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Original article

Characteristics of haze weather in Chongqing, China and its determinants analysis based on automatic monitoring stations

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ABSTRACT

Statistical analyses were carried out on the characteristics of haze weather and their relation with air quality and meteorological factors using data recorded by the national air quality and meteorological monitoring network of Chongqing, China in 2013. The results showed that the hourly occurrence rate of haze in Chongqing was 81.3% and that 67.2% of the total number of haze hours was at the level of mild to light haze. Haze was more likely to occur in autumn and winter (67.2% of the total number of hours; occurrence rate 97.5%) and was more likely to occur between 22:00 and 10:00. Haze mainly occurred when the wind speed was $<1.2 \text{ m s}^{-1}$ and the relative humidity was $>50\%$. Haze rarely occurred when the wind speed was $>3.0 \text{ m s}^{-1}$ and the relative humidity was $<30\%$. There was a positive correlation between temperature and visibility. The occurrence rate was higher with positive variations in the 24-h temperature records. The main factor affecting haze was the level of $\text{PM}_{2.5}$ pollution. Haze mainly occurred when $\rho(\text{PM}_{2.5})$ was between 35 and $250 \mu\text{g m}^{-3}$, accounting for 86.4% of the total number of hours of haze. When $\rho(\text{PM}_{2.5})$ was $>75 \mu\text{g m}^{-3}$, the occurrence rate of haze was 100.0%. The mean value of $\rho(\text{PM}_{2.5})/\rho(\text{PM}_{10})$ during the hours of haze was 72.9%, 17.7% higher than that at other times. The number of hours with air pollution accounted for 48.8% of the total number of hours, far less than the occurrence of haze. When the ambient air quality was excellent or good, haze was present in 65.4% of hours. We suggest that there are differences between the assessment of air quality and the definition of haze used in China. The relationship between haze and air quality would be better matched if we used the World Meteorological Organization's definition of haze (visibility $< 5.0 \text{ km}$).

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1. Introduction

Haze is an atmospheric phenomenon in which dust, smoke and other dry particles obscure the clarity of the sky (China Meteorological Administration, 2010). It has been shown that haze weather reduces visibility and affects road traffic safety

(Hassan and Abdel-Aty, 2011). In addition, inhalation of the substances present in haze often causes adverse effects on the respiratory and circulatory systems of the human population (Nel, 2005), leading to an increased risk of death, high rates of admission to hospital and increased levels of unexpected infant mortality during the weather conditions that contribute to haze (Thach et al., 2010; Ge et al., 2011; Guttikunda and Goel, 2013; Liu et al., 2014; Othman et al., 2014; Gao et al., 2015). The reduction in the number of hours of sunshine caused by haze also affects the growth of crops (Moran et al., 2014). Many studies have been carried out on the haze weather, including the changing trends in the occurrence of haze (Husar et al., 2000; Ghim et al., 2005; Wu et al., 2013; Hand et al., 2014), the temporal and spatial distribution of haze (Wang

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et al., 2006; Wu et al., 2009, 2012; Zhao et al., 2011; Tian et al., 2014), the cause of haze (Sansuddin et al., 2011; Zhi et al., 2014), the source characteristics of the aerosol particles present in haze (Norela et al., 2013; Sun et al., 2013) and the distribution of these particles (Kang et al., 2013; Lin et al., 2014). These studies have mainly focused on process analysis techniques (Cheng et al., 2013; Sun et al., 2013) and the data used were obtained from manual monitoring or satellite. Automatic online monitoring provides continuous data about meteorological conditions and has many advantages for the analysis of long time series of data. However, there have been few published reports on haze weather conditions using automatic monitoring data (Chen et al., 2010).

The Beijing–Tianjin–Hebei region, the Yangtze River Delta area, the Pearl River Delta region and the Sichuan Basin are the four areas in China recognized as having a high incidence of haze (Wu et al., 2009). Much detailed research has been published on haze in the Beijing–Tianjin–Hebei region, the Yangtze River Delta area and the Pearl River Delta region (Wang et al., 2006; Wu et al., 2009, 2012; Zhao et al., 2011; Cheng et al., 2013; Sun et al., 2013; Lin et al., 2014; Tian et al., 2014). However, few studies of haze have been carried out in the Sichuan Basin. The characteristics of the haze phenomenon in the Sichuan Basin are different from other regions as a result of specific geographical, climatic conditions and industrial structure (Dai et al., 2013). A study of the haze phenomenon and the mechanisms involved in haze formation in the Sichuan Basin would therefore enrich related research and help our understanding of regional differences in the production of haze.

