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Key Points:

- Light precipitation with duration time less than 1 hr and amount less than 0.5 mm increases the $PM_{2.5}$ mass concentration
- Heavy precipitation with duration time less than 1 hr and amount larger than 10 mm decreases the $PM_{2.5}$ mass concentration
- With the increase of aerosol amount, $PM_{2.5}$ is more prone to decrease with precipitation

Correspondence to:

C. Zhao,
czhao@bnu.edu.cn

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Distinct Impacts of Light and Heavy Precipitation on $PM_{2.5}$ Mass Concentration in Beijing

Yue Sun¹, Chuanfeng Zhao¹, Yunfei Su¹, Zhanshan Ma¹, Jiming Li², Husi Letu³, Yikun Yang¹, and Hao Fan¹

¹College of Global Change and Earth System Science, and State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, China, ²Key Laboratory for Semi-Arid Climate Change of the Ministry of Education, College of Atmospheric Sciences, Lanzhou University, Lanzhou, China, ³State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China

Abstract Using hourly observation data of precipitation and $PM_{2.5}$ at 12 sites in Beijing from 2015 to 2017, this study investigates the impacts of different types of precipitation on $PM_{2.5}$ mass concentration, along with the characteristics of precipitation and $PM_{2.5}$. There were totally 91–123 precipitation events annually, 69.7–79.4% of which has precipitation amount less than 5 mm. By investigating the differences of $PM_{2.5}$ mass concentration between 1 hr after and before the precipitation events, this study finds distinct impacts of different types of precipitation on $PM_{2.5}$ mass concentration. For precipitation events with amount of 0.1–0.5 mm, $PM_{2.5}$ mass concentration increased with precipitation amount with a rate of 0.85 $\mu g/m^3$ per 0.1 mm. For precipitation events with amount of 0.5–10 mm, there was no clear relationship between precipitation amount and $PM_{2.5}$ mass concentration. For precipitation events with amount larger than 10 mm, $PM_{2.5}$ mass concentration decreased with precipitation amount with a rate of 0.17 $\mu g/m^3$ per 1 mm. Further analysis shows that weak precipitation less than 10 mm increased PM_{10} , and heavy precipitation larger than 10 mm decreased PM_{10} . The aerosol amount also affects the response of $PM_{2.5}$ to precipitation, with weak pollution prone to increase with precipitation and heavy pollution prone to decrease with precipitation. Likely mechanisms are discussed, which include the aerosol hygroscopic growth and gas-particle conversion that increase aerosol amount and precipitation scavenging that decreases aerosol amount. Shortly, the mechanisms that increase (decrease) aerosol amount more probably dominate when precipitation is light (heavy).

1. Introduction

With the acceleration of urbanization, air pollution has become one of the most important ecological and environmental problems in China. Among the various air pollution components, aerosol particles, particularly those with dynamic diameter less than 2.5 μm ($PM_{2.5}$), whose main pollutant sources are industrial emissions, coal burning, dust, and motor vehicle emissions, have been found as the primary contributor and studied broadly (Huang et al., 2017; Lu et al., 2018; Lv et al., 2017; Qiu et al., 2014; Song et al., 2012; Sun et al., 2018; Wang et al., 2017; Wu et al., 2017; Zhao et al., 2019).

Aerosol particles could modify the weather and climate by changing the surface radiation balance, cloud properties, and precipitation (Creamean et al., 2013; Li et al., 2011, 2016; Yang, Zhao, et al., 2018; Yang, Zhou, et al., 2018; Zhao & Garrett, 2015; Li, Lv, et al., 2017; Zhao, Li, et al., 2018; Zhao, Lin, et al., 2018). For example, by serving as cloud condensation nuclei, aerosol particles can change cloud microphysical properties and then precipitation (Albrecht, 1989; Andreae & Rosenfeld, 2008; Guo et al., 2018; Rosenfeld et al., 2008; Yang et al., 2019; Zhao, Li, et al., 2018; Zhao, Lin, et al., 2018) and radiation (Garrett & Zhao, 2006; Twomey, 1977). Furthermore, aerosol can change meteorological conditions by modifying the surface radiation balance. Aerosol direct radiation effect changes the thermodynamic stability and convective potential of the lower atmosphere, resulting in a decrease in air temperature and an increase in atmospheric stability (Andreae & Rosenfeld, 2008; Z. Li, Guo, et al., 2017; Pan et al., 2018; Yang et al., 2016).

On the other hand, the meteorology, including the planetary boundary layer (PBL), temperature, pressure, relative humidity, wind speed, wind direction, and precipitation, also exerts strong impacts on the $PM_{2.5}$ mass concentration (Chen et al., 2017; Garrett et al., 2010; Guo et al., 2019; He & Lin, 2017; He, Lin & Liu,

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2017; Li, Feng, et al., 2017; Li, Guo, et al., 2017; Lou et al., 2019; Pearce et al., 2011). The variation of PBL height governs the concentrations of atmospheric pollutants near the surface since the aerosol particles generally concentrate within the PBL height (Garratt, 1994; Guo et al., 2019; Seidel et al., 2010). $PM_{2.5}$ mass concentration has negative relationship with temperature and relative humidity while has positive relationship with pressure, by affecting the growth and transport of pollutants (Li, Feng, et al., 2017; Li, Guo, et al., 2017; Yue et al., 2016; Zhao et al., 2014). Wind is a very important meteorological factor influencing pollutants, which influence the horizontal and vertical transport of air pollutants. Moreover, wind speed has different impacts on fine and coarse particles. It was shown that the fine PM concentrations decreased gradually with the increase of wind speed, while coarse PM concentrations would increase due to dust resuspension under strong winds (X. Li, Feng, et al., 2017; B. Zhang, Jiao, et al., 2018; Zhou et al., 2003).

There are also many studies regarding the impacts of precipitation on $PM_{2.5}$. In the natural removal of pollutants, precipitation scavenging efficiency is typically much larger than dry deposition (Garrett et al., 2010), which highly correlates with a variety of atmospheric chemical components and associates with the physical and chemical processes. Precipitation scavenging includes in-cloud and below-cloud scavenging mechanisms. The three most important removal mechanisms in below-cloud-scavenging process are Brownian diffusion, interception, and inertial impaction, which wash out the aerosol particles from the atmosphere (Mircea et al., 2000; Rodhe & Grandell, 1972; Yao et al., 1999). In-cloud-scavenging process is that aerosol particles enter the cloud as cloud condensation nuclei and grow into raindrops that land on the ground. Previous study showed that the scavenging efficiency of urban aerosol is higher than that of rural, remote continental, and marine aerosol, especially remote continental and marine aerosol (Mircea et al., 2000). Dong et al. (2016) and B. Zhang, Jiao, et al. (2018) showed that the efficiency of precipitation scavenging to $PM_{2.5-10}$ was more than twice as that to $PM_{2.5}$. The precipitation amount also shows a great influence on scavenging efficiency (Han et al., 2019; Luan et al., 2019; Mircea et al., 2000). Relatively intense precipitation events were more efficient in removing the polluted aerosols in the atmosphere (Andronache, 2003; Chate, 2005; Loosmore & Cederwall, 2004; Luan et al., 2019; Mircea et al., 2000; Yao et al., 1999). In general, the precipitation scavenging efficiency depends on various influential factors including both aerosol and cloud properties. Many studies regarding precipitation scavenging efficiency have focused on the relationship of the particle diameter, size distribution, aerosol types, precipitation intensity, and precipitation scavenging efficiency (Chate, 2005; Hales & Dana, 1978; Han et al., 2019; Luan et al., 2019; Mircea et al., 2000). However, previous studies did not consider the diurnal variation of $PM_{2.5}$ mass concentration, which is a very important factor that cannot be ignored. Particularly, there are generally obvious diurnal variation in the PBL, making $PM_{2.5}$ likely vary a lot with time in a day, which will make it challenging to identify the precipitation scavenging effect from the natural diurnal variation of $PM_{2.5}$ when precipitation occurs. Moreover, few studies have investigated the potential changes about the precipitation effects on $PM_{2.5}$ with magnitudes of precipitation and pollution. This study tries to answer this question by analyzing the changes of $PM_{2.5}$ between before and after precipitation in Beijing. Beijing ($39^{\circ}26' - 41^{\circ}03' N$, $115^{\circ}25' - 117^{\circ}30' E$) was chosen here simply because it is the political, economic, and cultural center of China, and its pollution status has been paid close attentions during recent years.

