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Variations in PM₁₀, PM_{2.5} and PM_{1.0} in an Urban Area of the Sichuan Basin and Their Relation to Meteorological Factors

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Abstract: Daily average monitoring data for PM₁₀, PM_{2.5} and PM_{1.0} and meteorological parameters at Chengdu from 2009 to 2011 are analyzed using statistical methods to replicate the effect of urban air pollution in Chengdu metropolitan region of the Sichuan Basin. The temporal distribution of, and correlation between, PM₁₀, PM_{2.5} and PM_{1.0} particles are analyzed. Additionally, the relationships between particulate matter (PM) and certain meteorological parameters are studied. The results show that variations in the average mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0} generally have the same V-shaped distributions (except for April), with peak/trough values for PM average mass concentrations appearing in January/September, respectively. From 2009 to 2011, the inter-annual average mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0} fall year on year. The correlation coefficients of daily concentrations of PM₁₀ with PM_{2.5}, PM₁₀ with PM_{1.0}, and PM_{2.5} with PM_{1.0} were high, reaching 0.91, 0.83 and 0.98, respectively. In addition, the average ratios of PM_{2.5}/PM₁₀, PM_{1.0}/PM₁₀ and PM_{1.0}/PM_{2.5} were 85%, 78% and 92%, respectively. From this, fine PM is determined to be the principal pollutant in the Chengdu region. Except for averaged air pressure values, negative correlations exist between other meteorological parameters and PM. Temperature and air pressure influenced the transport and accumulation of PM by

affecting convection. Winds promoted PM dispersion. Precipitation not only accelerated the deposition of wet PM, but also inhibited surface dust transport. There was an obvious correlation between PM and visibility; the most important cause of visibility degradation was due to the light extinction of aerosol particles.

Keywords: PM₁₀; PM_{2.5}; PM_{1.0}; meteorological parameters; Sichuan Basin

1. Introduction

Atmospheric particulate matter (PM) consists of minuscule particles of solid or liquid matter, with diameters ranging from 0.001 μm to 100 μm . The time for which PM is suspended in the atmosphere ranges from a few hours to a few weeks. The smaller a particle is, the longer it will stay in the air. Atmospheric particles can affect the climate by both direct and indirect radiative forcing [1], and serve as cloud condensation or ice nuclei modifying the microphysical characters of clouds [2,3]. Atmospheric PM concentrations exceeding guidelines may cause poor visibility [4,5] and induce the regional hazy weather frequently seen in China [6–8]. In addition, fine particles also damage respiratory and cardiovascular health, and even DNA [9].

There is a nationwide research focus on PM as the principal pollutant in China, including its physical, chemical and optical properties [10–12]. Most studies have focused on northern China [13–15], the Yangtze River delta [16,17], and the Pearl River delta [18]. As a measure of this concern, the latest ambient air quality standards published in 2012 (GB3095–2012) gave PM_{2.5} values for the first time [19].

The Sichuan Basin is located east of the Tibetan Plateau, with the Qin Mountains to the north and the Yunnan-Guizhou Plateau to the south. Due to the particular topography of the basin, average wind speeds in Sichuan are low. Sichuan is a wet, foggy area and mass concentrations of atmospheric particles are therefore always high there [20,21]. The 2009–2011 Environmental Conditions Bulletin (Sichuan Environment Condition Communique) [22–24] from 2009 to 2011 issued by the Department of Environmental Protection of Sichuan Province showed that the average mass concentration of inhalable particles (PM₁₀) in Sichuan was greater than 60 $\mu\text{g}/\text{m}^3$ for each of these three years. Although these values were in the second highest national pollution band, they do not fully reflect the PM levels resulting from the rapid economic development that has occurred in Sichuan over recent years.

Chengdu, in the central Sichuan Plain, is the provincial capital of Sichuan. Its present development and future economic trajectory is ideal for representing PM pollution in the Sichuan Basin [25–27]. The Chengdu Environmental Quality Gazette (2009, 2010, 2011, 2012) [28–31] shows that mean annual concentrations of inhalable particles (PM₁₀) in Chengdu exceeded 100 $\mu\text{g}/\text{m}^3$, and that daily rates exceeded the set standards by more than 14% (more than 24% regarding to the latest standards issued in 2012). Tao *et al.* [32] found that average mass concentrations of PM_{2.5} reached 165 $\mu\text{g}/\text{m}^3$ from April 2009 to January 2010 at the Chengdu Institute of Plateau Meteorology. Based on the average daily monitored data for PM₁₀, PM_{2.5} and PM_{1.0} at Mt. Chengdu from January 2009 to December 2011, this paper analyzes the correlations between PM₁₀, PM_{2.5} and PM_{1.0} and their temporal distribution characteristics. Additionally, the relations between PM and meteorological factors are studied. The results of this study could be used as a reference point for analyzing the pollution sources and

composition of atmospheric particulates in urban areas of the Sichuan Basin as well as formulating measures to counteract them. Subsequent observations of variations in mass concentrations of atmospheric PM could then highlight any deficiencies in pollution control.