Chongqing city is one of the four municipalities directly under the control of the central government of China and is the most important city in the Sichuan Basin. In this work, we used the automatic monitoring data recorded for the meteorological conditions and amount of gaseous pollutants in Chongqing in 2013. The characteristics of the haze phenomena and the factors influencing the formation of haze were analyzed to provide a case study of haze and a scientific basis for the control of haze pollution. As a particular air pollution type, haze is an objective reflection of air pollution to people's sense. However, haze and air pollution have independent judgmental standards. Then it occurred that heavy air pollution days may be judged as no haze phenomena while haze days may be judged as good air quality. Influence of $PM_{2.5}$ on haze was most focused on in previous studies, while their judgment agreement was rarely concerned. Taking Chongqing city as an example, this study analyzed the relation of haze and air pollution based on the haze characteristics, so as to make the judgment of air quality reach an agreement resulting from haze and air pollution.

2. Methodology and sources of data

2.1. Methodology

The accepted criteria used for the definition of haze are an hourly/daily visibility of <10.0 km and a relative humidity $\leq 90.0\%$ (China Meteorological Administration, 2010; Wu et al., 2013). The hours/days of haze weather influenced by precipitation, sandstorms and snowstorms are excluded. The precipitation data available from the Chinese meteorological data sharing service network are the daily precipitation; hourly precipitation data are not available. Daily precipitation data were not analyzed for the days with obvious precipitation (daily precipitation ≥ 1.0 mm). According to the Chinese national industrial standard of *observation and forecasting levels of haze* (China Meteorological Administration, 2010), the severity of haze can be divided into four levels based on visibility: severe haze (visibility < 2.0 km); moderate haze ($2.0 \text{ km} \leq \text{visibility} < 3.0 \text{ km}$); mild haze

($3.0 \text{ km} \leq \text{visibility} < 5.0 \text{ km}$); and slight haze ($5.0 \text{ km} \leq \text{visibility} < 10.0 \text{ km}$).

The main basis of air quality assessment in China is the *Technical Regulations on Ambient Air Quality Index (AQI) (on trial)* (HJ 633-2012) (Ministry of Environmental Protection of the People's Republic of China, 2012b). However, because the results of this assessment do not always reflect the changing situation with respect to air quality, the Chinese Environmental Monitoring Center modified the calculation method to give an hourly AQI. The hourly AQI is calculated according to adjusted calculation methods, whereas the daily AQI is calculated according to the original regulations (Ministry of Environmental Protection of the People's Republic of China, 2012b).

The hourly AQI is calculated by the following method: Hourly concentrations of PM_{10} , $PM_{2.5}$, SO_2 , NO_2 , CO and O_3 are subdivided into seven classes, which correspond to seven AQI classes (Table 1). Air Quality Index for pollution x (AQI_x) is calculated by

$$AQI_x = \frac{AQI_{x_up} - AQI_{x_low}}{C_{x_up} - C_{x_low}} \times (C_x - C_{x_low}) + AQI_{x_low} \quad (1)$$

where C_x is the hourly concentration of air pollutant x ; C_{x_up} and C_{x_low} are the upper and lower thresholds of the concentration ranges for the air pollutant x , respectively; AQI_{x_up} and AQI_{x_low} are the AQI_x values corresponding to C_{x_up} and C_{x_low} .

Then, the hourly AQI is calculated by

$$AQI = \max(AQI_x) \quad (x = 1, 2, \dots, 6) \quad (2)$$

The calculation of daily AQI is similar to that of the hourly AQI but with a different classification table (Table 2).

