

Research Article

Effects of Rainfall on PM_{2.5} and PM₁₀ in the Middle Reaches of the Yangtze River

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Based on the PM_{2.5} and PM₁₀ mass concentration data obtained from 51 national air quality monitoring stations and the corresponding rainfall intensity data in automatic meteorological stations in Hubei Province from 1 January 2015 to 31 December 2017, the impact of rainfall intensity on PM mass concentrations under relatively different humidity conditions was analyzed. The results showed that light rain occurred most frequently in the pollution process, with Xiangyang being affected for up to 587 h. PM concentration would not change drastically under the effect of precipitation. Mean rainfall intensity responsible for wet growth of PM₁₀ and PM_{2.5} was mainly <0.5 mm/h, while that responsible for wet removal of PM_{2.5} was significantly higher (>1.4 mm/h) than that of PM₁₀ (>1.0 mm/h). Precipitation was more likely to produce a wet removal effect for a greater initial value of PM mass concentration, and on the contrary, a wet growth effect was more likely, with the threshold of PM₁₀ mass concentration being 150 $\mu\text{g}/\text{m}^3$ and that of PM_{2.5} mass concentration being 95 $\mu\text{g}/\text{m}^3$. Wet removal played a leading role in lower humidity (~60%) and greater rainfall intensity, but wet growth played a leading role in higher humidity (~90%) and lower rainfall intensity. As the precipitation level increased (rainfall $\geq 1.5 \text{ mm}\cdot\text{h}^{-1}$), the wet removal to PM₁₀ mass concentration was enhanced more obviously. The variations of PM_{2.5} had similar distributions to those of PM₁₀ under the effect of precipitation, but the wet removal effect of precipitation was weakened and the wet growth effect was enhanced.

1. Introduction

Atmospheric aerosols, the suspended systems of liquid or solid particles in the air, constitute an important part of the atmosphere [1–3] and are a key factor affecting environmental and climate change. Atmospheric pollution is a weather phenomenon caused by accumulation of atmospheric aerosols through local emissions and regional transmission [4–7]. The emission source intensity of atmospheric pollutants determines the atmospheric pollution degree, while meteorological conditions determine the outbreak, persistence, and elimination of pollution weather.

As a key meteorological element affecting pollutant concentration, precipitation dominates the process of wet removal in the atmosphere as one of the most important mechanisms in self-purification of the atmosphere [8]. Wet

removal of aerosol particles is the process in which particles eventually fall to the ground after being removed by atmospheric coagulants, mainly caused by Brownian diffusion and inertial collision [9]. However, the humidification effect of precipitation on the near ground significantly enhances the influence of hygroscopic growth on aerosols and accelerates formation of secondary aerosols, resulting in increased mass concentration [10]. The impact of precipitation on aerosols involves a quite complicated mechanism, which closely concerns not only the characteristics of precipitation intensity, rainfall, raindrop spectrum, and final velocity of raindrops [11, 12], but also the aerosol particle size, spectral distribution, and chemical composition [13, 14].

Research on wet removal of precipitation has mainly considered efficiency of precipitation in removing aerosol particles of different particle sizes in observational

experiments. Related studies have pointed out that precipitation mainly removes aerosol particles of size $<1\ \mu\text{m}$ and $2.5\text{--}10\ \mu\text{m}$ [15, 16], while those of $0.2\text{--}2\ \mu\text{m}$ are difficult to remove [17–19]. Precipitation intensity directly affects aerosol removal efficiency. Short-term heavy precipitation helps remove particles of diameter $<2.2\ \mu\text{m}$, but long-term weak precipitation facilitates removal of particles $>2.2\ \mu\text{m}$ [20]. In general, increased precipitation intensity will enhance its wet removal ability. Yao et al. [21] and Zhao and Zheng [22] further established a model on correlation between precipitation intensity and aerosol removal coefficient. At the same time, wet removal effect of precipitation also concerns initial concentration of aerosol before precipitation. For a higher initial concentration, the wet removal effect is more significant in the same context. Xu et al. [23] pointed out that, under $70\ \mu\text{g}/\text{m}^3$ in winter and $45\ \mu\text{g}/\text{m}^3$ in other seasons, the $\text{PM}_{2.5}$ mass concentration decreased in more than 80% of precipitation processes. Related research also shows that $\text{PM}_{2.5}$ mass concentration does not decrease but increases after precipitation in actual observations [24]. Yue et al. [25] demonstrated that processes with daily precipitation $<10\ \text{mm}$ produce a humidification effect significantly stronger than its wet removal effect on $\text{PM}_{2.5}$. The wet removal effect of precipitation is closely related to ambient humidity. The scouring coefficient of hygroscopic particles constitutes a function of relative humidity. To achieve the same removal effect, the precipitation intensity required for 50% ambient humidity is twice the intensity required for 95% ambient humidity [26, 27]. The rapid formation of secondary aerosols in high humidity and low wind-speed environments is the main reason for the increase of $\text{PM}_{2.5}$ mass concentration following precipitation [28, 29].

The Twain-Hu Basin (THB) with a special geographical location connecting the major haze pollution areas, represented by Hubei Province, is a hub of regional transport of atmospheric pollutants in China. As the development center of the Yangtze River Economic Belt and a city cluster in the middle reaches of the Yangtze River, the THB area has special “subbasin” topography, which promotes accumulation of atmospheric pollutants. In addition, there are quite developed water systems in the THB [30, 31]. In recent years, the level of atmospheric aerosols in this area has shown an upward trend [32]. The high humidity weather and high concentration pollution have significantly worsened regional visibility [33, 34], leading to gradual formation of a new core region of pollution.

