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A study on variations of concentrations of particulate matter with different sizes in Lanzhou, China

Shigong Wang, Xinyuan Feng*, Xiaoqing Zeng, Yuxia Ma, Kezheng Shang

The Gansu Key Laboratory of Arid Climate Change and Reducing Disaster, College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, PR China

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ABSTRACT

Lanzhou is one of the most air-polluted cities in China and in the world, and its primary air pollutant is particulate matter (PM). Different size particulate matter (TSP, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$) have different sources and affect the environment and human health differently, so it is very important to study the pollutant characteristics of different particles in order to deeply understand the pollution situation of Lanzhou city and establish reasonable preventive countermeasures. TSP, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ concentrations were simultaneously measured in Lanzhou to detect the annual and diurnal variations of concentrations of PM with different sizes and possible causes. The main results are as follows: (1) The annual distribution of monthly average concentrations for coarse particles (TSP and PM_{10}) is bimodal with the highest peak in April, which is different from the situation in other cities not affected by sand-dust events. However, the annual distribution for fine particles ($PM_{2.5}$ and $PM_{1.0}$) is unimodal with the peak in December. This difference between coarse and fine particles indicates that sand-dust events in spring carry much more coarse than fine particles to Lanzhou. This result is supported by the correlation between springtime wind speed and concentrations of PM with different sizes. (2) Under normal conditions (without dust intrusions), the diurnal distribution of coarse particle concentration in Lanzhou is bimodal. However, the distribution is trimodal during dust intrusions in April, with an extra peak in the afternoon. (3) In general, the highest concentration peaks of the diurnal variations for TSP, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ occur at about the same time. However, there are obvious differences in the occurrence time of the minimum concentrations among different kinds of PM. The differences in the occurrence time of minima between coarse and fine particles are due to their different diffusion behaviors in the atmospheric boundary layer.

1. Introduction

Particulate matter (PM) is the primary air pollutant in most Chinese cities, especially in Lanzhou. PM size generally ranges from 0.01 to 100 μm. Based on size, PM can be classified into total suspended particles (TSP), PM_{10}, $PM_{2.5}$ and $PM_{1.0}$—particles with aerodynamic diameters of less than 100, 10, 2.5 and 1.0 μm, respectively. Although its content in the atmosphere is very limited, PM attracts more and more attention due to its important role in many atmospheric processes. For example, PM can affect air quality, human health and climate change directly or indirectly.

With increasing studies on the physical and chemical characteristics of PM, there are more and more evidences that PM with different sizes have complex and many-sided effects on human health. Epidemiological researches have pointed out that both the incidence and mortality rate of diseases increase with urban aerosol concentration (BéruBé et al., 1999). Particles with different sizes deposit in different sections of the human respiratory system and have various effects on human health (Berico et al., 1997). Compared with coarse particles, fine particles do more harm to human health, the reason being that most fine particles are not only toxic material themselves, but also carriers and reactants for toxic and harmful substances. Therefore, it is very important to study the variation of concentration of PM with different sizes.

There are several important factors which affect PM concentrations in Lanzhou, including a large emission from local pollution sources, special landform, poor atmospheric diffusion conditions (Wang et al., 2000; Jiang et al., 2001) and dust intrusions from upstream regions (Wang et al., 1999; Liu et al., 2004; Ta et al., 2004). These factors make Lanzhou one of the most severely air-polluted cities in China and in the world. Some preliminary studies have been carried out to evaluate the influence of particulate pollution on human health in the urban districts of Lanzhou (Huang et al., 2001; Yang et al., 2005). As mentioned above, different kinds of PM

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* Corresponding author. Tel.: +86 931 8912702; fax: +86 931 8914278
E-mail address: fengxy_lzu@163.com (X. Feng).

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come from different sources and their effects on the environment and human health are also different. However, previous work was mainly directed to TSP and PM_{10} concentrations in Lanzhou, and very little has been done to detect the variation of $PM_{2.5}$ and $PM_{1.0}$ concentrations. Especially, no work has been done to simultaneously measure the concentrations of PM with different sizes and comparatively analyze their temporal variations.