2.2. Data sources and processing

In this study, hourly concentrations of six air pollutants (PM_{10} , $PM_{2.5}$, SO_2 , NO_2 , O_3 and CO) and six meteorological factors (visibility, temperature, relative humidity, wind speed, wind direction and air pressure) at Lijia air quality monitoring site (106.6° E, 29.6° N) in Chongqing during 2013 were used. The Lijia air quality monitoring site is a state site from China National Ambient Air Quality Monitoring Network. It is not in the immediate vicinity of traffic intersections or major industrial polluters, and is sufficiently distant from any other emission sources. Thus, the monitoring data reflect the general urban air pollution level and meteorological conditions in Chongqing. Because the national ambient air quality monitoring sites are not equipped with rain gauges, we used precipitation data from the Shapingba meteorological observation station in Chongqing (coordinates: 106.3° E, 29.4° N), part of the Chinese meteorological data sharing service network (<http://cdc.cma.gov.cn/home.do>) operated by National Meteorological Information Center. Missing data were replaced or supplemented with monitoring data from adjacent sites through an interpolation method. The environment monitoring was implemented according to the related Chinese environmental protection standards (Ministry of Environmental Protection of the People's Republic of China, 2005) and weather data monitoring according to those meteorological standards (China Meteorological Administration, 2007a, 2007b, 2007c, 2007d). The statistical analysis and outliers determination of the sample data were according to the national standards.

China National Environmental Monitoring Center is the official environmental monitoring agency of Ministry of Environmental Protection of The People's Republic of China. National Meteorological Information Center is the official data released agency. The two agencies owed strict and integral data quality control and

Table 1Assignment of hourly AQI_x and air pollution specific hourly concentration.

AQI _x value	PM ₁₀ (μg m ⁻³)	PM _{2.5} (μg m ⁻³)	SO ₂ (μg m ⁻³)	NO ₂ (μg m ⁻³)	CO (mg m ⁻³)	O ₃ (μg m ⁻³)	Classification
0–50	0–50	0–35	0–150	0–100	0–5.0	0–160	Excellent
51–100	51–150	36–75	151–500	101–200	5.1–10	161–200	Good
101–150	151–250	76–115	501–650	201–700	10.1–35	201–300	Slight pollution
151–200	251–350	116–150	651–800	701–1200	35.1–60	301–400	Moderate pollution
201–300	351–420	151–250		1201–2340	60.1–90	401–800	Severe pollution
301–400	421–500	251–350		2341–3090	90.1–120	801–1000	Serious pollution
401–500	501–600	351–500		3091–3840	120.1–150	1001–1200	

AQI_x will not be calculated if the concentration of pollutant *x* is larger than the maximum value of *x* in the table. It is then denoted as AQI_x > 500 (or AQI_x > 200 for SO₂).

Table 2Assignment of daily AQI_x and air pollution specific daily concentration.

AQI _x value	PM ₁₀ (μg m ⁻³)	PM _{2.5} (μg m ⁻³)	SO ₂ (μg m ⁻³)	NO ₂ (μg m ⁻³)	CO (mg m ⁻³)	O ₃ ^a (μg m ⁻³)	Classification
0–50	0–50	0–35	0–50	0–40	0–2	0–100	Excellent
51–100	51–150	36–75	51–150	41–80	2.1–4	101–160	Good
101–150	151–250	76–115	151–475	81–180	4.1–14	161–215	Slight pollution
151–200	251–350	116–150	476–800	181–280	14.1–24	216–265	Moderate pollution
201–300	351–420	151–250	801–1600	281–565	24.1–36	266–800	Severe pollution
301–400	421–500	251–350	1601–2100	566–750	36.1–48		Serious pollution
401–500	501–600	351–500	2001–2620	751–940	48.1–60		

AQI_x will not be calculated if the concentration of pollutant *x* is larger than the maximum value of *x* in the table. It is then denoted as AQI_x > 500 (or AQI_x > 300 for O₃).

^a The maximum value of all 8-h moving average concentrations.

quality assurance measures and the released data were the most authoritative.

3. Results

3.1. Statistical analysis of haze weather

In 2013, the total number of days of haze weather in Chongqing was 301 (7224 h), excluding days with precipitation or sandstorms. Haze occurred on 247 days (5872 h) (Fig. 1), i.e. on 82.1% of the monitored days and 81.3% of the monitored hours.

Previous data have shown that the frequency of occurrence of haze on non-precipitation days was 21.2% in Beijing, 15.9% in Shanghai, 24.7% in Guangzhou and 57.0% in Chengdu in 2009 (Dai et al., 2013), 67.2% in Suzhou between June 2009 and May 2010 (Zheng et al., 2013), and 47% in Xi'an in 2012 (Kang et al., 2013). The frequency of occurrence of haze in Chongqing in 2013 was therefore higher than in the other cities.

We mainly used hourly data for haze in our analysis because, as a result of statistical ratios, the hourly occurrence frequency of haze (81.3%) is almost the same as the daily occurrence frequency of haze (82.1%). Daily data were only used in the analysis of the relationship between haze and the AQI.