The difference in rainfall intensity, variable humidity, and different pollution characteristics result in many uncertainties in the impact of precipitation on PM ($\text{PM}_{2.5}$ and PM_{10}), which is the main reason for errors in judgment of pollution levels with the occurrence of precipitation. Due to the lack of analysis on the correlation between large-area, long-term sequence precipitation and PM concentration, there is currently no quantitative understanding of the general laws and characteristics of precipitation effects on $\text{PM}_{2.5}$ and PM_{10} mass concentrations. In the middle reaches of the Yangtze River, some weather conditions during heavy pollution, such as low pressure with an inverted trough and a cold front, are often accompanied by precipitation [35].

Precipitation can occur during 70–80% of pollution events under the effects of cold fronts [36]. Therefore, it is necessary to analyze the variations of long-sequence precipitation and PM in combination with observation data, explore the distributions of rainfall intensity under different pollution conditions, summarize the variation of PM concentrations at the beginning and ending of precipitation hours under different humidity conditions, and determine the different effects of wet removal and wet growth on PM in the presence of precipitation. This will effectively improve the accuracy of aerosol concentration prediction during precipitation and enhance understanding of the variation mechanisms in pollution processes under high-impact weather.

2. Data and Methods

The $\text{PM}_{2.5}$ and PM_{10} mass concentration data were obtained from 51 national air quality monitoring stations (Figure 1) managed by Hubei Environmental Monitoring Central Station in Enshi (ES), Shiyan (SY), Xiangyang (XY), Jingmen (JM), Jingzhou (JZ), Yichang (YC), Suizhou (SZ), Xiaogan (XG), Wuhan (WH), Huanggang (HG), Ezhou (EZ), Huangshi (HS), and Xianning (XN) in Hubei Province. The data length was from 1 January 2015 to 31 December 2017. The time resolution is 1 h. The mass concentrations of $\text{PM}_{2.5}$ and PM_{10} were measured using β absorption and micro-oscillating balance methods. The observation equipment was regularly cleaned and calibrated according to the operational specifications, and observation data were subject to quality control to ensure accuracy and validity. Observational data were taken into account when effective data of $\text{PM}_{2.5}$ and PM_{10} exceeded 20 h in one day. At the same time, according to the standard of the Ministry of Environmental Protection (GB 3095-2012) [37], pollution weather was divided into light (LP), moderate (MP), severe (SP), and terrible pollution (TP), as shown in Table 1.

The collected data included precipitation, relative humidity, and wind speed. In order to match the precipitation and pollutant data more accurately, 2539 automatic meteorological stations in Hubei Province were used, which were maintained by Hubei Meteorological Information and Technology Support Center.

For the summer half-year, there is more local precipitation; for the winter half-year, regional precipitation is the main phenomenon. In order to ensure that when the meteorological automatic station observed precipitation, there was also occurrence of precipitation in the adjacent national air quality monitoring station, we adopted the following main principles: (1) priority selection of the automatic weather station closest to the national air quality monitoring station; (2) using the observation data of the next closest automatic weather station when the observations of the closest automatic weather station were missing. The time-space consistency could be guaranteed in meteorological and pollutant concentration data.

Because we mainly used hourly precipitation, rainfall intensity was classified into light rain (LR), moderate rain (MR), heavy rain (HR), torrential rain (TR), and downpour

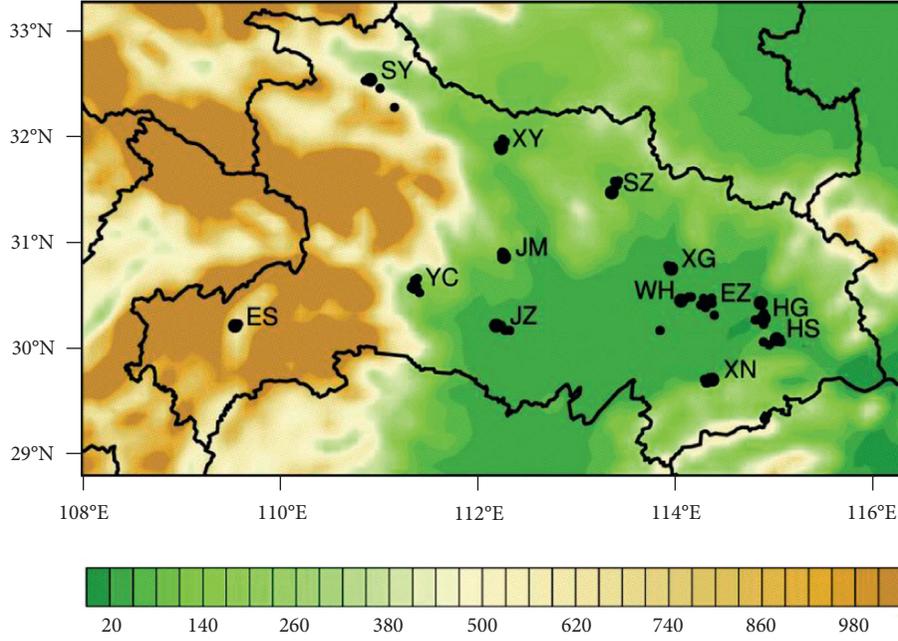


FIGURE 1: Distribution of 51 air quality monitoring stations in 13 cities of Hubei Province; note that the air quality monitoring sites are marked by black dots (unit: m).

TABLE 1: Grade classification of pollution weather.