2. Methodology

PM₁₀, PM_{2.5} and PM_{1.0} data were collected from a building rooftop next to the Chengdu City Meteorological Bureau (104°02'E, 30°39'N; 587.0 m), 91 m above the ground, from 2009 to 2011. The PM monitoring station is located in the west urban area of Chengdu city. Aerosol samples collected from a 91 m-tall building. There are few factories around. The sampling height is above the urban canopy without much local pollution disturbance. Thus the sampling could be representative the pollution level of Chengdu region. Chengdu region belongs to the subtropical monsoon climate. The average annual temperature is around 16.5 degrees centigrade with an average annual rainfall of 1124.6 mm. The wind speed is low with the average annual wind speed is 1–1.5 m/s. The annual sunshine averages 1042–1412 h. The data were measured using a Grimm-180 device (German online PM monitor). This instrument uses an optical method to measure PM concentration of PM₁₀, PM_{2.5}, and PM_{1.0}. The measuring range is 1–1500 µg/m³ with an accuracy of ±2%. The instrument monitored for 24 h at a time, and transferred data once every five minutes. The measuring principle of Grimm-180 is the scattering light measurement of the single particles, where a semiconductor laser serves as light source. The 90° scattered light with an opening angle of about 60° is being lead via a mirror onto a receiver diode. When particles cross the laser beam they emit a light pulse. This electric signal of the diode will be classified into 31 different size channels after an adequate amplification. This enables a size determination of the particles and establishes also a weighting curve for PM₁₀ and PM_{2.5}. The sample air is being volume controlled sucked through the optical measurement chamber and a fine filter. The pump also provides the rinsing air, which is generated via the pumps exhaust air and a subsequent fine filter. It is being held constant by a rinsing air controller. The rinsing air prevents the laser optics and measurement chamber from pollution and furthermore being used as particle-free reference air during the self-test. During the January 2009 to December 2011 period, 833 valid samples were acquired (excluding calibration instrument failures, missing data, abnormal data and instrument calibration times). The meteorological data, from the Chengdu Meteorology Observatory (104°01'E, 30°40'N; 507.3 m), included daily wind speed, air pressure, temperature, precipitation, relative humidity (RH) and visibility from 2009 to 2011. The Chengdu Meteorology Observatory is located in the west suburban region of Chengdu. And it is surrounded by the farmland and 15 km west from the PM monitoring station. Chengdu Meteorology Observatory is a national principal station and the observations are used to present the meteorological features of Chengdu region.

A linear correlation method was used to analyze the correlation between PM₁₀ and PM_{2.5}, and between PM₁₀ and PM_{1.0}. The total average concentrations of these three particle sizes were calculated using the sum of their daily average mass concentrations divided by the sum of valid days.

3. Results and Discussion

3.1. Monthly, Seasonal and Inter-Annual Variations in Mass Concentrations of PM₁₀, PM_{2.5} and PM_{1.0}

Variations in the monthly, seasonal and inter-annual average mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0} are shown in Figure 1. Figure 1a presents the monthly average mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0}. Trends for these three PM sizes are similar, presenting a concave parabolic shape for January to April, and April to December. Peak monthly values for average mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0} appeared in January, reaching 118 $\mu\text{g}/\text{m}^3$, 101 $\mu\text{g}/\text{m}^3$ and 93 $\mu\text{g}/\text{m}^3$, respectively. The lowest values were in September and reached 45 $\mu\text{g}/\text{m}^3$, 42 $\mu\text{g}/\text{m}^3$ and 39 $\mu\text{g}/\text{m}^3$, respectively. The highest monthly average concentrations were 2.64 times (PM₁₀), 2.42 times (PM_{2.5}) and 2.37 (PM_{1.0}) times the lowest monthly average concentrations, respectively. Concentrations of PM_{2.5} in December and January significantly exceeded daily average PM₁₀ and PM_{2.5} concentrations by 150 $\mu\text{g}/\text{m}^3$ and 75 $\mu\text{g}/\text{m}^3$ as defined by the ambient air quality standard GB3095-2012, indicating PM_{2.5} pollution in the Chengdu urban area is severe during the winter.

Figure 1b shows clear variations in the seasonal average mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0}. The seasons were demarcated as spring (March to May), summer (June to August), fall (September to November) and winter (December to February). Seasonal variations evidenced a concave parabola shape. PM₁₀, PM_{2.5} and PM_{1.0} maxima appeared in winter, reaching 98 $\mu\text{g}/\text{m}^3$, 83 $\mu\text{g}/\text{m}^3$ and 77 $\mu\text{g}/\text{m}^3$, respectively. Minimum PM₁₀, PM_{2.5} and PM_{1.0} values of 49 $\mu\text{g}/\text{m}^3$, 43 $\mu\text{g}/\text{m}^3$ and 40 $\mu\text{g}/\text{m}^3$, respectively, occurred during the summer.

