values were 0.832, 0.668, and 0.661 ppm, respectively. The mean CO concentrations have decreased continuously. The reduction was approximately 19.7% from 2015 to 2016 and was 1.05% from 2016 to 2017. During the observed three-year period, the mean CO concentration ranged between 0.532 and 1.21 ppm in Wuhu and between 0.465 and 1.16 ppm in Bengbu, for which the corresponding mean values were 0.831 and 0.720 ppm, respectively. The concentration of CO in both Wuhu and Bengbu were lower than the WHO air quality eight-hour average regulated standard (8.00 ppm) of CO, which indicated that CO does not present a serious impact on the air quality of these two cities. On the other hand, Wuhu has a subtropical humid monsoon climate with a higher atmospheric water vapor content, and Bengbu enjoys a semi-moist monsoon climate with a lower atmospheric water vapor content. Kato *et al* (2016) demonstrated that higher CO tends to appear with a higher water vapor content; thus the level of CO in Wuhu was found to be slightly higher than that in Bengbu.

In Wuhu, in 2015, the three highest monthly mean CO concentration were observed in January (1.21 ppm), December (1.04 ppm), and February (1.01 ppm). In 2016, the three highest monthly mean values were observed in December (1.15 ppm), March (1.15 ppm), and November (1.06 ppm), and in 2017, the three highest monthly mean values were observed in January (1.15 ppm), February (0.889 ppm), and December (0.885 ppm). The three lowest monthly mean CO concentrations were observed in July (0.532 ppm), September (0.544 ppm), and August (0.565 ppm) in 2015 and were observed in June (0.574 ppm), July (0.581 ppm), and August (0.596 ppm) in 2016 and in March (0.606 ppm), July (0.733 ppm), and October (0.748 ppm) in 2017. As for Bengbu, during 2015, the three highest monthly mean CO concentrations were observed in February (1.16 ppm), December (1.11 ppm), and January (1.08 ppm). In 2016, the three highest monthly mean values were observed in December (1.01 ppm), January (0.842 ppm), and February (0.800 ppm), and in 2017, the three highest monthly mean values were observed in January (0.973 ppm), December (0.875 ppm), and February (0.780 ppm). The three lowest monthly mean CO concentrations were observed in July (0.526 ppm), June (0.574 ppm), and August (0.591 ppm) in 2015. They were observed in July (0.480 ppm), June (0.530 ppm), and August (0.537 ppm) in 2016, and in July (0.465 ppm), August (0.522 ppm), and June (0.542 ppm) in 2017. The dates indicated that the highest CO concentrations mainly occurred before or after the winter and that the lowest values mainly occurred before or after the summer.

As for seasonal variations in CO concentrations, in Wuhu, in 2015, the concentrations of CO were 0.874, 0.603, 0.704, and 1.09 ppm in spring, summer, fall, and winter, respectively, and those in 2016 were 0.970, 0.583, 0.805, and 1.05 ppm, respectively. Those in 2017 were 0.757, 0.768, 0.802, and 0.976 ppm, respectively. As for Bengbu, in 2015, the concentrations of CO were 0.898, 0.564, 0.751 and 1.12 ppm in spring, summer, fall, and winter, respectively; and those in 2016 were 0.637, 0.516, 0.634, and 0.885 ppm, respectively. Those in 2017 were 0.633, 0.510, 0.626, and 0.876 ppm, respectively. This indicated that the concentration of CO varied significantly from season to season and that the cold season always achieved the maximum levels, and the warm season achieved the minimum levels, while the values were very similar in spring and fall, where both were at intermediate levels. In general, the three-year mean CO concentration of Wuhu in summer (0.651 ppm) was 37.2% lower than that in winter (1.04 ppm), and the value of Bengbu in summer (0.530 ppm) were 44.7% lower than those in winter (0.958 ppm). The seasonal variations in CO may be related to the air temperature, where in summer, a lower CO concentration is always accompanied with a higher air temperature, which concurs with the report of Kato *et al.* (2016). While the meteorological factors during winter are not conducive to the long-range transport of CO, a higher concentration of CO in winter is mainly a result of the accumulation of CO.

O_3 Concentration

Ozone (O_3) is generated by photochemical reactions with precursors including oxides of nitrogen (NO_x), volatile organic compounds (VOCs), carbon monoxide (CO), methane (CH_4), and monmethane hydrocarbons (NMHC) (Tu *et al.*, 2007; Lan *et al.*, 2015; Wu *et al.*, 2015; Gong *et al.*, 2018), which work as peroxy radical sources (Kato *et al.*, 2016). Tropospheric O_3 is an important greenhouse gas and a secondary air pollutant. High O_3 levels have an adverse impact on plant growth and directly create risks to human health (Solomon *et al.*, 2000; Silva *et al.*, 2013; Lelieveld *et al.*, 2015; Kato *et al.*, 2016). In polluted atmospheres, the greatest contributor of precursors to the formation of O_3 are NO_x and VOCs, especially unsaturated VOCs. The simplified general equations that regulate atmospheric photochemistry may be summarized as follows:

Nitrogen dioxide dissociates to form nitric oxide (NO) and atomic oxygen radical:

$$NO_2 + h\nu(\lambda \leq 430\ nm) \rightarrow NO + O \quad (3)$$

Atomic oxygen radical combines with molecular oxygen to form ozone:

$$O + O_2 \rightarrow O_3 \quad (4)$$

Ozone is decomposed by reacting with nitric oxide, forming nitrogen dioxide and molecular oxygen:

$$NO + O_3 \rightarrow NO_2 + O_2 \quad (5)$$

The reaction of nitric oxide with atmospheric peroxides (RO_2) is the main cause of disturbances in the photochemical equilibrium, as presented in reaction 6:

$$NO + RO_2 \rightarrow NO_2 + RO \quad (6)$$

Atmospheric peroxides are formed by the oxidation of VOCs as represented in the equations below, which describe the oxidation of an alkene:

$$RCHCHR + O \rightarrow RCH_2 + RCO \quad (7)$$
(generation of free radicals)

$$RCH_2 + O_2 \rightarrow RCH_2O_2 \quad (8)$$
(generation of peroxides)

$$RCH_2O + O_2 \rightarrow RCHO + HO_2 \quad (9)$$
(generation of aldehydes)

$$RCH_2O_2 + NO_2 \rightarrow RCH_2O_2NO_2 \quad (10)$$
(generation of organic nitrates)

Ozone (O_3) formed through a series of complex reactions in the atmosphere are driven by the energy transferred to nitrogen dioxide (NO_2) molecules when they absorb light from solar radiation. There are several classes of VOCs in the atmosphere, mainly in emissions from large urban centers and industrial areas, where high solar radiation can increase the complexity of photochemical reactions.

The ambient concentration of ozone depends on the concentration of NO_x and VOCs and the ratio of VOCs to NO_x. The VOCs: NO_x ratio most favorable to ozone formation lies in the range of 4:1 to10:1. Meteorological factors, such as air temperature, humidity, and wind speed are the major contributors to the dispersion, transport, and dilution of O_3, while anthropogenic activities, including industrial emissions and transportation, also play an important role in the variations and process of O_3. Figs. 3(a), 3(b) and 3(c) show the variations in the monthly average O_3 concentration in Wuhu and Bengbu in 2015, 2016, and 2017, respectively.

In Wuhu, the monthly mean concentrations of O_3 were between 13.5 and 31.7 ppb, with an average of 22.8 ppb in 2015 and ranging between 29.8 and 57.3 ppb, with an average of 38.7 ppb in 2016. The concentrations were between 20.0 and 77.4 ppb, with an average of 46.1 ppb in 2017. O_3 concentrations rose significantly, rose by approximately 41.1% from 2015 to 2016, and approximately 50.5% from 2016 to 2017, which may be related to the rapid growth in the number of vehicles in recent years. Cheng *et al.* (2018) indicated that temporary traffic management, such as improving fuel quality, promoting clean energy and green energy vehicles, and the odd-and-even license plate rule, have achieved outstanding benefits on the reduction of NO_x emissions during the air quality assurance efforts in Beijing. Without the effective implementation of vehicle emission control measures in Wuhu, the NO_x emissions from vehicles increased considerably, which led to greater amounts of precursors for the formation of O_3. As a whole, the three-year mean O_3 concentration ranged between 13.5 and 77.4 ppb, with an average of 35.9 ppb. The results show that O_3 concentrations in Wuhu can meet the WHO air quality regulated standard of 46.6 ppb for O_3. On the other hand, following the increasing tendency of O_3 concentrations, the annual O_3 levels in Wuhu may easily exceed the WHO air quality regulated standard. Moreover, the number of days exceeding the WHO air quality regulated standard (zero day in 2015, 82 days in 2016, and 149 days in 2017) have increased substantially over the years. The change in the O_3 concentration poses serious threats to the air quality and human health. Therefore, it should be viewed as urgent and should receive more public attention.