Haze occurred in Chongqing in every month of 2013. However, the ratio of the occurrence of haze varied from month to month and plotted as a “U” shape. More than 500 h of haze occurred between January/March and September/December and the occurrence ratio was >90.0%. The haze occurred more in winter (December–February) and autumn (September–November) than in summer (June–August). Haze occurred most often and with the highest occurrence ratio in winter. A total of 32.3% of the annual occurrence of haze was in winter and the ratio of haze occurrence reached 99.9%. The occurrence of haze in autumn was 27.9% of the annual occurrence of haze and the occurrence ratio was 94.8%. The occurrence of haze in spring (25.0%) was similar to that in autumn, but the occurrence ratio (82.6%) was slightly lower. The lowest occurrence of haze was in summer, although the occurrence ratio was 47.8%.

The haze weather in Chongqing was mainly classified as slight or mild haze, accounting for 37.2% and 30.0% of the annual occurrence of haze, respectively. Moderate and severe haze accounted for 19.0% and 13.8% of the total, respectively. Severe haze mainly occurred in winter, with an occurrence ratio of 78.5% of the total hours of severe haze.

Haze occurred least in the afternoon to early evening (13:00–19:00 h) (Fig. 2). Haze frequently occurred from 22:00 to 10:00 h. However, the frequency of occurrence of haze in Chongqing city was >80.0%. The maximum number of hours of haze was 259 in 9:00, while the minimum number of hours of haze was 226 in 15:00, 16:00 and 17:00. However, the difference is rather small.

In the 301 days of effective monitoring over the whole year, there were only 14 days without any haze. More than 80.0% of the total days had a visibility of <10.0 km for more than half of the day. There were 187 days with 24 h of haze (Table 3).

3.2. Comparison of haze weather and non-haze weather

Through calculating the meteorological and pollution factors in the hours with and without haze, it was found that there was a significant difference in pollution during haze and non-haze weather. The increase in pollution during haze weather was usually >30.0%. Among the pollutants measured, $\rho(\text{PM}_{10})$ and $\rho(\text{PM}_{2.5})$ varied the most and both values increased by more than 100% during haze weather. $\rho(\text{O}_3)$ was the only factor with an obviously decreased concentration during haze weather. The variations in the meteorological factors such as wind speed, temperature and relative humidity during haze weather were similar to each other (Table 4). Atmospheric pressure only slightly increased during haze weather, showing that it has little effect on the haze phenomena.

3.3. Analysis of meteorological factors during haze weather

3.3.1. Wind velocity and wind vector

Wind, convection and turbulence are the most direct factors that determine the diffusion of pollutants in the atmosphere. Under certain conditions of atmospheric turbulence, higher wind speeds

Fig. 1. Land use and distribution of research site in Chongqing.

Fig. 2. Monthly data for hours of haze weather and proportion of hours in which haze occurred in Chongqing in 2013.

Table 3

Number of days with different haze hours per day in Chongqing in 2013.

Number of hours of haze per day/h	Total number of days/d
0	14
1–6	17
7–12	21
13–18	31
19–23	31
24	187

are more favorable for the transport and diffusion of atmospheric pollutants. Such conditions are less favorable for the formation of haze. Haze mainly occurred in Chongqing in 2013 when the wind velocity was $<2.0 \text{ m s}^{-1}$ and, in particular, when the wind speed was $<1.2 \text{ m s}^{-1}$ (Fig. 3); below this wind velocity, the number of hours of haze accounted for 74.4% of the total. The occurrence ratio for haze showed an obvious negative relationship with wind velocity. The occurrence frequency for haze showed a downwards

Table 4

Comparison of meteorological indices and concentrations of gaseous pollutants during haze and non-haze weather in Chongqing in 2013.