Level		LP	MP	SP	TP
Concentration ($\mu\text{g}\cdot\text{m}^{-3}$)	PM_{10}	150–250	250–350	350–420	>420
	PM_{25}	75–115	115–150	150–250	>250

(SR) according to the local standard of neighboring province (DB 34/T 1592-2012) [38], as shown in Table 2.

We selected time periods with PM_{10} concentration $>150 \mu\text{g}/\text{m}^3$ or $\text{PM}_{2.5}$ concentration $>75 \mu\text{g}/\text{m}^3$. Some parameters were determined to explore the impact of precipitation on the change in PM concentration. $V_{\text{PM}_{2.5}}$, $V_{\text{PM}_{10}}$, and $C_{\text{PM}_{2.5}/\text{PM}_{10}}$ were determined according to (1)–(3), respectively:

$$V_{\text{PM}_{2.5}} = \frac{M_{\text{PM}_{2.5}}^{\text{end}} - M_{\text{PM}_{2.5}}^{\text{beg}}}{M_{\text{PM}_{2.5}}^{\text{beg}}}, \quad (1)$$

$$V_{\text{PM}_{10}} = \frac{M_{\text{PM}_{10}}^{\text{end}} - M_{\text{PM}_{10}}^{\text{beg}}}{M_{\text{PM}_{10}}^{\text{beg}}}, \quad (2)$$

$$C_{(\text{PM}_{2.5}/\text{PM}_{10})} = \frac{M_{\text{PM}_{25}}^{\text{end}}}{M_{\text{PM}_{10}}^{\text{end}}} - \frac{M_{\text{PM}_{25}}^{\text{beg}}}{M_{\text{PM}_{10}}^{\text{beg}}}, \quad (3)$$

where $M_{\text{PM}_{2.5}}^{\text{end}}$ and $M_{\text{PM}_{10}}^{\text{end}}$ are the $\text{PM}_{2.5}$ and PM_{10} mass concentrations at the end moment of the precipitation hour, respectively. $M_{\text{PM}_{2.5}}^{\text{beg}}$ and $M_{\text{PM}_{10}}^{\text{beg}}$ are the $\text{PM}_{2.5}$ and PM_{10} mass concentrations at the beginning moment of the precipitation hour, respectively. Some researchers term these the initial concentrations [16, 18]. Precipitation data when wind speed exceeded 3 m/s were eliminated to ensure a low wind-speed environment condition [23].

3. Results and Discussion

3.1. Distribution of Pollution Weather at Different Levels. Figure 2 shows the distribution of different-level pollution days in 13 regions of Hubei Province during 2015–2017. Judging from the total days with pollution weather, we found that the pollution weather was most frequent in XY and YC, reaching 335.3 and 304.1 d, respectively. Pollution weather occurs in one-third of days throughout the year in these two cities. These two cities are also typical representative areas affected by the transmission of an external pollution source and accumulation of a local pollution source. The heavy pollution weather in XY is often accompanied by a strong northerly wind and a weak inversion layer, whereas low wind speed and a multilayer inversion often occur in YC during heavy pollution weather [39, 40]. Pollution weather for ES, HG, SY, and XN occurred in less than 160 d, mainly located in the mountainous areas of Hubei Province, where pollution days were significantly lower than other areas.

LP days accounted for $>60\%$ of total pollution days, especially in areas with less pollution such as XN and HG where LP days represented $>80\%$ of the total pollution days, reaching >100 d. MP days mainly accounted for 18–23%, with differences of less than 30 d among regions. SP days were significantly fewer, representing about half of MP days. However, it is worth noting that XY and YC showed no obvious reduction in SP days. In particular, SP days in XY

TABLE 2: Grade classification of rainfall intensity.

Level	LR	MR	HR	TR	SR
Rainfall ($\text{mm}\cdot\text{h}^{-1}$)	$0 < R < 1.5$	$1.5 \leq R < 3.5$	$3.5 \leq R < 8.0$	$8.0 \leq R < 20$	$20 \leq R < 50$

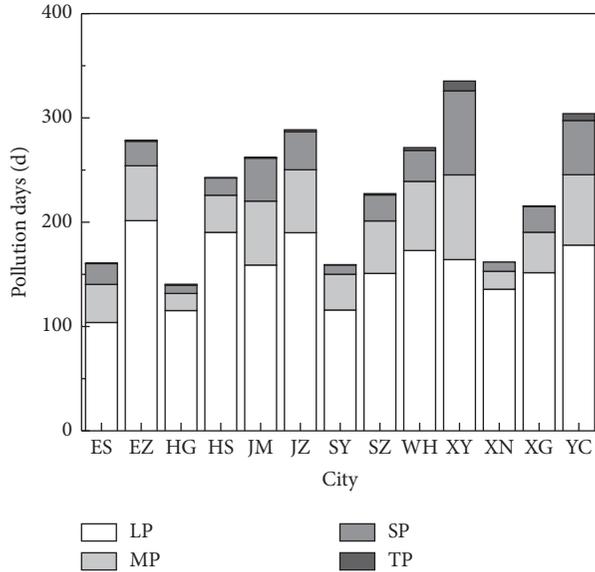


FIGURE 2: Distribution of different-level pollution days in 13 regions of Hubei Province during 2015–2017.

were similar to MP days, both about 80 d, which was about 2–10 times those in other areas.

3.2. Characteristics of Precipitation during Pollution Weather Days. The distributions of precipitation hours during pollution days in Hubei Province from 2015 to 2017 (Figure 3) revealed that the mean value of LR during pollution weather in each area was 298 h. LR was the most frequent in XY, reaching 587 h, with a mean value of 497 h. Occurrence of MR was lower than LR by an order of magnitude, with a mean value of 21 h. XY, YC, and WH subject to heavy pollution processes were less affected by MR which lasted for only about 10 h. The occurrence of HR was consistent in each region, mainly in the range of 5–12 h. National air quality monitoring stations of WH and EZ located in Wuhan City Circle showed significant differences in occurrence of HR, with values exceeding 10 h. Regions where TR occurred during pollution weather were mainly located in Wuhan City Circle, all within 7 h. The SR occurred rarely, with only 1 h in the four cities.