In Bengbu, the monthly mean concentrations of O_3 were between 23.8 and 58.7 ppb, with an average of 40.5 ppb in 2015, were between 24.7 and 64.8 ppb, with an average of 43.3 ppb in 2016, and were between 26.6 and 74.1 ppb, with an average of 49.9 ppb in 2017. Comparing the annual mean O_3 concentrations, we can see that the levels of O_3 increased continuously from 2015 to 2017 and rose by approximately 6.47% from 2015 to 2016 and by approximately 13.2% from 2016 to 2017. As in Wuhu, this also may be associated with an increase in emissions of NO_x and VOCs. As a whole, the three-year mean O_3 concentrations ranged between 23.8 and 74.1 ppb, with an average of 44.7 ppb. The observed dates show that O_3 concentrations in Bengbu were above or below the WHO air quality regulated standard of 46.6 ppb during the three

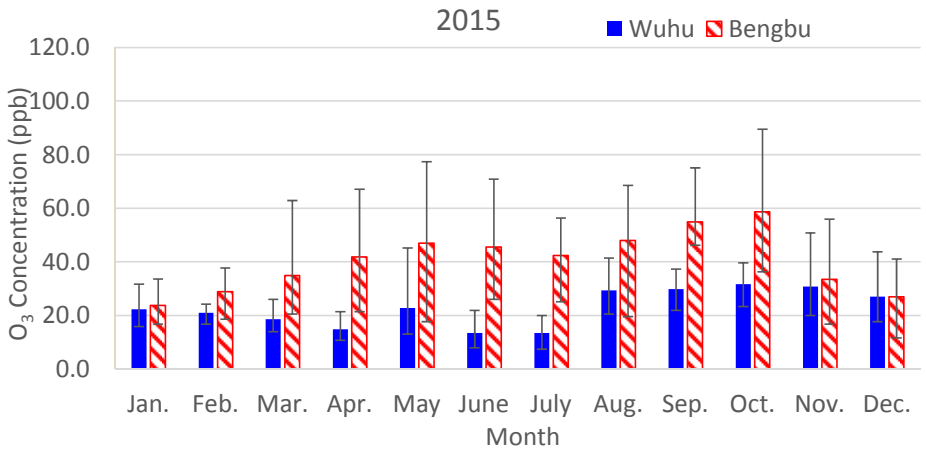

Fig. 3(a). Monthly average atmospheric O_3 concentrations in Wuhu and Bengbu in 2015.

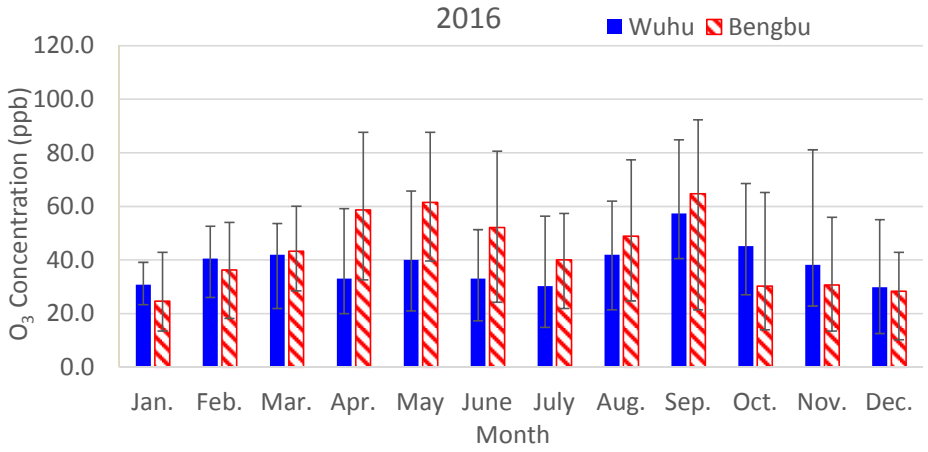

Fig. 3(b). Monthly average atmospheric O_3 concentrations in Wuhu and Bengbu in 2016.

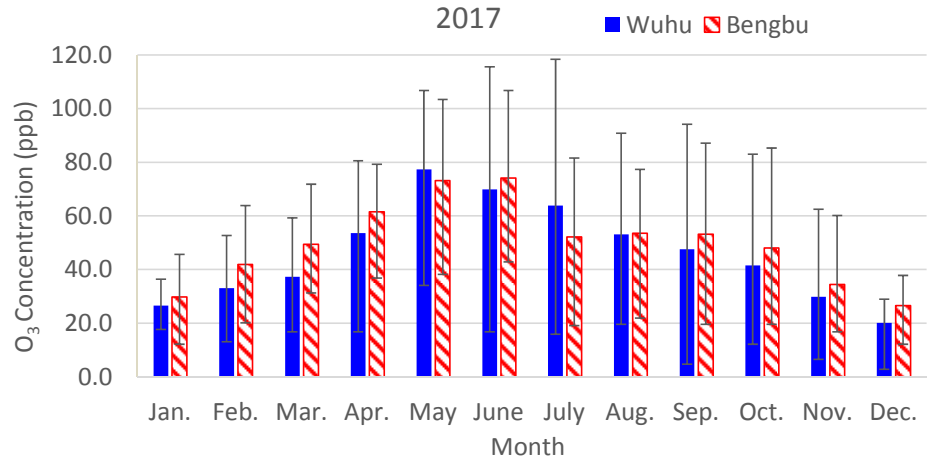

Fig. 3(c). Monthly average atmospheric O_3 concentrations in Wuhu and Bengbu in 2017.

years, but on many days, they exceeded the WHO air quality regulated standard (130 days in 2015, 139 days in 2016, and 183 days in 2017, respectively), and the number of days exceeding 74.6 ppb increased obviously, which was 7 days in 2015, 26 days in 2016, and 42 days in 2017, respectively. In recent years, the O_3 level has grown rapidly and thus poses a serious challenge in the efforts to improve the air quality in both Wuhu and Bengbu.

Due to the differences in meteorological conditions and ozone precursors emission distributions, the seasonal variations in O_3 concentration exhibit distinct spatial-temporal characteristics. In Wuhu, in 2015, the seasonal

mean concentrations of ozone in the spring, summer, fall, and winter were 18.6, 18.6, 30.8 and 23.3 ppb, respectively; while in 2016, the values were 38.2, 35.0, 47.1, and 33.6 ppb, respectively. In 2017, the values were 55.9, 62.4, 39.6, and 26.6 ppb, respectively. In Bengbu, the seasonal average O_3 concentrations during 2015 were 41.5, 45.2, 48.9, and 26.6 ppb in spring, summer, fall, and winter, respectively. In 2016, they were 54.5, 47.1, 41.9, and 29.8 ppb in spring, summer, fall, and winter, respectively, and in 2017, they were 61.5, 60.1, 45.2, and 32.6 ppb in spring, summer, fall, and winter, respectively. Generally, the seasonal distribution of O_3 can be classified into three patterns for the two cities during 2015–2017. In Wuhu during 2015, the first pattern displays a relatively uniform distribution in the four seasons, with lower O_3 levels throughout the year of 22.8 ppb. This pattern was similar to the results for Xiamen, where the O_3 concentrations were 35.9, 35.0, 36.3 and 29.8 ppb in spring, summer, fall, and winter, respectively (Gong *et al.*, 2018). The unclear seasonal variations may mainly be limited by the concentration of precursors (NO_x and VOCS) in the atmosphere, where when O_3 is at a lower level, the meteorological conditions have less effect on its formation. As seen in Wuhu during 2016 and Bengbu during 2015, the second pattern is where the highest mean values are in the fall, and the lowest mean values in are the winter; while the spring and summer exhibit similar values, and both are at intermediate levels, with the annual mean O_3 concentrations ranging between 38.7 and 40.5 ppb. Previous studies (Kato *et al.*, 2016; Li *et al.*, 2017b; Gong *et al.*, 2018) have indicated that the atmospheric relative humidity is negatively correlated with the O_3 concentration and that low relative humidity is conducive to the formation of O_3 during the dry fall season. When the air pollutant concentration is not very high, high temperatures and wind speeds are favorable to the dispersion and dilution of air pollutants during warm seasons (defined as late spring and summer), the decreasing precursors can hinder the formation of O_3. Thus, the warm summer season exhibits a lower O_3 level than the fall. On the other hand, high temperatures and strong UV radiation will increase ozone production rates in warm seasons, which have higher O_3 levels than in the winter. As seen in Wuhu during 2017 and Bengbu during 2016–2017, the third pattern shows the highest mean values occurred both in the spring and summer, where the lowest mean values occurred in the winter, and in the fall were at intermediate levels, where the annual mean O_3 concentration ranged between 43.3 and 49.9 ppb. From Fig. 3(c), it can be seen that the high O_3 concentration in spring occurred in late spring, under the condition of a high VOC concentration, where higher air temperature and strong UV radiation in late spring and summer directly impact on the chemical reaction rates, which are conducive to O_3 formation. At lower temperatures and a less UV radiation, the processes are not favorable for photochemical reactions in winter.