In this study, the concentrations of four kinds of particulate matter (TSP, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$) have been simultaneously measured during January 2005–February 2006 in Lanzhou, China. The aim of this study is to detect the annual and diurnal variations of the concentrations of PM with different sizes and their possible causes as well as to evaluate the effects of local meteorological elements on the PM concentrations in Lanzhou.

2. Materials and methods

2.1. Data of particulate matter in the ambient air

2.1.1. Description of study area

Lanzhou, the capital of Gansu province and the geographically geometric centre of China (Fig. 1), 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 Qinghai-Tibetan Plateau. Its altitude is 1520 m. The climate in Lanzhou is of the continental semi-arid type. Annual average air temperature and annual precipitation are 9.3 °C and 327.7 mm, respectively. Due to the special topography of the valley basin, the frequencies of thermal inversion in the atmospheric boundary layer in winter are very high (Jiang et al., 2001). The total area of Lanzhou city is 210 km^2 and the population is 1.5 million. Major industries in the urban area are petrochemical refinery and manufacturing, which are highly polluting industries. And coal is the main energy source in Lanzhou.

As shown in Fig. 1, in China, there are two main areas ((A) the Tarim basin region and (B) the Alashan-northeast of Hexi Corridor region) where sand-dust storms happen most frequently. Unfortunately, Lanzhou is located right in the downstream region and on the migratory path of the sand-dust storms from these two areas. And the topographic characteristics of the upstream regions of Lanzhou intensify the effect of sand-dust storms on Lanzhou. For example, wind speed is greatly increased due to the narrow pipe effect caused by the topography of the Hexi Corridor and the strong wind transports a large amount of dust to Lanzhou. During spring, a large input of sand and dust from sand-dust events in the upstream regions causes heavy particulate pollution in Lanzhou. Some studies on eolian loess have pointed out that the thickest loess deposits in the world are observed at Jiuzhoutai, which is on the north bank of the Yellow River in Lanzhou (Teng and Shen, 1995). Thus it can be concluded that the severe impact of sand-dust storms on the air quality in Lanzhou has been existing since ancient times.

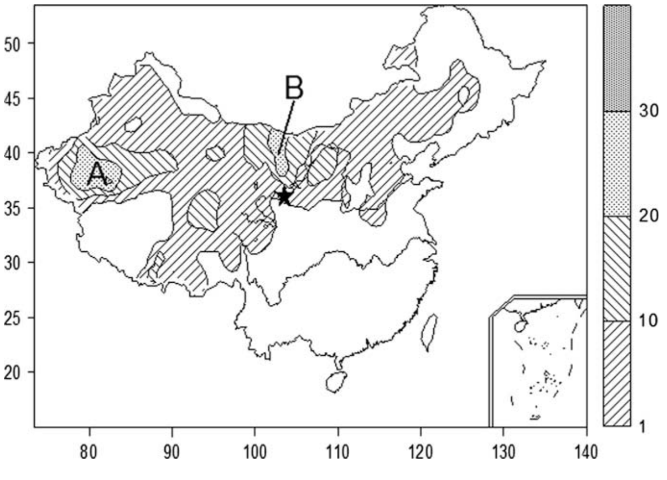

Fig. 1. Location of Lanzhou (as shown by five star) and spatial distribution of 47-year mean annual occurrence days of sand-dust storms in China during 1954–2000. (Labels "Latitude" along the ordinate and "Longitude" along the abscissa. Labels "A" and "B" represent two high-frequency centers of annual days of sand-dust storms.) The data of occurrence days of sand-dust storms used in this figure are from 701 meteorological observation stations in China during 1954–2000.

From the above analysis, it can be concluded that the heavy PM pollution in Lanzhou is the joint result of three factors: emission from local pollution sources, poor diffusion conditions due to the special landform, and intrusions of sand-dust storms. Therefore, selecting Lanzhou city to monitor PM concentrations has great significance in terms of evaluating the joint effects of complex factors on urban particulate pollution.