The paper is organized as follows. Section 2 describes the data and method used in this study. Section 3 shows the analysis and results. The summary and discussion are provided in section 4.

2. Data and Methods

2.1. Data

This study takes use of the hourly precipitation and $PM_{2.5}$ observation data from 2015 to 2017 obtained at 12 sites in Beijing, including Wanshouxigong (WSXG), Dingling (DL), Dongsi (DS), Tiantan (TT), Nongzhanguan (NZG), Guanyuan (GY), Haidian Wanliu (HDWL), Shunyi Xincheng (SYXC), Huairou Town (HRT), Changping Town (CPT), Olympic Sports Center (OSC), and Gucheng (GC), as shown in Figure 1. The hourly China Merged Precipitation Analysis Version 1.0 product is used in this study, which is obtained from the national automatic weather stations and Climate Precipitation Center Morphing product (Tian et al., 2019). This product has a spatial resolution of 0.1° and a temporal resolution of 1 hr in China. The hourly precipitation product is downloaded online (<ftp://nwpc.nmc.cn>), and the hourly $PM_{2.5}$

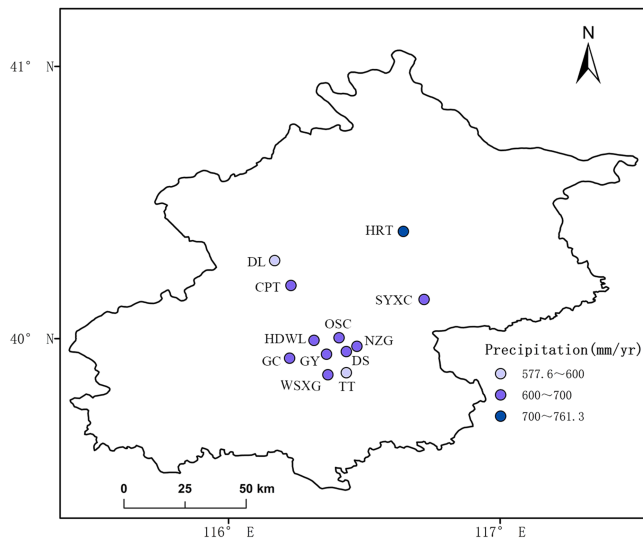


Figure 1. The distribution of 12 meteorological sites in Beijing with annual precipitation amount during the study period.

and PM_{10} data at 12 sites are downloaded from <http://beijingair.sinaapp.com>. Note that the $PM_{2.5}$ and PM_{10} data website is provided by the China Environmental Monitoring Station of the national air quality real-time release platform with data quality assurance.

2.2. Analysis Method

The impact of precipitation on $PM_{2.5}$ is studied here by calculating the changes of $PM_{2.5}$ between 1 hr after and before the precipitation event, which is

$$R = PM_{2.5\text{endtime}} - PM_{2.5\text{starttime}}, \quad (1)$$

where R is the change of $PM_{2.5}$ mass concentration between 1 hr after and before precipitation, $PM_{2.5\text{endtime}}$ is the $PM_{2.5}$ at time 1 hr after the precipitation, and the $PM_{2.5\text{starttime}}$ is the $PM_{2.5}$ at time 1 hr before the precipitation. A precipitation event is defined as the event that precipitation continuously exists in all adjacent hours. Once there is no precipitation for 1 hr or more, new precipitation event will be searched. Similar methods have been used by previous studies. For example, Luan et al. (2019) defined R as the change of $PM_{2.5}$ mass concentration between time during and before the rain; Feng and Wang (2012) and Olszowski (2016) defined R as the change of $PM_{2.5}$ mass concentration between time after and

before the rain. To exclude the impact of natural daily changes of $PM_{2.5}$ mass concentration, we only choose precipitation events with duration time no more than 1 hr. It should be more reasonable than the method defined by Luan et al. (2019) due to constraining the precipitation events within 1 hr. The impact of precipitation on PM_{10} is also studied with the similar method by calculating the changes of PM_{10} between 1 hr after and before the precipitation event, which is

$$R_{10} = PM_{10\text{endtime}} - PM_{10\text{starttime}}, \quad (2)$$

where R_{10} is the change of PM_{10} mass concentration between 1 hr after and before precipitation, $PM_{10\text{endtime}}$ is the PM_{10} at time 1 hr after the precipitation, and the $PM_{10\text{starttime}}$ is the PM_{10} at time 1 hr before the precipitation.

For the selected precipitation cases, we classify the precipitation into four types according to precipitation amount, which are 0–1, 1–10, 10–20, and 20–50 mm with sample numbers of 1,021, 2,637, 357, and 71, respectively. Noting that there are different sample volumes for different types of precipitation, we further classify each type of precipitation into different number of bins for statistical analysis. Table 1 shows the details of the classification. The changes of $PM_{2.5}$ and PM_{10} by precipitation are analyzed for every type of precipitation using equations (1) and (2).

3. Analysis and Results

3.1. Precipitation Characteristics in Beijing

Figure 1 shows that the annual average precipitation amount in unit of millimeters for the period of 2015–2017 over all sites in Beijing, which was generally 577.6–761.4 mm. The average precipitation amount for

all sites during the study period was 639.6 mm. Among all sites, the precipitation at HRT site was the maximum with the annual average precipitation above 700 mm. Compared to other sites, the precipitation amounts at DL and TT sites were relatively low with the annual average precipitation less than 600 mm. In general, the precipitation amount for a precipitation event in the study region was 0.02–331.2 mm. Figure 2 shows the maximum and minimum precipitation amounts for all precipitation events at every site during the study period. There are significant differences in the precipitation amount for the maximum precipitation events among the sites. The minimum precipitation amount of each site was less 0.12 mm, which was generally similar in absolute values among the sites.

Table 1
Classification of Four Precipitation Types With Different Precipitation Amount, Which Has Different Sample Volume

Precipitation amount (mm)	Bin width (mm)	Sample volume
$0 < P \leq 1$	0.1	1,021
$1 < P \leq 10$	1	2,637
$10 < P \leq 20$	2	357
$20 < P \leq 50$	5	71

Note. For every type of precipitation, it is further classified into 10, 10, 5, and 6 bins, respectively, with different bin width.

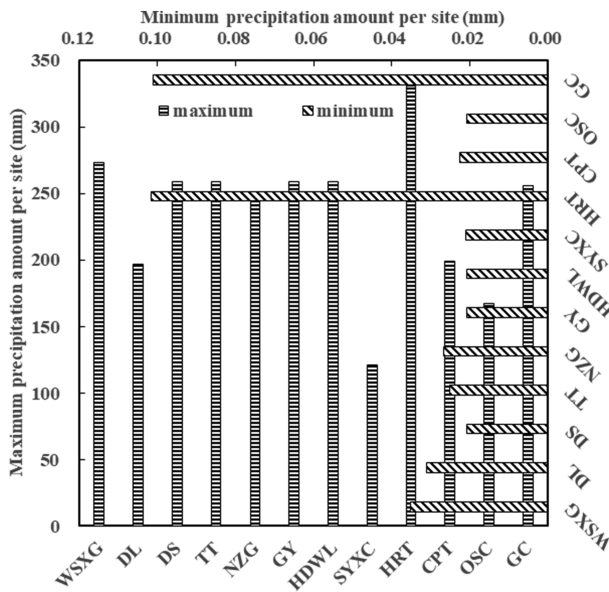


Figure 2. The maximum (the left and low axis) and minimum (the right and up axis) precipitation amount in Beijing per site during the study period. The horizontal line is the maximum precipitation amount in Beijing per site during the study period, and the wide diagonal is the minimum.

than 20% and 5%, respectively. These results imply that the precipitation in Beijing was dominated by light precipitation events.

We also examine the relationship between precipitation amount and duration time of precipitation events at 12 sites in Beijing for the time period 2015–2017, which is shown in Figure 5. To limit the potential errors from binning method, the data have been analyzed in Figure 5 only when sample volume of precipitation events for each 1-hr duration time bin is more than 50. In general, there was a good positive correlation ($r = 0.68$, $p < 0.05$) between the amount of precipitation and the duration time of precipitation. Quantitatively, the precipitation amount increased about 1.5 mm for an increase of 1-hr precipitation duration time when precipitation amount was less than 50 mm.