Index	Haze weather ^a	Non-haze weather ^b	Variation during haze weather (%) ^c
Visibility (km)	4.6	13.5	−65.9
Wind speed (m s^{-1})	1.0	1.5	−33.3
Temperature ($^{\circ}\text{C}$)	18.3	29.2	−37.3
Air pressure (kPa)	97.2	96.3	1.0
Relative humidity (%)	65.6	48.9	34.2
$\rho(\text{SO}_2)$ ($\mu\text{g m}^{-3}$)	36	25	43.0
$\rho(\text{NO}_2)$ ($\mu\text{g m}^{-3}$)	49	36	35.3
$\rho(\text{PM}_{10})$ ($\mu\text{g m}^{-3}$)	129	64	102.6
$\rho(\text{PM}_{2.5})$ ($\mu\text{g m}^{-3}$)	93	38	147.6
$\rho(\text{CO})$ ($\mu\text{g m}^{-3}$)	1.12	0.67	67.5
$\rho(\text{O}_3)$ ($\mu\text{g m}^{-3}$)	36	82	−56.6
$\rho(\text{PM}_{2.5})/\rho(\text{PM}_{10})$	72.9%	61.7%	18.2

Note: $c = (a - b)/b$. **Fig. 3.** Total hours of haze for each hour of the day in Chongqing in 2013.

linear trend with increasing wind velocity. Haze almost always occurred when the wind velocity was $<0.3 \text{ m s}^{-1}$. The occurrence frequency for haze was $>90.0\%$ when the wind velocity was $<1.2 \text{ m s}^{-1}$ and decreased to 40% when the wind velocity was $>3.0 \text{ m s}^{-1}$. This shows that the wind conditions on the ground are important factors in the formation of haze.

Haze occurred when the dominant wind direction on the ground in Chongqing was to the south, the southeast and south southwest (Fig. 4). The frequency of haze for these three wind directions was 41.1% of the total number of hours of haze. This is slightly higher than the 39.6% frequency of wind from these three

wind directions. The occurrence frequency of severe haze was highest for these three wind directions, with an average of 17.1%, much higher than the average frequency of severe haze (12.2%).

3.3.2. Relative humidity

$\text{PM}_{2.5}$ is the most important factor in haze formation, however, relative humidity also have an effect on haze. Previous studies indicated that moisture absorption of aerosol increased with relative humidity increasing, and then lead to the extinction and scattering ability of the aerosol to increase, and further resulted in the visibility of the atmosphere reducing (Day and Malm, 2001; Malm and Day, 2001; Qu et al., 2015). Otherwise, relative humidity showed positive relation with the aerosol concentration (Howell et al., 2006). Relative humidity increase will further aggravate air pollution, while the aerosol was the most important factor in haze formation. So the higher humidity is conducive to the haze formation. Especially in the heavy fog weather, the impact may be even greater than that from the aerosol particles (Yao et al., 2014). Studies have shown that relative humidity and visibility are negatively correlated, especially when the relative humidity is $>80.0\%$, and that the visibility decreases in a geometric series (Tian et al., 2014). Our results further support this argument (Table 5). The correlation coefficient for relative humidity and visibility is -5.4×10^{-1} ($p < 0.01$) in Chongqing. When the relative humidity was $<30.0\%$, less haze occurred; however, when the relative humidity increased to 50.0%, the occurrence frequency of haze increased to about 80.0%. Haze mainly appeared between 50.0% and 90.0% relative humidity and this range accounted for 81.2% of the number of hours of haze.

3.3.3. Temperature

Temperature is another important factor affecting visibility. The higher the surface ground temperature, the more dramatic of the air convection and particle's Brown movement. So, the more violent air convection and particle's Brown movement are conducive to atmospheric dispersion and reduction of particulate matter concentration of surface near ground, when the atmosphere temperature is high. When the atmosphere temperature is low, the particulate matter concentration is higher and the visibility is worse, and then it is prone to result in the haze weather (Tsang et al., 1988). The average daily visibility showed a strong positive correlation with the daily maximum and minimum temperatures in Chongqing (Fig. 5). The Spearman rank correlation coefficients of visibility and daily maximum and minimum temperatures were 6.9×10^{-1} and 7.0×10^{-1} ($p < 0.01$), respectively. The correlation coefficient of visibility and the average daily temperature was 7.1×10^{-1} ($p < 0.01$). The correlation between visibility and instantaneous temperature (6.6×10^{-1}) showed a weak correlation ($p < 0.01$). There is a reciprocal causation relationship between

Fig. 4. Number of hours of haze at different wind velocities in Chongqing in 2013.

Table 5

Haze conditions at different values of relative humidity in Chongqing in 2013.