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

2.1.2. Instruments and monitoring methods

PM concentrations are measured with an Environmental Dust Monitor (EDM) (LN5, Munro Environmental, a division of The Munro Group, Britain). EDM is a direct-reading real-time monitor. The monitor uses a light scattering technique to determine the concentration of airborne particles. This monitor works by continuously drawing the air sample via a volume controlled pump (600 cc min^{-1}) through a flat beam of laser light. The amount of light scatter generating while the particles cross this beam determines the particle mass concentration. EDM can simultaneously measure concentrations of four different sizes of particles (mass concentrations of TSP, PM_{10} and $PM_{2.5}$ and number concentrations of $PM_{1.0}$). Time resolution of the measurements is 5 min. Monitoring on PM with EDM started at 1 Jan, 2005 and continued until 28 Feb, 2006, running 24 h each day during the monitoring period except for some short breaks in 2 Apr, 30 Nov and 7–15 Dec 2005.

Filter-based gravimetric measurements of TSP, PM_{10} and $PM_{2.5}$ at the same monitoring site are also done by using two high-volume (1000 L min^{-1}) samplers and one medium-volume (100 L min^{-1}) sampler, respectively. The measurements of the three particles are done two times a week. The time interval is 12 h (TSP) and 24 h (PM_{10} and $PM_{2.5}$). The measurements are conducted strictly according to the Chinese National Standards of Ambient Air Quality Monitoring, including 'GB/T 15432', 'GB 6921-86' and 'HJ/T 194-2005' (http://www.zhb.gov.cn/tech/index.htm).

In China, PM measurements are often conducted with the filter-based gravimetric method. In order to evaluate the comparability of different PM monitoring methods, 12-h average of TSP concentration and 24-h averages of PM_{10} and $PM_{2.5}$ concentrations based on the measurements by EDM during each filter sampling are calculated. Then, the comparison is done between PM concentrations obtained with the gravimetric method and the EDM during the same sampling period. The result shows the following: for the same kind of particles, the EDM method is found to correlate well with the gravimetric method ($r^2 = 0.89$ for TSP, $r^2 = 0.92$ for PM_{10} and $r^2 = 0.84$ for $PM_{2.5}$, $p < 0.001$). This result indicates that it is highly feasible to use EDM for monitoring PM concentration in Lanzhou.

2.2. Meteorological data

All the meteorological data (including air temperature, atmospheric pressure, dew point temperature, surface wind speed, 6-h precipitation and horizontal visibility) are collected from Lanzhou surface meteorological station of China Meteorological Administration (CMA). The station makes eight times of meteorological observations daily.

3. Results

3.1. Annual variations of PM concentrations

Fig. 2 shows the annual variations of the monthly averages of TSP, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ concentrations in Lanzhou in 2005. In general, they show high values in winter and spring and low values in summer and autumn. As shown in Fig. 2, there are also some differences in the annual distributions of the concentrations of PM with different sizes. These characteristics can be described as follows: the annual distribution of the monthly average concentrations for coarse particles (TSP and PM_{10}) is bimodal, the highest value being in April (899.1 and 541.9 μg m^{-3} for TSP and PM_{10}, respectively). The second highest values of TSP and PM_{10} are in December with 726.2 and 460.5 μg m^{-3}, respectively. Their minimum values are in July with 310.1 and 164.9 μg m^{-3}, respectively. However, the annual distribution of PM concentrations for fine particles ($PM_{2.5}$ and $PM_{1.0}$) is unimodal, the highest value being in December (164.9 μg m^{-3} and 161.5 cm^{-3} for $PM_{2.5}$ and $PM_{1.0}$ respectively). The lowest monthly average concentrations occur in June and are 37.8 μg m^{-3} and 30.3 cm^{-3} for $PM_{2.5}$ and $PM_{1.0}$ respectively.

Local pollutant emission only cannot explain why the highest peaks of monthly averages of TSP and PM_{10} concentrations appear in April, because the largest amount of anthropogenic pollutant emission of the whole year happens in winter due to house-heating. Therefore, this peak of coarse particles in April should be due to dust events. As shown by Wang et al. (2006), in China, most dust events occur in spring, especially in April. A large input of dust from the upstream regions during sand-dust events is the main reason for the highest peak of the concentration for coarse particles in April. In comparison, there is not an observable peak for fine particles in April, as shown in Fig. 2. This indicates that sand-dust transport caused by dust events contributed more to coarse than to fine particle pollution in Lanzhou. Low concentrations of coarse particles 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.