AQI Analysis

The Air Quality Index (AQI) plays a crucial role in evaluation of air status and its associated health risks. Air pollution has become particularly severe issue due to the acceleration of economic growth and urbanization in China over recent decades. The AQI can provide guidance for the government to inform the public of the status of air quality and thus help them take proper health protection measures. From 2015–2017, the day fractions of the six AQI categories in different seasons for Wuhu and Bengbu are shown in Figs. 4(a)–4(f), and the cumulative number of days of primary pollutants are shown in Tables 3(a)–3(b).

In Wuhu, the daily AQI ranged from 23 to 298, with an annual value of 81 in 2015. The daily AQI ranged from 33 to 290, with an annual average value of 80 in 2016 and ranged from 34 to 278, with an annual average value of 90 in 2017. In Bengbu, the daily AQI ranged from 23 to 288, with an annual value of 88 during 2015. It ranged from 32 to 286, with an annual value of 89 in 2016 and ranged from 27 to 500, with an annual value of 97 in 2017. In general, based on the annual mean values, the air quality did not improve obviously during the three-year observation period

Table 3(a). Cumulative number of days of primary pollutants for Wuhu from 2015–2017.

Year	AQI	Spring				Summer				Fall				Winter			
	Class	$PM_{2.5}$	PM_{10}	NO_x	O_3	$PM_{2.5}$	PM_{10}	NO_x	O_3	$PM_{2.5}$	PM_{10}	NO_x	O_3	$PM_{2.5}$	PM_{10}	NO_x	O_3
2015	51–100	50	15	3	1	29	10	19	0	41	5	22	0	28	3	9	0
	101–150	9	0	0	0	1	0	0	0	15	0	4	0	29	0	3	0
	151–200	3	0	0	0	0	0	0	0	5	0	0	0	10	0	0	0
	201–300	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0
	> 300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2016	51–100	45	12	13	0	24	13	5	12	26	5	12	23	23	4	15	0
	101–150	12	0	1	0	1	0	0	0	10	0	0	2	29	0	1	0
	151–200	0	1	0	0	0	0	0	0	3	0	0	0	13	0	0	0
	201–300	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0
	> 300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2017	51–100	3	32	8	15	0	3	1	40	15	6	21	9	16	6	30	0
	101–150	5	3	2	18	0	0	0	18	12	0	0	6	29	0	0	0
	151–200	0	1	0	4	0	0	0	8	1	0	0	0	6	0	0	0
	201–300	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
	> 300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3(b). Cumulative number of days of primary pollutants for Bengbu from 2015–2017.

Year	AQI Class	Spring				Summer				Fall				Winter			
		$PM_{2.5}$	PM_{10}	NO_x	O_3	$PM_{2.5}$	PM_{10}	NO_x	O_3	$PM_{2.5}$	PM_{10}	NO_x	O_3	$PM_{2.5}$	PM_{10}	NO_x	O_3
2015	51–100	49	16	4	5	37	15	0	12	45	4	0	11	37	4	0	0
	101–150	16	2	0	1	7	2	0	0	13	2	0	1	27	0	0	0
	151–200	0	0	0	0	1	0	0	0	10	0	0	0	12	0	0	0
	201–300	0	0	0	0	0	0	0	0	2	0	0	0	5	0	0	0
	> 300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2016	51–100	25	11	1	20	28	18	0	27	20	21	5	13	26	14	3	0
	101–150	19	0	0	11	1	0	0	3	8	1	0	10	20	1	0	0
	151–200	2	0	0	0	0	0	0	0	2	0	0	0	19	0	0	0
	201–300	0	0	0	0	0	0	0	0	1	0	0	0	9	0	0	0
	> 300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2017	51–100	14	25	0	14	3	12	0	42	16	13	5	18	23	19	2	0
	101–150	18	0	0	16	0	1	0	17	14	0	0	4	27	0	0	0
	151–200	1	0	0	3	0	0	0	1	3	0	0	0	13	0	0	0
	201–300	0	1	0	0	0	0	0	0	0	0	0	0	8	0	0	0
	> 300	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

in either Wuhu or Bengbu. The data also indicated that the AQI values in Bengbu were higher than those in Wuhu, which means that the air pollution of the former was more severe than that of the latter. In addition, every year, the two cities exhibited obvious fluctuations in daily AQI values. This can be attributed to the air pollutant emission characteristics and meteorological conditions in different seasons.

Air quality can be classified into six classes based on the ranges of the AQI values: Grade I: 0–50; Grade II: 51–100; Grade III: 101–150; Grade IV: 151–200; Grade V: 201–300; Grade VI: 301–500. The proportions of different AQI classes in the different seasons for Wuhu and Bengbu from 2015–2017 are further discussed. Firstly, as for the distribution of six AQI classes of spring throughout the observed three-year period, in Wuhu, Fig. 4(a)-(A), Fig. 4(c)-(A), Fig. 4(e)-(A) show that during 2015, the proportion of levels with Grade I, II, III, IV, V, and VI were 13%, 74%, 10%, 3%, 0% and 0%, respectively; while in 2016, these proportions were 13%, 72%, 14%, 1%, 0%, and 0%, respectively, and in 2017, they were 2%, 62%, 31%, 5%, 0%, and 0%, respectively. Comparing the proportions of the different AQI classes from 2015 to 2017, both grades I and II continuously decreased by about 84.6% and 16.2%, respectively, and grades III and IV continuously increased by approximately 67.7% and 40.0%, respectively. The decreasing proportion of good (Grade I) and moderate (Grade II) levels and increasing proportion of pollution (Grade III and IV) levels indicate that the air quality in Wuhu in spring has gradually deteriorated. Both Grade V and VI remain constant at 0%, indicating that there are no heavy air pollution events in the spring in Wuhu, which is likely due to the favorable meteorological conditions for pollutant dilution and dispersion, as well as increasing vegetation coverage, which absorbs pollutants in the spring. Moreover, Table 3(a) shows that $PM_{2.5}$ is the most frequent primary air pollutant and that its levels have declined, but O_3 as the primary pollutant rose significantly during the observed years. This result highlights that controlling O_3 pollution is essential to improving air quality in addition to reducing PM pollution in the spring.

In Bengbu, Fig. 4(b)-(A), Fig. 4(d)-(A), Fig. 4(f)-(A) present that during 2015, the proportion of levels with Grade I, II, III, IV, V and VI was 4%, 76%, 20%, 0%, 0%, and 0%, respectively; while in 2016, the proportions were 4%, 61%, 33%, 2%, 0%, and 0%, respectively, and in 2017, the proportions were 1%, 55%, 38%, 4%, 1%, and 1%, respectively. As in Wuhu, from 2015–2017, the proportions of different AQI classes in Bengbu show that Grade I and II continuously decreased by about 75.0% and 27.6%, respectively, and Grade III and IV continuously increased by about 47.4% and 100.0%, respectively, which also indicated that the air quality in Bengbu in spring has gradually deteriorated. This was the same in Wuhu, where Table 3(b) also shows that the most frequent primary air pollutant was $PM_{2.5}$, which has declined annually, but O_3 the as primary pollutant rose significantly. Both Grade V and VI represented 1% in 2017, indicating that heavy air pollution events occurred in spring in 2017 in Bengbu and that the primary pollutant is PM_{10}. Therefore, appropriate measures aiming to lessen PM_{10} pollution should be taken to improve the heavy pollution status in spring in Bengbu. It can be seen that the proportions of AQI levels in grades I and II in Wuhu were higher than those in Bengbu, and the proportions AQI levels of grades III and IV in Wuhu were lower than those in Bengbu, in summary, Wuhu had better air quality in spring than Bengbu.

