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A Simple New Method for Calculating Precipitation Scavenging Effect on Particulate Matter: Based on Five-Year Data in Eastern China

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Abstract: A "rain-only" method is proposed to find out the precipitation effect on particle aerosol removal from the atmosphere, and this method is not only unique and novel but also very simple and can be easily adapted to predict aerosol particle scavenging over any region across the world irrespective of the topographical, orographical, and climatic features. By using this simple method, the influences of the rain intensity and particle mass concentration on the aerosol scavenging efficiency are discussed. The results show that a higher concentration, a higher rain intensity, and a larger particle size lead to a higher scavenging efficiency and a higher scavenging rate. The greater the rain intensity, the higher the scavenging efficiency. The scavenging efficiency of PM_{10} by precipitation is better than that of $PM_{2.5}$. When the rain intensity is 10 mm h^{-1}, the scavenging efficiency of $PM_{2.5}$ reaches 5.1 μg m^{-3} h^{-1}, and the scavenging efficiency of PM_{10} reaches 15.8 μg m^{-3} h^{-1}. The scavenging rate increases faster when accumulative precipitation is below 15 mm. The scavenging rate has obvious monthly variation, and the scavenging rate of coastal areas is less than that of inland Jiangsu. The growth of the particle mass concentration after precipitation is divided into two stages: the rapid growth stage after precipitation ends, and the slow growth stage about 24 h after precipitation ends.

Keywords: air pollution; China; particulate matter; precipitation scavenging; scavenging efficiency; scavenging rate

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1. Introduction

In our previous article, we discussed the adverse meteorological variables (such as precipitation, wind speed and direction, humidity, inversion, and mixing layer height) that affect air pollution and the surface synoptic situation patterns related to air pollution in eastern China, where the threshold values of meteorological elements are summarized [1]. From the previous article, we found that wind speed, RHs, inversion intensity (ITI), height difference in the temperature inversion (ITK), the lower height of temperature inversion (LHTI), and mixed layer height (MLH) in terms of a 25–75% high-probability range were, respectively, within 0.5–3.6 m s^{-1}, 55–92%, 0.7–4.0 °C 100 m^{-1}, 42–576 m, 3–570 m, and 200–1200 m. The probability of RPHPDs without rain was above 92% with the daily and hourly precipitation of all RPHPDs below 2.1 mm and 0.8 mm [1]. In this article, we will discuss the precipitation scavenging effect conducive to air pollution removal. Scavenging of atmospheric aerosols by precipitation is a major removal mechanism for airborne particles [2]. Atmospheric aerosol wet scavenging directly affects the air quality by controlling the aerosol mass concentrations, and temporal and spatial distributions [3,4]. The scavenging of atmospheric aerosols also has a large impact on the chemical composition of rainwater [5,6]. Thus, the understanding and quantification of aerosol scavenging processes are very important for air quality and its improvements.

The wet process can be described by a wet scavenging coefficient [7–10]. The wet scavenging of atmospheric pollutants includes in-cloud scavenging processes [11–13] and below-cloud scavenging processes [14–27]. Below-cloud atmospheric particles are removed by raindrops via Brownian diffusion, interception, and impaction [28]. Bae et al. [16] noted that the collection efficiency, terminal velocity of raindrops, raindrop size distribution, and particle size distribution are important factors affecting below-cloud scavenging. In the later period of rainstorms, high concentrations of aerosols improved the precipitation efficiency significantly, resulting in more centralized clusters of intense precipitation [29].

Tai et al. [30] reported that precipitation is strongly negatively correlated with all $PM_{2.5}$ components. The collection efficiency diameter is a function of both terminal velocity and collection mechanisms. When considering Brownian diffusion and interception, the most penetrating particle sizes increase as the drop diameter increases, which shows that the most penetrating particle sizes depend on the collection efficiency mechanism, vertical velocity, and collector diameter [28]. Chate et al. [20] found that the predicted rainwater concentration for a relative humidity (RH) of 50% is about two times larger than that for an RH of 95% in the case of hygroscopic particles. Using field observations and modeling, McLachlan and Sellström [31] found that the differences between ground-level and in-cloud temperatures should be considered when calculating the scavenging ratio.

The air pollution in the eastern part of China is quite serious and has become a serious environmental problem [32]; therefore, natural clearance (dry deposition and wet deposition) is very important, and especially precipitation scavenging is most important. Therefore, the understanding and quantification of aerosol scavenging processes are of extreme importance due to their impact on the physical and chemical characteristics of aerosols as well as precipitations [3].

In most parts of China, raindrop and aerosol particle spectra are not widely observed. However, atmospheric aerosol mass concentrations are widely observed. These common observation data of aerosol mass concentrations are helpful for us to analyze the clearance effect of precipitation on aerosols. In addition, scavenging schemes used by various aerosol transport models follow the theoretical estimation of scavenging and have become a high source of uncertainty for such models [33]. Therefore, it has become necessary to study precipitation scavenging in a more simple and quantitative way with a higher number of samples to analyze the dataset with high statistical significance. This would, in turn, reduce the uncertainties associated with the various chemical transport models used to study precipitation scavenging.