The ratio of $PM_{2.5}/PM_{10}$ can represent the relative content of the fine fraction ($PM_{2.5}$) in PM_{10}. The average value of this ratio in Lanzhou in 2005 is 26.4%, indicating that PM_{10} is mainly consisted of coarser particles ($PM_{2.5-10}$). This ratio is lower in Lanzhou than in many other Chinese cities, e.g. Nanjing, Guangzhou and Beijing (Wei et al., 2001; Huang et al., 2002; Yang et al., 2002). The main reason for the above difference is the geographical position of Lanzhou and the topographic characteristics of its upstream regions. As mentioned in section 2.1, these unique geographical and topographic characteristics make Lanzhou vulnerable to the invasion of sand and dust (mainly coarse particles) from sand-dust events in the upstream regions. Therefore, compared with southern cities (such as Nanjing and Guangzhou) and eastern cities (such as Beijing) of China, coarse particle pollution in Lanzhou is more severe.

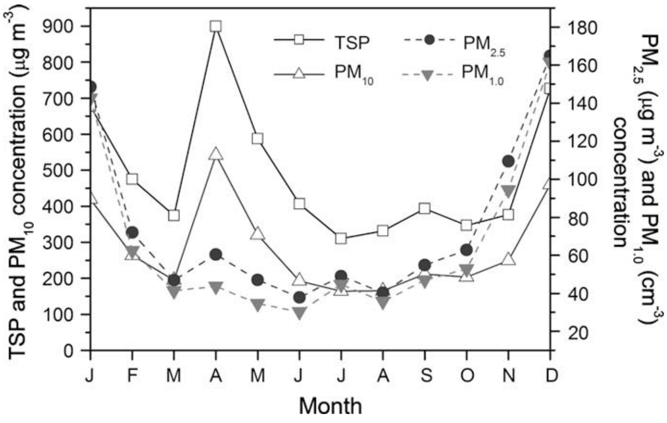

Fig. 2. Annual variations of monthly averages of TSP, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ concentrations in Lanzhou in 2005.

3.2. Diurnal variations of PM concentrations

As mentioned above, certain weather processes such as local dust blowing and sand-dust intrusions from upstream regions have a strong impact on PM concentrations in Lanzhou. Some studies have pointed that dust events in China most frequently occur in April every year (Qian et al., 2004; Wang et al., 2005). Thus, the figure of the average diurnal variation in April 2005 (Fig. 3) is selected to show TSP and PM_{10} diurnal distributions both under normal conditions (without dust intrusions) and during dust intrusions. The average diurnal variations of TSP and PM_{10} under normal conditions (see Fig. 3a) show the typical bimodal distribution, with the two peaks at 9:00 and 22:00 respectively. However, the average diurnal distribution of coarse particle concentrations during dust intrusions (see Fig. 3b) became trimodal. One of the three peaks happened at 16:00 when a low valley appeared under normal conditions. The occurrence of this afternoon peak for TSP and PM_{10} is due to dust intrusions. As has been shown by Zhou (2002) and Wang et al. (2005), most dust storms in China occur in the afternoon in spring. For $PM_{2.5}$ and $PM_{1.0}$, however, there is no significant variation in average diurnal distribution in April, dust events or not. This indicates that the impact of dust events on the concentrations of fine particles is not significant, and the fine particle pollution in Lanzhou is mainly caused by local emissions and poor diffusion conditions due to the local special landform.

Comparing the two types of diurnal distributions (Fig. 3a and b), we can conclude that the diurnal distribution of coarse particle concentration in Lanzhou can be dramatically changed by dust intrusions in spring. Therefore, the days of dust events are excluded in calculating the average diurnal variations in order to show the seasonal variation of the general patterns of PM concentrations in Lanzhou.