Secondly, in regard to the distribution of the six AQI classes of summer, in Wuhu, Fig. 4(a)-(B), Fig. 4(c)-(B), Fig. 4(e)-(B) illustrate that the proportions of grades I, II, III, IV, V and VI were 38%, 61%, 1%, 0%, 0%, and 0% in 2015, respectively, were 42%, 57%, 1%, 0%, 0%, and 0% in 2016, respectively, and were 25%, 47%, 19%, 9%, 0%, and 0% in 2017, respectively. From 2015–2016, the total fraction of grades I and II were extremely high at 99%, and the remaining AQI classes only represented 1%, which indicated that the air quality is good and moderate in general and that there are rarely pollution issues in the

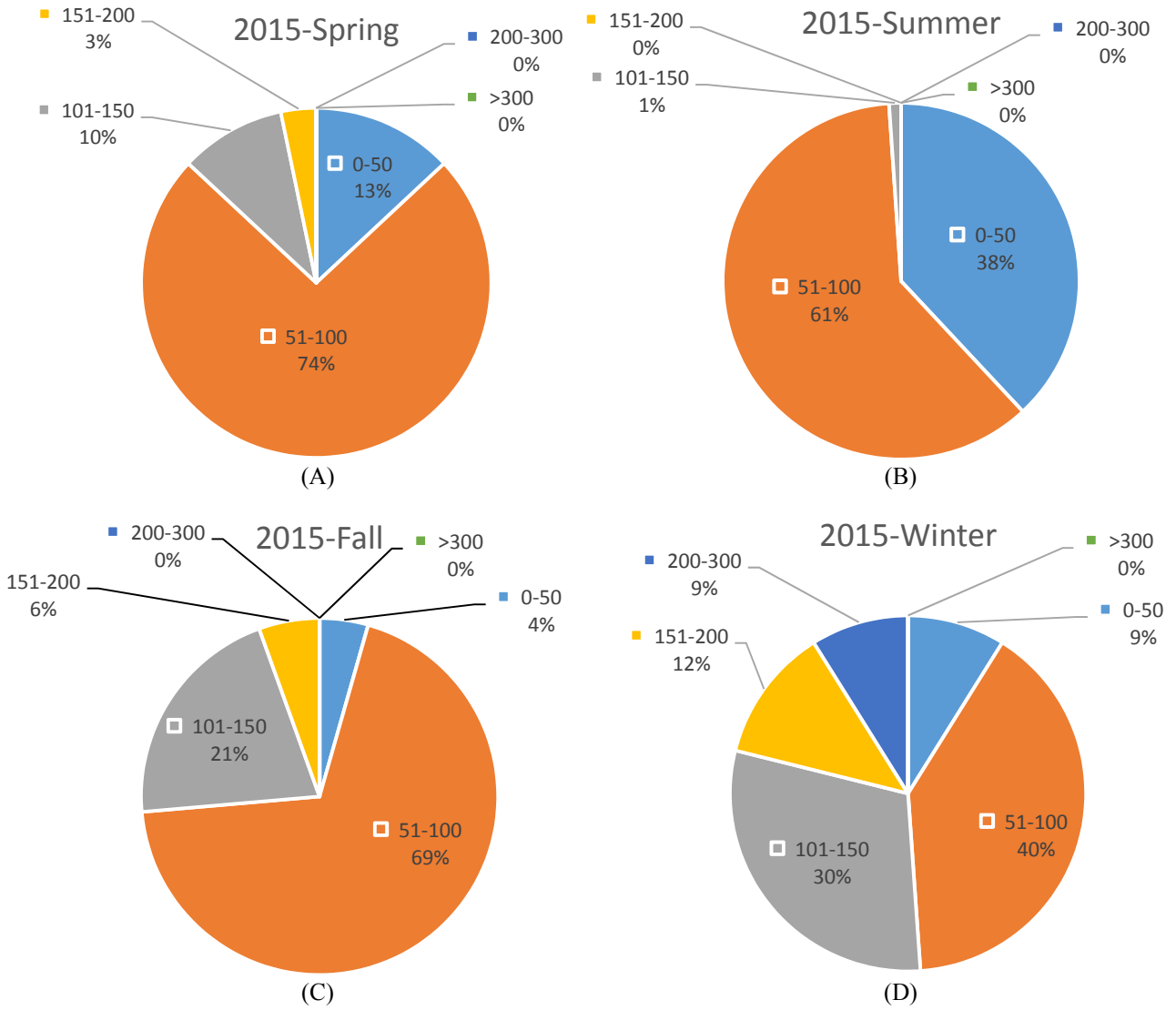

Fig. 4 (a). The fractions of the six AQI categories for Wuhu in Spring (A), Summer (B), Fall (C), and Winter (D) in 2015.

summer of Wuhu. However, in 2017, the total fraction of grades I and II reduced to 72%, and grades III and IV rose significantly to 28% although the levels of grades V and VI remained constant at 0%. Therefore, the air quality in the summer in Wuhu exhibited a marked trend of deterioration. From Table 3(a), initially, $PM_{2.5}$ was the most frequent primary pollutant, followed by NO_x and PM_{10}, but O_3 gradually become significant primary pollutant in 2017 and dominated $PM_{2.5}$, NO_2 and PM_{10}. The serious O_3 pollution during summer might be attributed to the higher VOC emissions, which provide high precursor concentrations for the formation of O_3, and the high air temperature and strong solar radiation can facilitate photochemical production of O_3. This result is consistent with the findings of previous studies (Atkinson and Arey, 2003; Zhang and Ying *et al.*, 2011; Li *et al.*, 2012a; He *et al.*, 2017; Shen *et al.*, 2017).

As for Bengbu, Fig. 4(b)-(B), Fig. 4(d)-(B), Fig. 4(f)–(B) illustrate that the proportion of grades I, II, III, IV, V and VI were 21%, 68%, 10%, 1%, 0%, and 0% in 2015, respectively, were 19%, 77%, 4%, 0%, 0%, and 0% in 2016, respectively, and were 18%, 61%, 20%, 1%, 0%, and 0% in 2017, respectively. The fraction of Grade I slowly decreased by about 14.3% from 2015 to 2017, but the fraction of Grade II increased by about 11.7% from 2015 to 2016 and then decreased by about 20.8% from 2016 to 2017. The fraction of Grade III decreased by about 60.0% from 2015 to 2016, and then increased by about 80.0% from 2016 to 2017. With the exception of 2016, the AQI class of Grade IV occurred in both 2015 and 2017. In general, the air quality in Bengbu in summer was good and moderate, and the best air quality state occurred in 2016, but the air quality state in 2017 was worse than that in 2015. Similar to Wuhu, Table 3(b) shows that the primary pollutant changed from $PM_{2.5}$ to O_3. O_3 pollution may be an important factor contributing to the deterioration of air quality in the summer. This result underscores that more efforts are urgently needed to improve the air quality through lessening O_3 pollution during the summer.

Thirdly, as for the distribution of six AQI classes in fall, Fig. 4(a)–(C), Fig. 4(c)–(C), Fig. 4(e)–(C) show the