Precipitation hours of the same level differed for the different national air quality monitoring stations in the same city. As heavy precipitation was usually concentrated in local areas, average deviation of occurrence in LR, MR, and HR gradually increased, with 14.75%, 26.42%, and 35.01%, respectively. The greater the rainfall intensity was, the larger the difference in occurrence of precipitation was at national air quality monitoring stations in the same area, showing that the research on the separate occurrences of precipitation

in different national air quality monitoring stations was reasonable.

Strong-thick inversion layers and low altitude mixed layers that often occur at night or in the early morning are typical conditions that aggravate pollution weather [41–43]. Their strong inhibition of pollutant diffusion means that the peak concentration of pollutants often occurs at night. Bai et al. [44] found that daily variation of $\text{PM}_{2.5}$ concentrations in Hubei Province showed a bimodal distribution in winter, with peak values during 11:00–14:00 caused by transportation and peak values during 21:00–24:00 caused by accumulation. The frequency of precipitation during different pollution periods can indirectly reflect the impact degree of precipitation on pollution weather. Figure 4 shows diurnal variation of the occurrence of different levels of precipitation during pollution weather in Hubei Province from 2015 to 2017. The daily variations of precipitation showed a unimodal distribution regardless of precipitation level during pollution weather, with peak values during 20:00–23:00. Over time, the ratio of LR to MR and HR at each time was reduced from 17 and 110 during 00:00–03:00 to 6 and 30 during 19:00–23:00, respectively; HR was concentrated during 17:00–23:00. These moments were during the period when $\text{PM}_{2.5}$ mass concentration reached its peak value. With increased rainfall intensity, precipitation was more concentrated at night, indicating that occurrence of precipitation during the pollution process may have had a great impact on the change of PM mass concentration.

3.3. Variation Characteristics of PM Mass Concentration before and after Precipitation during Pollution Process. The value of PM mass concentration is, on the one hand, affected by wet removal caused by inertia coagulation of the precipitation particles during their falling and, on the other hand, affected by aerosol hygroscopic growth and secondary aerosol formation caused by the humidification effect of precipitation. At the same time, the variation law in background concentration of PM under the joint action of local-source emission, external-source transportation, and air mass diffusion also affects the value of PM concentration. Therefore, this section statistically analyzes $\text{PM}_{2.5}$, PM_{10} , and their ratios before and after precipitation to reveal distribution laws governing PM concentration under the influence of precipitation. Table 3 shows the distributions of $V_{\text{PM}_{2.5}}$ and $V_{\text{PM}_{10}}$ under different $C_{\text{PM}_{2.5}/\text{PM}_{10}}$ intervals during rainfall hours. With the ending of precipitation, PM_{10} and $\text{PM}_{2.5}$ concentrations decreased by 61.5% and 52.3% in hours, respectively. Absolute values of the decrease ratios of PM_{10} and $\text{PM}_{2.5}$ were larger than those of the increase ratios of PM_{10} and $\text{PM}_{2.5}$. The effect of precipitation on wet removal was significant. Moreover, PM_{10} was more affected by wet removal of precipitation, which was relatively consistent with the results of Xu et al. on wet removal of precipitation in

