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CONTENTS

Aquatic environment

Atmospheric environment

Terrestrial environment

Environmental biology

Environmental health and toxicology

Environmental catalysis and materials

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Influence of different weather events on concentrations of particulate matter with different sizes in Lanzhou, China

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Abstract

The formation and development of weather events has a great impact on the diffusion, accumulation and transport of air pollutants, and causes great changes in the particulate pollution level. It is very important to study their influence on particulate pollution. Lanzhou is one of the most particulate-polluted cities in China and even in the world. Particulate matter (PM) including TSP, $PM_{>10}$, $PM_{2.5-10}$, $PM_{2.5}$ and $PM_{1.0}$ concentrations were simultaneously measured during 2005–2007 in Lanzhou to evaluate the influence of three kinds of weather events – dust, precipitation and cold front – on the concentrations of PM with different sizes and detect the temporal evolution. The main results are as follows: (1) the PM pollution in Lanzhou during dust events was very heavy and the rate of increase in the concentration of $PM_{2.5-10}$ was the highest of the five kinds of particles. During dust-storm events, the highest peaks of the concentrations of fine particles ($PM_{2.5}$ and $PM_{1.0}$) occurred 3 hr later than those of coarse particles ($PM_{>10}$ and $PM_{2.5-10}$). (2) The major effect of precipitation events on PM is wet scavenging. The scavenging rates of particles were closely associated with the kinds of precipitation events. The scavenging rates of TSP, $PM_{>10}$ and $PM_{2.5-10}$ by convective precipitation were several times as high as those caused by frontal precipitation for the same precipitation amount, the reason being the different formation mechanism and precipitation characteristics of the two kinds of precipitation. Moreover, there exists a limiting value for the scavenging rates of particles by precipitation. (3) The major effect of cold-front events on particles is clearance. However, during cold-front passages, the PM concentrations could sometimes rise first and decrease afterwards, which is the critical difference in the influence of cold fronts on the concentrations of particulate pollutants vs. gaseous pollutants.

Key words: particulate matter with different sizes; dust event; precipitation event; cold-front event

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Introduction

Particulate matter (PM) in the atmosphere not only causes adverse effects on air quality, visibility and human health, but also affects climate change directly or indirectly. In most Chinese cities, PM is the primary air pollutant. Lanzhou is one of the most particulate-polluted cities in China and even in the world – it has been listed as one of the ten most air-polluted cities worldwide. Particulate pollution, as the main environmental problem in many Chinese cities, especially in Lanzhou, has attracted more and more attention in the last two decades.

Several important factors make Lanzhou one of the most particulate-polluted cities, which are large emission from local pollution sources, special topography, poor atmospheric diffusion conditions and dust intrusions from upstream regions (Chu et al., 2008; Wang et al., 1999; Yu et al., 2009; Zhang, 2001). PM concentrations in Lanzhou show high values in winter and spring and low values in summer and autumn. The peak in spring is due to dust events. Low concentrations in summer and autumn are due to better diffusion and wet deposition. The peak in winter is caused by the large amount of emission due to house heating and by the poor diffusion conditions due to low wind speed and a stable inversion layer. Recent studies have been carried out to detect the diurnal variations (under normal conditions) of the concentrations of PM with different sizes in Lanzhou (Wang et al., 2009).

As is well known, PM concentration is affected by the atmospheric diffusion conditions in the boundary layer, which are governed by the evolution of weather events. Thus the formation and development of weather events is most likely to cause great changes in the PM pollution level. However, the diurnal variations of PM concentration under normal conditions (without weather events occurring) cannot explain the drastic changes of PM concentration during weather events. Therefore, it is important to study the influence of different weather events on PM concentration to deeply understand the nature of

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*Corresponding author. E-mail: fengxy@cuit.edu.cn urban PM pollution and establish reasonable preventive countermeasures.

Dust events are the major source of PM in arid and semi-arid regions. Some studies have pointed out that dust events can cause heavy PM pollution (Gao et al., 2004; Han et al., 2008; Wang et al., 2008; Xie et al., 2005). Rodríguez et al. (2001) showed that Saharan dust events account for most of the excess PM_{10} daily concentration in southern Spain. In some cities of the western United States, sometimes the contribution of dust to the PM_{10} concentration can even reach 79.5% (Gertler et al., 1995).

The wet scavenging of particles by precipitation is the major process by which the atmospheric self-purification and a balance between the sources and sinks of atmospheric aerosols are maintained (Seinfeld and Pandis, 1998). A number of studies have pointed out that, in the microphysical framework of the below-cloud-scavenging process, the wet scavenging coefficient of precipitation depends on the spectral distribution of aerosol particles and raindrops, collision efficiency of aerosol particles with raindrops, raindrop terminal velocity and precipitation intensity (Kim et al., 2007; Mircea et al., 2000).

A cold front is a narrow zone of transition between cold and warm air masses. The most distinctive characteristic during cold-front passages is the abrupt changes in meteorological elements, which can cause atmospheric diffusion conditions to change and thus affect the concentration of air pollutants. Wang et al. (2000) has pointed out that cold-front events have a great impact on atmospheric diffusion conditions, that is, the minimum value of the average Maximum-Mixing-Depth occurs before cold-front passages, and the maximum value is in the front of the Mongolia high-pressure system after the cold front in winter. Bornstein et al. (1981) addressed the fact that SO_2 concentration increases when the city is in the warm air mass before the cold-front passage and decreases in the cold air mass after the cold-front passage.

However, previous studies on dust events in China were mainly directed to the case-based study of dust-storm effects on TSP and PM_{10} concentrations, and few studies have been done to detect its effect on fine particle concentrations. In particular, no work has been done to comparatively analyze the variation of the concentrations of PM with different sizes during dust events. The previous studies on the effect of precipitation focused on the microphysical process of aerosol particles and raindrops, while very little has been done to evaluate its effect on the macroscopic atmospheric-environment. Previous work on cold fronts was more limited, and was mainly directed to the influence of cold fronts on the concentrations of gaseous pollutants such as SO_2, CO_x and NO_x. Then, is there any difference in the influence of dust events on PM concentrations among particles with different sizes? For different kinds of precipitation events, is there any difference in their scavenging effects on PM concentrations? What is the impact of cold-front events on the concentration of particulate pollutants? And is there any difference in the influence of cold fronts on air pollution between particulate and gaseous pollutants? The answers to these questions remain unclear.