Relative humidity (%)	Number of hours of haze/h	Number of hours monitored/h	Proportion of hours with haze (%)
0–10.0	0	0	–
10.1–20.0	2	8	25.0
20.1–30.0	54	134	40.3
30.1–40.0	345	671	51.4
40.1–50.0	703	1072	65.6
50.1–60.0	1066	1342	79.4
60.1–70.0	1135	1297	87.5
70.1–80.0	1252	1345	93.1
80.1–90.0	1315	1355	97.0

Fig. 5. Number of hours of haze in Chongqing in 2013 during different wind vector.

surface temperature and haze. On one side, haze weather can be easily formed when the temperature is low. On the other side, since haze decrease visibility and solar radiation, it can decrease the temperature (Takemura et al., 2005; Zhang et al., 2010).

To eliminate the influence of seasonal temperature differences on haze, we studied the effect of 24-h temperature changes on haze (Table 6). In general, positive 24-h temperature changes often indicate stable synoptic situation. It is beneficial to accumulate the pollution. At the same time, temperature increase in short time can increase the particulate matter's hygroscopicity and decrease the atmospheric visibility, and it then forms haze. On the contrary, negative 24-h temperature changes often mean changes in synoptic situation and there is usually air mass transit. It is conducive to pollution dilution and diffusion, which thereby reducing haze occurrence probability. As a result of the scavenging effect of pollutants, the frequency occurrence of haze was lower when the 24-h temperature changes were negative than when the 24-h temperature changes were positive.

Table 6Haze condition in different ΔT_{24} in Chongqing in 2013.

24 h Temperature change ($^{\circ}\text{C}$)	Number of haze days	Total number of days	Proportion of days with haze (%)
>0	107	120	89.2
0	11	14	78.6
<0	129	167	77.2

3.4. Analysis of effect of pollutants on haze

3.4.1. Air quality

Meteorological factors are external causes of the formation of haze weather; air pollutants are internal causes (Wu et al., 2009) and are the material basis of haze formation. Table 7 gives the occurrence of haze and the corresponding air quality grade in Chongqing in 2013. The number of hours of polluted air accounted for 48.8% of the total number of hours of haze, far less than the proportion for the occurrence of haze (81.3%). The occurrence frequency for haze was more than 96.5% when the air quality reached pollution grade. When the air quality was severe or serious, haze was always present, and severe haze occurred most often. However, when the ambient air quality was excellent or good, haze was still present in 65.4% of the monitoring hours; 41.2% of the total number of haze hours was evaluated as having excellent or good air quality.

To quantitatively analyze the relationship between visibility and the AQI, a scatter diagram was plotted using the daily average visibility and the AQI (Fig. 6). The visibility decreased rapidly with a power exponent with increasing values of the AQI. The regression equation of the goodness of fit was 65.1%.

The relation between air quality and visibility was calculated using the regression equation with different degrees of haze. When the visibility was >10.0 km, the AQI was <56 and the air quality was excellent; when the visibility was between 5 and 10 km, the AQI was between 56 and 107 and the air quality was good; and when the visibility was between 3 and 5 km, the AQI was between 107 and 170 and the air quality showed slight to moderate pollution. Thus from the relationship between haze and air quality in Chongqing, the haze judgment standard showed a slightly serious degree of air pollution.

Based on the 2008 criteria of the World Meteorological Organization (World Meteorological Organization, 2008), the significant characteristic of haze is that the visibility is ≤ 5.0 km. Only conditions of mild haze or above were judged as haze according to the standards used in China and the WMO criteria were obviously less stringent than our current standards. According to the WMO standards, the occurrence ratio for haze would decrease from 81.3% to 51.4% in Chongqing in 2013. This ratio is closer to the ratio of the air quality pollution (48.8%) and therefore the relationship between haze and air quality would be better matched.

Table 7

Haze conditions for different grades of air quality in Chongqing in 2013.

Air quality grade	No haze (h)	Slight haze (h)	Mild haze (h)	Moderate haze (h)	Severe haze (h)	Proportion of hours with haze (%)
Excellent	345	188	67	21	2	44.6
Good	937	1369	575	148	49	69.6
Slight pollution	68	581	819	392	111	96.5
Moderate pollution	2	40	252	368	119	99.7
Severe pollution	0	7	47	188	510	100.0
Serious pollution	0	0	0	0	19	100.0

Fig. 6. Trend of daily visibility and minimum and maximum temperatures using a five-day moving average in Chongqing in 2013.