Thus, the present study is an attempt (1) to establish a “rain-only” method on particle aerosol removal from the atmosphere which is not only unique and novel but also very simple, (2) to investigate how aerosol scavenging depends on the precipitation intensity, precipitation duration, particle mass concentrations, and precipitation volumes, (3) to determine the threshold values of the precipitation intensity and duration below and above which aerosol scavenging behaves differently, and (4) to establish whether air pollution can be quantitatively predicted if one holds only the information of the precipitation intensity, precipitation duration, particle mass concentrations, and precipitation volumes for a given pollution level. Such a simple methodology can be easily adapted to predict aerosol particle scavenging over any region across the world irrespective of the topographical, orographical, and climatic features.

We examine aerosol scavenging by precipitation in eastern China. The remainder of this paper is organized as follows: The study area, observations, and analysis methods used are described in Section 2. We analyze precipitation scavenging on aerosols in Section 3. The conclusions are given in Section 4.

2. Study Area and Methodology

2.1. Study Area

Jiangsu Province is located at the Yangtze River in eastern China. The region has a long coastline of 954 km. We also chose 17 environmental monitoring stations close to these 17 weather stations. The distribution of meteorological stations and state-controlled environmental protection stations (SCEPSs) in Jiangsu is shown in Figure 1.

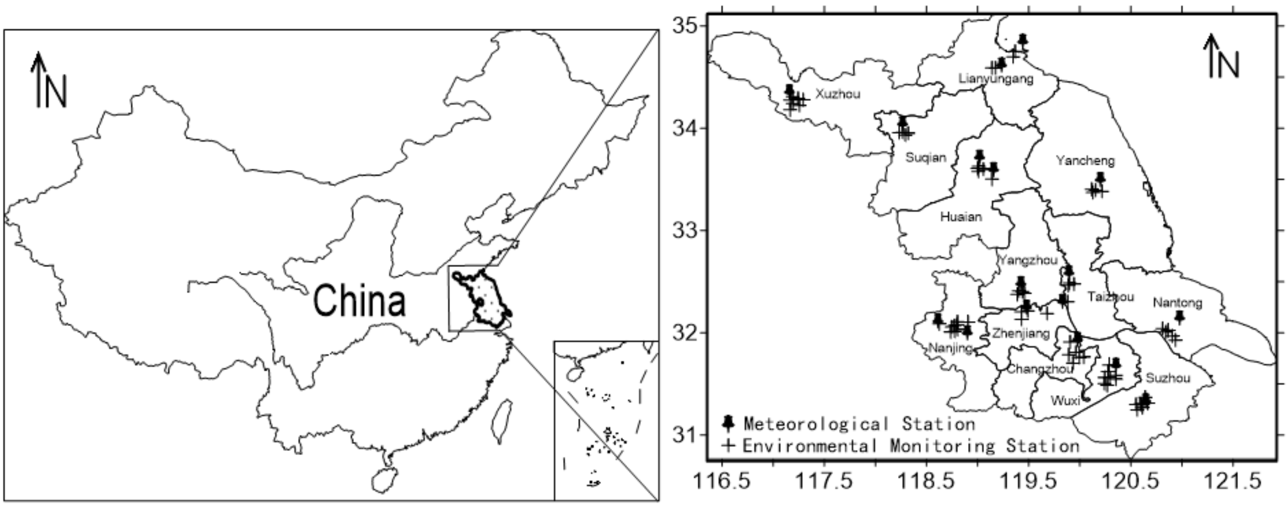

Figure 1. Geographical location of Jiangsu Province, the distribution of environmental monitoring stations, and their nearest weather stations in the study area.

2.2. Observations

The observation period was from 2013 to 2017, including hourly precipitation, wind speed, wind direction, and PM_{10} and $PM_{2.5}$ particulate concentrations. The PM_{10} and $PM_{2.5}$ particle monitors used were BAM1020 particle monitors (Met One Instruments INC, Grants Pass, OR, USA) produced by the American company METONE (https://metone.com/products/bam-1020/, accessed on 10 June 2021). The BAM-1020, on an hourly basis, automatically measures and records airborne particulate concentration levels (in micrograms per cubic meter) using the industry-proven principle of beta ray attenuation, which can obtain the PM_{10} and $PM_{2.5}$ mass concentrations in the environment in real time.

2.3. Analysis Methodology

Precipitation event: A precipitation process starts in the first hour when precipitation reaches at least 0.1 mm. If precipitation in an hour was zero after the beginning of the precipitation process, that hour was recorded as an interrupted hour, and the end of the process appeared when three consecutive precipitation interruptions occurred. The hour before the interrupted hour was recorded as the last hour of the precipitation process. As a result, we obtained 27,219 precipitation processes in total.

The effects of concentration and precipitation on the removal rate were analyzed by classifying precipitation processes (0–1 mm, 1–5 mm, 5–10 mm, 10–20 mm, 20–30 mm, 30–50 mm, >50 mm).