The higher concentrations of PM₁₀, PM_{2.5} and PM_{1.0} in December and January are probably related to geographic factors. Tao *et al.* [25] showed that the higher PM concentrations during winter in Sichuan Basin are due to the lower mixing height and low wind speeds. Additionally, the sampling point was located at a busy city intersection with high levels of vehicle exhaust emissions: Chen *et al.* [33] states that lower wet particulate deposition is the major cause of pollution in winter. PM concentrations increased in the spring, most likely because Chengdu is occasionally affected by northerly sand and dust storms. Due to the larger size of dust particles, PM₁₀ concentrations increased significantly, contrary to fine PM concentrations. In the summer there are more intensive convective air currents and more rainfall, so PM is more effectively removed, leading to minimum PM concentrations. The mixing ventilation coefficient is larger, so contaminant dispersion is rapid. In addition, rainwater aids the removal of coarse particles, but has less effect on fine particles [34]. This could account for PM_{2.5} concentrations being higher in summer. In September, atmospheric RH decreases and the hygroscopic growth of particles is correspondingly inhibited, a contributory factor for the minimum PM concentration. Conversely, owing to the influence of fall rain in West China after September, atmospheric RH increases and the hygroscopic growth of particles is strengthened, leading to a recovery in mass concentration values for all three PM sizes [35].

Figure 1c shows that the annual average mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0} declined significantly from 2009 to 2011. This could be attributed to the efficacy of pollution control measures introduced in Chengdu, such as limiting the number of cars on the road, closing the worst-polluting factories and banning straw-burning [32].