In this article, the influence of the three kinds of weather events – dust, precipitation and cold front – on the concentrations of PM with different sizes in Lanzhou has been studied by using the monitoring data of the concentrations of five kinds of PM (TSP, $PM_{>10}$, $PM_{2.5-10}$, $PM_{2.5}$ and $PM_{1.0}$) which were measured during 2005–2007. The aim of this study was to evaluate the influence of different weather events on the PM concentrations in Lanzhou and detect the temporal evolution, and then to provide the scientific basis for improving urban air quality.

1 Material and methods

1.1 Description of study area

Lanzhou (36°03′N, 103°53′E), the capital of Gansu Province, is located in a narrow (2–8 km) but long (approximately 35 km) NW-SE oriented valley basin of the Yellow River on the northeast side of Tibetan Plateau. Its altitude is 1520 m. The total area of Lanzhou is 210 km^2 and the population is 1.5 million. The climate in Lanzhou is of the continental semi-arid type. The annual average air temperature and annual precipitation are 9.8°C and 311.7 mm, respectively. Due to the special topography of the valley basin, the monthly average surface wind speed is approximately 0.8 m/sec, and the frequencies of both calm wind and thermal inversion in the atmospheric boundary layer are very high (Jiang et al., 2001; Wang et al., 1997).

1.2 Monitoring methods and data

The monitoring site was located on the roof of an office building of Lanzhou University, which is in the eastern part of Lanzhou. The monitoring height was 55 m above ground, high enough to avoid the direct affect of re-suspended dust due to human activities. Around the monitoring site, there are no significant pollution sources.

PM concentrations were measured with an Environmental Dust Monitor (LN5, Munro Environmental, a division of The Munro Group, Britain), which uses the light scattering technique. The monitor can simultaneously measure concentrations of four different sizes of particles (mass concentrations of TSP, PM_{10} and $PM_{2.5}$ and number concentrations of $PM_{1.0}$). Monitoring of PM was carried out from 1 Jan 2005 to 30 Sep 2006 and from 13 Apr 2007 to 25 Nov 2007, running 24 hr each day. The time resolution of the measurements was 5 min. The PM_{10} concentration was subtracted from the TSP concentration and $PM_{2.5}$ from PM_{10} give the concentrations of $PM_{>10}$ (particles with the aerodynamic diameter > 10 μm) and $PM_{2.5-10}$ (aerodynamic diameter between 2.5–10 μm).

In China, dust events are divided into three kinds based on meteorological observation criteria, namely dust storm, blowing dust and floating dust. During the monitoring period, there were 15 dust events (including dust storm, blowing dust and floating dust events), 225 precipitation events and 222 cold-front events.

All the meteorological data (including air temperature, atmospheric pressure, dew point temperature, wind speed and direction, precipitation amount, horizontal visibility and weather phenomena) are from the MICAPS routine meteorological records obtained from the meteorological observation network of the China Meteorological Administration (CMA), which takes meteorological observations eight times a day.

2 Results and discussion

2.1 Influence of dust events on the concentrations of PM with different sizes

During the fifteen dust events, the daily concentrations of TSP, $PM_{>10}$, $PM_{2.5-10}$, $PM_{2.5}$ and $PM_{1.0}$ respectively increased by 1.9–15.0 times, 0.5–4.9 times, 4.2–29.7 times, 0.5–4.7 times and 0.2–2.7 times compared with the values before dust events, indicating that the PM pollution in Lanzhou during dust events is very heavy.

As shown in Table 1, in the dust-event occurrence days, the rate of increase in the concentrations of $PM_{2.5-10}$ during dust periods was the highest of the five kinds of particles, and that of $PM_{1.0}$ the lowest. This result is in agreement with measurements done by other researchers. As shown by Quan et al. (2005), the concentration of particles with size ranging from 1.1 to 9.0 μm during a dust storm in Lanzhou increased most. During non-dust periods after dust periods, the PM concentration gradually decreased due to the effects of gravity and atmospheric diffusion on the particles. Of the five kinds of particles, the rate of decrease in the $PM_{2.5-10}$ concentration was the highest, as shown in Table 1.

The variations in concentrations of PM with different sizes and relevant meteorological elements during the regional dust-storm occurring on 31 March 2006 are shown in Fig. 1. With a cold front arriving in Lanzhou at 13:00 on 31 March, surface wind speed rose and horizontal visibility was down to less than 1 km as shown in Fig. 1. The dust storm appeared. At this time, the $PM_{2.5-10}$ concentration reached its peak value (Fig. 1a). However, the concentration of $PM_{1.0}$ (mainly from local emission) continuously decreased at the same time due to the wind diffusion (Fig. 1b). After 14:00, the amount of blowing local dust reduced due to the decrease of wind speed, and then the intensity of the dust storm diminished, with the visibility gradually rising (Fig. 1). Meanwhile, the amount of the dust transported by cyclonic activity from upstream regions gradually increased. The maximum concentrations of $PM_{2.5}$ and $PM_{1.0}$ occurred at 16:00 (Fig. 1b) (3 hr later than the maximum concentration of $PM_{2.5-10}$). The dust storm continued until 19:00, 31 March. From the above analysis, the temporal evolution of the concentrations of PM with different sizes during the dust storm can be summarized as follows. At the beginning of the cold-front passage, while the strong wind generated by the cold front diffuses fine particles (mainly from local emissions), it also blows a large amount of dust (mainly coarse particles) from the ground, which results in the occurrence of a local dust storm and the maximum concentration of $PM_{2.5-10}$. After reaching the maximum, the concentration of $PM_{2.5-10}$ decreases, resulting from the decrease of the amount of blowing local dust due to wind speed reduction. Then, the dust from upstream regions where dust events have occurred is gradually brought to Lanzhou and exerts an influence on its PM concentrations. The average size of the dust from upstream regions becomes smaller during the long-distance transport due to the deposition of larger particles. The concentration of $PM_{2.5}$ in Lanzhou continues to increase, which results in the maximum concentration of $PM_{2.5}$ being 3 hr later than that of $PM_{2.5-10}$.