Scavenging efficiency (*SE*): *SE* is the particle mass concentration change in unit time (t). In an hour with a particle mass concentration CON_{before} before the rain starts and with a particle mass concentration CON_{after} after the rain stops, the *SE* is expressed as

$$SE = \left(CON_{after} - CON_{before}\right)/t$$

Scavenging rate (*SR*): *SR* is the percentage change of particle mass concentration changes. For a precipitation process with a particle mass concentration CON_{before} before the rain starts and a particle mass concentration CON_{after} after the rain stops, we defined *SR* as

$$SR = \frac{CON_{before} - CON_{after}}{CON_{before}} \times 100\% \quad (1)$$

In some cases, the rain did not remove the particles, but the concentration continued to increase. Therefore, we made a rule that if the *SR* is positive, it is a positive scavenging process, and if the *SR* is negative, it is a negative scavenging process (which means the precipitation had a very limited scavenge).

3. Results and Discussion

3.1. Relationship between Precipitation, Particle Mass Concentration, and SE

First, we investigated potential size effects on the scavenging efficiencies. The figure shows the relationship between the *RI* and *SE*. In the distribution of the precipitation intensity, most precipitation intensities are lower than 5 mm/h. A precipitation intensity above 5 mm/h takes a relatively low proportion in the samples. Therefore, for the segment with rainfall less than 1 mm, a 0.2 mm interval is adopted, while for the segment with rainfall greater than 1 mm, a 2 mm interval is adopted. From Figure 2, we can see that when the rain intensity (*RI*) is less than 0.4 mm h^{-1}, the *SE* of $PM_{2.5}$ is almost zero, but the *SE* of PM_{10} can reach ~2 μg m^{-3} h^{-1}. The concentration of $PM_{2.5}$ often rises during weak precipitation (*RI* lower than 0.5 mm h^{-1}); when the *RI* is 7 mm h^{-1}, the *SEs* of $PM_{2.5}$ and PM_{10} are 2.7 and 6.3 μg m^{-3} h^{-1}, respectively. The *SE* is positively correlated with the *RI*: the greater the *RI*, the higher the *SE*. When the *RI* is 10 mm h^{-1}, the *SE* of $PM_{2.5}$ reaches 5.1 μg m^{-3} h^{-1}, and the *SE* of PM_{10} reaches 15.8 μg m^{-3} h^{-1}.

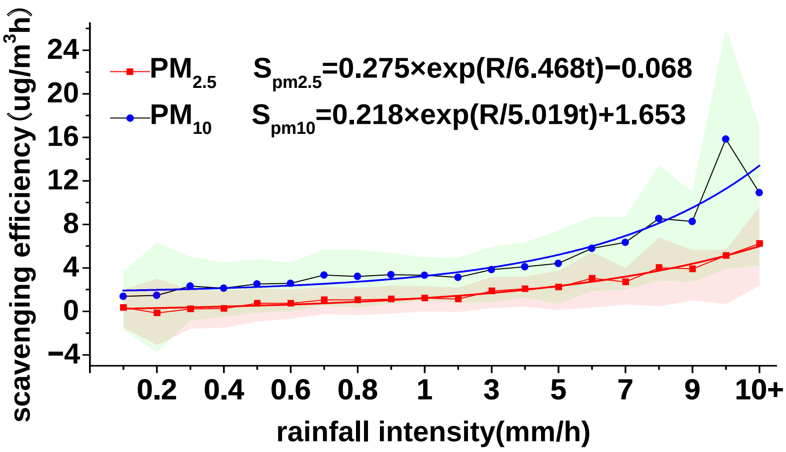

Figure 2. Relationship between precipitation intensity and scavenging efficiency (*SE*) (the dashed lines are the fitted curves, the green area is the interquartile span of PM_{10}, the red area is the interquartile span of $PM_{2.5}$, and the gray area is the overlapping region).

By using functions to fit the rainfall intensity and scavenging efficiency, where $SE_{pm2.5}$ and SE_{pm10} are the *SEs* of precipitation on $PM_{2.5}$ and PM_{10}, respectively, *RI* is precipitation, and *t* is the precipitation duration, we relate the *RI* and *SE* as follows:

$$SE_{pm2.5} = 0.275 \times exp\left(\frac{RI}{6.468 \times t}\right) - 0.068 \quad (2)$$

$$SE_{pm10} = 0.218 \times exp\left(\frac{RI}{5.019 \times t}\right) + 1.653 \quad (3)$$

The changes in $PM_{2.5}$ and PM_{10} caused by precipitation under a stable *RI* (the precipitation intensity remains unchanged) are as follows:

$$CON_{pm2.5} = \left[0.275 \times exp\left(\frac{RI}{6.468 \times t}\right) - 0.068\right] \times t \tag{4}$$

$$CON_{pm10} = \left[0.218 \times exp\left(\frac{RI}{5.019 \times t}\right) + 1.653\right] \times t \tag{5}$$

The derivatives of Equations (3) and (4), respectively, are

$$CON'_{pm2.5} = 0.275 \times exp\left(\frac{RI}{6.468 \times t}\right) \times \left(1 - \frac{RI}{6.468 \times t}\right) - 0.068 \tag{6}$$

$$CON'_{pm10} = 0.218 \times exp\left(\frac{RI}{5.019 \times t}\right) \times \left(1 - \frac{RI}{5.019 \times t}\right) + 1.653 \tag{7}$$

Therefore, when $CON'_{pm2.5}$ or CON'_{pm10} is equal to zero, changes in $CON_{pm2.5}$ and CON_{pm10} caused by precipitation reach the maximum values; the corresponding *RI* reaches 5.8 mm/h and 10.1 mm h^{-1}, respectively.