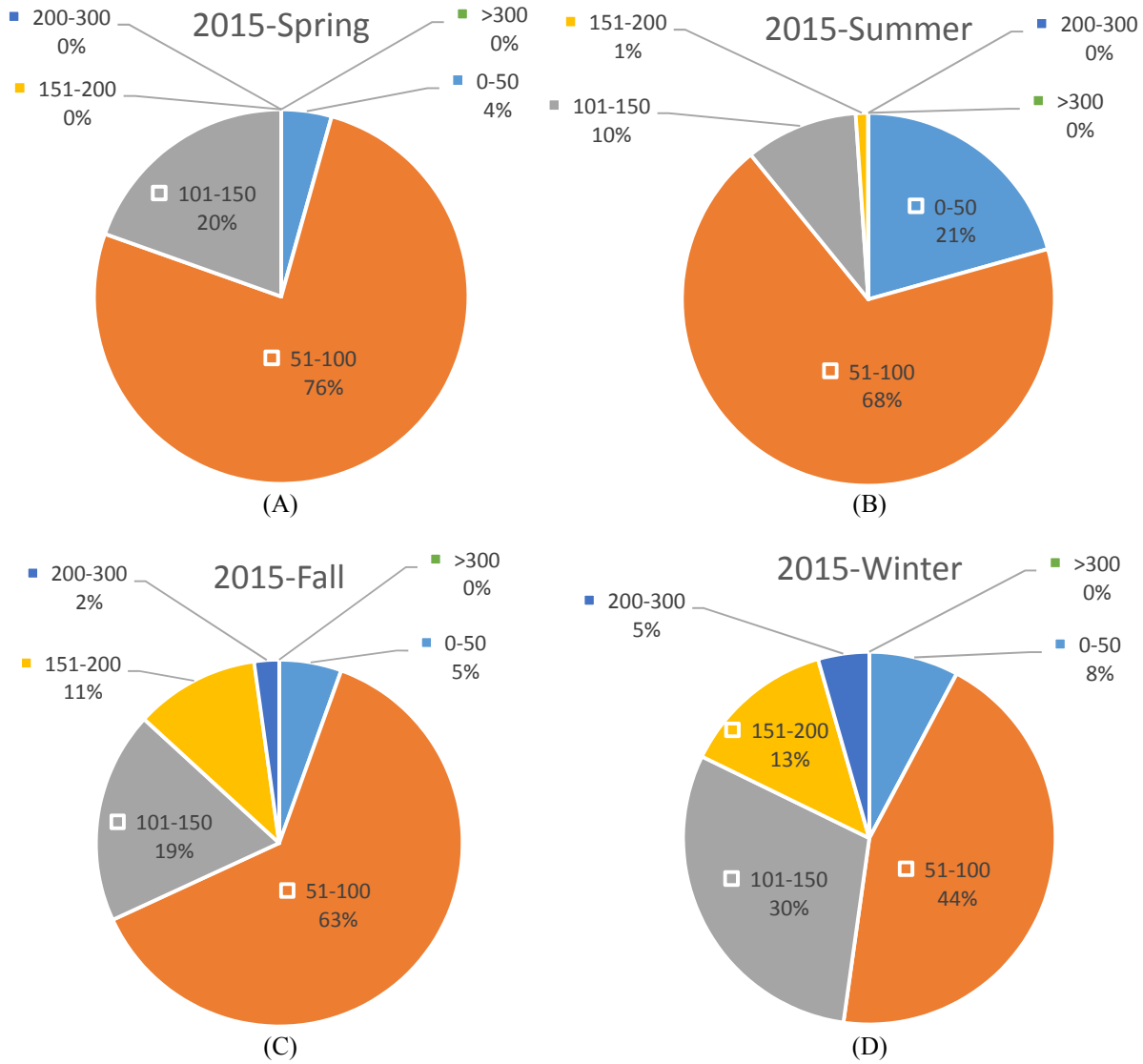

Fig. 4 (b). The fractions of the six AQI categories for Bengbu in Spring (A), Summer (B), Fall (C), and Winter (D) in 2015.

proportions in Wuhu, in 2015, where the fraction of grades I, II, III, IV, V, and VI were 4%, 69%, 21%, 6%, 0%, and 0%, respectively; in 2016, these fractions were 11%, 73%, 13%, 3%, 0%, and 0%, respectively, and in 2017, they were 26%, 53%, 20%, 1%, 0%, and 0%, respectively. It should be noted that the air quality level of Grade I obviously increased by an appropriate 84.6%, which means that the good air quality has been improved in the autumn in Wuhu in the three years under observation. Grade II is the dominant level. Table 3(a) shows the most frequent primary air pollutant changed from particulate matter to gaseous species, which was $PM_{2.5}$ in 2015, O_3 in 2016, and NO_2 in 2017. The increasing pollution of gaseous species may reflect a change in a complex source of air pollution, such as increasing traffic emissions; the fraction of Grade III fluctuated from 2015 to 2017, and $PM_{2.5}$ was the most frequent primary pollutant; O_3 and NO_2 also were occasionally the primary pollutants. The fraction of Grade IV obviously decreased by 83.3%, and the primary pollutant was $PM_{2.5}$. $PM_{2.5}$ was the typical primary pollutant during polluted days, which may be related to the fact that the low ground temperature led to the accumulation of $PM_{2.5}$, as well as the high $PM_{2.5}$ concentration air current blowing from the northern cities of China during the late fall (Tang *et al.*, 2017; Wang *et al.*, 2018). The levels of grades V and VI remained constantly at 0%, indicating that no heavy air pollution events occurred in the fall in Wuhu.

In Bengbu, Fig. 4(b)-(C), Fig. 4(d)-(C), Fig. 4(f)-(C) illustrate the proportion of different levels in fall in 2015, where the fractions of grades I, II, III, IV, V and VI were 5%, 63%, 19%, 11%, 2% and 0%, respectively; while in 2016, these fractions were 15%, 61%, 21%, 2%, 1%, and 0%, respectively, and in 2017, they were 42%, 45%, 12%, 1%, 0% and 0%, respectively. The calculated dates are remarkably similar to the fall in Wuhu, where the air quality of Grade I significantly rose by an appropriate 88.1%, and the level of Grade II accounted for the largest percentage among these six classes. Table 3(b) shows that the most frequent primary air pollutant was $PM_{2.5}$ in 2015, which then changed into O_3 in 2016 and 2017. The fraction

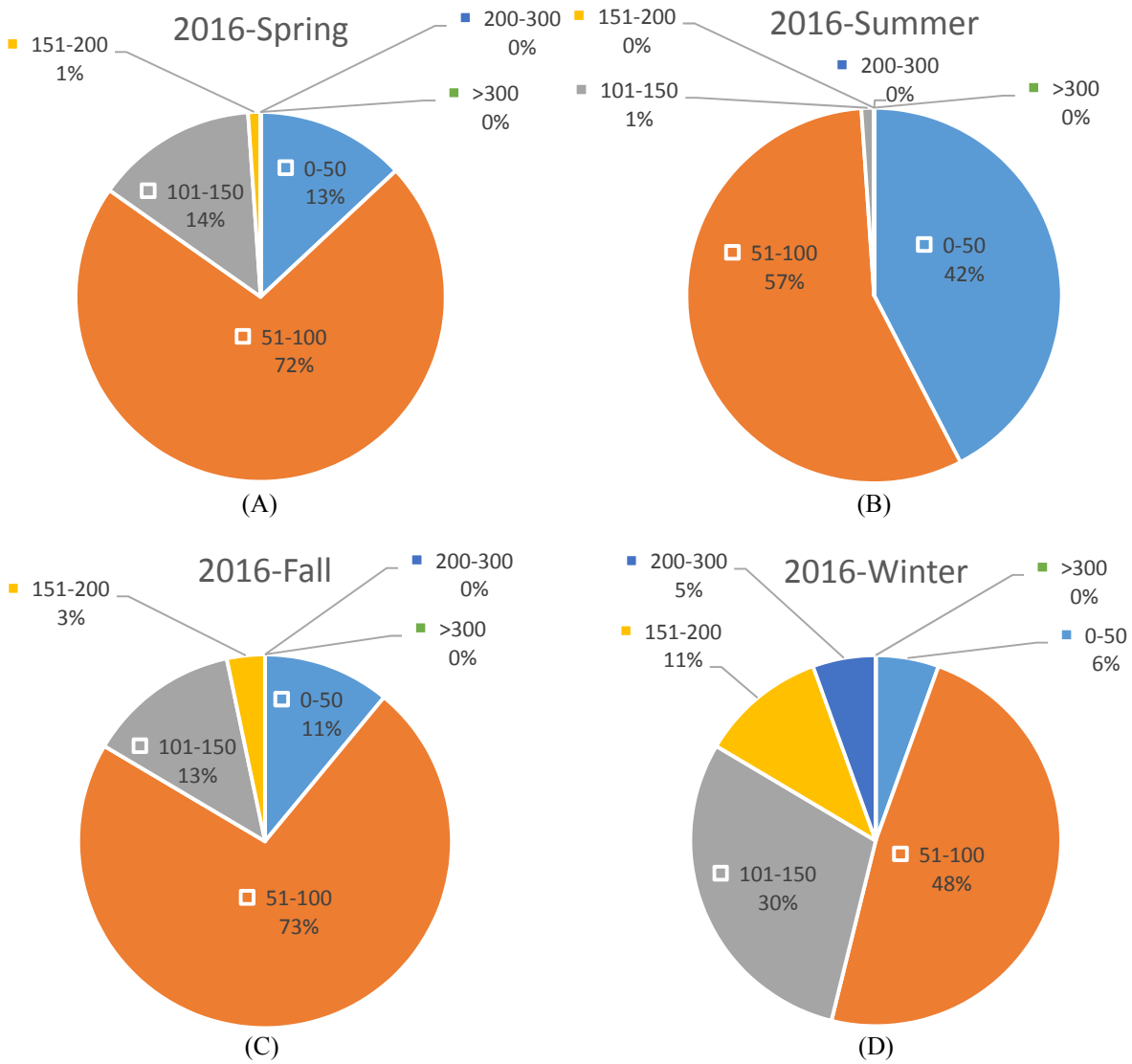

Fig. 4 (c). The fractions of the six AQI categories for Wuhu in Spring (A), Summer (B), Fall (C), and Winter (D) in 2016.

of Grade III fluctuated during the observed period, where the most frequent primary air pollutant was $PM_{2.5}$ in 2015 and 2017, O_3 in 2016, and where PM_{10} also was occasionally the primary pollutant. The proportion of grades IV and V dramatically reduced by 90.9% and 100%, respectively, and $PM_{2.5}$ was also the primary pollutant during heavily polluted days. Overall, our study showed clearly that $PM_{2.5}$ is the most frequent primary pollutant, so it is of great significance to control $PM_{2.5}$ pollution to reduce the air pollution in the fall in both Wuhu and Bengbu. It is also important to note the controlling of gaseous pollutants, especially O_3 pollution, which may dominate over $PM_{2.5}$ and become the most important air contaminant in the fall. Moreover, these results also show that the heavy air pollution in the fall in Bengbu is worse than that in Wuhu.