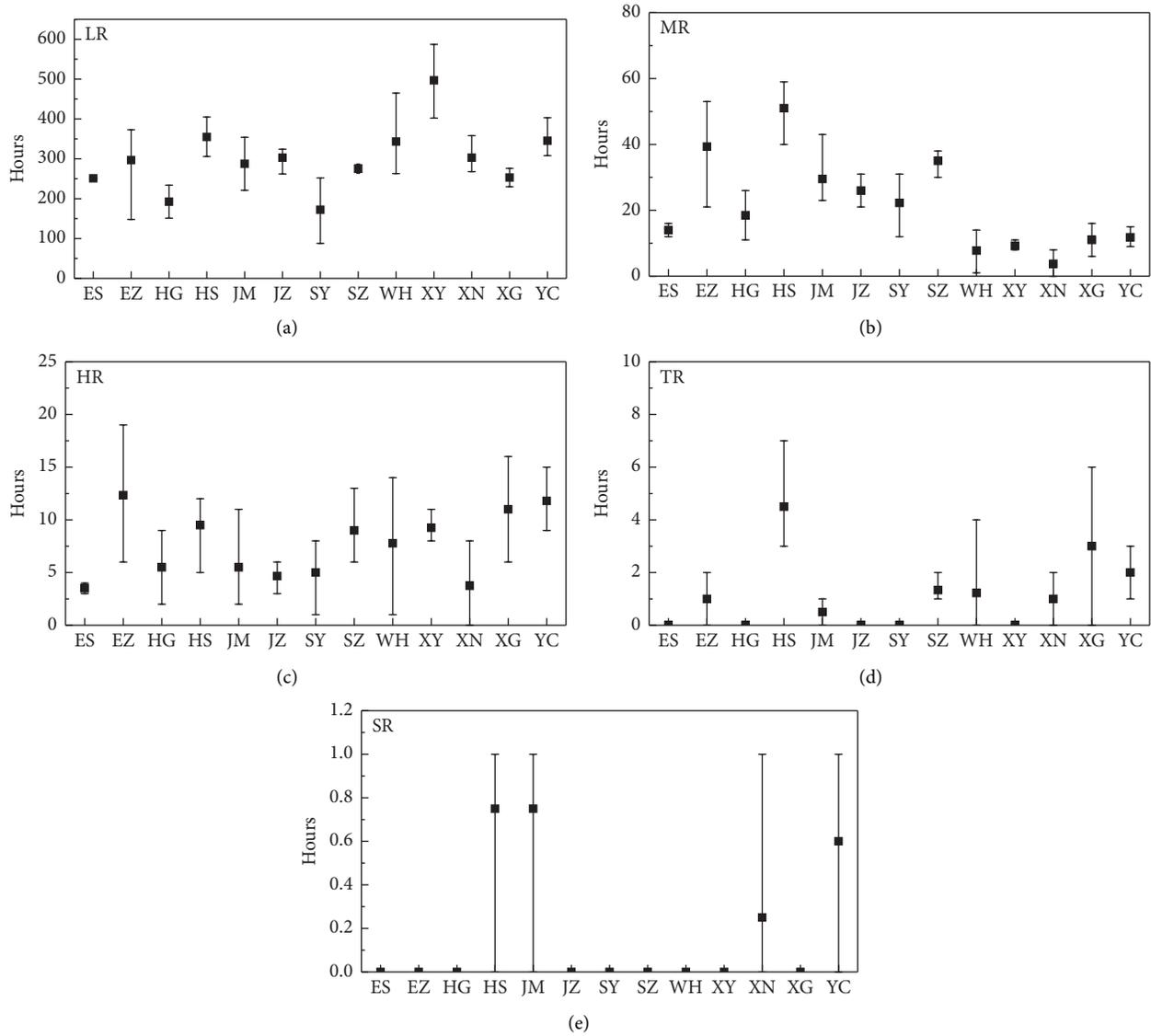


FIGURE 3: Distributions of precipitation hours at different levels during pollution days in Hubei Province from 2015 to 2017: (a) rainfall intensity < 1.5 mm/h; (b) 1.5 mm/h ≤ rainfall intensity < 3.5 mm/h; (c) 3.5 mm/h ≤ rainfall intensity < 8.0 mm/h; (d) 8.0 mm/h ≤ rainfall intensity < 20.0 mm/h; (e) 20.0 mm/h ≤ rainfall intensity < 50.0 mm/h.

Shanghai [23]. They showed that precipitation in Shanghai mainly removed atmospheric aerosol particles of diameters < 1 μm and 2.5–10 μm, while PM₁₀ contained aerosol particles of both these particle size ranges. At the same time, the formation of secondary aerosols under the influence of precipitation also made PM_{2.5} concentration subject to a weaker wet removal effect than PM₁₀ concentration.

The distributions of $V_{PM_{2.5}}$ and $V_{PM_{10}}$ were further compared under different intervals of $C_{PM_{2.5}/PM_{10}}$. Figure 5 shows the relationships between $V_{PM_{2.5}}$ and $V_{PM_{10}}$ for different values of $C_{PM_{2.5}/PM_{10}}$. There was a good positive correlation between $V_{PM_{2.5}}$ and $V_{PM_{10}}$ in different intervals, with correlation coefficients > 0.7, but there were differences in correlations between them for different $C_{PM_{2.5}/PM_{10}}$ intervals. The values of $C_{PM_{2.5}/PM_{10}}$ were mainly concentrated within the range of -0.6 to 0.5. When the values of $C_{PM_{2.5}/$

PM_{10} were negative (-0.6 to -0.1), the fitted line had a slope greater than 1 in each ratio interval, showing that the values of $V_{PM_{10}}$ exceeded those of $V_{PM_{2.5}}$. When $C_{PM_{2.5}/PM_{10}}$ increased (0.1–0.5), the fitted line had a slope less than 1 in each ratio range, and the values of $V_{PM_{2.5}}$ exceeded those of $V_{PM_{10}}$. When $C_{PM_{2.5}/PM_{10}}$ approached 0 (-0.1 to 0.1), the fitted line had a slope close to 1, and $V_{PM_{2.5}}$ and $V_{PM_{10}}$ demonstrated relatively consistent variability.

3.4. Effect of Rainfall Intensity on the PM Mass Concentration.

The analysis in the above two sections provided a preliminary understanding of the distributions of precipitation and PM concentration in the pollution process. Therefore, we then combined the two to investigate the law governing the effect of precipitation on variations of PM concentration.

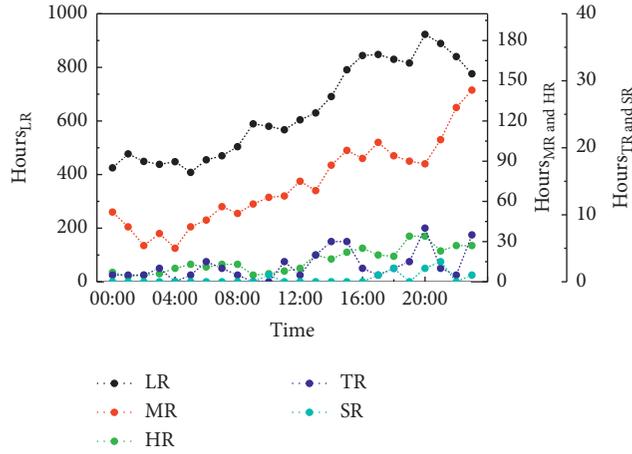


FIGURE 4: Diurnal variation of the occurrence of different-level precipitation during pollution weather in Hubei Province from 2015 to 2017.