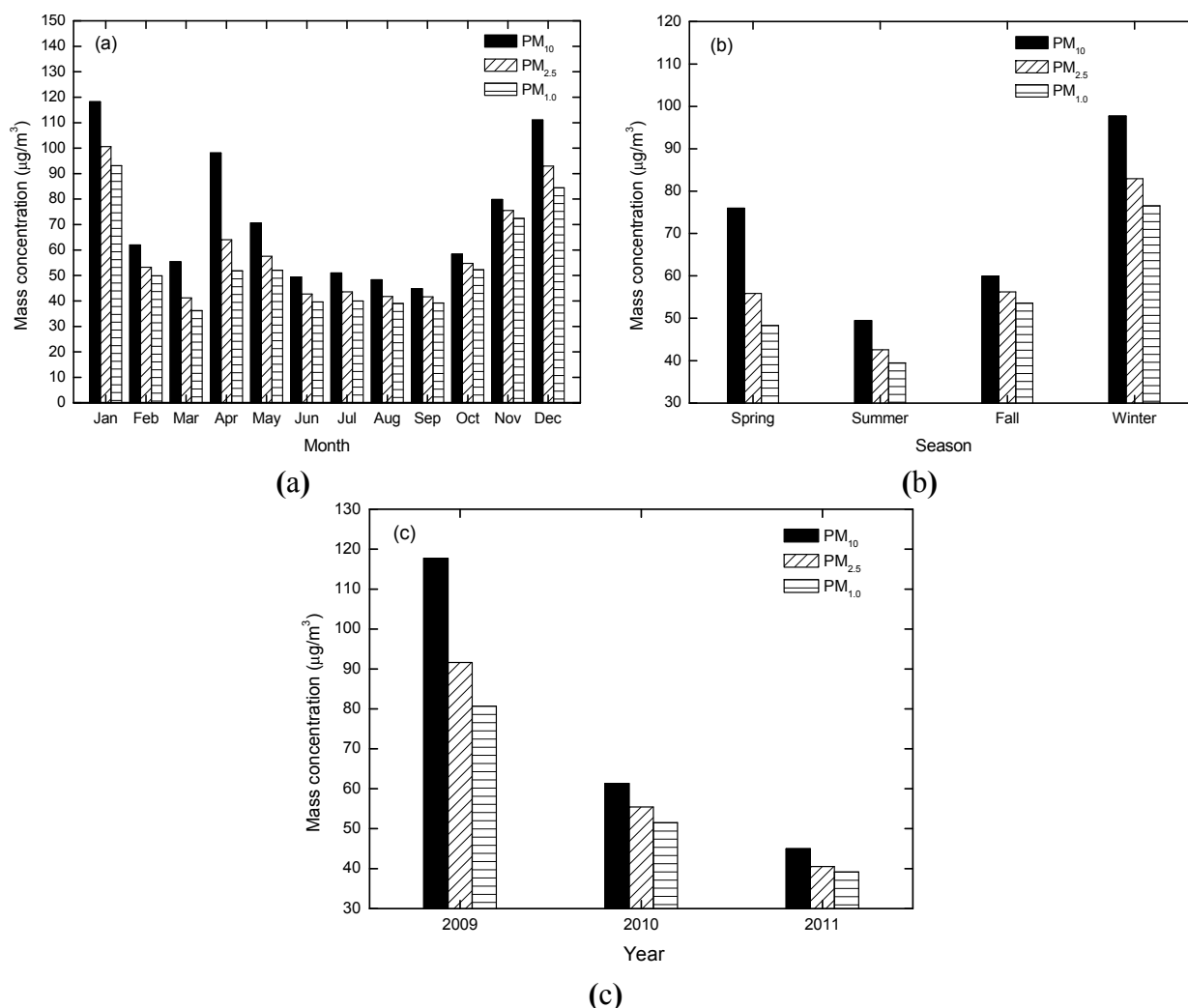


Figure 1. Monthly (a), seasonal (b) and inter-annual (c) average mass concentration variations of PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ values.

3.2. Relations between PM_{10} , $PM_{2.5}$ and $PM_{1.0}$

The relations between PM_{10} and $PM_{2.5}$, PM_{10} and $PM_{1.0}$, and $PM_{2.5}$ and $PM_{1.0}$ are shown in Figure 2a–c, respectively. The correlation coefficients between them were 0.92, 0.84 and 0.98, meaning the correlations between PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ were significant. This result is consistent with previous findings by Deng *et al.* [36]. The ratios of $PM_{2.5}$ to PM_{10} , $PM_{1.0}$ to PM_{10} , and $PM_{1.0}$ to $PM_{2.5}$ are illustrated in Figure 3. The average $PM_{2.5}/PM_{10}$, $PM_{1.0}/PM_{10}$ and $PM_{1.0}/PM_{2.5}$ values were 85%, 78% and 92%, respectively, and ranged between 74%–94%, 64%–89% and 87%–95%, respectively. The proportions of $PM_{2.5}$ contained within PM_{10} were quite high, further proving that fine particles were the greatest contributor to PM air pollution in Chengdu. The average $PM_{2.5}/PM_{10}$ and $PM_{1.0}/PM_{10}$ ratios were 72% and 61% in spring, lower than in other seasons. Northerly dust and sandstorms may be a possible cause.

3.3. The Relation between Concentrations of PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ and Meteorological Factors

Previous studies have indicated that atmospheric particle pollution is influenced by both the emissions of particles and meteorological factors [37–39]. When particle emissions in urban areas are stable,

atmospheric PM pollution is principally caused by meteorological factors, such as the dispersion and transport by wind, and an acceleration of the scavenging by precipitation, of atmospheric PM. Additionally, photochemical reactions depend upon favorable temperature, RH, solar radiation and other conditions. The accumulation and transport of particles is closely related to the synoptic system and atmospheric circulation.