Shown in Fig. 4 are the average diurnal variations of TSP, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ concentrations for the four seasons of 2005 in Lanzhou. In general, the diurnal patterns of the four kinds of particles show a bimodal distribution for the whole year (except for fine particles in spring and summer). The highest peak is observed before or at noon and the secondary peak is observed before or at midnight. These characteristics can be described as follows: the two peaks of TSP occur at 9:00 (Beijing Time, the same hereinafter) and 21:00 in spring, 9:00 and 22:00 in summer, 11:00 and 18:00 in autumn, and 12:00 and 19:00 in winter. The two peaks of PM_{10} occur at 9:00 and 0:00 in spring, 9:00 and 22:00 in summer, 11:00 and 20:00 in autumn, and 12:00 and 19:00 in winter. The two peaks of $PM_{2.5}$ and $PM_{1.0}$ occur at 11:00 and 23:00 in autumn, and 12:00 and 20:00 in winter. In spring and summer, there is only one peak of fine particles, being at 10:00 in spring and 9:00 in summer. Low concentrations of all particles happen in the early morning and in the late afternoon.

As shown in Fig. 4 and Table 1, the average diurnal patterns of the four kinds of PM for the same season are rather similar.

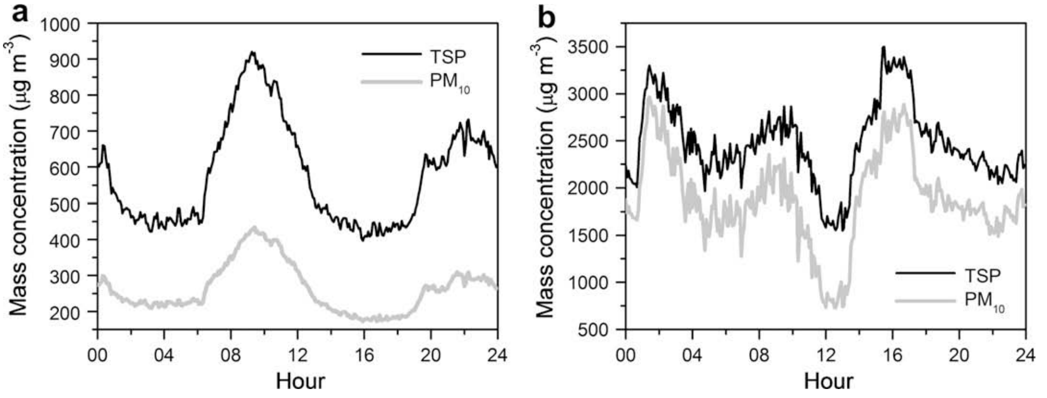

Fig. 3. Average diurnal variations of TSP and PM_{10} mass concentrations in April 2005, calculated for (a) days without dust events and (b) days with dust events (including 7–9, 18 and 30 Apr 2005), respectively.

However, there are still some differences in the occurrence time of maximum and minimum concentrations among PM with different sizes. In general, the highest peaks of TSP, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ occur at about the same time. However, there are obvious differences in the occurrence time of minimum concentrations among different kinds of PM. Namely, TSP concentration minima occur at 2:00–3:00 am in all seasons; PM_{10} minima occur at 2:00–3:00 am in autumn and winter, but in the afternoon in spring and summer; the concentration minima of fine particles all occur before dark except in winter (see Table 1). These differences in the occurrence time of minima between coarse and fine particles are due to their different diffusion behaviors in the atmospheric boundary layer. The mass of a fine particle is relatively small, so it can suspend in the air for a long time. Therefore, the concentrations of fine particles are mainly affected by atmospheric diffusion conditions. In the afternoon, the dissipation of the boundary layer inversion and the development of a mixing layer are helpful for fine particles to diffuse, which results in the concentration minimum before dark. Compared with fine particles, coarse particles are heavier and cannot be suspended easily in the air for a long time. Thus, their concentrations mainly depend on the variation of local emission. In general, the amount of local emission after midnight reaches the minimum of the day. On the other hand, re-suspension generated by traffic and other human activities also drops to the lowest point