TABLE 3: Distributions of $V_{PM_{2.5}}$ and $V_{PM_{10}}$ under different $C_{PM_{2.5}/PM_{10}}$ intervals during rainfall hours.

$C_{PM_{2.5}/PM_{10}}$	$V_{PM_{10}} \geq 0$		$V_{PM_{10}} < 0$		$V_{PM_{2.5}} \geq 0$		$V_{PM_{2.5}} < 0$	
	Hours	Average value	Hours	Average value	Hours	Average value	Hours	Average value
-0.6~-0.4	8	0.10	3	-0.05	0	0.00	11	-0.58
-0.4~-0.2	76	0.29	21	-0.16	19	0.06	78	-0.23
-0.2~-0.1	212	0.17	270	-0.11	112	0.07	370	-0.14
-0.1~0	2218	0.07	2323	-0.07	1694	0.06	2847	-0.08
0~0.1	1674	0.06	3500	-0.09	2897	0.07	2277	-0.07
0.1~0.2	93	0.07	602	-0.16	486	0.12	209	-0.09
0.2~0.4	18	0.06	146	-0.25	116	0.25	48	-0.09
0.4~0.5	0	0.00	11	-0.43	8	0.25	3	-0.22
Ratio (%)		38.50		61.50		47.70		52.30
Average values of V_{PM}		0.10		-0.16		0.11		-0.19

Studies have shown that aerosol concentrations before precipitation are closely related to the wet removal effect of precipitation [16, 18], so this section concentrates on analyzing the relationships between $V_{PM_{2.5}}$ and $V_{PM_{10}}$, rainfall intensity, and values of $M_{PM_{2.5}}^{beg}$ and $M_{PM_{10}}^{beg}$. Figure 6 shows the distributions of average $M_{PM_{2.5}}^{beg}$ and $M_{PM_{10}}^{beg}$, average rainfall intensity, and mean values of $V_{PM_{2.5}}$ and $V_{PM_{10}}$ with intervals of 0.05. When the average rainfall intensity was < 0.5 mm/h, the mean values of $V_{PM_{10}}$ were in the interval 0.4–0.8, and average $M_{PM_{10}}^{beg}$ also had a low value ($< 140 \mu\text{g}/\text{cm}^3$; Figure 6(a)). This indicated that precipitation resulted in aerosol hygroscopic growth and that formation of secondary aerosol was stronger than its wet removal, which thereby led to the increase in PM_{10} mass concentration. When the average rainfall intensity was > 1.0 mm/h, the mean values of $V_{PM_{10}}$ were negative (i.e., -0.66 to -0.20), showing the wet removal effect caused by precipitation. It is noteworthy that when average rainfall intensity was 0.5–1.0 mm/h and average $M_{PM_{10}}^{beg}$ was 110–180 $\mu\text{g}/\text{m}^3$, there were both positive and negative values of $V_{PM_{10}}$, with absolute values lower than those for rainfall intensities of < 0.5 and > 1.0 mm/h.

The effect of precipitation on $PM_{2.5}$ mass concentration (Figure 6(b)) was similar to that of PM_{10} . The range of mean

rainfall intensity responsible for wet growth was mainly < 0.5 mm/h, but the range of mean rainfall intensity responsible for wet removal of $PM_{2.5}$ was significantly higher than that of PM_{10} , with a value > 1.4 mm/h. Particles with smaller size need greater rainfall intensity to be significantly cleared by precipitation. At the same time, the initial value of $PM_{2.5}$ or PM_{10} mass concentration was the dominant factor under the rainfall intensity range in which wet growth and wet removal had similar effects. Precipitation was more likely to have a wet removal effect for a greater initial value of mass concentration, and, on the contrary, wet growth effect was more likely. The threshold of PM_{10} mass concentration was $150 \mu\text{g}/\text{m}^3$, and that of $PM_{2.5}$ mass concentration was $95 \mu\text{g}/\text{m}^3$, relatively consistent with the results of Xu et al. [23] on initial concentration threshold of $PM_{2.5}$ corresponding to wet removal in Shanghai.

3.5. Effect of Relative Humidity on the Change of PM Mass Concentration during Precipitation. Aerosol hygroscopic growth and secondary aerosol formation play a key role in formation of heavy pollution. Sun [29] clarified the important role of rapid growth of secondary aerosols in heavy pollution formation in the North China Plain, pointing out that secondary aerosol accounts for 70% of heavy pollution,

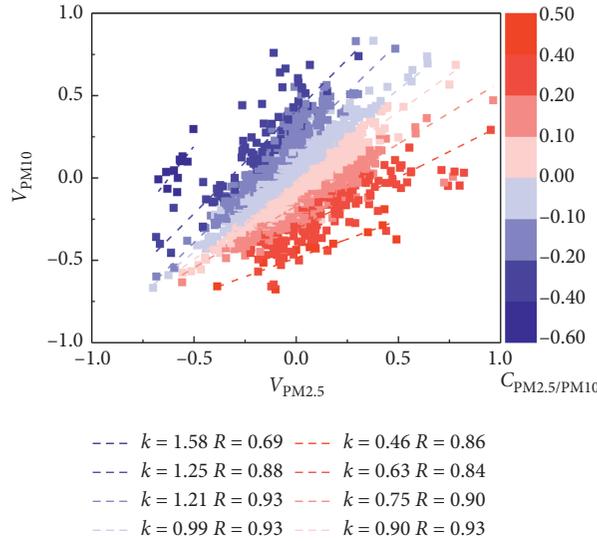


FIGURE 5: Relationships between $V_{PM2.5}$ and V_{PM10} for different values of $C_{PM2.5/PM10}$.