Figures 2–5 show the characteristics of precipitation in Beijing during the study period, with light precipitation and short-term precipitation dominating: 70% of all precipitation events are with precipitation amount less than 5 mm, and 61% of all precipitation events are with duration time no more than 1 hr. The different types of precipitation events could have different impacts on the $PM_{2.5}$ mass concentration, which will be investigated in section 3.3.

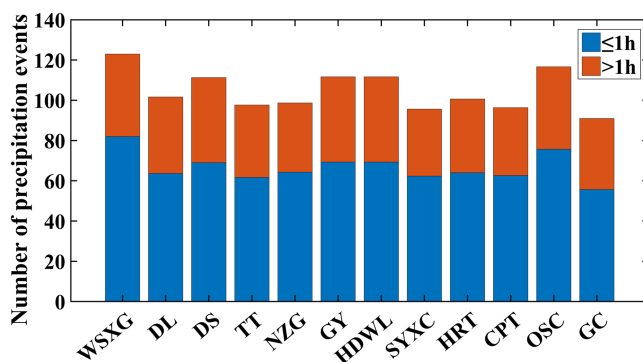


Figure 3. The annual average times of precipitation events at 12 sites in Beijing, including precipitation events with duration time both less than 1 hour and longer than 1 hour. The blue bars represent the number of precipitation events with duration time less than 1 hour, and the red bars represent the number of precipitation events with duration time longer than 1 hour.

The precipitation amounts for the most serious precipitation events at every station were 121.2–331.2 mm, with the largest value at HRT and the smallest value at SYXC.

Figure 3 shows the annual average number of precipitation events at 12 sites, including precipitation events with duration time less than 1 hr and longer than 1 hr. There are 91–123 precipitation events annually in Beijing, with the most frequent precipitation occurrence at WSXG and the least frequent occurrence at GC. For most sites, there were more than 60% short-term precipitation events with duration time less than 1 hr. The all-site average ratio of precipitation events with duration time less than 1 hr to total was 61%, with the largest value of 67% at WSXG.

Figure 4 further shows the normalized probability distribution function of precipitation with different precipitation amount during the period 2015–2017. Around 50% precipitation events were light precipitation with amount less than 1 mm. Specifically, the probability of precipitation with amount less than 1 mm was more than 40% for all 12 sites, and the probability of precipitation with amount less than 1 mm was even more than 50% at NZG, HDWL, and OSC. Accumulatively, the annual average probabilities of precipitation events with amount less than 5 and 10 mm were 69.7–79.4% and 78.7–89.4%, respectively. In contrast, the probabilities of precipitation events with amount larger than 10 and 50 mm were generally less

3.2. Characteristics of $PM_{2.5}$ in Beijing

Figure 6 shows the temporal variations of annual and seasonal average $PM_{2.5}$ mass concentrations at 12 sites in Beijing for the time period 2015–2017. For all observation sites, it was clear that the annual average $PM_{2.5}$ mass concentration decreased in the recent 3 years, implying the gradually improving air quality in Beijing. Combined with Figure 1, we can find that the $PM_{2.5}$ mass concentration in the north of Beijing was obviously lower than that in other areas, which is associated with terrain, meteorological conditions, and ecosystem. For example, mountains lie in the north and west of Beijing while there are plains in the middle and east, which facilitates the transport of pollutants from north to south by valley wind, especially during nighttime (Li et al., 2015; Xin et al., 2010; Zhao et al., 2014; Zhou et al., 2003). Xu et al. (2004) showed that pollutants from cities around

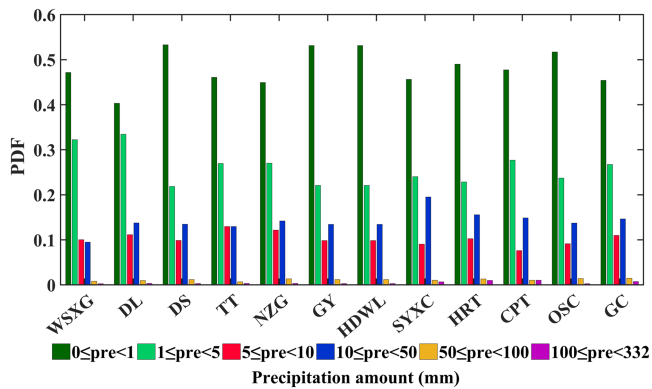


Figure 4. The probability distribution function (PDF) of precipitation amount with different precipitation levels over 12 sites during the years 2015–2017yr. The deep green, light green, red, blue, yellow, and purple represent precipitation amount 0–1 mm, 1–5 mm, 5–10 mm, 10–50 mm, 50–100 mm, and 100–332 mm, respectively.

tion makes corresponding variations of mixed boundary layer height, further causing $PM_{2.5}$ mass concentration high at night and low at noon. The combination of anthropogenic activities and mixed boundary layer height diurnal variation could make $PM_{2.5}$ diurnal variation different in each season. In winter, the diurnal variation of $PM_{2.5}$ mass concentration was the strongest with high values at night and low values in day time. The maximum $PM_{2.5}$ mass concentration occurred at around 22:00 local time with a value of $108 \mu\text{g}/\text{m}^3$, and the minimum $PM_{2.5}$ mass concentration occurred near noon time with a value of $73 \mu\text{g}/\text{m}^3$. In contrast, the bimode diurnal variation patterns were found in spring, summer, and autumn, with maximum values at both night and near noon time and minimum values in the morning and evening time. Specifically, the maximum $PM_{2.5}$ mass concentration occurred around noon time with a value of $58 \mu\text{g}/\text{m}^3$ in summer, around 10:00 with a value of $73 \mu\text{g}/\text{m}^3$ in spring and around 20:00 with a value of $79 \mu\text{g}/\text{m}^3$ in autumn. The minimum $PM_{2.5}$ mass concentration occurred around 18:00 with a value of $49 \mu\text{g}/\text{m}^3$ in summer, around 18:00 with a value $59 \mu\text{g}/\text{m}^3$ in spring, and around 7:00 with a value of $60 \mu\text{g}/\text{m}^3$ in autumn. The bimodal diurnal pattern of $PM_{2.5}$ in summer is associated with the solar radiation, which determines the diurnal variation of PBL height, anthropogenic emissions, and hygroscopic growth (Liu et al., 2015; Zhao et al., 2009). The peak value at night should be more associated with the low PBL height at night, while the peak value at noon is more likely caused by the hygroscopic growth of fine aerosols.

We can also find from Figure 7 that the magnitude of diurnal variation of $PM_{2.5}$ was the largest in winter and smallest in summer, with that in spring and autumn as between. The magnitude of diurnal variation was slightly larger in autumn than in spring. From spring to winter, the magnitude of diurnal variation was 13.2, 8.6, 18.5, and $35.2 \mu\text{g}/\text{m}^3$ in turn. In the next section, when we analyze the change of $PM_{2.5}$ between before and after precipitation, the natural diurnal variation of $PM_{2.5}$ may also contribute to the change of $PM_{2.5}$. In order to reduce the uncertainty caused by diurnal variation of $PM_{2.5}$, we only select precipitation with duration time no more than 1 hr as the research object.

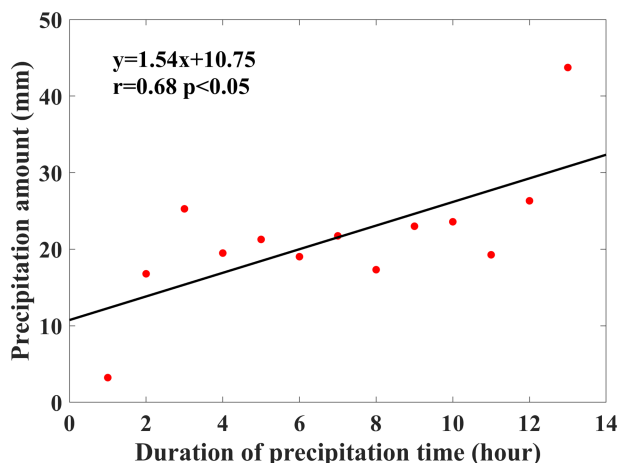


Figure 5. Change of the precipitation amount with duration time of precipitation among the 12 sites during the study period.

southern Beijing cannot be transported efficiently long distance due to the terrain. Due to the dry air mass from Siberia, the main wind direction in winter is north and northwest in Beijing, which causes the pollutants to be transported to the south of Beijing with the flow (Zhao et al., 2014). Figure 6 also shows that the seasonally average $PM_{2.5}$ mass concentrations decreased with time for all four season. Note that the decreasing trends of $PM_{2.5}$ is the strongest in winter and the weakest in summer. The reduction in pollutant emission was the primary cause for the decrease in $PM_{2.5}$ mass concentration and other pollutants such as SO_2 and NO_2 (Z. Zhang, Ma, et al., 2018).