Based on the analysis of the 27,219 precipitation processes from 2013 to 2017 in Jiangsu Province, we find that the effect of precipitation is greater on coarse particles than on smaller particles.

Figure 3 shows the effect of the particle mass concentration on the *SE* under different *RI*s when precipitation processes are classified according to the *RI*. Higher particle mass concentrations under the same *RI* and heavy rain under the same particle mass concentration all have a higher *SE*. The precipitation *SE* on PM_{10} is higher than that of $PM_{2.5}$ for the same *RI* and the same particle mass concentration. The *SE* is an increasing function of both the *RI* and the initial concentration. Precipitation has a limited effect on particulate matter and even has no effective clearance when the particle mass concentration is below the thresholds ($PM_{2.5}$ below 40 μg m^{-3} and PM_{10} below 60 μg m^{-3}). The precipitation *SE* on the particle is significantly enhanced with the increase in the particle mass concentration. The precipitation *SE* with an intensity below 0.5 mm h^{-1} can reach more than 15 μg m^{-3} h^{-1} when the concentration of $PM_{2.5}$ or PM_{10} is above 140 μg m^{-3}. This also explains why sometimes the particle mass concentration rises after strong precipitation and why sometimes the particle mass concentration decreases after weak precipitation. This is because the *SE* is not only determined by accumulative precipitation or the *RI* but also by the two combined. Strong precipitation with a low particle mass concentration may result in a negative clearance effect, and a high particle mass concentration with weak precipitation may lead to a positive *SE*. This result is similar to the numerical model simulation results, in that the same amount of precipitation may lead to different removal efficiencies of atmospheric aerosols [2]. Jose Nicolás et al. [34] and Yoo et al. [35] also found a higher atmospheric removal efficiency for coarse particles than for fine particles.

3.2. Relationship between SR, Precipitation, and Particle Mass Concentration

The scavenging ratio *SR* indicates precipitation effects on the particle mass concentration. Figure 4 shows that the *SR* is positively correlated with accumulative precipitation. The data corresponding to the position of 5 mm on the X-axis are the *SR*s of the precipitation process between 0 and 5 mm; similarly, the position of 10 mm is the average *SR* of the precipitation process with precipitation of 5–10 mm in Figure 4. From the figure, we can see that it increases faster when accumulative precipitation is below 15 mm and more slowly when accumulative precipitation is above 15 mm. The *SR* of PM_{10} is higher than the *SR* of $PM_{2.5}$ under the same accumulative precipitation, and when accumulative precipitation is above 50 mm, the precipitation *SR*s of $PM_{2.5}$ and PM_{10} are about 50% and 60%, respectively.

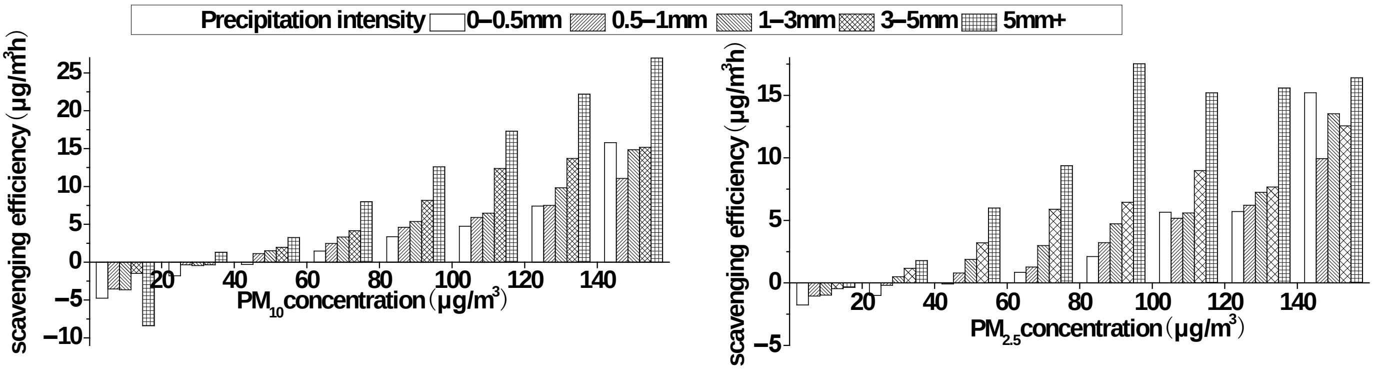

Figure 3. Effects of different rain intensities (*RI*s) and particle mass concentrations on scavenging efficiency (*SE*).