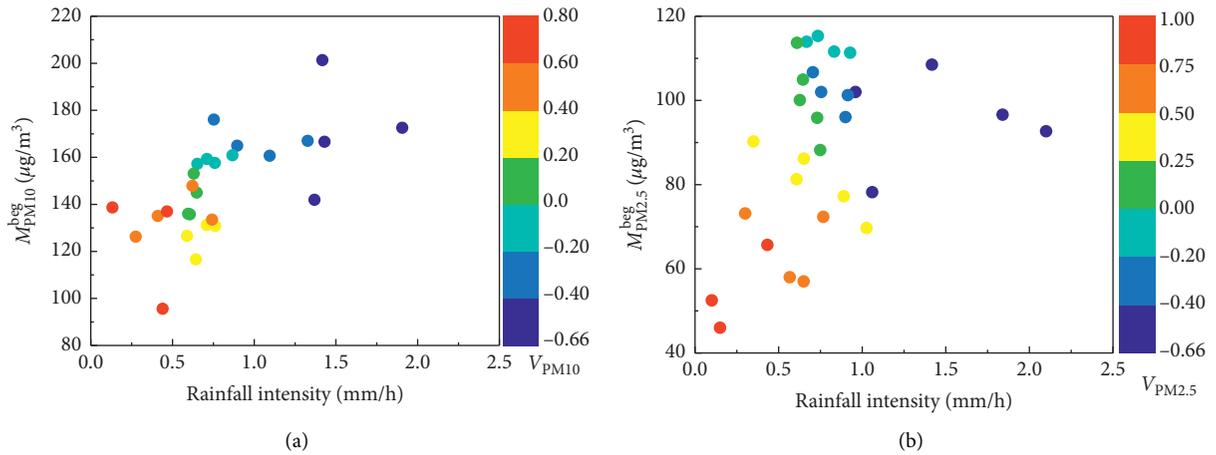


FIGURE 6: The distributions of average $M_{PM2.5}^{beg}$ and M_{PM10}^{beg} , average rainfall intensity, and mean values of $V_{PM2.5}$ and V_{PM10} with intervals of 0.05: (a) $PM_{2.5}$; (b) PM_{10} .

while high humidity and low wind speed are important environmental factors for aerosol hygroscopic growth and secondary aerosol formation [45, 46]. Precipitation significantly increases the relative humidity of the environment, and the elimination of data when the wind speed reaches 3 m/s or more will maintain the low wind-speed environmental conditions. Therefore, precipitation would also affect the formation of secondary aerosols. Figure 7 shows the distributions of V_{PM10} in each relative humidity range (0–100% with 1% intervals). Different panels of Figure 7 correspond to different levels of precipitation. The relative humidity was <40% only during LR, with the values of V_{PM10} ranging from -0.32 to -0.2 , showing that precipitation played a significant role in wet removal of PM_{10} in a dry environment. As the relative humidity increased, wet growth

gradually played a more significant role. The PM_{10} mass concentration in the relative humidity range of 40–65% was subject to the combined action of wet removal and wet growth. When relative humidity was 65–90%, PM_{10} mass concentration increased under the impact of aerosol hygroscopic growth and secondary aerosol formation, while in the near-saturated relative humidity range (90–100%), PM_{10} mass concentration was slightly affected by wet removal, with values of V_{PM10} concentrated within -0.05 to 0 . As the precipitation level increased (MR, HR, and TR), the wet removal to PM_{10} mass concentration was enhanced more obviously, especially in the near-saturated relative humidity range (90–100%). For the relative humidity range (40–90%) under the combined action of wet removal and wet growth, wet removal played a leading role in lower humidity (about