3.4.2. Particulate matter

In our total 5872 h of haze, 79.4% of the hours had $PM_{2.5}$ as the primary pollutant. It implied that the $PM_{2.5}$ pollution was the most serious, and the multiple exceeding the standard was the greatest. The multiple exceeding the standard equals to the contaminant concentration divided by its standard limit minus one. The hours with PM_{10} as the primary pollutant accounted for 16.2% of the total. The hours with both $PM_{2.5}$ and PM_{10} as the primary pollutants accounted for 2.0% of the total number of hours. In total, the hours with particulate matter as the primary pollutant accounted for 97.7% among hours with haze weather. The correlation coefficient between the hourly visibility and the hourly $\rho(PM_{2.5})$ was -6.8×10^{-1} . This is the highest for all the meteorological and pollution factors. The correlation coefficient between the hourly visibility and $\rho(PM_{10})$ was -6.0×10^{-1} , which is just less than that between the $\rho(PM_{2.5})$ and relative humidity. Thus particulate matter, especially $PM_{2.5}$, is the main pollution factor in haze weather.

Through analyzing the distribution of $PM_{2.5}$ concentrations when haze occurred, we found that haze mainly occurred when

$35 \mu g m^{-3} < \rho(PM_{2.5}) < 250 \mu g m^{-3}$ (Fig. 7). This occurrence accounted for 86.4% of the total number of hours of haze. The haze occurrence frequency was 100% when $\rho(PM_{2.5}) > 75 \mu g m^{-3}$. Severe haze mainly occurred when $\rho(PM_{2.5}) > 150 \mu g m^{-3}$. The percentage of this occurrence accounted for 63% of the total occurrence of severe haze. The arithmetic mean of $\rho(PM_{2.5})$ was calculated for haze under different degrees of pollution. $\rho(PM_{2.5})$ increased linearly with the occurrence and aggravation of haze. For mild haze, $\rho(PM_{2.5})$ exceeded the second standard limit of the daily average specified in the *Ambient Air Quality Standard* (GB 3095-2012) (Ministry of Environmental Protection of the People's Republic of China, 2012a).

Effects of particulate matter on atmospheric extinction coefficient mainly reflect in scattering and adsorption on the visible light of different particle size and components of the aerosol particles. While particles with size $0.25\text{--}1.0 \mu m$ cover the visible wavelength range and contribute most to its scattering efficiency to the visible light and to the extinction coefficient of the visible light. This is why $PM_{2.5}$ has an important influence on the visibility and haze.

3.4.3. Ratio of $\rho(PM_{2.5})$ and $\rho(PM_{10})$

The average ratio of $\rho(PM_{2.5})$ and $\rho(PM_{10})$ in the air in Chongqing during haze was 70.8%. The ratio during hours of haze was 72.9%, 17.7% higher than in non-haze hours. When the haze was mild or above, the $\rho(PM_{2.5})/\rho(PM_{10})$ was higher than the annual mean. When severe haze occurred, the ratio further increased to 83.1% and was 33.9% higher than in non-haze hours (Fig. 8).

The analysis of $\rho(PM_{2.5})/\rho(PM_{10})$ shows that: (1) the mean of the $\rho(PM_{2.5})/\rho(PM_{10})$ ratio for haze hours was 72.9% and 78.2% of this ratio was $>60.0\%$ and that the mean of this ratio in non-haze hours was 61.7% and only 52.3% of this ratio was $>60.0\%$; and (2) the $\rho(PM_{2.5})/\rho(PM_{10})$ ratio increased when $\rho(PM_{2.5})$ increased. The correlation coefficient was 4.2×10^{-1} (Figs. 9 and 10).

4. Discussion

The frequency of haze occurrence in Chongqing city was relatively higher. The most likely reasons are as follows. (1) The

Fig. 7. Scatter diagram for daily visibility and daily AQI in Chongqing in 2013. **Fig. 8.** Concentration of $PM_{2.5}$ under different levels of haze in Chongqing in 2013.

Fig. 9. Concentration ratio of $\text{PM}_{2.5}$ and PM_{10} under different levels of haze in Chongqing in 2013.