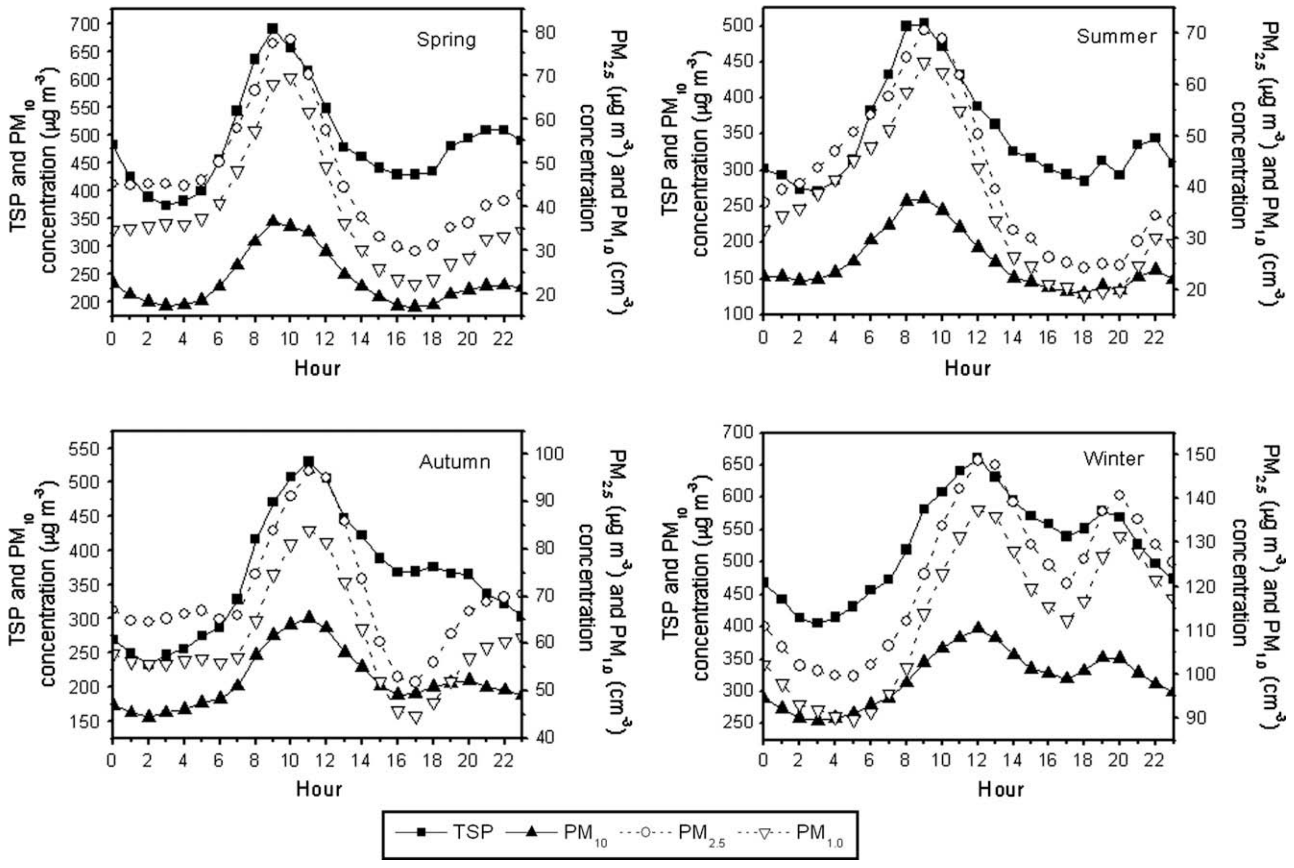

Fig. 4. Diurnal variations of TSP, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ concentrations for the four seasons of 2005 in Lanzhou. The winter is from Dec 2005 to Feb 2006.

Table 1
Occurrence time (Beijing Time) of maximum/minimum concentrations of PM diurnal variations.