It can be observed from Fig. 1 that the PM concentrations increase rapidly and decrease slowly during dust events. The increase/decrease rate of PM concentrations per hr during burst periods and deposition periods for the fifteen dust events was statistically analyzed. The result shows that the rate of increase in the concentrations of TSP, $PM_{>10}$, $PM_{2.5-10}$, $PM_{2.5}$ and $PM_{1.0}$ per hr during burst periods was respectively 6.5 times, 3.5 times, 7.1 times, 6.5 times and 5.7 times as much as the rate of decrease per hr during deposition periods.

2.2 Influence of precipitation events on the concentrations of PM with different sizes

2.2.1 Influence of precipitation amount

The scavenging rate (r) of particles by precipitation represents the particle removal rate from the atmosphere. This is calculated by the following equation:

$$r = (\rho_{\text{before precipitation}} - \rho_{\text{after precipitation}})/\rho_{\text{before precipitation}} \times 100\% \qquad (1)$$

where, ρ is the PM concentration. As shown in Fig. 2, the scavenging rates of all kinds of particles increased with the precipitation amount. Coarse particles ($PM_{>10}$ and $PM_{2.5-10}$) were scavenged more efficiently than fine particles ($PM_{2.5}$ and $PM_{1.0}$), and the scavenging rates of fine particles were generally low. This is because the wet scavenging coefficient of particles with the semidiameter of $0.1 < r < 1.0$ μm by raindrops is quite low, namely the 'Greenfield gap' (Greenfield, 1957; Mason, 1978). In addition, other factors (such as local emissions and

Table 1 Average increase-rate and decrease-rate of PM concentrations during dust and subsequent non-dust periods

Item	TSP	$PM_{>10}$	$PM_{2.5-10}$	$PM_{2.5}$	$PM_{1.0}$
Rate of PM increase during dust periods[a] (%)	1113.9	280.7	2402.0	292.3	133.5
Rate of PM decrease during non-dust periods[b] (%)	–76.9	–36.0	–85.8	–58.2	–56.0

[a] The rate of PM increase is defined as the ratio of the increase in the PM concentration during the dust period to the concentration before the dust period.

[b] The rate of PM decrease is defined as the ratio of the increase in the PM concentration after the dust period to the concentration during the dust period. A negative value represents a decreasing PM concentration.

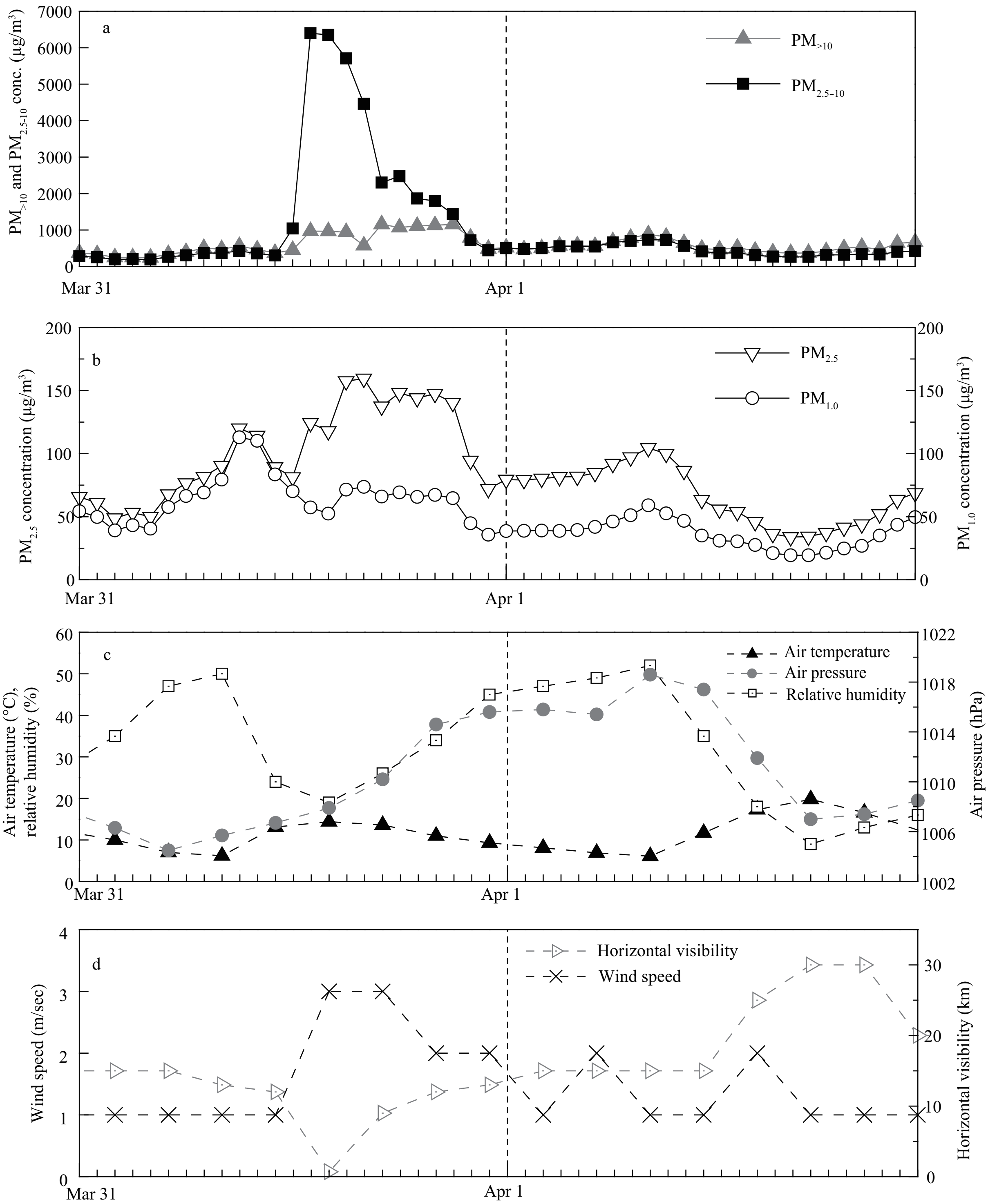

Fig. 1 Variations of concentrations of PM with different sizes and relevant meteorological elements during the dust storm from 31 Mar to 1 Apr 2006. The meteorological observations were made once every three hours.