We also investigated the diurnal variation of hourly average $PM_{2.5}$ in spring, summer, autumn, and winter during the study period, which is shown in Figure 7. The $PM_{2.5}$ mass concentration showed significant different diurnal variations in all seasons, which is associated with anthropogenic activities, atmospheric mixing and dilution by vertical convection, and so on (Chen et al., 2015; Li et al., 2015; Liu et al., 2015, 2006; Zhao et al., 2009). For example, the diurnal variation of solar radiation

3.3. Impacts of Precipitation on $PM_{2.5}$

We here investigate the impacts of precipitation on $PM_{2.5}$ mass concentration by analyzing the differences of $PM_{2.5}$ between 1 hr before and 1 hr after the precipitation. After several tests of the threshold values, we find that 0.5 and 10 mm were the turning points for precipitation impacts on $PM_{2.5}$. The threshold values generally depend on the aerosol type strongly, making them different in various locations (Mircea et al., 2000; Svenningsson et al., 2006). To identify the impacts on $PM_{2.5}$ from different types of precipitation, we then

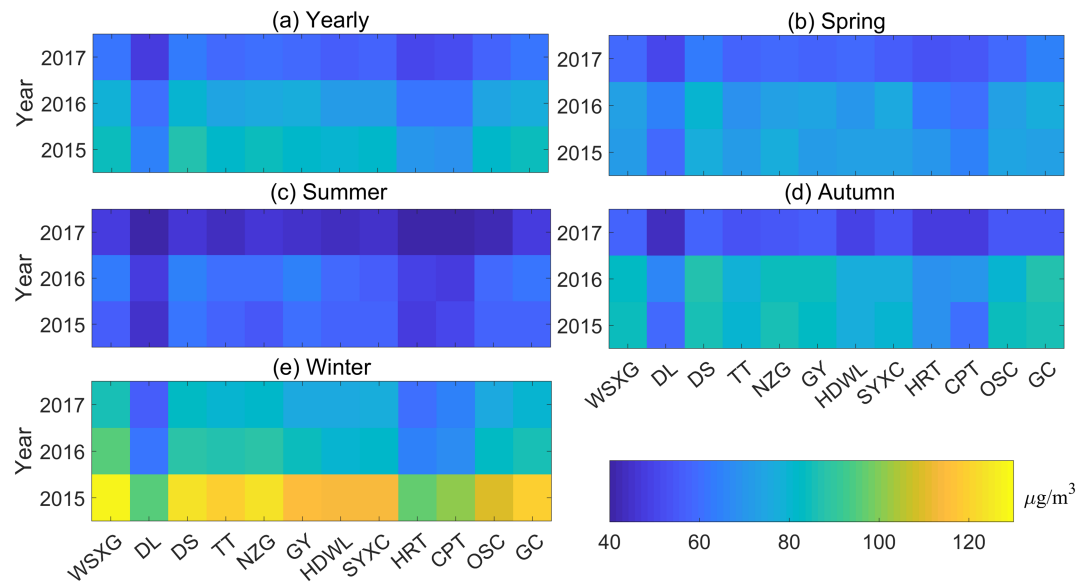


Figure 6. The temporal variations of (a) annual and (b), (c), (d), (–e) seasonal averaged PM_{2.5} mass concentration at 12 sites in Beijing during the study period.

classify the precipitation events into three types based on these two threshold values, which are 0–0.5, 0.5–10, and 10–50 mm in precipitation amount.

Figure 8 shows the change of PM_{2.5} between 1 hr after and 1 hr before precipitation with precipitation amount. The impact of precipitation on PM_{2.5} mass concentration was completely different for three types of precipitation. As shown in Figure 8a, for precipitation with amount 0–0.5 mm, the PM_{2.5} mass concentration increased with increasing precipitation amount. This positive linear relationship was significant with $r = +0.91$ and p value less than 0.05. This observational phenomenon is likely associated with the hygroscopic growth of aerosol particles and the gas-particle conversion (secondary formation) of aerosols. While the precipitation scavenging might reduce the aerosol amount, the weak precipitation limits its significance. Instead, the hygroscopic growth and secondary formation of aerosols dominate the change of PM_{2.5}, making it increase with precipitation amount (Su et al., 2016; Wu et al., 2018). Quantitatively, for a 0.1-mm increase of precipitation amount, the PM_{2.5} mass concentration increased by 0.85 $\mu\text{g}/\text{m}^3$.

As shown in Figure 8b, for precipitation with amount 0.5–10 mm, the PM_{2.5} mass concentration shows no clear relationship with the precipitation amount. While it seemed that PM_{2.5} mass concentration increased with the precipitation amount, the increasing trend was weak, and the correlation was quite poor. It is likely

that the precipitation scavenging effect increases with the increasing precipitation amount, which competes with the effect of hygroscopic growth and secondary formation of aerosols (Kulmala et al., 2000, 2004, 2005; Zhang et al., 2014; Zhao, Li, et al., 2018), making the relationship between PM_{2.5} and precipitation amount unclear for this type of precipitation.

Figure 8c shows that the PM_{2.5} mass concentration decreased clearly with increasing precipitation for the precipitation events with amount 10–50 mm. The negative relationship was significant at a confidence level of 95% with a strong correlation coefficient ($r = -0.68$, $p < 0.05$) between the PM_{2.5} mass concentration and the precipitation amount. For every 10-mm increase of precipitation amount, the PM_{2.5} mass concentration was reduced by 1.7 $\mu\text{g}/\text{m}^3$. For these relatively heavy precipitation events, the precipitation scavenging effect plays the dominant role, making the PM_{2.5} mass

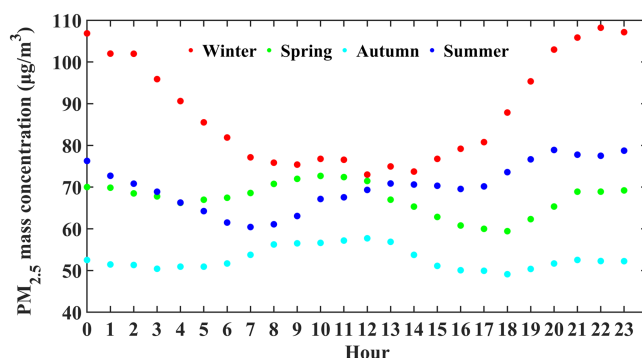


Figure 7. The diurnal variation of hourly averaged PM_{2.5} mass concentration in spring, summer, autumn, and winter during the study period in Beijing.

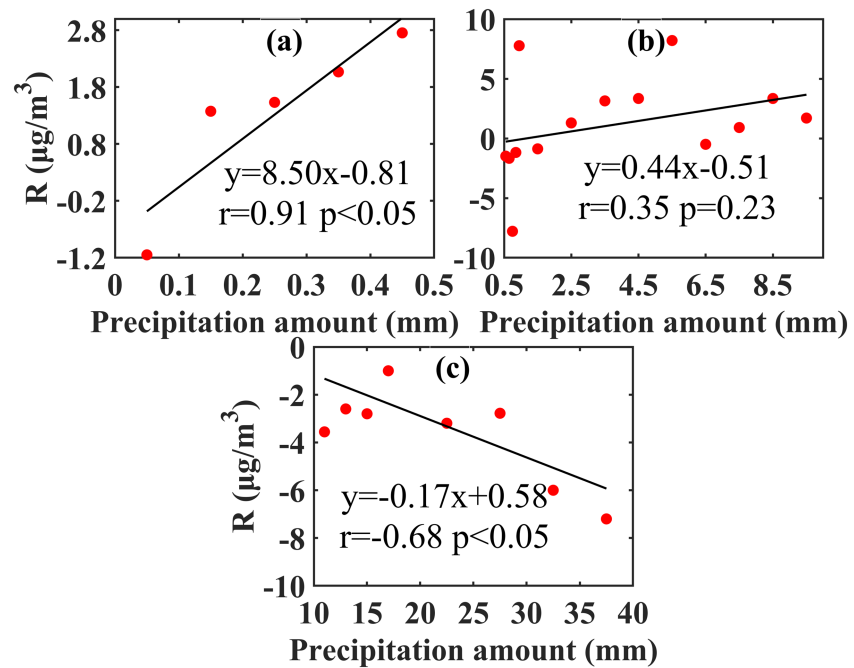


Figure 8. The change of R with precipitation amount change for three different ranges, along with the linear fitting regression: (a) 0–0.5 mm, (b) 0.5–10 mm, (c) 10–50 mm. The R is the change of $\text{PM}_{2.5}$ mass concentration between 1 hour after and before precipitation.