Finally, in winter, Fig. 4(a)–(D), Fig. 4(c)–(D), Fig. 4(e)–(D) present the distribution of the six AQI classes in Wuhu, where the proportion of levels with grades I, II, III, IV, V and VI were 9%, 40%, 30%, 12%, 9%, and 0% in 2015, respectively, were 6%, 48%, 30%, 11%, 5%, and 0% in 2016, respectively, and were 1%, 58%, 32%, 6%, 3%, and 0% in 2017, respectively. From 2015 to 2017, the fraction of Grade I decreased by about 88.9%, but the fraction of Grade II increased by about 31.0%, and from Table 3(a), the most frequent primary air pollutant was $PM_{2.5}$ in 2015 and 2016, after which NO_2 become the mainly primary air pollutant in 2017. PM_{10} also was a primary pollutant occasionally; while Grade IV and V continuously decreased by about 50.0% and 66.7%, respectively, and the primary pollutant was $PM_{2.5}$ at these two pollution levels. This result suggests that the days with moderate air quality have increased and that the heavy pollution status has improved in the winter in Wuhu, which can be attributed to the effort to derive air pollution control strategies and control actions. The analyses of primary pollutants indicated that $PM_{2.5}$ was the typical primary air pollutant in the winter in Wuhu, followed by NO_2, which can be attributed to unfavorable metrological conditions hindering the diffusion of $PM_{2.5}$ and the low vegetation coverage obstructing the absorption of NO_2. Therefore, the controlling of $PM_{2.5}$ and NO_2 may

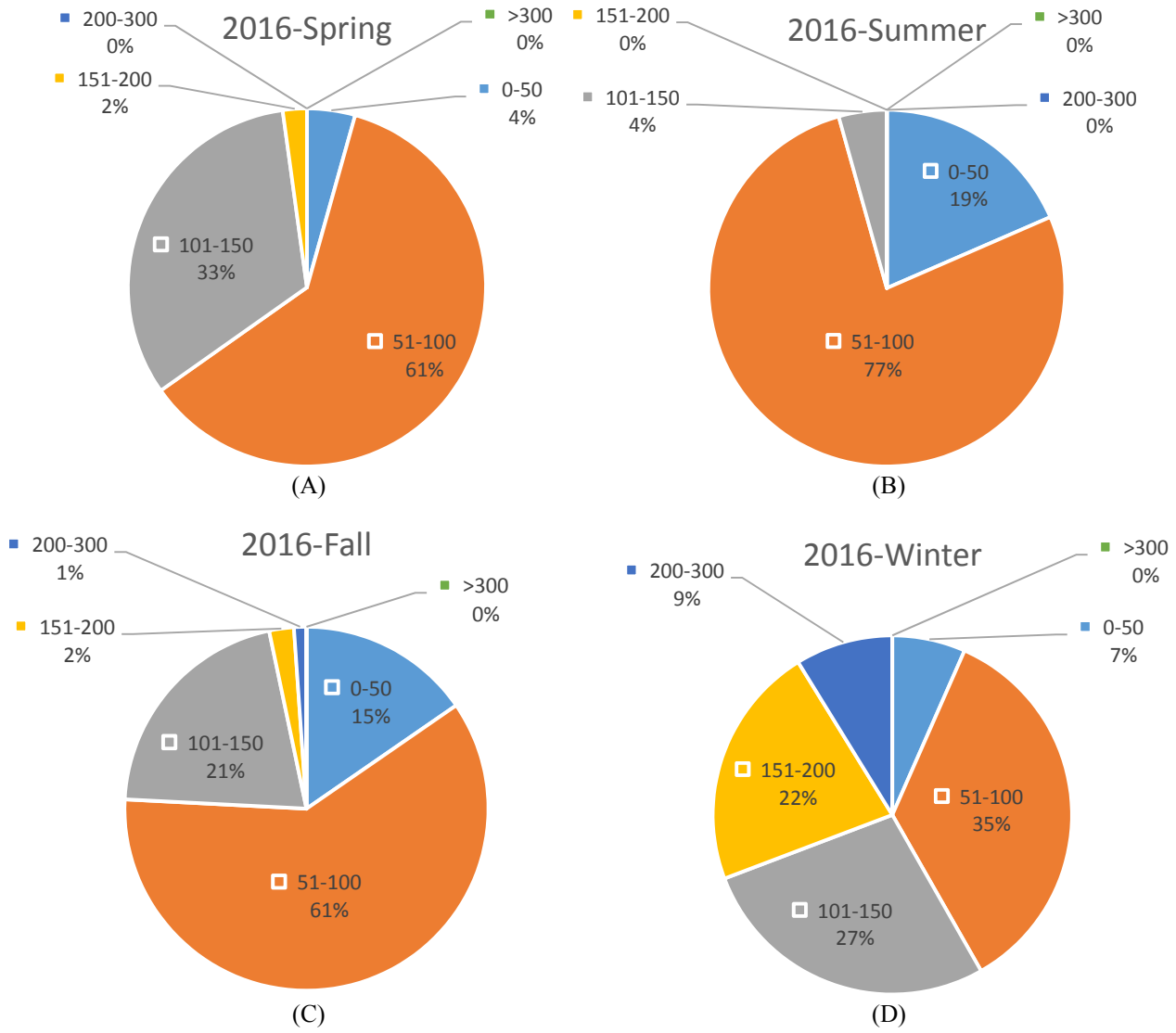

Fig. 4 (d). The number fractions of the six AQI categories for Bengbu in Spring (A), Summer (B), Fall (C), and Winter (D) in 2016.

be a valid way to improve the air quality of Wuhu in the winter.

Fig. 4(b)-(D), Fig. 4(d)-(D), Fig. 4(f)-(D) present the distribution of the six AQI classes in Bengbu, where the proportion of grades I, II, III, IV, V and VI were 8%, 44%, 30%, 13%, 5%, and 0% in 2015, respectively, were 7%, 35%, 27%, 22%, 9%, and 0% in 2016, respectively, and were 14%, 31%, 36%, 16%, 3%, and 0% in 2017, respectively. In contrast to Wuhu, from 2015 to 2017, the fraction of Grade I increased by about 42.9%, but the fraction of Grade II decreased by about 29.5%. Table 3(b) shows that $PM_{2.5}$ was the main primary air pollutant, followed by PM_{10} and NO_2, which were primary pollutants very few days; while Grade III, IV and V fluctuated, with mean proportions of 31.0%, 17.0% and 5.7%, respectively, of which $PM_{2.5}$ was the primary pollutant. It should be noted that the changes in the air quality in the winter in Bengbu are complex, but the days with good air quality have increased. The analyses of primary pollutants also suggest that $PM_{2.5}$ was the typical primary air pollutant, followed by PM_{10}. It is important to note that there was little O_3 pollution in the winter in both Wuhu and Bengbu due to the low ground temperature and weak solar radiation during winter. Hence, taking effective actions to lessen PM pollution has important significance in guiding improving the air quality of Bengbu's winter.