atmospheric diffusion conditions) counteract the decrease of the concentration of fine particles. As a result of both factors, the scavenging rates of fine particles are low, and the concentrations of fine particles sometimes even increase – if the increase in the PM concentration caused by other factors (such as local emissions and atmospheric diffusion conditions) is greater than the wet scavenging caused by raindrops, the PM concentration will increase. Compared with fine particles, coarse particles are scavenged by raindrops more efficiently. On the other hand, precipitation makes the ground wet, which helps to depress re-suspension (mainly coarse particles) generated by traffic and other human activities. As a result, the scavenging rates of coarse particles are greater than those of fine particles.

When the $P_{3\,\mathrm{hr}}$ (3 hr-precipitation amount) was below 1.0 mm, the precipitation had very little influence on the concentrations of all kinds of particles (Fig. 2).

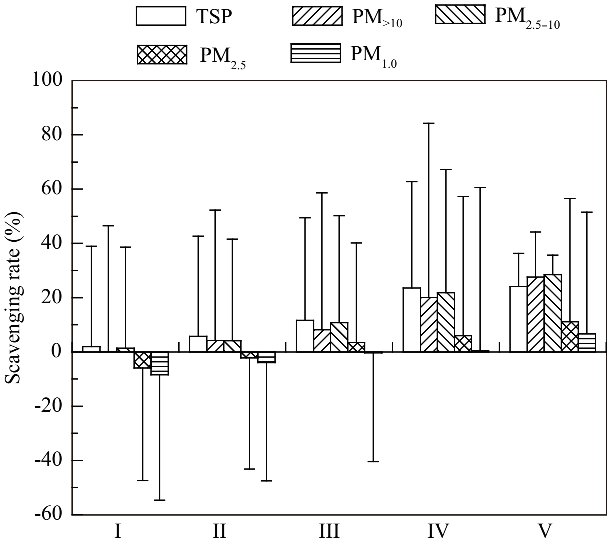

Fig. 2 Average scavenging rates of particles with different sizes by precipitation during 2005 – 2007. I, II, III, IV and V represent the $P_{3\ \mathrm{hr}}$ (3hr-precipitation amount) ≤ 0.1 mm, 0.1 < $P_{3\ \mathrm{hr}}$ < 1.0 mm, 1.0 ≤ $P_{3\ \mathrm{hr}}$ < 5.0 mm, 5.0 ≤ $P_{3\ \mathrm{hr}}$ < 10.0 mm and $P_{3\ \mathrm{hr}}$ ≥ 10.0 mm, respectively. The numbers of samples (*n*) for different $P_{3\ \mathrm{hr}}$ are 409, 159, 157, 25 and 5, respectively. Error bars represent the standard deviation.

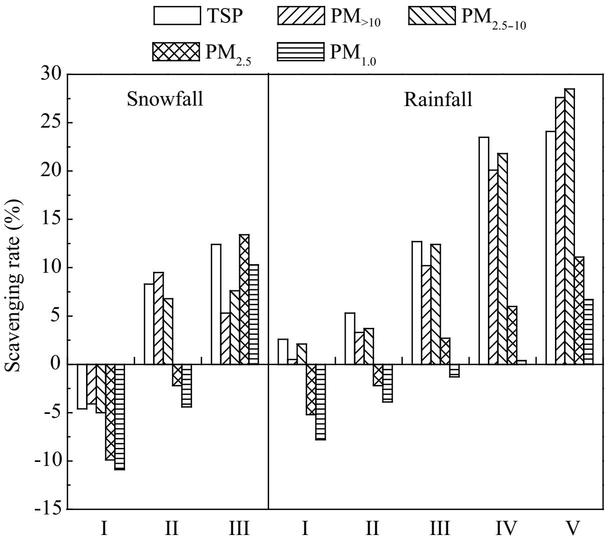

Fig. 3 Average scavenging rates of particles with different sizes by snowfalls and rainfalls during 2005–2007. I, II, III, IV and V represent the $P_{3\ \mathrm{hr}} \leqslant 0.1$ mm, 0.1 < $P_{3\ \mathrm{hr}}$ < 1.0 mm, 1.0 ⩽ $P_{3\ \mathrm{hr}}$ < 5.0 mm, 5.0 ⩽ $P_{3\ \mathrm{hr}}$ < 10.0 mm and $P_{3\ \mathrm{hr}} \geqslant 10.0$ mm, respectively. The numbers of samples (*n*) with different $P_{3\ \mathrm{hr}}$ are 53, 23, 13, 0, 0 for snowfalls and 356, 136, 144, 25, 5 for rainfalls, respectively.

2.2.2 Comparison of scavenging effects of different kinds of precipitation events on PM concentrations

Because the formation mechanism, phase state and precipitation characteristics of various kinds of precipitation differ, there could be some differences in the scavenging effects for various kinds of precipitation. Based on the phase state of the precipitation material, the precipitation can be classified into rainfall and snowfall. Based on the precipitation characteristics, the precipitation can be classified into continuous precipitation (precipitation without observable change in intensity) and shower precipitation (precipitation with rapidly changing intensity). Based on the different kinds of weather systems which generate precipitation, the precipitation can be classified into convective precipitation and frontal precipitation. The routine meteorological records of the CMA meteorological observation network include observations of the precipitation type (from weather phenomena). In this section, the influences of the different kinds of precipitation on PM concentrations are evaluated by using these records of precipitation type.