concentration decrease with precipitation amount (Loosmore & Cederwall, 2004; Luan et al., 2019; Mircea et al., 2000). We use the same method to investigate the impacts of precipitation on PM_{10} mass concentration. After several tests of the threshold values, we find that 10 mm was the turning point for precipitation impacts on PM_{10} . We then classify the precipitation events into two types based on this threshold value, which were 0–10 and 10–50 mm in precipitation amount. Figure 9 shows the change of PM_{10} between 1 hr after and 1 hr before precipitation with precipitation amount. As shown in Figure 9a, for precipitation with amount 0–10 mm, PM_{10} mass concentration roughly increased with the precipitation amount ($r = 0.56$, $p < 0.05$). The phenomenon may also be due to the fact that precipitation scavenging effect competes with the effect of hygroscopic growth and secondary formation of aerosols, making the relationship between PM_{10} and precipitation amount complicated.

Figure 9b shows that the PM_{10} mass concentration decreases clearly with increasing precipitation for the precipitation events with amount 10–50 mm. The negative relationship was significant with a strong correlation

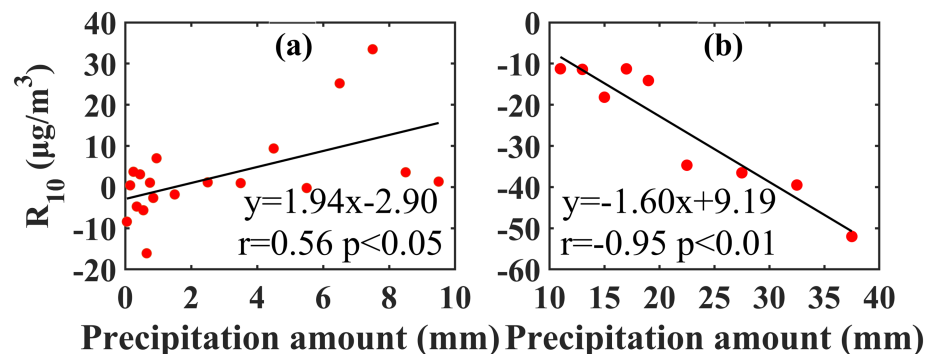


Figure 9. Variation of R_{10} with the precipitation amount for two different ranges, along with the linear fitting regression: (a) 0–10 mm, (b) 10–50 mm. The R_{10} is the change of PM_{10} mass concentration between 1 hour after and before precipitation.

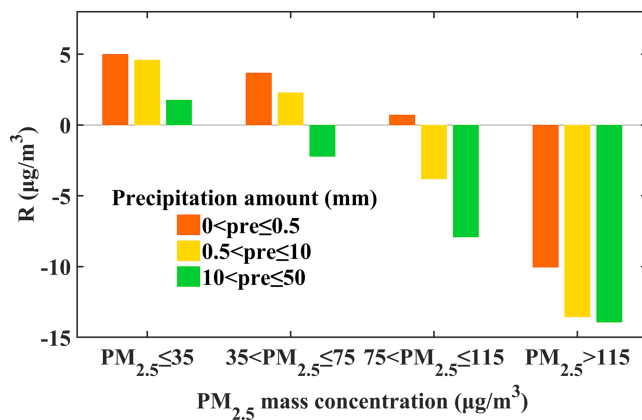


Figure 10. The R value of three types of precipitation on $PM_{2.5}$ mass concentration during the same $PM_{2.5}$ mass concentration interval. The R is the change of $PM_{2.5}$ mass concentration between 1 hour after and before precipitation.

coefficient ($r = -0.95$, $p < 0.01$) between the PM_{10} mass concentration and the precipitation amount. For every 10-mm increase of precipitation amount, the PM_{10} mass concentration was reduced by $4.0 \mu\text{g}/\text{m}^3$, 11% of which was the $PM_{2.5}$ mass concentration. This indicates that precipitation is more efficient for the scavenging of large particles, such as $PM_{2.5-10}$ (Dong et al., 2016; Loosmore & Cederwall, 2004).

3.4. The Effect of $PM_{2.5}$ Mass Concentration on Precipitation Scavenging Efficiency

In order to study the relationship between the different effects of precipitation on $PM_{2.5}$ and the $PM_{2.5}$ mass concentration before precipitation, we selected the $PM_{2.5}$ mass concentration data at time 1 hr before precipitation and divided them into four groups: $0 < PM_{2.5} \leq 35$, $35 < PM_{2.5} \leq 75$, $75 < PM_{2.5} \leq 115$, and $PM_{2.5} > 115 \mu\text{g}/\text{m}^3$, representing clean, semiclean, semipollution, and pollution condition, respectively. Under different pollution conditions, the precipitations

are also divided into three groups using the two threshold values classified earlier, which are 0–0.5, 0.5–10, and 10–50 mm in precipitation amount.

Figure 10 shows the relationship between the $PM_{2.5}$ mass concentration before precipitation and the impacts of different types of precipitation on $PM_{2.5}$ under different pollution conditions. It shows that the different impacts of precipitation on $PM_{2.5}$ were related to the $PM_{2.5}$ mass concentration before precipitation. When the $PM_{2.5}$ mass concentration before precipitation was $\leq 35 \mu\text{g}/\text{m}^3$, all types of precipitation, even including heavy precipitation, can enhance $PM_{2.5}$ mass concentration, with an average increase of $PM_{2.5}$ mass concentration by 1.76 – $5.00 \mu\text{g}/\text{m}^3$. For light pollution cases, precipitation is less likely to scavenge aerosol particles by collision due to few aerosol particles under clean conditions (Chate, 2005; Dong et al., 2016). In contrast, the hygroscopic growth of aerosol particles and the gas-particle conversion or secondary formation of aerosols promote $PM_{2.5}$ mass concentration (Su et al., 2016; Wu et al., 2018; Zhao, Li, et al., 2018; Zhao, Qiu, et al., 2018). For $PM_{2.5}$ mass concentration in the range of 35 – $75 \mu\text{g}/\text{m}^3$, the light precipitation with amount 0–10 mm can enhance $PM_{2.5}$ mass concentration with an average increase of $PM_{2.5}$ mass concentration by 2.28 – $3.68 \mu\text{g}/\text{m}^3$; however, the heavy precipitation with amount 10–50 mm can scavenge aerosol particles and make $PM_{2.5}$ mass concentration decrease while the scavenging efficiency was relatively low. For the $PM_{2.5}$ mass concentration in the range of 75 – $115 \mu\text{g}/\text{m}^3$, the scavenging efficiency also increased with precipitation amount. The scavenging efficiency was negligible under cases with 0–0.5-mm precipitation amount, while significant when precipitation amount was larger than 0.5 mm. When the $PM_{2.5}$ mass concentration was $> 115 \mu\text{g}/\text{m}^3$, the scavenging efficiency also increased with precipitation amount. The above results show that the more the aerosols and the heavier the precipitation (for large precipitation), the higher the scavenging efficiency under normal circumstances (Loosmore & Cederwall, 2004).

We should note that precipitation scavenging is indeed related to many factors, such as precipitation amount, precipitation intensity, aerosol particle numbers, and winds. Precipitation is often accompanied by winds, which can also help reduce the $PM_{2.5}$. As indicated earlier, by limiting our study to precipitation with duration time no more than 1 hr, we could reduce uncertainties caused by factors other than precipitation. Of course, uncertainties could still exist, which is beyond the scope of current study. Shortly, this study did not discuss in depth the effects of various meteorological factors on the precipitation scavenging. Instead, we try to find out the statistical relationship between the precipitation amount and $PM_{2.5}$ mass concentration from the observational view.