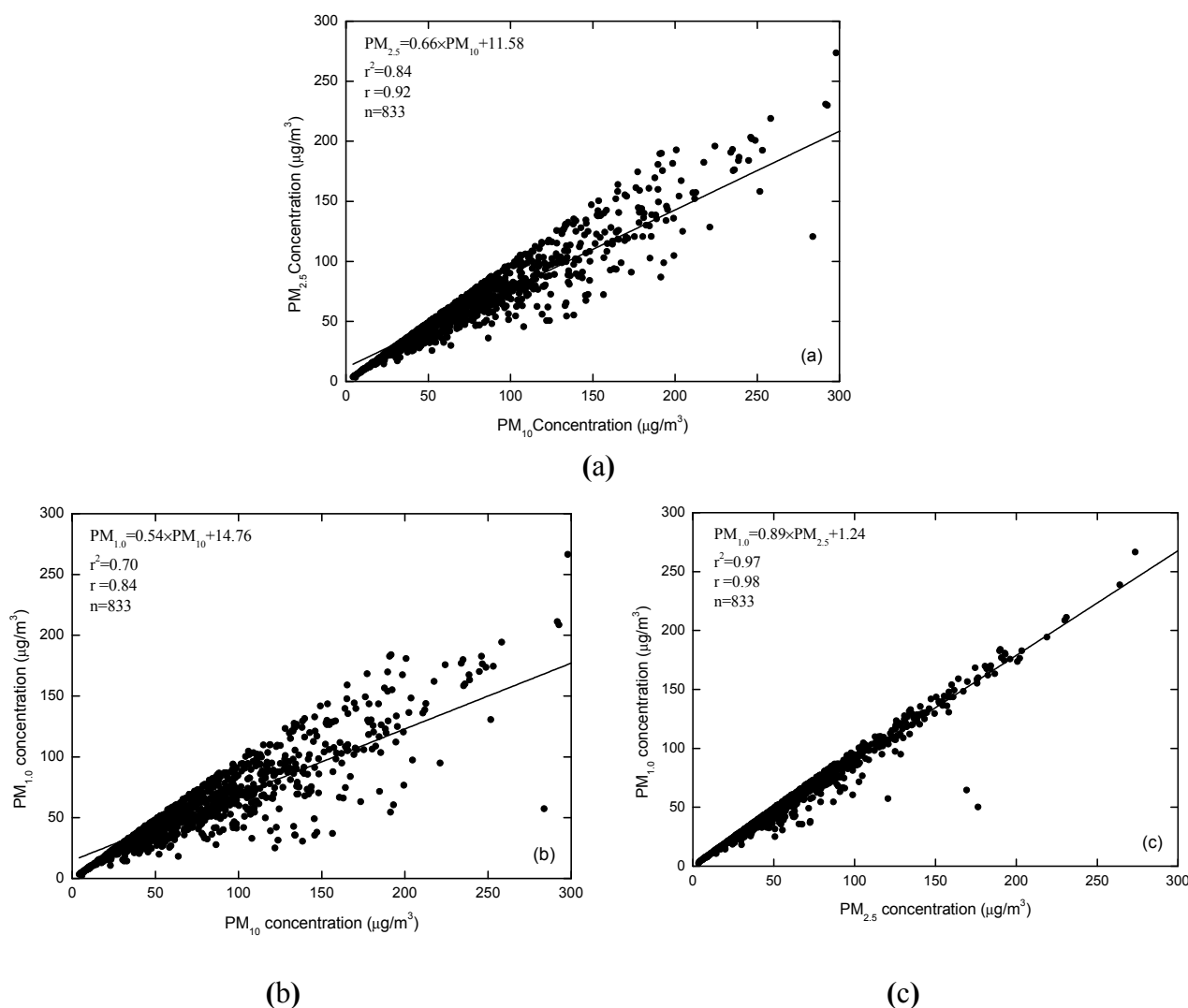


Figure 2. Correlation between average mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0}:
(a) PM₁₀ vs. PM_{2.5}, (b) PM₁₀ vs. PM_{1.0}, (c) PM_{2.5} vs. PM_{1.0}.

Table 1 shows that mass concentration of atmospheric PM has a positive relation with air pressure and negative relations with other meteorological factors. The relation between mass concentration of atmospheric PM and visibility is the clearest. The correlations between meteorological factors of air pressure, temperature, precipitation and atmospheric PM pollution are also obvious. However, the correlations between wind speed, RH and PM concentration are not a simple linear one. For example, RH displays no clear correlation with PM concentration.

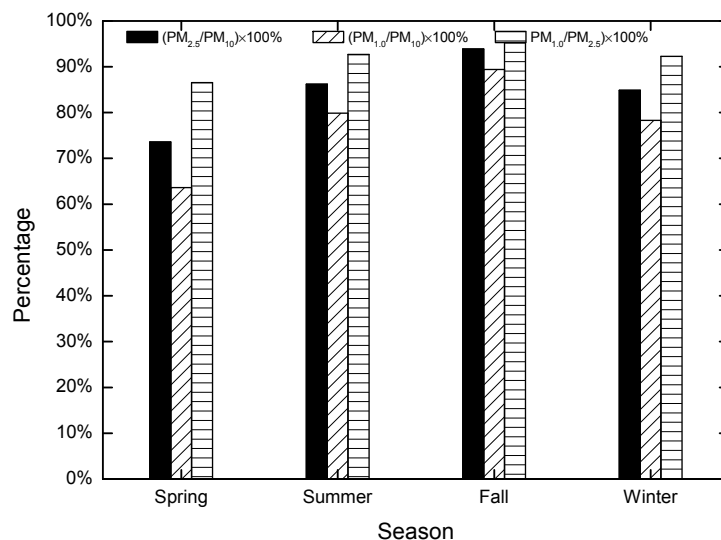


Figure 3. PM_{2.5}/PM₁₀; PM_{1.0}/PM_{2.5}; and PM₁₀/PM_{2.5} ratios.

Table 1. Correlation coefficients between mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0} and average meteorological factors: wind speed, air pressure, air temperature, precipitation, RH and visibility.

Correlation Coefficient	PM ₁₀	PM _{2.5}	PM _{1.0}
Average wind speed	−0.35	−0.56	−0.62 *
Average air pressure	0.71 *	0.77 **	0.77 **
Average air temperature	−0.73 **	−0.75 **	−0.75 **
Monthly precipitation	−0.59 *	−0.58 *	−0.57
Average RH	−0.25	−0.06	−0.00
Visibility	−0.75 **	−0.88 **	−0.91 **

The * means significance of $p < 0.05$, the ** means significance of $p < 0.01$.