Based on the phase state of the precipitation material, the precipitation can be classified into rainfall and snowfall. As shown in Fig. 3, the rainfalls with the $P_{3\ \mathrm{hr}}$ below 1.0 mm had very little influence on the PM concentrations, while the snowfalls with 0.1⩽ $P_{3\ \mathrm{hr}}$ < 1.0 mm could reduce the concentrations of coarse particles. Rainfall and snowfall are in the form of raindrops and ice crystals respectively. The collision efficiencies of aerosol particles with raindrops or ice crystals vary due to their different phase state, falling velocity, impact process and surface shape. Thus there are some differences in the scavenging effects of rainfalls and snowfalls on particles.

Based on the characteristics of the precipitation, rainfalls can be classified into continuous precipitation and shower precipitation. According to the meteorological observation criterion, continuous precipitation is rainfall without observable change in intensity. However, the intensity of shower precipitation changes rapidly. The start and stop of shower precipitation are sudden and the raindrops are often larger. As shown in Fig. 4a, for continuous precipitation, the scavenging rates of particles with 5.0 ⩽ $P_{3\ \mathrm{hr}}$ < 10.0 mm were the greatest, and when the $P_{3\ \mathrm{hr}}$ was below 1.0 mm, the precipitation had very little influence on the PM concentrations. However, for shower precipitation, as shown in Fig. 4b, precipitation with different $P_{3\ \mathrm{hr}}$ (including the precipitation with $P_{3\ \mathrm{hr}}$ < 1.0 mm) could all scavenge TSP, $\mathrm{PM}_{>10}$ and $\mathrm{PM}_{2.5-10}$ efficiently, and the scavenging rates by precipitation with $P_{3\ \mathrm{hr}}$ > 10.0 mm were the greatest. By comparing Fig. 4a, b, it can be found that, for the precipitation with $P_{3\ \mathrm{hr}}$ < 5.0 mm – in Lanzhou, most 3 hr-precipitation amounts are below 5.0 mm – shower precipitation could scavenge TSP, $\mathrm{PM}_{>10}$ and $\mathrm{PM}_{2.5-10}$ more efficiently than continuous precipitation. It can be concluded that shower precipitation has more impact on PM concentrations in Lanzhou.

Based on the different kinds of weather systems which generate precipitation, the rainfalls can be classified into convective precipitation (thunderstorm precipitation) and frontal precipitation. Thunderstorm precipitation is caused by atmospheric convective motion and accompanies thunderstorms. Frontal precipitation is generated by the cooling condensation of warm and wet air as it ascends along the front. In China, thunderstorm precipitation mainly occurs during May – August. Thus, the thunderstorm precipitation and frontal precipitation during this period are analyzed to compare their scavenging rates.

As shown in Fig. 5, the scavenging rates of TSP, $\mathrm{PM}_{>10}$ and $\mathrm{PM}_{2.5-10}$ by thunderstorm precipitation are significantly greater than those by frontal precipitation with the same $P_{3\ \mathrm{hr}}$. Why is there a several-fold difference in the

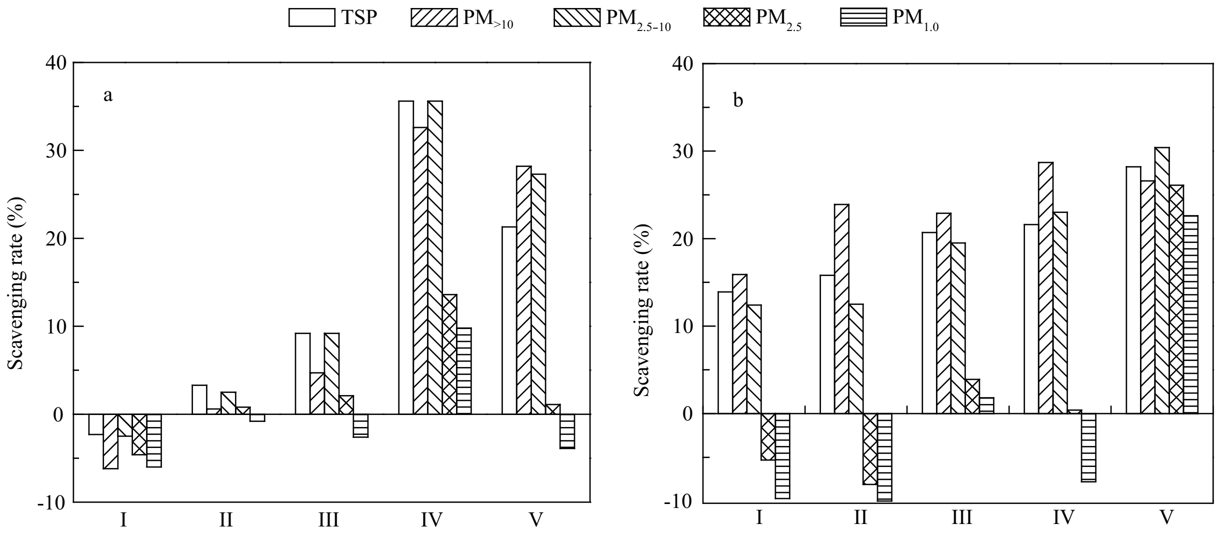

Fig. 4 Average scavenging rates of particles with different sizes by continuous precipitation (a) and shower precipitation (b) during 2005–2007. I, II, III, IV and V represent $P_{3\text{ hr}} \leqslant 0.1$ mm, $0.1 < P_{3\text{ hr}} < 1.0$ mm, $1.0 \leqslant P_{3\text{ hr}} < 5.0$ mm, $5.0 \leqslant P_{3\text{ hr}} < 10.0$ mm and $P_{3\text{ hr}} \geqslant 10.0$ mm, respectively. The numbers of samples (n) with different $P_{3\text{ hr}}$ are 243, 98, 100, 15, 3 for continuous precipitation and 113, 38, 44, 10, 2 for shower precipitation, respectively.