4. Summary and Discussion

This study first examines the characteristics of precipitation and $PM_{2.5}$ and then focuses on the impacts of different types of precipitation on $PM_{2.5}$ mass concentration using the hourly observation of precipitation and $PM_{2.5}$ at 12 sites in Beijing from 2015 to 2017. It shows that there was 577.6 – 761.4 mm/year precipitation amount during the study period. Precipitation events were totally 91–123 annually with a big difference in

precipitation amount per event in Beijing. Almost 50% precipitation events were precipitation with amount less than 1 mm, with the probability of less than 5-mm precipitation between 69.7% and 79.4%. The precipitation in Beijing was dominated by light precipitation events, and more than 60% precipitation events were short-term precipitation with duration time less than 1 hr. The annual average $PM_{2.5}$ mass concentration was $57.3\text{--}76.6\text{ }\mu\text{g}/\text{m}^3$ during the study period and decreased yearly in Beijing with better air quality in suburban North Beijing area than that in south Beijing region. The seasonal variation of $PM_{2.5}$ mass concentration was clear, high in winter and low in summer. Clear diurnal variation of $PM_{2.5}$ mass concentration also existed, which was the most obvious in winter.

By investigating the changes of $PM_{2.5}$ mass concentration between 1 hr after and before the precipitation events, the impacts of precipitation on $PM_{2.5}$ have been investigated. It is found that there are clear differences regarding the impacts of precipitation on $PM_{2.5}$ mass concentration for different types of precipitation. For precipitation events with amount of 0.1–0.5 mm, $PM_{2.5}$ mass concentration increased with precipitation amount with a rate of $0.85\text{ }\mu\text{g}/\text{m}^3$ per 0.1 mm ($r = +0.91$, $p < 0.05$). For precipitation events with amount of 0.5–10 mm, there were no clear relationships between precipitation amount and $PM_{2.5}$ mass concentration. For precipitation events with amount larger than 10 mm, $PM_{2.5}$ mass concentration significantly decreased with precipitation amount with a rate of $0.17\text{ }\mu\text{g}/\text{m}^3$ per 1 mm. When the precipitation is light, aerosol hygroscopic growth and gas-particle conversion increase aerosol amount. When the precipitation is heavy, precipitation can scavenge aerosol particles more efficiently to decrease $PM_{2.5}$ mass concentration.

The impacts of different types of precipitation on $PM_{2.5}$ mass concentration are also related to the actual $PM_{2.5}$ mass concentration. Different types of precipitation are found to all enhance $PM_{2.5}$ mass concentration under clean conditions. With the increase of aerosol pollution, the scavenging efficiency also increases, making $PM_{2.5}$ more prone to decrease. In a short summary, the more aerosol particles and the more precipitation, the higher the scavenging efficiency, which make the $PM_{2.5}$ mass concentration prone to decrease. We should note that this study has not taken different meteorological factors into account, for example, winds. Further study about the impacts from other meteorological factors on $PM_{2.5}$ is demanded in future.

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References

- Albrecht, B. A. (1989). Aerosols, cloud microphysics, and fractional cloudiness. *Science*, 245(4923), 1227–1230. <https://doi.org/10.1126/science.245.4923.1227>
- Andreae, M. O., & Rosenfeld, D. (2008). Aerosol-cloud-precipitation interactions. Part 1. The nature and sources of cloud-active aerosols. *Earth-Science Reviews*, 89(1–2), 13–41. <https://doi.org/10.1016/j.earscirev.2008.03.001>
- Andronache, C. (2003). Estimated variability of below-cloud aerosol removal by rainfall for observed aerosol size distributions. *Atmospheric Chemistry and Physics*, 3(1), 131–143. <https://doi.org/10.5194/acp-3-131-2003>
- Chate, D. M. (2005). Study of scavenging of submicron-sized aerosol particles by thunderstorm rain events. *Atmospheric Environment*, 39(35), 6608–6619. <https://doi.org/10.1016/j.atmosenv.2005.07.063>
- Chen, W., Tang, H. Z., & Zhao, H. M. (2015). Diurnal, weekly and monthly spatial variations of air pollutants and air quality of Beijing. *Atmospheric Environment*, 119, 21–34. <https://doi.org/10.1016/j.atmosenv.2015.08.040>
- Chen, Z. Y., Cai, J., Gao, B. B., Xu, B., Dai, S., He, B., & Xie, X. M. (2017). Detecting the causality influence of individual meteorological factors on local $PM_{2.5}$ concentration in the Jing-Jin-Ji region. *Scientific Reports*, 119, 21–34. <https://doi.org/10.1016/j.atmosenv.2015.08.040>
- Creamean, J. M., Suski, K. J., Rosenfeld, D., Cazorla, A., DeMott, P. J., Sullivan, R. C., et al. (2013). Dust and biological aerosols from the Sahara and Asia influence precipitation in the Western U.S. *Science*, 339(6127), 1572–1578. <https://doi.org/10.1126/science.1227279>
- Dong, Q., Zhao, P. S., & Chen, Y. N. (2016). Impact of collision removal of rainfall on aerosol particles of different sizes. *Environmental Sciences*, 37(10), 3686–3692. <https://doi.org/10.13227/j.hjx.2016.10.002>
- Feng, X., & Wang, S. (2012). Influence of different weather events on concentrations of particulate matter with different sizes in Lanzhou, China. *Journal of Environmental Sciences*, 24(4), 665–674. [https://doi.org/10.1016/S1001-0742\(11\)60807-3](https://doi.org/10.1016/S1001-0742(11)60807-3)
- Garratt, J. R. (1994). The atmospheric boundary layer. *Earth Science Reviews*, 37(1–2), 89–134. [https://doi.org/10.1016/0012-8252\(94\)90026-4](https://doi.org/10.1016/0012-8252(94)90026-4)
- Garrett, T. J., & Zhao, C. (2006). Increased Arctic cloud longwave emissivity associated with pollution from mid-latitudes. *Nature*, 440(7085), 787–789. <https://doi.org/10.1038/nature04636>
- Garrett, T. J., Zhao, C., & Novelli, P. (2010). Assessing the relative contributions of transport efficiency and scavenging to seasonal variability in Arctic aerosol. *Tellus Series B: Chemical and Physical Meteorology*, 62(3), 190–196. <https://doi.org/10.1111/j.1600-0889.2010.00453.x>
- Guo, J., Li, Y., Cohen, J. B., Li, J., Chen, D., Xu, H., et al. (2019). Shift in the temporal trend of boundary layer height in China using long-term (1979–2016) radiosonde data. *Geophysical Research Letters*, 46, 6080–6089. <https://doi.org/10.1029/2019GL082666>
- Guo, J., Liu, H., Li, Z., Rosenfeld, D., Jiang, M., Xu, W., et al. (2018). Aerosol-induced changes in the vertical structure of precipitation: a perspective of TRMM precipitation radar. *Atmospheric Chemistry and Physics*, 18(18), 13,329–13,343. <https://doi.org/10.5194/acp-18-13329-2018>
- Hales, J. M., & Dana, M. T. (1978). Precipitation scavenging of urban pollutants by convective storm systems. *Journal of Applied Meteorology*, 18(3), 294–316. [https://doi.org/10.1175/1520-0450\(1979\)018<0294:PSOUPB>2.0.CO;2](https://doi.org/10.1175/1520-0450(1979)018<0294:PSOUPB>2.0.CO;2)
- Han, X. D., Li, H. J., Liu, Q., Liu, F. Z., & Arif, A. (2019). Analysis of influential factors on air quality from global and local perspectives in China. *Environmental Pollution*, 248, 965–979. <https://doi.org/10.1016/j.envpol.2019.02.096>