As shown in Figure 4, the wind speed range in Chengdu was very small (0.8–1.4 m/s), thus, mass PM concentrations in the Chengdu urban area were high but changed little with wind speed. There was a negative correlation between wind speed and PM₁₀, PM_{2.5} and PM_{1.0}, with correlation coefficients of −0.35, −0.56 and −0.62, respectively (Table 1) in the Chengdu urban area. The correlation coefficients of the win speed with atmospheric PM follow the pattern PM_{1.0} > PM_{2.5} > PM₁₀. However, the correlation coefficients between wind speed and PM₁₀, PM_{2.5} were not significantly obvious with $p > 0.05$. But the coefficient between wind speed and PM_{1.0} showed clear correlation with $p < 0.05$.

As shown in Figure 5, air pressure values first decreased from January to July, then increased from July to December, showing an inverted parabolic distribution. Mass PM concentrations display a positive relation with air pressure, with significant correlation coefficients ($p < 0.05$) for PM₁₀, PM_{2.5} and PM_{1.0} of 0.71, 0.77 and 0.77, respectively. The surface experiences a convergence up draft when controlled by low pressure; the up draft promotes the dispersion of PM from the ground up into the air, and PM concentrations at the sampling point are subsequently reduced. Conversely, when there was high pressure, the down draft restrains the upward movement of PM, causing an accumulation of particles [40].

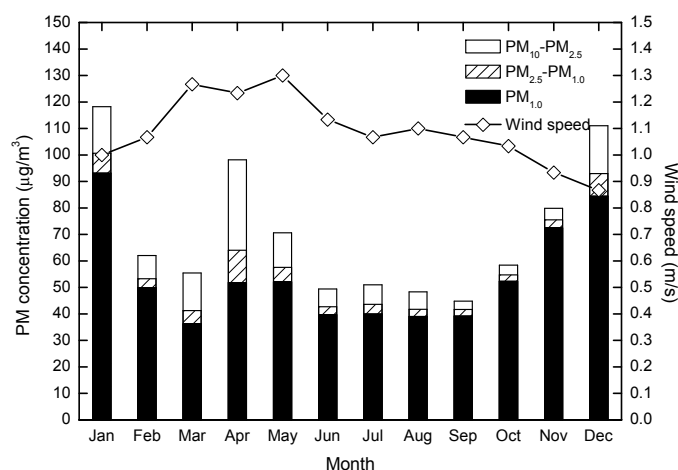


Figure 4. Variations in monthly mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0} related to average wind speed.

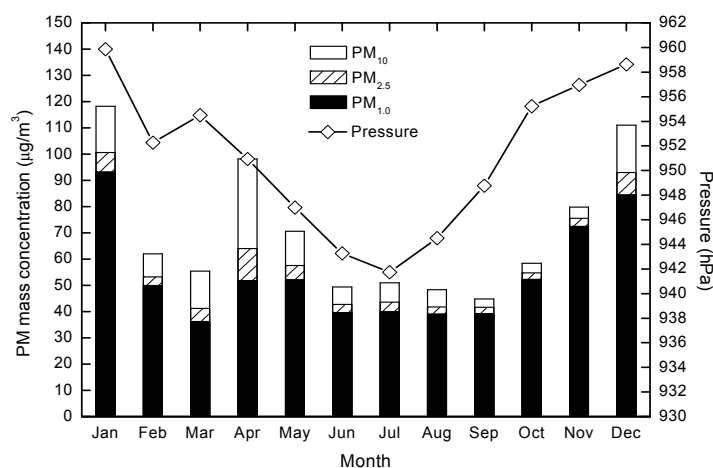


Figure 5. Variations in monthly mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0} related to air pressure.

Figure 6 clearly shows that there was a negative relation between the temperature and PM concentrations, with correlation coefficients ($p < 0.01$) of -0.73 , -0.75 and -0.75 for PM₁₀, PM_{2.5} and PM_{1.0}, respectively. High temperatures are clearly conducive to intense convection: Atmospheric PM is transported quickly and effectively, allowing its accelerated dispersion, and thus decreasing local mass concentrations. Conversely, low temperatures and the temperature inversion layer caused by radiative cooling weakens convection [41]; in these circumstances, atmospheric PM remains suspended under the inversion layer, leading to higher atmospheric PM concentrations.

Figure 7 shows that PM concentrations have a negative correlation with precipitation, especially in winter (January and December) and summer (July), with correlation coefficients of -0.59 ($p < 0.05$), -0.58 ($p < 0.05$), and -0.57 ($p > 0.05$), respectively. The influence of precipitation on atmospheric PM is twofold. First, the effect of the microphysical processes of raindrops upon PM, including adsorption and collision, lead to the wet deposition of PM. Second, after rainy weather dust and fugitive dust

previously suspended in the atmosphere is notably reduced, leading to a significant decrease in mass PM concentrations [42].