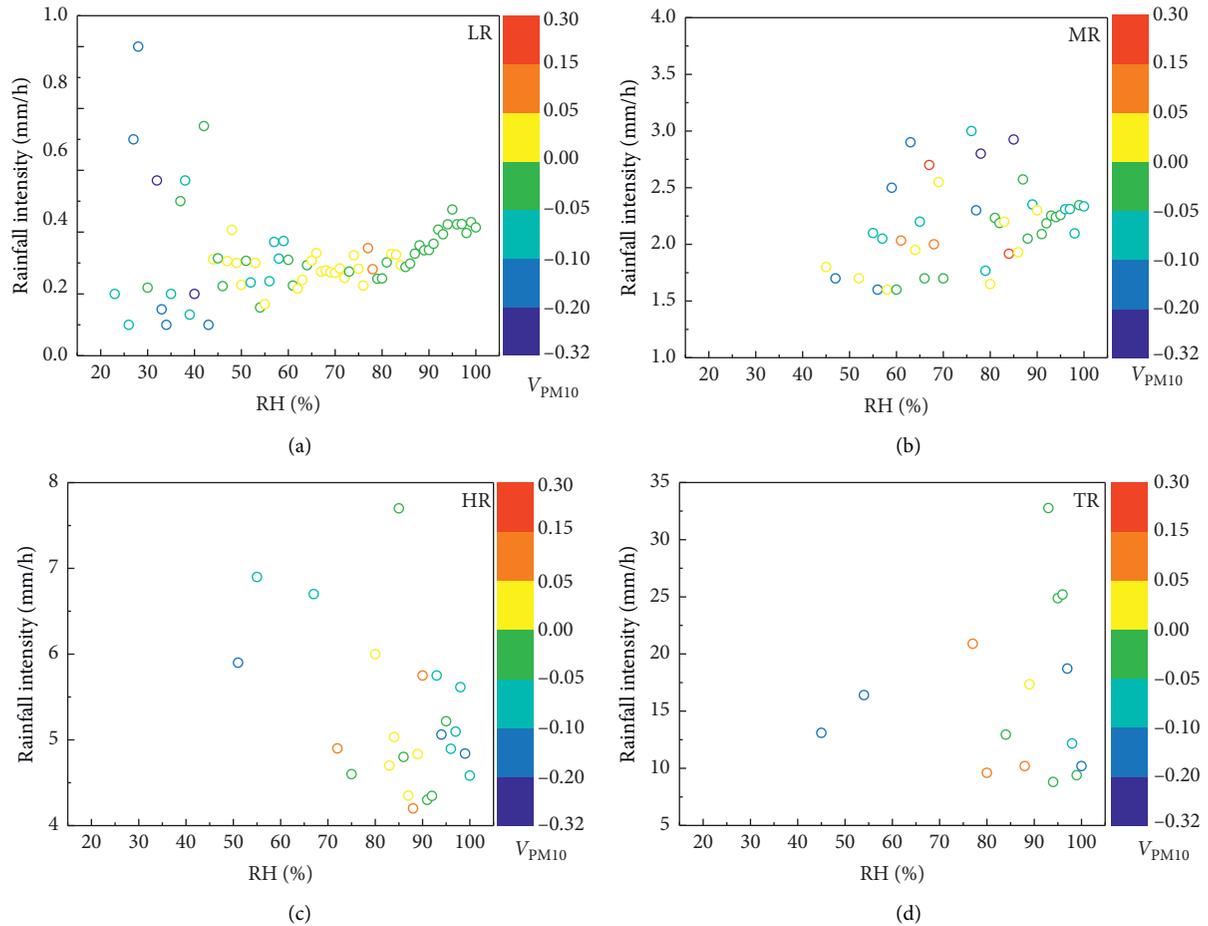


FIGURE 7: Distributions of $V_{PM_{10}}$ in each relative humidity range (0–100% with 1% intervals) for different levels of precipitation: (a) LR; (b) MR; (c) HR; (d) TR.

60%) and greater rainfall intensity, but wet growth played a leading role in higher humidity ($\sim 90\%$) and lower rainfall intensity.

The variations of $V_{PM_{2.5}}$ had distributions similar to those of PM_{10} (figure omitted), but the wet removal effect of precipitation was weakened in the near-saturated relative humidity range (90–100%), and the wet growth effect was enhanced under the higher humidity ($\sim 90\%$) and lower rainfall intensity.

4. Conclusions

In this study, the characteristics of precipitation, distributions of PM concentrations, RH conditions, and evolution of PM under the effect of precipitation during pollution days in Hubei from 2015 to 2017 were comprehensively analyzed. Due to wet removal and wet growth, the PM concentrations varied widely under different rainfall intensities and relative humidity environments.

- (1) The LR occurred most frequently in the pollution process, with XY being the most affected, up to 587 h. Occurrence of MR was lower than LR by an order of magnitude, with a mean value of 21 h. The

occurrence of HR was consistent in each region, mainly in the range of 5–12 h. SR was rare. The greater the rainfall intensity was, the larger the difference in occurrence of precipitation was at national air quality monitoring stations in the same area. Rainfall was more concentrated during 19:00–23:00.

- (2) With the ending of precipitation, PM_{10} and $PM_{2.5}$ concentrations decreased by 61.5% and 52.3% of hours, respectively, showing that PM_{10} was more affected by wet removal of precipitation. When the values of $C_{PM_{2.5}/PM_{10}}$ were negative (-0.6 to -0.1), the values of $V_{PM_{10}}$ exceeded those of $V_{PM_{2.5}}$. When $C_{PM_{2.5}/PM_{10}}$ increased (0.1 – 0.5), the values of $V_{PM_{2.5}}$ exceeded those of $V_{PM_{10}}$. When $C_{PM_{2.5}/PM_{10}}$ approached 0 (-0.1 to 0.1), $V_{PM_{2.5}}$ and $V_{PM_{10}}$ demonstrated relatively consistent variability.
- (3) Mean rainfall intensity responsible for wet growth of PM_{10} and $PM_{2.5}$ was mainly <0.5 mm/h, but the ranges responsible for wet removal of $PM_{2.5}$ (>1.4 mm/h) and for wet removal of PM_{10} (>1.0 mm/h) were significantly higher. In the rainfall intensity range for which wet growth and wet removal had

similar effects, precipitation was more likely to produce a wet removal effect for greater initial values of mass concentration, and, on the contrary, a wet growth effect was more likely. The threshold of PM_{10} mass concentration was $150 \mu\text{g}/\text{m}^3$ and that of $PM_{2.5}$ mass concentration was $95 \mu\text{g}/\text{m}^3$.

- (4) Precipitation played a significant role in wet removal of PM_{10} in a dry environment (relative humidity <40%), with a weaker wet removal effect in the near-saturated relative humidity range (90–100%). When relative humidity was 40–90%, the effects of wet removal and wet growth were similar. As the precipitation level increased (MR, HR, and TR), the wet removal of PM_{10} mass concentration was enhanced more obviously. Wet removal played a leading role in lower humidity (~60%) and greater rainfall intensity, but wet growth played a leading role in higher humidity (~90%) and lower rainfall intensity. The effect of precipitation on $PM_{2.5}$ was similar to that on PM_{10} , but the wet removal effect of precipitation was weakened in the near-saturated relative humidity range (90–100%), and the wet growth effect was enhanced under higher humidity (~90%) and lower rainfall intensity.

Data Availability

The $PM_{2.5}$ and PM_{10} mass concentration, precipitation, relative humidity, and wind-speed data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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