The AQI values fluctuated greatly in both Wuhu and Bengbu. Generally, the air quality in Wuhu was better than that in Bengbu. As a whole, during the three years studied, in Wuhu, the mean proportions of grades I, II, III, IV, V and VI were 9.33%, 69.3%, 18.3%, 3.00%, 0%, and 0% in spring, were 35.0%, 55.0%, 7.00%, 3.00%, 0%, and 0% in summer, were 13.6%, 65.0%, 18.0%, 3.33%, 0%, and 0% in fall, and were 5.33%, 48.7%, 30.7%, 9.67%, 5.67%, and 0% in winter. In Bengbu, the mean proportions of grades I, II, III, IV, V and VI were 3.00%, 64.0%, 30.3%, 2.67%, 0.333%, and 0.333% in spring, were 19.3%, 68.7%, 11.3%, 0.667%, 0%, and 0% in summer, were 20.7%, 56.3%,

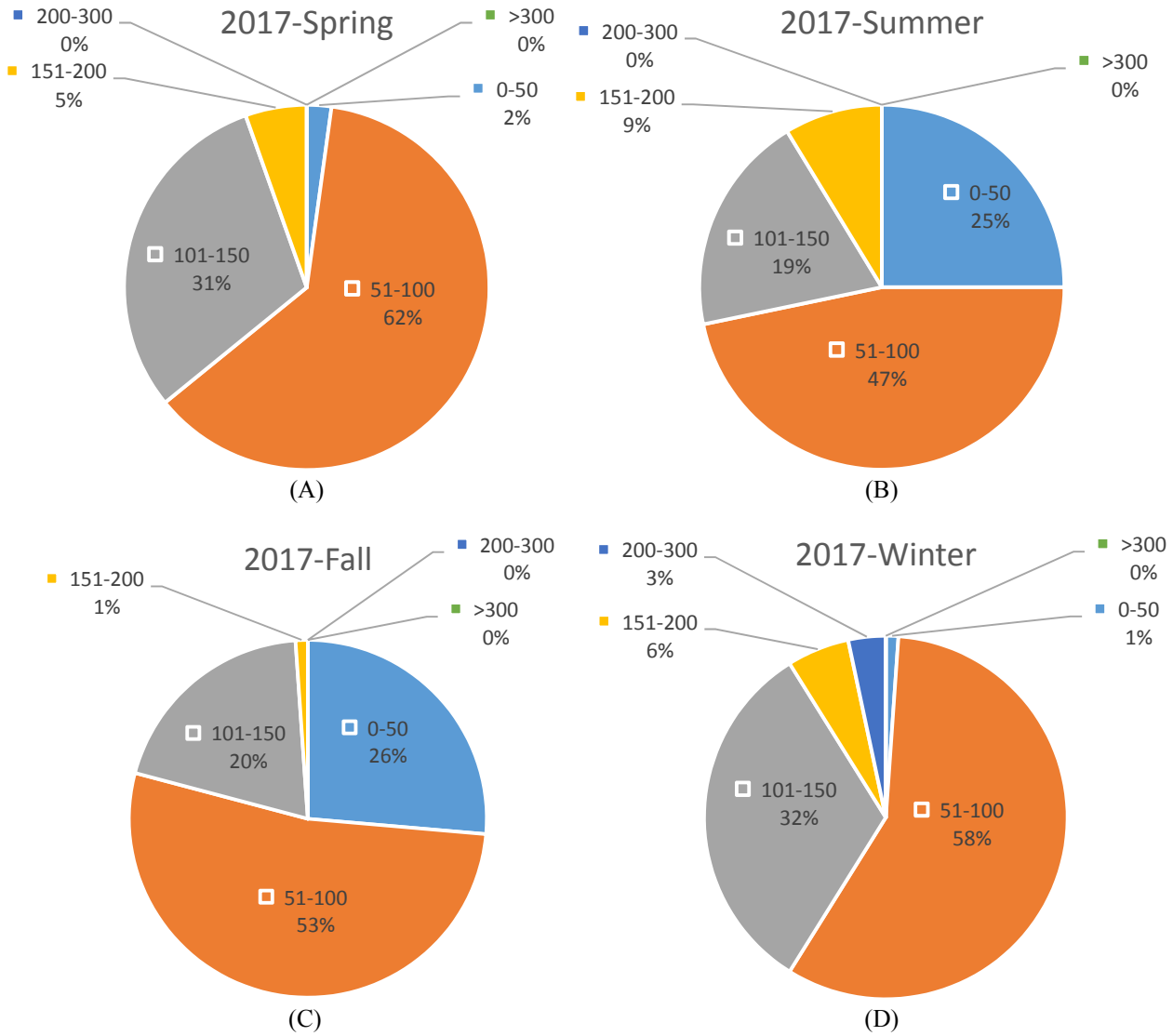

Fig. 4 (e). The fractions of the six AQI categories for Wuhu in Spring (A), Summer (B), Fall (C), and Winter (D) in 2017.

17.3%, 4.67%, 1.00%, and 0% in fall, and were 9.67%, 36.7%, 31.0%, 32.0%, 5.67%, and 0% in winter. Generally, the air quality in the two cities were in the following order: summer > fall > spring > winter, which concurs with the results of Shen *et al.* (2017). As for the primary air pollutants, when AQIs were 101–150, in Wuhu, $PM_{2.5}$, PM_{10}, NO_2, and O_3 were primary air pollutants for 54, 0, 7, and 0 days in 2015, respectively, for 52, 0, 2, and 2 days in 2016, respectively, and for 46, 3, 2, and 42 days in 2017, respectively. In Bengbu, $PM_{2.5}$, PM_{10}, NO_2 and O_3 were primary air pollutants for 63, 6, 0, and 2 days in 2015, respectively, for 48, 2, 0, and 24 days in 2016, respectively, and for 59, 1, 0 and 37 days in 2017, respectively. When AQIs were 151–200, in Wuhu, $PM_{2.5}$, PM_{10}, NO_2 and O_3 were primary air pollutants for 18, 0, 0, and 0 days in 2015; were 16, 1, 0 and 0 in 2016; were 7, 1, 0 and 12 in 2017. In Bengbu, $PM_{2.5}$, PM_{10}, NO_2 and O_3 were primary air pollutants for 23, 0, 0, and 0 days in 2015, respectively, for 23, 0, 0, and 0 days in 2016, respectively, and for 17, 0, 0, and 4 days in 2017, respectively. When AQIs were 201–300, in Wuhu, $PM_{2.5}$, PM_{10}, NO_2, and O_3 were primary air pollutants for 8, 0, 0, and 0 days in 2015, respectively, for 5, 0, 0, and 0 in 2016, respectively, and for 3, 0, 0, and 0 days in 2017, respectively. In Bengbu, $PM_{2.5}$, PM_{10}, NO_2, and O_3 were primary air pollutants for 7, 0, 0, and 0 days in 2015, for 10, 0, 0, and 0 in 2016, and for 8, 1, 0 and 0 days in 2017. When AQIs were 301–500, which did not occur in Wuhu from 2015–2017 or in Bengbu from 2015–2016, $PM_{2.5}$, PM_{10}, NO_2 were dominant for 0, 1, 0, and 0 days in Bengbu in 2017.

With regard to the seasonal variations in the air quality statuses in the two cities, in the spring in Wuhu, the levels of good and moderate days have declined without heavy pollution events, and $PM_{2.5}$ is the most frequent primary pollutant, while the number of days that O_3 is a primary pollutant have increased significantly. To improve the air quality of Wuhu in the spring, it is necessary to control $PM_{2.5}$ and lessen O_3 pollution. The air quality worsens gradually in the spring in Bengbu, and its primary pollutant situation is similar to that of Wuhu. While the primary