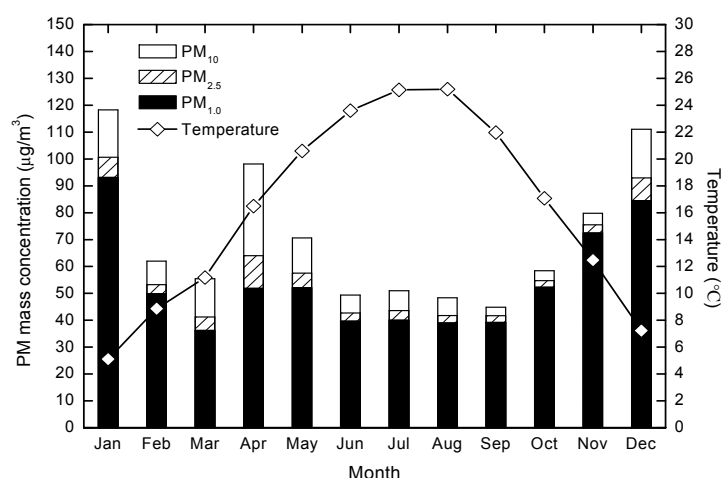


Figure 6. Variations in monthly mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0} related to temperature.

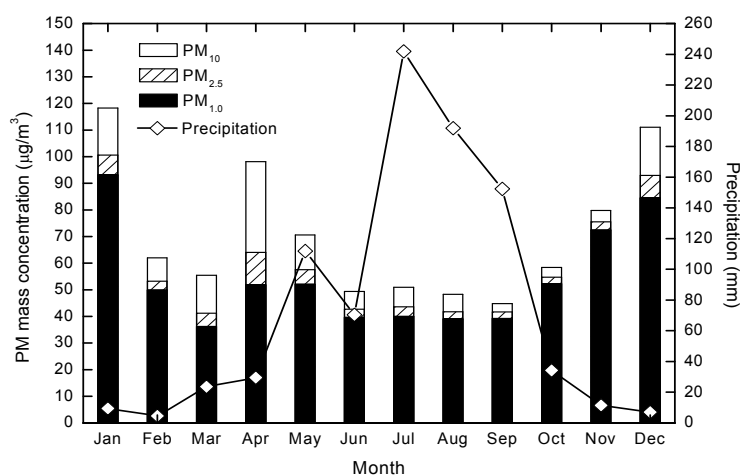


Figure 7. Variations in monthly mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0} related to precipitation.

The relation between concentrations of PM₁₀, PM_{2.5} and PM_{1.0} and RH are illustrated in Figure 8. It shows that RH in the Chengdu urban area was >70% all year round and that there were higher RH values in fall and summer than that in spring. There was no apparent correlation all year around. The correlation coefficients between RH and PM₁₀, PM_{2.5} and PM_{1.0} were less than −0.25. In late summer and early fall, RH values remained high, but because of the high temperatures, unstable atmosphere, intense convection and abundant rainfall, the dispersion of atmospheric PM, wet deposition and cloud condensation nuclei played a leading role. PM pollution, which was caused by the growth of hygroscopicity under high RH conditions, usually in the stable atmospheric strata, but also sometimes when there was a gentle breeze, or within the thermal inversion layer [43].

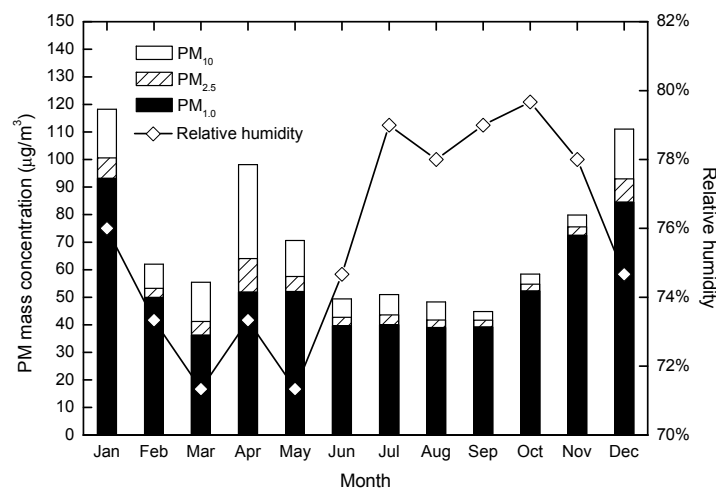


Figure 8. Variations in monthly mass concentrations of PM₁₀, PM_{2.5} and PM_{1.0} related to RH.