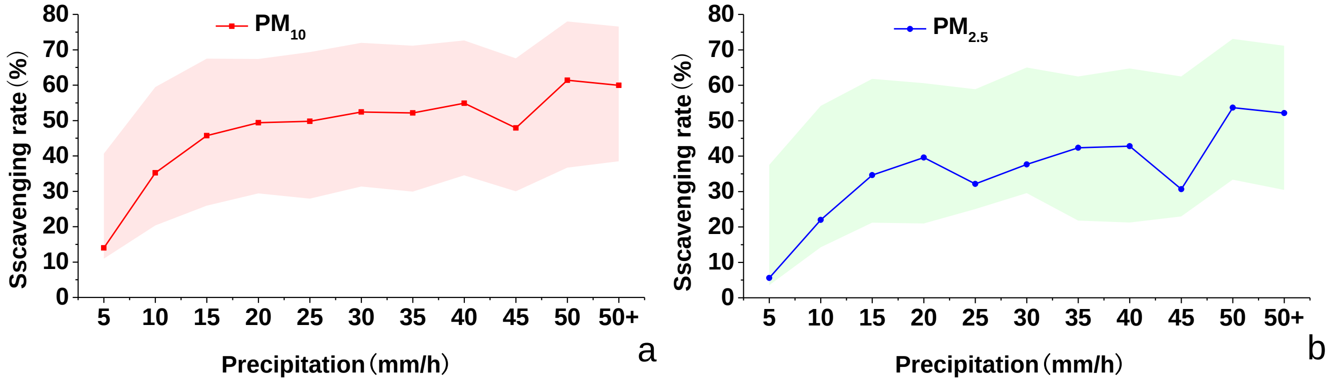

Figure 4. Relationship between precipitation and scavenging rate (*SR*) about the particle mass concentrations ((**a**), PM_{10}; (**b**), $PM_{2.5}$). (The solid line is the arithmetic mean of the *SR*, and the shaded area is the 25% and 75% percentile values of all the individual cases).

The precipitation effect on the removal of particles is not only related to precipitation but also related to the particle mass concentration before precipitation starts. Figure 5 shows the effect of the particle mass concentration on the *SR* under different precipitation volumes. We can see that the *SR* and particle mass concentration before the rain are positively correlated, the arithmetic mean *SR* of precipitation at any level is above zero while the $PM_{2.5}$ concentration is higher than 50 μg m^{-3}, and the average *SR* of precipitation at almost any level is less than zero while the $PM_{2.5}$ concentration is lower than 20 μg m^{-3} (which means precipitation had a very limited scavenge). In addition, the *SR* increases faster with the increase in the particle mass concentration when the particle mass concentration is below 50 μg m^{-3}, and it increases more slowly when the particle mass concentration is higher than 50 μg m^{-3}.

Assuming that the *SR*s of $PM_{2.5}$ and PM_{10} are, respectively, $SR_{pm2.5}$ and SR_{pm10}, the particulate matter concentration before precipitation is *C*, and the process of rainfall is *P*, the quadric surface fitting is performed on the segmentation statistical results in Figure 5 (not for all samples, but for the classification analysis of samples as shown in Figure 5), and the results are as follows:

$$SR_{pm2.5} = -66.6 + 1.4323P + 1.4241C - 0.0148P^2 - 0.0053C^2 + 0.0032P \times C \quad (8)$$

$$SR_{pm10} = -85.04 + 1.2770P + 1.8157C - 0.0126P^2 - 0.0070C^2 + 0.0024P \times C \quad (9)$$