- He, X., & Lin, Z. S. (2017). Interactive effects of the influencing factors on the changes of $PM_{2.5}$ concentration based on GAM model. *Environmental Science*, 38(1), 22–32. <https://doi.org/10.13227/j.hjx.201606061>
- He, X., Lin, Z. S., & Liu, H. Y. (2017). Analysis of influencing factors and system evolution of $PM_{2.5}$ concentration change based on statistical dynamic inversion model. *Ecology and Environmental Sciences (in Chinese)*, 26(11), 1916–1923. <https://doi.org/10.16258/j.cnki.1674-5906.2017.11.012>
- Huang, X. J., Liu, Z. R., Liu, J. Y., Hu, B., Wen, T. X., Tang, G. Q., et al. (2017). Chemical characterization and source identification of $PM_{2.5}$ at multiple sites in the Beijing-Tianjin-Hebei region, China. *Atmospheric Chemistry and Physics*, 17(21), 12,941–12,962. <https://doi.org/10.5194/acp-17-12941-2017>
- Kulmala, M., Petaja, T., Monkkonen, P., Koponen, I. K., DalMaso, M., Aalto, P. P., et al. (2005). On the growth of nucleation mode particles: Source rates of condensable vapor in polluted and clean environments. *Atmospheric Chemistry and Physics*, 5(2), 409–416. <https://doi.org/10.5194/acp-5-409-2005>
- Kulmala, M., Pirjola, L., & Makela, J. M. (2000). Stable sulphate clusters as a source of new atmospheric particles. *Nature*, 404(6773), 66–69. <https://doi.org/10.1038/35003550>
- Kulmala, M., Vehkamäki, H., Petaja, T., Dal Maso, M., Lauri, A., Kerminen, V.-M., et al. (2004). Formation and growth rates of ultrafine atmospheric particles: A review of observations. *Journal of Aerosol Science*, 35(2), 143–176. <https://doi.org/10.1016/j.jaerosci.2003.10.003>
- Li, J., Lv, Q., Zhang, M., Wang, T., Kawamoto, K., Chen, S., & Zhang, B. (2017). Effects of atmospheric dynamics and aerosols on the fraction of supercooled water clouds. *Atmospheric Chemistry and Physics*, 17, 1847–1863.
- Li, R. K., Li, Z. P., Gao, W. J., Ding, W. J., Xu, Q., & Song, X. F. (2015). Diurnal, seasonal, and spatial variation of $PM_{2.5}$ in Beijing. *Science Bulletin*, 60(3), 387–395. <https://doi.org/10.1007/s11434-014-0607-9>
- Li, X., Feng, Y. J., & Liang, H. Y. (2017). The impact of meteorological factors on $PM_{2.5}$ variations in Hong Kong. *Earth and Environmental Science*, 78, 012003. <https://doi.org/10.1088/1755-1315/78/1/012003>
- Li, Z., Guo, J., Ding, A., Liao, H., Liu, J., Sun, Y., et al. (2017). Aerosol and boundary-layer interactions and impact on air quality. *National Science Review*, 4(6), 810–833. <https://doi.org/10.1093/nsr/nwx117>
- Li, Z. Q., Lau, W. K. M., Ramanathan, V., Wu, G., Ding, Y., Manoj, M. G., et al. (2016). Aerosol and monsoon climate interactions over Asia. *Reviews of Geophysics*, 54, 866–929. <https://doi.org/10.1002/2015RG000500>
- Li, Z. Q., Niu, F., Fan, J. W., Liu, Y. G., Rosenfeld, D., & Ding, Y. N. (2011). Long-term impacts of aerosols on the vertical development of clouds and precipitation. *Nature Geoscience*, 4(12), 888–894. <https://doi.org/10.1038/NNGEO1313>
- Liu, D. M., Huang, J., Gao, S. P., Ma, Y. S., & An, X. H. (2006). The pollution level and influencing factors of atmospheric particulates from traffic in Beijing city during spring. *Earth Science Frontiers*, 34(6), 796–800. [https://doi.org/10.1016/S1872-2040\(06\)60041-8](https://doi.org/10.1016/S1872-2040(06)60041-8)
- Liu, Z. R., Hu, B., Ji, D. S., Wang, Y. H., Wang, M. X., & Wang, Y. S. (2015). Diurnal and seasonal variation of the $PM_{2.5}$ apparent particle density in Beijing, China. *Atmospheric Environment*, 120, 328–338. <https://doi.org/10.1016/j.atmosenv.2015.09.005>
- Loosmore, G. A., & Cederwall, R. T. (2004). Precipitation scavenging of atmospheric aerosols for emergency response applications: Testing an updated model with new real-time data. *Atmospheric Environment*, 38(7), 993–1003. <https://doi.org/10.1016/j.atmosenv.2003.10.055>
- Lou, M., Guo, J., Wang, L., Xu, H., Chen, D., Miao, Y., et al. (2019). On the relationship between aerosol and boundary layer height in summer in China under different thermodynamic conditions. *Earth and Space Science*, 6(5), 887–901. <https://doi.org/10.1029/2019EA000620>
- Lu, K. D., Guo, S., Tan, Z. F., Wang, H. C., Shang, D. J., Liu, Y. H., et al. (2018). Exploring atmospheric free-radical chemistry in China: The self-cleansing capacity and the formation of secondary air pollution. *National Science Review*, 6(3), 579–594. <https://doi.org/10.1093/nsr/nwy073>
- Luan, T., Guo, X. L., Zhang, T. H., & Guo, L. J. (2019). Below-cloud aerosol scavenging by different intensity rains in Beijing city. *Journal of Meteorological Research*, 33(1), 126–137. <https://doi.org/10.1007/s13351-019-8079-0>
- Lv, B., Cai, J., Xu, B., & Bai, Y. Q. (2017). Understanding the rising phase of the $PM_{2.5}$ concentration evolution in large China cities. *Scientific Reports*, 7, 46456. [https://doi.org/10.1038/srep46456\(2017\)](https://doi.org/10.1038/srep46456(2017))
- Mircea, M., Stefan, S., & Fuzzi, S. (2000). Precipitation scavenging coefficient: influence of measured aerosol and raindrop size distributions. *Atmospheric Environment*, 34(29–30), 5169–5174. [https://doi.org/10.1016/S1352-2310\(00\)00199-0](https://doi.org/10.1016/S1352-2310(00)00199-0)
- Olczowski, T. (2016). Changes in PM_{10} concentration due to large-scale rainfall. *Arabian Journal of Geosciences*, 9(2), 160. <https://doi.org/10.1007/s12517-015-2163-2>
- Pan, B. W., Wang, Y., Hu, J. X., Lin, Y., Hsieh, J. S., Logan, T., et al. (2018). Impacts of Saharan dust on Atlantic regional climate and implications for tropical cyclones. *Journal of Climate*, 31(18), 7621–7644. <https://doi.org/10.1175/JCLI-D-16-0776.s1>
- Pearce, J. L., Beringer, J., Nicholls, N. E., Hyndman, R. J., & Tapper, N. J. (2011). Quantifying the influence of local meteorology on air quality using generalized additive models. *Atmospheric Environment*, 45(6), 1328–1336. <https://doi.org/10.1016/j.atmosenv.2010.11.051>
- Qiu, C., Ye, C. L., Yang, L. Y., & Ye, C. B. (2014). Environment analysis on controlling $PM_{2.5}$ in Beijing. *Applied Mechanics and Materials*, 508, 259–262. <https://doi.org/10.4028/AMM.508.259>
- Rodhe, H., & Grandell, J. A. N. (1972). On the removal time of aerosol particles from the atmosphere by precipitation scavenging. *Tellus*, 24(5), 442–454. <https://doi.org/10.1111/j.2153-3490.1972.tb01571.x>
- Rosenfeld, D., Lohmann, U., Raga, G. B., O'Dowd, C. D., Kulmala, M., Fuzzi, S., et al. (2008). Flood or drought: How do aerosols affect precipitation? *Science*, 321(5894), 1309–1313. <https://doi.org/10.1126/science.1160606>
- Seidel, D. J., Ao, C. O., & Li, K. (2010). Estimating climatological planetary boundary layer heights from radiosonde observations: Comparison of methods and uncertainty analysis. *Journal of Geophysical Research*, 115, D16113. <https://doi.org/10.1029/2009JD013680>
- Song, S. J., Wu, Y., Jiang, J. K., Yang, L., Cheng, Y., & Hao, J. M. (2012). Chemical characteristics of size-resolved $PM_{2.5}$ at a roadside environment in Beijing, China. *Environmental Pollution*, 161, 215–221. <https://doi.org/10.1016/j.envpol.2011.10.014>
- Su, J., Zhao, P. S., & Chen, Y. N. (2016). Characteristics of number concentration size distributions of aerosols under different weather processes in Beijing. *Environmental Sciences*, 37(4), 1208–1218. <https://doi.org/10.13227/j.hjx.2016.04.004>
- Sun, Y., Li, Z., Zhang, D., Zhang, H., & Zhang, H. F. (2018). The influence of $PM_{2.5}$ coal power plant emissions on environment $PM_{2.5}$ in Jilin Province, China. *Earth and Environmental Science*, 121, 032038. <https://doi.org/10.1088/1755-1315/121/3/032038>
- Svenningsson, B., Rissler, J., Swietlicki, E., Mircea, M., Bilde, M., Facchini, M. C., et al. (2006). Hygroscopic growth and critical supersaturations for mixed aerosol particles of inorganic and organic compounds of atmospheric relevance. *Atmospheric Chemistry and Physics*, 6(7), 1937–1952. <https://doi.org/10.5194/acp-6-1937-2006>
- Tian, F. Y., Wu, Z. Y., Xu, Z. G., Ma, X. Y., Sun, Q. Y., & Gao, Q. (2019). Evaluation of Hourly Precipitation Fusion Dataset CMPA V1.0 in Typical Basins of Loess Plateau. *Water Resources and Power*, 37(2), 5–9.
- Twomey, S. (1977). The influence of pollution on the shortwave albedo of clouds. *Journal of the Atmospheric Sciences*, 34, 1149–1152. [https://doi.org/10.1175/1520-0469\(1977\)034<1149:TIOPTO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1977)034<1149:TIOPTO>2.0.CO;2)