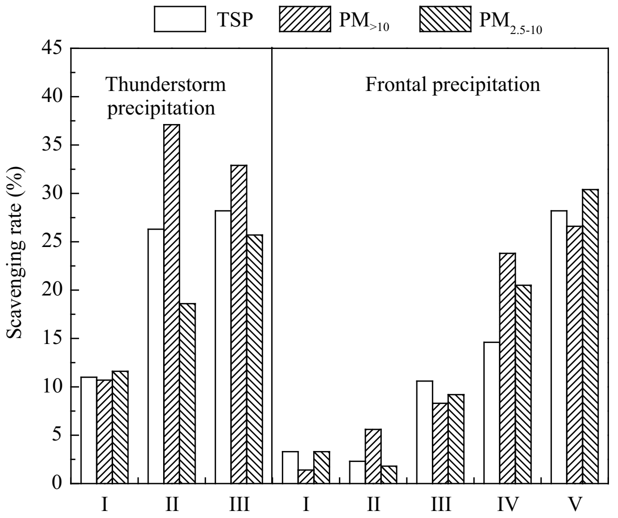

Fig. 5 Average scavenging rates of particles with different sizes by thunderstorm precipitation and frontal precipitation during May – August in 2005–2007. I, II, III, IV and V represent $P_{3\text{ hr}} \leqslant 0.1$ mm, $0.1 < P_{3\text{ hr}} < 1.0$ mm, $1.0 \leqslant P_{3\text{ hr}} < 5.0$ mm, $5.0 \leqslant P_{3\text{ hr}} < 10.0$ mm and $P_{3\text{ hr}} \geqslant 10.0$ mm, respectively. The numbers of samples (n) with different $P_{3\text{ hr}}$ are 14, 7, 15, 0, 0 for thunderstorm precipitation and 84, 28, 43, 3, 2 for frontal precipitation, respectively.

scavenging rates between the two kinds of precipitation? This is due to their different formation mechanism and precipitation characteristics. That is, strong gusts caused by thunderstorms generally blow local dust, which causes the concentrations of coarse particles to rapidly rise. Then, the precipitation immediately following scavenges coarse particles efficiently. Besides, the intensity of thunderstorm precipitation is generally great and its duration is short. As a result, the scavenging rates of TSP, $PM_{>10}$ and $PM_{2.5-10}$ by thunderstorm precipitation are much greater than those by frontal precipitation.

It can be observed from Fig. 5 that the thunderstorm precipitation with different $P_{3\text{ hr}}$ (including the precipitation with $P_{3\text{ hr}} < 1.0$ mm) could all scavenge particles efficiently. However, for frontal precipitation, only the precipitation with the $P_{3\text{ hr}} > 1.0$ mm could scavenge particles efficiently.

2.2.3 Temporal evolution of scavenging rates of particles during precipitation

The continuous precipitation events which lasted more than 10 hr were selected to show the temporal evolution of the cumulative scavenging rates for the duration of precipitation. In the initial stage of precipitation, as shown in Fig. 6, the cumulative scavenging rates of particles (as shown by lines) increased with the duration. When the precipitation continued for 5 hr, the cumulative scavenging rates of TSP, $PM_{>10}$ and $PM_{2.5-10}$ rose to more than 60%. Then, the values fluctuated around 60%, as shown in Fig. 6.

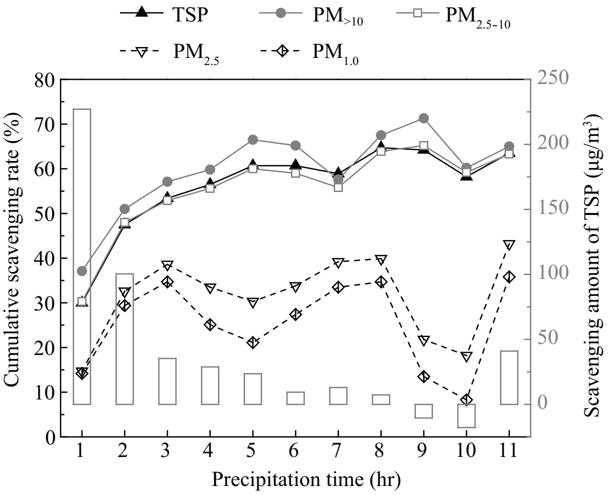

Fig. 6 Temporal variations of the cumulative scavenging rates of particles and hourly scavenging amount of TSP for the duration of precipitation. The lines represent the cumulative scavenging rate of PM with different sizes during continuous precipitation events. The cumulative rate is the scavenging rate during first hour, first two hours, first three hours of precipitation, and so on. The columns represent the hourly scavenging amount of TSP – the hourly decrease in the TSP concentration during the continuous precipitation events. This is calculated by the TSP concentration each hour minus the concentration one hour before. The number of continuous precipitation events was 10.

For fine particles, there was a similar phenomenon, that is, after the precipitation continued for 3 hr and the cumulative scavenging rates rose to more than 30%, the values could be found to fluctuate (Fig. 6). The phenomenon indicates that there exists a limiting value of the scavenging rates of particles by precipitation. When the precipitation continues for several hours and the cumulative scavenging rates reach a certain value, the PM concentrations will have decreased to quite a low level. At this time, the extent of scavenging of PM concentrations caused by raindrops is so low that it is almost cancelled out by the increase in PM caused by other factors. From this point on, the values of the scavenging rates can be found to fluctuate around this limiting value. This result is supported by the variation of the hourly scavenging amounts of particles (the hourly decrease in PM concentrations) during precipitation. As shown in Fig. 6, the hourly scavenging amounts of TSP (as shown by columns) decreased with the duration. After the precipitation continued several hours, the hourly scavenging amount was small and its value fluctuated around zero.