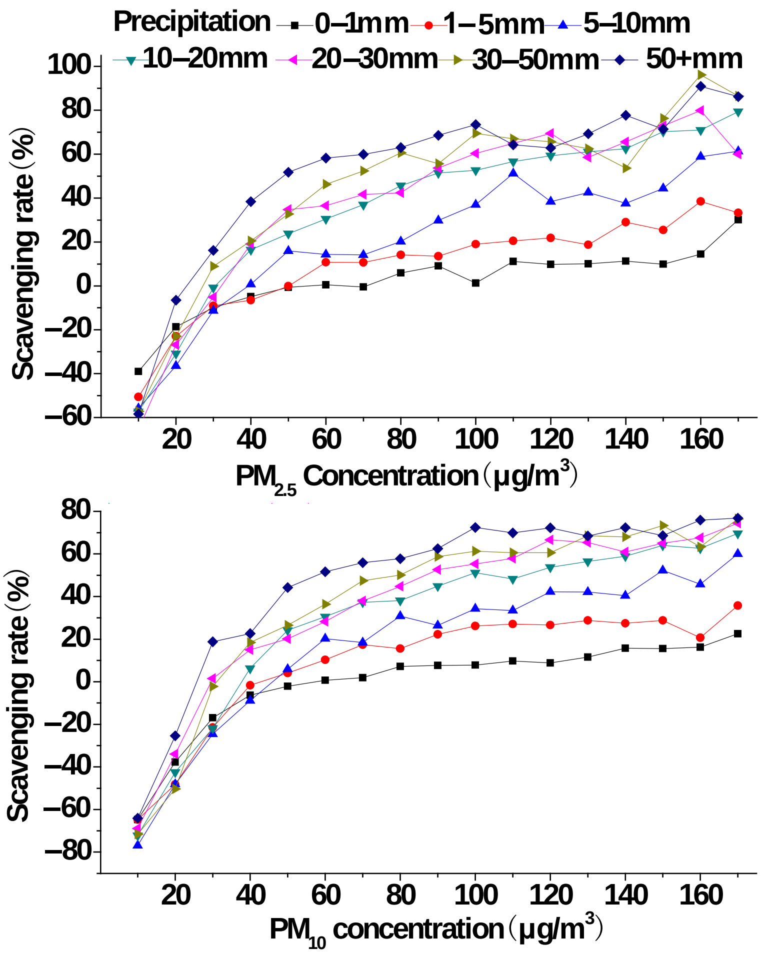

Figure 5. Effect of particle concentration on *SR* under different precipitation volumes. Rain ranges: 0–1, 1–5, 5–10, 10–20, 20–30, 30–50, >50 mm.

The Adj. R-Square of the two equations is 0.87 and 0.90, respectively, which means that the deviation between the fitting data and the statistical data is small, and the fitting effect is good.

3.3. Region Difference of SR

In this section, it is discussed whether there are any differences between different regions for the precipitation, *RI*, particle mass concentration, and *SR* in Jiangsu. Figure 6 shows the relationship among precipitation, particle mass concentration, and *SR* in Jiangsu. The average concentration of $PM_{2.5}$ in the 10 inland cities was 51.0 μg m^{-3}, and the average concentration of PM_{10} was 80.5 μg m^{-3}, higher than the average concentration of $PM_{2.5}$ in the coastal areas, which was 40.4 μg m^{-3}, and the average concentration of PM_{10}, which was 63.0 μg m^{-3}. The *SR* of coastal areas is less than the *SR* of inland Jiangsu, which is consistent with the distribution of the particle mass concentration because the inland concentration is higher than the coastal concentration. However, precipitation is also an important factor. The increase in the *RI* and mean precipitation accumulation was beneficial to the increase in the *SR*. The *SR* in coastal areas is relatively low because the concentration of particulate matter is lower than that in inland areas. The higher the precipitation, the higher the *SR* and *SE*. Therefore, the precipitation distribution center in south Jiangsu shows the *SR* is higher in southwest Jiangsu.

Table 1. Relationships between precipitation, *RI*, particle mass concentration, and *SR* in Jiangsu from 2013 to 2017 (data are consistent with Figure 6).

	SR		*RI*	Precipitation	Concentration	
	$PM_{2.5}$	PM_{10}			$PM_{2.5}$	PM_{10}
Xuzhou	0.10	0.24	1.16	9.42	54.07	101.08
Changzhou	0.18	0.24	1.31	12.68	47.26	79.98
Zhenjiang	0.20	0.25	1.08	10.45	50.45	79.44
Lianyungang	0.16	0.25	1.3	10.46	39.44	65.65
Nantong	0.13	0.26	1.15	12.03	46.67	70.29
Wuxi	0.14	0.28	1.21	11.54	53.84	77.17
Suzhou	0.13	0.28	1.24	11.95	45.58	69.41
Yancheng	0.15	0.28	1.01	9.64	35.02	53.11
Suqian	0.17	0.28	1.19	10.15	50.63	76.88
Huaian	0.16	0.28	1.19	9.76	49.29	74.35
Taizhou	0.20	0.29	1.04	11.16	53.56	84.3
Yangzhou	0.27	0.31	1.13	11.19	52.08	79.87
Nanjing	0.22	0.32	1.07	10.13	53.63	82.83