Fig. 10. Scatter diagram for concentration of $\text{PM}_{2.5}$ and PM_{10} during (a) haze weather and (b) non-haze weather in Chongqing in 2013.

particular climatic conditions of the Sichuan Basin mean that Chongqing is situated in a region more favorable for the formation of haze weather. The Sichuan Basin, where the Chongqing city is located, is the most important industrial base in southwest China. Air pollution is rather heavy there. It is surrounded by mountains with low wind speed and stable atmospheric stratification. It is easy to appear temperature inversion and static wind, which is not conducive to the spread of atmospheric aerosols. So the haze appears frequently in the region. According to the existing research

(Wu et al., 2013), the frequencies of haze occurrence in Chongqing city were just after Shenyang and Xingtai city during 1951–2005. (2) In 2013, haze occurred more frequently due to the extreme deterioration of the national environmental quality. $\text{PM}_{2.5}$ was the major cause of haze weather. Chongqing city began to carry out regular online monitoring of $\text{PM}_{2.5}$ since 2013. The rate of over standards for daily mean of $\text{PM}_{2.5}$ was 47.2% in Lijia monitoring site in 2013, while that was just 31.6% in 2014. (3) From the time series, the missing data were mainly those in spring and summer. While haze occurred least during the two seasons, thus the missing data would lead to raise the frequency of haze occurrence. The effective sample size of this article was 301 days with 64 days missing due to days of precipitation eliminated and certain period of power off and data without uploading. 48 days (75.0%) of the missing days occurred in Month 4–9, while the average occurrence frequency of haze in Month 4–9 was 34.0% lower than that in the other months. (4) The meteorological conditions in Chongqing in 2013 were favorable for the formation of haze weather. The winter precipitation was 40.0% below the average and the annual precipitation was similar to that in previous years, although there was a higher frequency of rainstorms. The average temperature was 1.0 °C higher throughout the year and the weather in spring and summer was the second hottest on record, behind only 2006.

The haze occurrence frequency was higher in our study, but it was not much different compared with previous researches. According to the existing research (Wu et al., 2013), the annual haze days remained at about 300 days and thus haze occurrence frequency was 80% in Chongqing city. The observation results of China Meteorological Bureau showed that haze occurred most in 2013 since 1961 (Ministry of Environmental Protection of the People's Republic of China, 2014).

Stratification of the boundary layer is an important meteorological factor affecting the $\text{PM}_{2.5}$ concentration and further the haze. Mixing layer height is the major factor to explain hourly variation trend (Fig. 2) of haze pollution. But it is a pity that we could only get the publicly released data by the meteorological department, while the meteorological department has not released boundary layer height data, due to a smooth data sharing channels has not been established between Chinese environmental protection departments and the meteorological department.

5. Conclusions

- As a result of its geographical location and particular meteorological and pollution conditions, the occurrence of haze was high in Chongqing in 2013 and the haze occurrence ratio reached 81.3%. Haze occurred most often in winter and autumn, accounting for more than 60.0% of the frequency of the annual occurrence of haze and the occurrence frequency was >90.0%.
- With respect to the haze-related meteorological factors, the visibility had a positive correlation with the wind velocity and temperature and a negative correlation with the relative humidity. Haze appeared in Chongqing when wind velocity was $<1.2 \text{ m s}^{-1}$ and the relative humidity was $>50.0\%$. Haze rarely occurred when the wind velocity was $>3 \text{ m s}^{-1}$ and the relative humidity was $>30.0\%$. When the 24-h temperature changes were positive, haze occurred more frequently and the visibility and temperature were positively correlated.
- Particulates, especially $\text{PM}_{2.5}$, are the primary pollution factors in haze. The correlation coefficient of $\text{PM}_{2.5}$ and visibility was the highest of all the meteorological and pollution factors. Haze appeared in Chongqing mainly when $\rho(\text{PM}_{2.5}) > 35 \mu\text{g m}^{-3}$. The occurrence frequency for haze was 100% when $\rho(\text{PM}_{2.5}) > 75 \mu\text{g m}^{-3}$.

4. The $\rho(\text{PM}_{2.5})/\rho(\text{PM}_{10})$ ratio increased with increasing haze. The mean of the $\rho(\text{PM}_{2.5})/\rho(\text{PM}_{10})$ ratio for haze hours was 72.9% and 78.2% of this ratio was >60.0%. The mean ratio in non-haze hours was 61.7% and only 52.3% of this ratio was >0.6.
5. The results of the air quality evaluation showed an almost positive correlation with the appearance of haze. However, when the air quality was evaluated as excellent or good, 65.4% hours were still classified as haze. Through the fitting of the curve for visibility and AQI, we found that the visibility was correlated with excellent or good air quality when the visibility was >5.0 km. Therefore the appearance of haze would be better matched with air quality if the haze standard set by the WMO was used.

Conflicts of interests

All authors declare they have no conflict of interest to disclose in the context of this study.

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