2.3 Influence of cold-front events on the concentrations of PM with different sizes

2.3.1 Clearance rates of particles by cold fronts

The clearance rate (R) of particles by a cold front is defined by the percentage of the difference between PM concentrations before and after the cold front compared to the PM concentration before the cold front, that is,

$$R = (\rho_{\text{before}} - \rho_{\text{after}})/\rho_{\text{before}} \times 100\% \qquad (2)$$

As shown in Table 2, the major effect of the cold fronts on particles with different sizes was clearance. This result is similar to measurements of gaseous pollutants (Liu et al., 2002; Wang et al., 1998). The clearance rates of particles increased with the cold-front intensity and coarse particles could be cleared more efficiently (Table 2). The cold-front passages usually generate precipitation, so the clearance rates of particles by cold fronts without or with little precipitation (below 1.0 mm) were also statistically analyzed. The result shows that, after removing the wet-scavenging effect of precipitation, the clearance rates of particles by cold fronts are still associated with the cold-front intensity. The most distinctive characteristic during cold-front passages is the abrupt changes in meteorological elements, which have a great impact on the atmospheric diffusion conditions. With the passages of cold fronts, there are abrupt changes in meteorological elements, including air pressure, temperature, humidity, wind speed and direction, and so on. The inversions in the atmospheric boundary layer are broken and a mixing layer develops quickly. The wind speed and its vertical gradient in the boundary layer increase rapidly. The vertical turbulent transport becomes strong. Thus the atmospheric diffusion conditions in the boundary layer improve greatly, which results in the reduction of the PM concentration. The greater the cold-front intensity, the better the diffusion conditions. Moreover, the particulate pollution could be mitigated more efficiently if the cold front was accompanied by precipitation.

Table 2 Average clearance rates of PM with different sizes by cold fronts during 2005–2007

Cold-front intensity[a]	TSP	$PM_{>10}$	$PM_{2.5-10}$	$PM_{2.5}$	$PM_{1.0}$
Weak cold-front	21.1%	24.1%	19.2%	6.3%	5.9%
General cold-front	23.9%	23.8%	22.3%	17.6%	18.1%
Strong cold-front	34.5%	35.1%	32.6%	23.3%	22.5%

[a] Standard for the cold-front intensity: based on ΔT_{24} (24-hr temperature change), cold fronts can be classified into weak cold-front, general cold-front and strong cold-front – cold front with $-\Delta T_{24} < 3.0$°C, $3.0 \leq -\Delta T_{24} < 6.0$°C and $-\Delta T_{24} \geqslant 6.0$°C, respectively.

2.3.2 Variations of PM concentrations during cold-front passages

Based on the variations of PM concentrations at the beginning of cold-front passages, the distributions of PM concentrations during cold fronts can be classified into two types: increasing-first-and-decreasing-afterwards type (type I) and continuous-decreasing type (type II).

Shown in Fig. 7 are the variations of the concentrations of PM with different sizes during the cold-front event on 14 August 2005. This was a case of type-I behavior. It can be observed that, during the cold-front passage, the concentrations of coarse particles first rose rapidly and then fell slowly. For fine particles, there was a similar but less pronounced variation. At the beginning of the cold-front passage, blowing dust caused by strong wind generated by the cold front sharply increased the PM concentrations. However, the duration of the blowing dust was short due to lack of other conditions (such as sufficient dust sources and thermal instability). Furthermore, no dust was transported by cyclonic activity from upstream regions. As a result, the PM concentrations soon ceased to rise, and began to decrease due to the wind diffusion. After the cold-front passage, the PM concentrations were clearly lower than before. Liu (2006) studied the variations of the concentrations of gaseous pollutants during cold-front passages, and found that the concentrations of SO_2, NOx and COx continuously decreased during cold-front passages. The mechanism of the influence of cold fronts on the concentrations of particulate pollutants is more complex, as compared with that of gaseous pollutants. This is because the PM concentration can be affected by blowing dust caused by cold-front passages. Therefore, this characteristic – where the PM concentrations rise first and decrease afterwards – is the critical difference in the influence of cold fronts on the concentrations of particulate vs. gaseous pollutants.

The variations of the PM concentrations during the cold-front event on 21 November 2005 are shown in Fig. 8. This was a case of type-II behavior. At the beginning of the cold-front passage, there was no observable increase of the PM concentrations, indicating no blowing dust caused by the cold front. During the cold-front passage, the concentrations of PM with different sizes continuously decreased due to the better diffusion conditions in the boundary layer.

Why do the variations of PM concentrations differ greatly at the beginning of the cold-front events? To answer