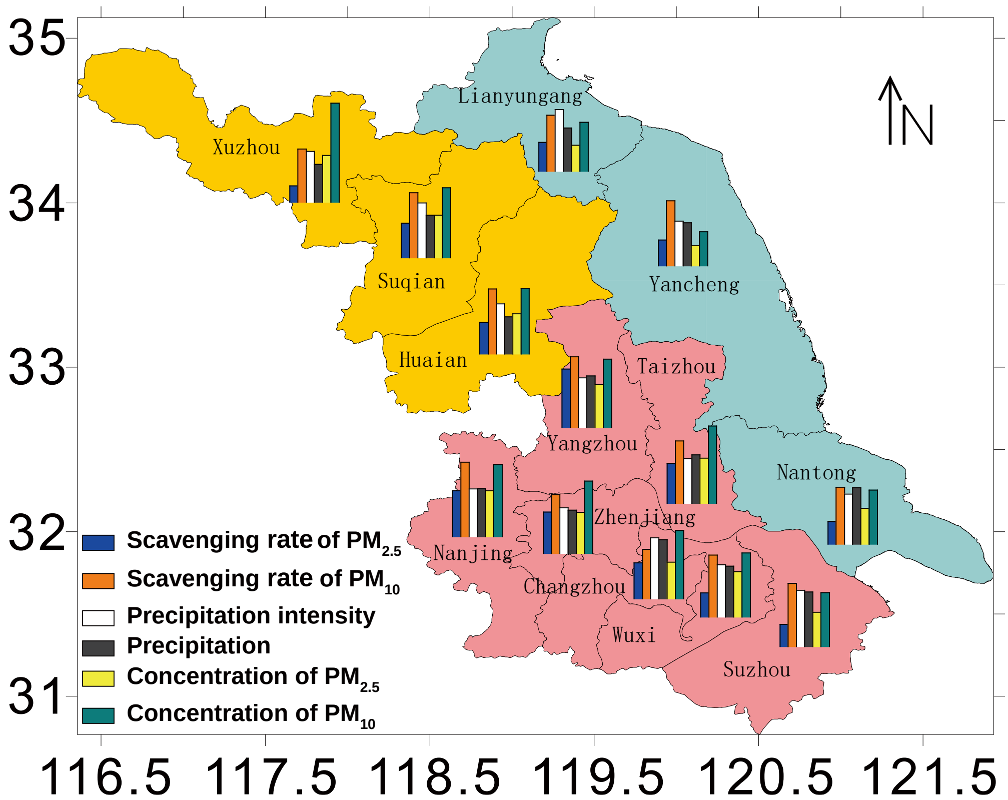

Figure 6. Relationships between precipitation, *RI*, particle mass concentration, and *SR* in Jiangsu from 2013 to 2017 (the data in Table 1). (The average PM concentration is based on the mean hourly particulate concentration of all stations in each city over a five-year period. The average values of precipitation and the precipitation rate are the average values of all precipitation processes in the region in 5 years. Three colors in the map: red, the southern inland area; blue, coastal areas; and orange, the northern inland area.)

In this section, it is discussed why the *SR* of $PM_{2.5}$ in the northern coastal area of Jiangsu is higher than that in the southern coastal area though the $PM_{2.5}$ concentration and average precipitation in the northern coastal area are less than those in the southern coastal area. This is due to the influence of the *RI*, which is larger in the northern coastal area. The *SR* of PM_{10} is less affected by the *RI* compared with the *SR* of $PM_{2.5}$. Therefore, the *SR* of

PM_{10} in southeast Jiangsu is higher than that in the northeast region in spite of the larger *RI* in the northeast. Therefore, the *SR* of $PM_{2.5}$ is more affected by the *RI*. Precipitation with a low *RI* has almost no *SE* on $PM_{2.5}$. Therefore, continuous drizzle can cause a large amount of precipitation over a long time period but cannot effectively reduce the concentration of $PM_{2.5}$. Since low-*RI* precipitation has some *SE* on PM_{10}, more precipitation (meaning high-*RI* precipitation or continuous drizzle) can reduce the PM_{10} concentration effectively.

3.4. Change in Particle Mass Concentration after Rain

The concentration of particulate matter in the atmosphere depends on the balance between emissions and atmosphere self-cleaning. When the emission source is not changed and the weather system is stable, the particle mass concentration should be around the equilibrium state. In the absence of external transport, the PM concentration in the atmosphere depends on environmental emissions and dry or wet deposition. In a relatively short period of time, it can be considered that environmental emissions before and after precipitation do not change much; therefore, the impact of precipitation on the particle concentration can be analyzed. When the effects of dry deposition and environmental emissions cancel out, the concentration of particulate matter stabilizes, which is the equilibrium state. Then, how does the particle mass concentration approach the equilibrium state after a precipitation process?

The change in the particle mass concentration within 168 h after precipitation ends was analyzed using 6882 processes. The results are shown in Figure 7. The average particle mass concentration is low at the end of precipitation, being about 50 μg m^{-3} for $PM_{2.5}$ and 70 μg m^{-3} for PM_{10}. The particle mass concentration increases gradually after the end of precipitation. The average concentrations of $PM_{2.5}$ and PM_{10} 168 h after precipitation are more than 65 and 115 μg m^{-3}, respectively. The growth of the particle mass concentration after precipitation was divided into two stages: 0–24 h after the end of precipitation is the rapid growth stage, and 24 h after the end of precipitation is the slow growth stage. The concentrations of $PM_{2.5}$ and PM_{10} increase at 0.46 and 1.35 μg m^{-3} per hour during the rapid growth phase, while they increase at 0.07 and 0.51 μg m^{-3}, respectively, in the slow growth stage.

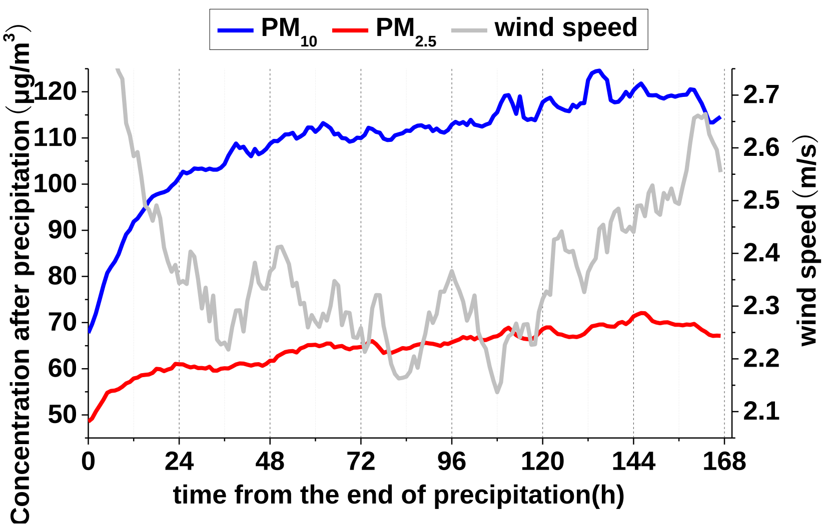

Figure 7. Changes in particle concentrations and wind speeds with time after precipitation ends.