3.4. Relation between PM₁₀, PM_{2.5}, PM_{1.0} and Horizontal Visibility

There are various ways in which atmospheric visibility can be affected, such as through light scattering and absorption caused by high concentrations of fine particles and the sulfate, nitrate and carbonate matter attached to them [44,45]. In addition, particles experiencing hygroscopic growth affect light extinction through their impact on the atmosphere's particle scattering efficiency. Combining Figure 9 and Table 1, we see that horizontal visibility in the Chengdu urban area is generally low, ranging from 7.5 km in January to 11.0 km in August. There was a negative correlation between horizontal visibility and concentrations of PM₁₀, PM_{2.5} and PM_{1.0}, with significant correlation coefficients ($p < 0.01$) of -0.75 , -0.88 and -0.91 , respectively. When mass concentrations of these three PM sizes exceed $100 \mu\text{g}/\text{m}^3$, visibility is < 8.0 km; when concentrations are $< 40 \mu\text{g}/\text{m}^3$, visibility exceeds 11.0 km.

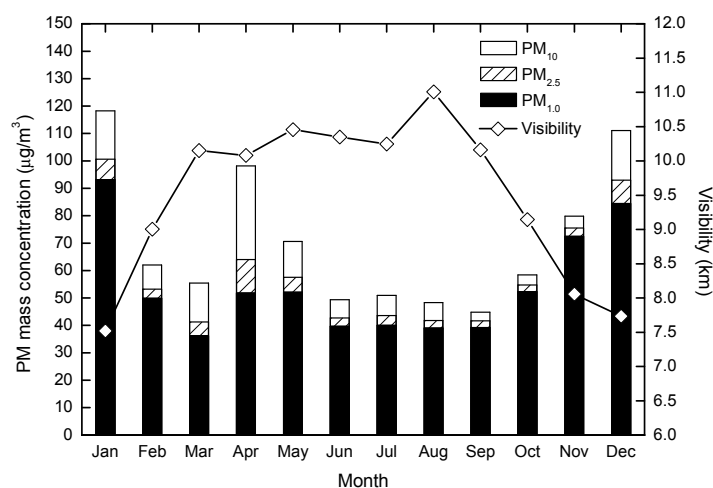


Figure 9. Variations in monthly mass concentrations of PM₁₀, PM_{2.5}, and PM_{1.0} related to horizontal visibility.

4. Conclusions

(1) Mass concentrations of PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ were higher in winter and lower in summer from 2009 to 2011 in the Chengdu urban area. Peak average mass concentrations of PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ appeared in January and were $118 \mu\text{g}/\text{m}^3$, $101 \mu\text{g}/\text{m}^3$ and $93 \mu\text{g}/\text{m}^3$ for 2009, 2010 and 2011, respectively. Minimum values occurred in September and were $45 \mu\text{g}/\text{m}^3$, $42 \mu\text{g}/\text{m}^3$ and $39 \mu\text{g}/\text{m}^3$ for 2009–2011, respectively. This shows an improvement in atmospheric PM pollution accompanied by annual falls in PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ concentrations.

(2) Analysis of the correlation between PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ shows that $PM_{10}/PM_{2.5}$, $PM_{10}/PM_{1.0}$ and $PM_{2.5}/PM_{1.0}$ mass concentration correlation coefficients were generally high, reaching 0.92, 0.84 and 0.98, respectively. In addition, $PM_{2.5}$ and $PM_{1.0}$ account for 66% and 54% of PM_{10} , respectively, and $PM_{1.0}$ to $PM_{2.5}$ mass loading reached 89%. This indicates that fine particles are the major contributor to PM air pollution, especially fine particles with an aerodynamic diameter $<1 \mu\text{m}$.

(3) Except for the relation with air pressure values, significant negative correlations existed between the other meteorological factors (e.g., temperature and precipitation) and PM. Temperature and air pressure influenced the transport and accumulation of PM through convection. Precipitation not only accelerated the wet deposition of PM, but also constricted the movement of surface dust. The correlation between RH and PM concentrations was not obvious. There was an obviously negative correlation between PM and visibility rates. Visibility degradation was primarily attributed to light extinction caused by PM.

This study makes a preliminary analysis of PM pollution and its relation to meteorological factors in Chengdu, representative of the Sichuan Basin urban area, relevant to improving local air quality. The results may support future policies directed at emissions control in China. However, there are still some limitations of the study. There is only one single site PM monitoring in this study because of the instruments limitation. More detailed observations, not only of PM mass concentrations but also of the chemical components and optical properties, from industrial areas, residential areas, and outlying suburbs of the Sichuan Basin are still needed to further study the PM pollution of this region. Also long term observations are needed to study the variation of aerosol in Sichuan Basin. In this study it just analyzed the relationship between the RH and PM basically. Actually, the RH has obvious effect on aerosol particle formation and conversion, more detailed works about the reaction of water vapor on aerosol particles at Sichuan Basin are needed in future.

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Author Contributions

Yang Li conceived and designed the experiment. The paper was written by Yang Li with a significant contribution by Quanliang Chen and Hujia Zhao. Lin Wang and Ran Tao analyzed the data and presented the results.

Conflicts of Interest

The authors declare no conflict of interest.

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