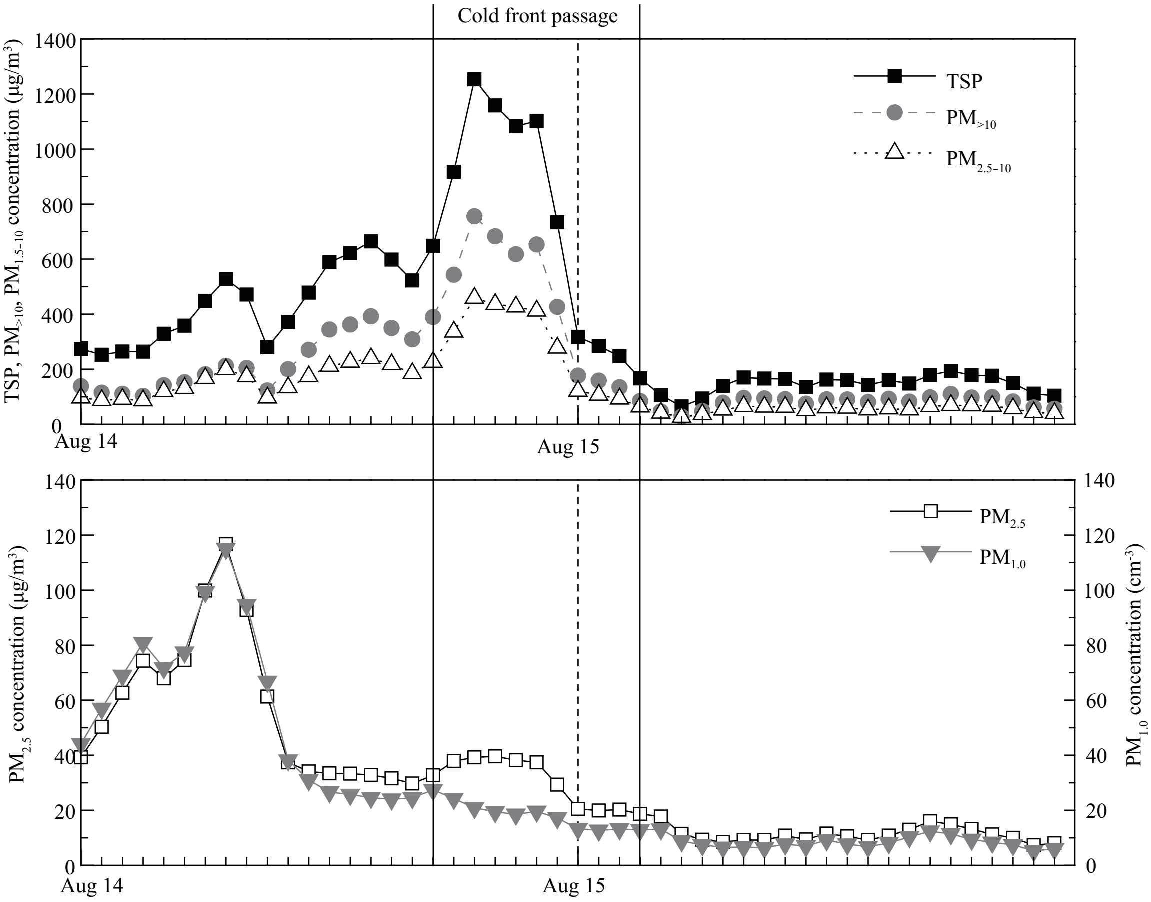

Fig. 7 Variations of the concentrations of PM with different sizes in Lanzhou during the cold-front event on 14 August 2005.

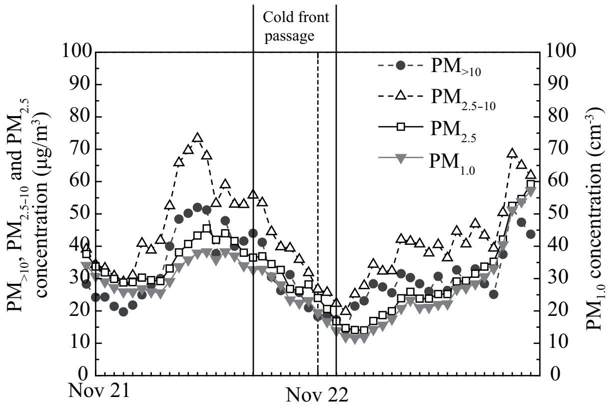

Fig. 8 Variations of the concentrations of PM with different sizes in Lanzhou during the cold-front event on 21 November 2005.

this question, the statistical characteristics of the meteorological elements in cold-front events during 2005–2007 were preliminarily analyzed, as shown in Table 3. The result shows that the average wind speed and the average maximum wind speed for type-I are greater than those for type-II. The strong wind caused by cold fronts can diffuse particles efficiently. However, it also can blow dust from the ground and thus increase the PM concentration if the wind speed is too great. The stronger wind is probably the most important cause of the sharp increase of PM concentrations at the beginning of the cold-front passages. Although the variations of PM concentrations differ in the beginning, the cold fronts still reduce the particulate pollution finally – the PM concentrations are lower after cold-fronts than before. The average clearance rates of coarse particles for type-I are higher than those for type-II.

3 Conclusions

The three kinds of weather events – dust, precipitation and cold front – have greater impacts on the concentrations of coarse particles ($PM_{>10}$ and $PM_{2.5-10}$) than those of fine particles ($PM_{2.5}$ and $PM_{1.0}$). The PM concentrations generally change violently at the beginning of the weather events, and then vary slowly.

Table 3 Average values of wind speed and clearance rates in cold-front events during 2005–2007

Item	Average wind speed (m/sec)	Average of maximum wind speed (m/sec)	Clearance rates of PM (%)				
			TSP	$PM_{>10}$	$PM_{2.5-10}$	$PM_{2.5}$	$PM_{1.0}$
Type I	1.9	2.6	37.7	40.4	34.7	18.5	19.5
Type II	1.6	2.1	33.5	34.8	32.3	22.2	20.8

During dust events, the PM pollution in Lanzhou was very heavy, and the PM concentrations increased rapidly and decreased slowly. Of the five kinds of PM with different sizes (TSP, $PM_{>10}$, $PM_{2.5-10}$, $PM_{2.5}$ and $PM_{1.0}$), the increase rate of the $PM_{2.5-10}$ concentration during dust periods was the highest, and that of $PM_{1.0}$ was the lowest. During dust storms, there were clear differences in the temporal evolution of the PM concentrations between coarse particles (mainly soil dusts and sands from the ground) and fine particles (mainly from anthropogenic emissions).

The major effect of precipitation events on PM was wet scavenging. The scavenging rates of all kinds of particles generally increased with the amount of precipitation, the rates for coarse particles being distinctly higher than for fine particles. There were clear differences in the scavenging rates of particles by different kinds of precipitation events. For precipitation with $P_{3\,\mathrm{hr}}$ (3 hr-precipitation amount) < 5.0 mm – (most $P_{3\,\mathrm{hr}}$ in Lanzhou is below 5.0 mm), shower precipitation could scavenge TSP, $PM_{>10}$ and $PM_{2.5-10}$ more efficiently than continuous precipitation. For precipitation caused by different kinds of weather systems, the scavenging rates of TSP, $PM_{>10}$ and $PM_{2.5-10}$ by convective precipitation were several times as high as those by frontal precipitation with the same precipitation amount. This is due to the different formation mechanism and precipitation characteristics of the two kinds of precipitation. Moreover, there exists a limiting value for the scavenging rates of particles by precipitation.

The major effect of cold fronts on particles was clearance. The clearance rates of particles increased with the cold-front intensity, and coarse particles could be cleared more efficiently. Based on the variations of PM concentrations at the beginning of the cold-front passages, the distribution of PM concentrations during cold fronts can be classified into increasing-first-and-decreasing-afterwards type and continuous-decreasing type. This characteristic – where the PM concentrations rise first and decrease afterwards during cold-front passages – is the critical difference in the influence of cold fronts on the concentrations of particulate vs. gaseous pollutants.

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