In this section, the reason for the growth rate of the particle mass concentration within 24 h after precipitation being greater than that after 24 h is discussed.

The factors that influence air pollution include internal factors (emission sources) and external factors (such as precipitation, wind speed and direction, humidity, inversion, and mixing layer height [36]) and were discussed in the previous article [1], showing that the threshold value is one of the criteria of pollution intensity. Analysis of the average wind speed within 168 h after the rain starts shows that the wind speed within 24 h after precipitation is greater than that after 24 h; the high wind is not conducive to the increase in the particle mass concentration. Meanwhile, emission sources are usually stable and can be considered as constant during the precipitation process. For a period of time after the end of precipitation, if the emission source is regarded as constant, the PM concentration change depends on the dry deposition and environmental emissions. When the concentration of particulate matter is high, the dry deposition effect is strong, exceeding the environmental emission, and the PM concentration decreases with time. When the PM concentration is low, the dry deposition effect is lower than that of environmental emissions, and the PM concentration increases with time. When the effects of dry deposition and environmental emissions cancel out, the concentration of particulate matter stabilizes, which is the equilibrium state. When the actual particle concentration is lower than the equilibrium concentration, dry deposition caused by the effect of the particle concentration decreases below the environmental emissions, which could lead to an increase in the particle concentration effect, where the PM concentration will increase to approach the equilibrium concentration. When there is a greater difference between the actual concentration and the equilibrium concentration, dry deposition caused by the effect of the PM concentration decreases below the environmental emissions, which could lead to an increase in the particle concentration effect, causing a greater particle concentration change over time. When the particle mass concentration approaches the equilibrium state, the closer it is to the equilibrium point, the more slowly it moves toward the equilibrium point. The particle mass concentration is far from the equilibrium point at the end of precipitation; therefore, the growth rate is relatively large. In the case of no rain within 168 h after the previous precipitation process, the weather is often sunny, and the particle mass concentration approaches the equilibrium state; therefore, the particle growth rate is slowed down significantly. Here, we choose the cases where there were more than 10 consecutive days without precipitation after the studied precipitation process. Additionally, we analyze particle concentration changes after the precipitation, in order to determine the above equilibrium concentration. According to the results of the 10-day or longer continuous observation, the arithmetic average concentrations of $PM_{2.5}$ and PM_{10} are finally stabilized at about 80 and 120 μg m^{-3}, which can be considered as the equilibrium points for $PM_{2.5}$ and PM_{10}.

4. Conclusions

Particle air pollution scavenging was jointly affected by the wind diffusion effect and precipitation scavenging effect. Precipitation is the most important factor in the balance of air pollution in ecosystems.

Deducing the threshold values of precipitation scavenging that were conducive to the pollution accumulation was very necessary to achieve better control of air pollution. This study provides a simple and quantitative way to establish a "rain-only" method on particle aerosol removal from the atmosphere. Such a simple methodology can be easily adapted to predict aerosol particle scavenging over any region across the world irrespective of the topographical, orographical, and climatic features. The threshold values of the precipitation intensity and duration below and above which aerosol scavenging behaves differently were developed.

A higher concentration, larger *RI*, and larger particle size lead to a higher *SE*. The greater the *RI*, the higher the *SE*, meaning the precipitation *SE* on PM_{10} is better than that on $PM_{2.5}$. *RI* = 8.0 mm h^{-1} has the best *SE* on $PM_{2.5}$, and *RI* = 11.3 mm h^{-1} has the best *SE* on PM_{10} when the total precipitation is fixed. The *SR* increases faster when accumulative precipitation is below 15 mm and more slowly when accumulative precipitation is above 15 mm. When accumulative precipitation is above 50 mm, the precipitation *SR*s of $PM_{2.5}$ and PM_{10} are about 50% and 60%, respectively. The *SR* of coastal areas is less than that of inland Jiangsu. In the future, if the regional $PM_{2.5}$ concentrations continue to decrease, the threshold values would remain applicable.

The growth of the particle mass concentration after precipitation was divided into two stages: the slow growth stage about 24 h after the end of precipitation, and the rapid growth stage 24 h after the end of precipitation. The concentrations of $PM_{2.5}$ and PM_{10} increase at 0.46 and 1.35 μg m^{-3} per hour, respectively, during the rapid growth phase, while they increase at 0.07 and 0.51 μg m^{-3}, respectively, in the slow growth stage.

The methods in this study just studied the "rain-only" effect on particle aerosol removal from the atmosphere, and the influence of wind was not discussed. The present long-term and large datasets are able to quantitatively predict aerosol scavenging at any part if only the rain rate and duration are available.

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