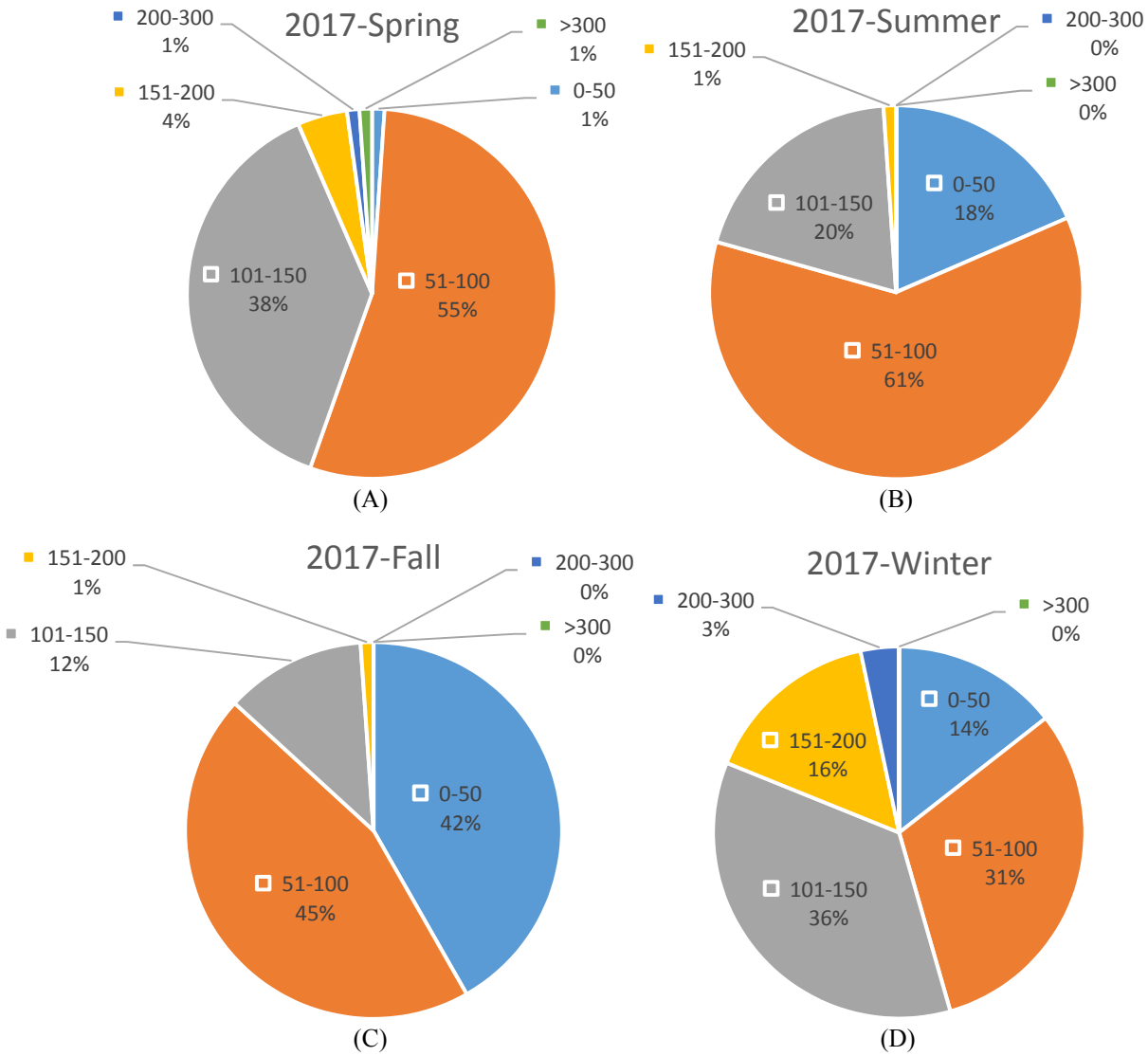

Fig. 4(f). The number fractions of the six AQI categories for Bengbu in Spring (A), Summer (B), Fall (C), and Winter (D) in 2017.

pollutant is PM_{10} during heavily polluted days, it may effective to improve the heavy pollution through reducing PM_{10} in Bengbu in the spring. The air quality mainly is good and moderate in the summer in both Wuhu and Bengbu, but it has deteriorated annually, which is very significantly related to the increasing O_3 pollution. Hence, taking proper actions for controlling O_3 is very important. The fraction of good air condition has increased, and the level of moderate air quality is the greatest in the fall in Wuhu. The most frequent primary air pollutant changed from particulate matter ($PM_{2.5}$) to gaseous species (O_3 and NO_2) during moderate air quality days, and the primary air pollutant was $PM_{2.5}$ during polluted days. The air quality status in the fall in Bengbu is similar to that in Wuhu, with the difference being the occurrence of heavily polluted days with $PM_{2.5}$ as the primary air pollutant. In the winter in Wuhu, the fraction of good air quality days has decreased; those of moderate air quality have increased, and those of heavily polluted air quality have improved. $PM_{2.5}$ was the typical primary air pollutant, followed by NO_2, and PM_{10} occurred occasionally. The change in the air quality status in Bengbu winter was opposite to that in Wuhu, where the typical primary air pollutant was $PM_{2.5}$, followed by PM_{10}, and NO_2, which occurred occasionally. Furthermore, the situation in which O_3 was the primary air pollutant, did not occur in either Wuhu and Bengbu in winter.

CONCLUSION

The results of this study on atmospheric deposition in Wuhu and Bengbu can be summarized as follows:

1. The PM_{10} concentrations in the focal three years in Wuhu were between 39 and 151 μg m^{-3}, with an average of 82 μg m^{-3}. For Bengbu, the figures were 55 to 144 μg m^{-3}, with an average of 95 μg m^{-3}. The PM_{10} level in Bengbu was higher than that in Wuhu. In general, the seasonal variations in the PM_{10} concentration in the summer in Wuhu (54 μg m^{-3}) were 50.5% lower than that in the

winter (109 μg m^{-3}), and the values in Bengbu in summer (68 μg m^{-3}) were 43.4% lower than those in winter (120 μg m^{-3}).

2. The fluctuation in the average SO_2 concentrations in the three-year period were 2.80–10.9 ppb in Wuhu and 4.20–11.9 ppb in Bengbu, for which the corresponding mean values were 6.54 and 7.88 ppb, respectively. The results indicated that SO_2 rarely presents a serious impact on the air quality of the two cities.
3. During the three-year period, the average concentrations of NO_2 were 9.30–38.5 ppb, with an average of 21.4 ppb in Wuhu and were 11.2–30.2 ppb, with an average of 18.0 ppb in Bengbu. Comparing the values from 2015 with those from 2017, the annual NO_2 concentration rose by 24.5% and 15.0% in Wuhu and Bengbu, respectively. Generally, the NO_2 concentrations in fall and winter were higher than the values in the spring and summer. NO_2 should be considered an important air pollutant and efficient vehicle emission control measures should be implemented to enhance the efforts aimed at improving the air quality in these cities.
4. During the observed three-year period, the mean CO concentration ranged between 0. 532 and 1.21 ppm in Wuhu and between 0.465 and 1.16 ppm in Bengbu, for which the corresponding mean values were 0.831 and 0.720 ppm, respectively. The CO concentrations are lower than the WHO air quality regulated standard of 8.00 ppm, indicating that CO never presents a serious impact on the air quality of the two cities. CO always reached the maximum level in the cold season and achieved the minimum level in the warm season, while the values were very similar in spring and fall, where both were at intermediate levels.
5. The three-year mean O_3 concentrations fluctuated between 13.5 and 77.4 ppb, with an average of 35.9 ppb in Wuhu, and ranged between 23.8 and 74.1 ppb, with an average of 44.7 ppb in Bengbu. The number of days exceeding the WHO air quality regulated standard (46.6 ppb) increased significantly, (0 d in 2015, 82 d in 2016, and 149 d in 2017 in Wuhu and 130 d in 2015, 139 d in 2016, and 183 d in 2017 in Bengbu). O_3 pollution has grown rapidly and is thus a serious challenge in the efforts to improve the air quality in the two cities.
6. In the spring in Wuhu, without heavy pollution events, the number of days at good or moderate levels have declined. $PM_{2.5}$ is the most frequent primary pollutant, while the days in which O_3 is a primary pollutant have increased significantly. In the spring in Bengbu, the air quality worsens gradually and the primary pollutant is similar to that of Wuhu, while the primary pollutant is PM_{10} during heavily polluted days.
7. In summer, the air quality mainly is at good or moderate levels but has deteriorated annually, which is clearly related to the increasing O_3 pollution. Hence, taking proper actions to control O_3 is an urgent concern.
8. The fraction of good air quality has increased, and the level of moderate air quality is dominant in the fall in Wuhu, where the most frequent primary air pollutant changes from particulate matter ($PM_{2.5}$) to gaseous species (O_3 and NO_2) during moderate air quality days, and the primary air pollutant is $PM_{2.5}$ during polluted days. The air quality status in the fall in Bengbu is similar to that in Wuhu, where the difference is the occurrence of heavily polluted days with $PM_{2.5}$ as the primary air pollutant.
9. In the winter in Wuhu, the fraction of good air condition decreased, moderate air quality increased, and heavily polluted air quality improved. $PM_{2.5}$ was the typical primary air pollutant, followed by NO_2, and PM_{10}, which occurred for a few days. The change in the air quality status in Bengbu winter was opposite to that of Wuhu, where the typical primary air pollutant was $PM_{2.5}$, followed by PM_{10}, and NO_2, which occurred for a few days. Furthermore, O_3 as a primary air pollutant did not occur in winter in either Wuhu and Bengbu.
10. The results of this study provide useful information for the establishment of air pollution control strategies and for the future studies of scientific communities.

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