- Wang, J. J., Zhang, M. G., Bai, X. L., Tan, H. J., Li, S., Liu, J. P., et al. (2017). Large-scale transport of PM_{2.5} in the lower troposphere during winter cold surges in China. *Scientific Reports*, 7, 13238. <https://doi.org/10.1038/s41598-017-13217-2>
- Wu, J., Sun, Z. B., Zhai, L., & Li, C. (2018). Effects of different types of precipitation on aerosol particles in Beijing. *China Environmental Science*, 38(3), 812–821.
- Wu, W. J., Chang, X., Xing, J., Wang, S. X., & Hao, J. M. (2017). Assessment of PM_{2.5} pollution mitigation due to emission reduction from main emission sources in the Beijing-Tianjin-Hebei region. *Environmental Sciences*, 38(3), 867–875. <https://doi.org/10.13227/j.hjxx.201607191>
- Xin, J. Y., Wang, Y. S., & Tang, G. Q. (2010). Variability and reduction of atmospheric pollutants in Beijing and its surrounding area during the Beijing 2008 Olympic Games. *Chinese Science Bulletin*, 55(18), 1937–1944. <https://doi.org/10.1007/s11434-010-3216-2>
- Xu, X. D., Zhou, L., Zhou, X. J., Yan, P., Tao, S. W., Mao, J. T., et al. (2004). Peripheral source influence area of urban environmental atmospheric heavy pollution process. *Science in China Series D: Earth Sciences*, 34(10), 958–966.
- Yang, X., Zhao, C., Guo, J., & Wang, Y. (2016). Intensification of aerosol pollution associated with its feedback with surface solar radiation and winds in Beijing. *Journal of Geophysical Research: Atmospheres*, 121, 4093–4099. <https://doi.org/10.1002/2015JD024645>
- Yang, X., Zhao, C., Zhou, L. J., Li, Z. Q., Cribb, M., & Yang, S. J. (2018). Wintertime cooling and a potential connection with transported aerosols in Hong Kong during recent decades. *Atmospheric Research*, 211, 52–61. <https://doi.org/10.1016/j.atmosres.2018.04.029>
- Yang, X., Zhou, L. J., Zhao, C., & Yang, J. (2018). Impact of aerosols on tropical cyclone-induced precipitation over the mainland of China. *Climatic Change*, 148(1–2), 173–185. <https://doi.org/10.1007/s10584-018-2175-5>
- Yang, Y. K., Zhao, C., Sun, L., & Wei, J. (2019). Improved aerosol retrievals over complex regions using NPP Visible Infrared Imaging Radiometer Suite observations. *Earth and Space Science*, 6(4), 629–645. <https://doi.org/10.1029/2019EA000574>
- Yao, K. Y., Kuo, J., Fu, Y. F., & Liu, Y. (1999). Rain scavenging of aerosol particles. *Climatic and Environmental Research*, 4(3), 297–302.
- Yue, Y. Y., Wang, X. L., Zhang, M. X., Cao, W. X., Zhou, Y., Chen, S. N., & Zhu, Y. (2016). Air quality condition in Wuhan and its relationship to meteorological factors. *Torrential Rain and Disasters*, 35(3), 271–278. <https://doi.org/10.3969/j.issn.1004-9045.2016.03.010>
- Zhang, B. E., Jiao, L. M., Xu, G., Zhao, S. L., Tang, X., Zhou, Y., & Gong, C. (2018). Influences of wind and precipitation on different-sized particulate matter concentrations (PM_{2.5}, PM₁₀, PM_{2.5-10}). *Meteorology and Atmospheric Physics*, 130(3), 383–392. <https://doi.org/10.1007/s00703-017-0526-9>
- Zhang, F., Li, Y., Li, Z., Sun, L., Li, R., Zhao, C., et al. (2014). Aerosol hygroscopicity and cloud condensation nuclei activity during the AC3Exp campaign: Implications for cloud condensation nuclei parameterization. *Atmospheric Chemistry and Physics*, 14(24), 13,423–13,437. <https://doi.org/10.5194/acp-14-13423-2014>
- Zhang, Z., Ma, Z. Q., & Kim, S. J. (2018). Significant decrease of PM_{2.5} in Beijing based on long-term records and Kolmogorov–Zurbenko filter approach. *Aerosol and Air Quality Research*, 18(3), 711–718. <https://doi.org/10.4209/aaqr.2017.01.0011>
- Zhao, C., & Garrett, T. J. (2015). Effects of Arctic haze on surface cloud radiative forcing. *Geophysical Research Letters*, 42, 557–564. <https://doi.org/10.1002/2014GL062015>
- Zhao, C., Li, Y. N., Zhang, F., Sun, Y. L., & Wang, P. C. (2018). Growth rates of fine aerosol particles at a site near Beijing in June 2013. *Advances in Atmospheric Sciences*, 35(2), 209–217. <https://doi.org/10.1007/s00376-017-7069-3>
- Zhao, C., Lin, Y., Wu, F., Wang, Y., Li, Z., Rosenfeld, D., & Wang, Y. (2018). Enlarging rainfall area of tropical cyclones by atmospheric aerosols. *Geophysical Research Letters*, 45(16), 8604–8611. <https://doi.org/10.1029/2018GL079427>
- Zhao, C., Qiu, Y., Dong, X., Wang, Z., Peng, Y., Li, B., & Wang, Y. (2018). Negative aerosol-cloud re relationship from aircraft observations over Hebei, China. *Earth and Space Science*, 5(1), 19–29. <https://doi.org/10.1002/2017EA000346>
- Zhao, C., Wang, Y., Shi, X., Zhang, D., Wang, C., Jiang, J. H., et al. (2019). Estimating the contribution of local primary emissions to particulate pollution using high density station observations. *Journal of Geophysical Research: Atmospheres*, 124, 1648–1661. <https://doi.org/10.1029/2018JD028888>
- Zhao, C. X., Wang, Y. Q., Wang, Y. J., Zhang, H. L., & Zhao, B. Q. (2014). Temporal and spatial distribution of PM_{2.5} and PM₁₀ pollution status and the correlation of particulate matters and meteorological factors during winter and spring in Beijing. *Environmental Sciences*, 35(2), 418–427. <https://doi.org/10.13227/j.hjxx.214.02.013>
- Zhao, X. J., Zhang, X. L., Xu, X. F., Xu, J., Meng, W., & Pu, W. W. (2009). Seasonal and diurnal variations of ambient PM_{2.5} concentration in urban and rural environments in Beijing. *Atmospheric Environment*, 43, 2893–2818, 2900. <https://doi.org/10.1016/j.atmosenv.2009.03.009>
- Zhou, L., Xu, X. D., Ding, G. A., Miao, Q. J., & Wei, F. Y. (2003). The correlation factors and pollution forecast model for PM_{2.5} concentration in Beijing area. *Acta Meteorologica Sinica*, 61(3), 761–768.