	TSP		PM_{10}		$PM_{2.5}$		$PM_{1.0}$	
	t_{max}	t_{min}	t_{max}	t_{min}	t_{max}	t_{min}	t_{max}	t_{min}
Spring	9:00	3:00	9:00	17:00	10:00	17:00	10:00	17:00
Summer	9:00	3:00	9:00	18:00	9:00	18:00	9:00	18:00
Autumn	11:00	2:00	11:00	2:00	11:00	17:00	11:00	17:00
Winter	12:00	3:00	12:00	3:00	12:00	5:00	12:00	5:00

t_{max} and t_{min} are the occurrence time of maximum and minimum concentrations, respectively.

after midnight. As a result, the concentration of coarse particles reaches a minimum at 2:00–3:00 am. In winter, due to the topographic influence of the valley basin, the thickness and the intensity of the ground-level inversion layer in Lanzhou is the greatest. Even in the afternoon, the inversion does not completely disappear (Wang et al., 2002). Therefore, winter minimum concentrations of both coarse particles and fine particles all occur in the early morning, not in the afternoon as in other seasons.

For the same kind of particles, seasonal differences in diurnal variation of PM concentration are also visible, as shown in Fig. 4 and Table 1. There are observable seasonal differences in the occurrence time of PM maxima (see Table 1). Namely, the highest peaks of the four kinds of PM occur approximately 1–3 h earlier in spring and summer than in autumn and winter. The above difference is closely related to the time of the local sunrise and the dissipation of the relevant inversion layer. As shown in Table 2, sunrise in Lanzhou is early in summer and late in winter. After sunrise, a mixing layer appears in the surface layer due to solar radiation, and this leads to the break and dissipation of the inversion layer which is formed at night. Right before the complete dissipation of the inversion layer, the concentrations of PM near the surface reach the maximum value of the day. The earlier the sunrise, the earlier the dissipation of the inversion layer and the earlier the occurrence of the concentration peak, and vice versa. Furthermore, the effect of human activities should also be considered. The earlier the sun rises, the earlier human activities begin, which helps to make the occurrence of the concentration peaks earlier.

To sum up, under normal conditions, there are several important factors affecting the diurnal variations of PM concentrations in Lanzhou, i.e. local sunrise time, human activities, atmospheric stratification situation in the boundary layer and the diurnal variations of local meteorological elements.

3.3. *Influence of local meteorological elements on PM concentrations*

Pre-existing studies have pointed out that, air pollutant concentration is mainly controlled by local meteorological situation when local emission is constant. In this study, the relation between pollutant concentrations and meteorological elements is statistically analyzed. The result shows that the meteorological elements correlate better with the logarithms of PM concentrations than with PM concentrations themselves. So, the correlation between local surface meteorological elements and the logarithms of PM concentration is statistically analyzed in order to evaluate the effects of local meteorological elements. The meteorological elements are air temperature, 24-h temperature change, atmospheric pressure, 24-h pressure change, surface wind speed, 6-h precipitation, horizontal visibility and relative humidity.

Table 2
Sunrise time (Beijing Time) on 15th of each month in Lanzhou.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sunrise time	7:10	6:47	6:11	5:27	4:54	4:42	4:54	5:18	5:42	6:06	6:36	7:03

The statistical analysis indicates that PM concentrations correlate well with the meteorological elements mentioned above—most of the correlation coefficients are significant at the 0.05 level (2-tailed *t*-test). At the same time, the effects of various meteorological elements on PM concentrations are remarkably different and show clear seasonal variations. Generally, of all the meteorological elements mentioned above, the correlation of PM concentrations with horizontal visibility, relative humidity and surface wind speed is particularly significant (Table 3).

Horizontal visibility is negatively correlated with PM concentrations and the wintertime correlation is the best (see Table 3). Small particles have a greater impact on visibility, and thus the correlation coefficient between PM concentrations and visibility is remarkably higher for fine particles than for coarse particles. This is due to the different optical properties of particles with different sizes.

Relative humidity affects the concentrations of coarse particles and fine particles differently and their correlation shows the seasonal difference, as shown in Table 3. In spring, autumn and winter, relative humidity is negatively correlated with TSP and PM_{10} concentrations, but positively correlated with $PM_{2.5}$ and $PM_{1.0}$ concentrations. In summer, however, relative humidity is positively correlated with PM_{10} as well as $PM_{2.5}$ and $PM_{1.0}$, and the smaller the particle size, the greater the correlation coefficient. This indicates that high relative humidity depresses the diffusion of particles in summer, and the depressing effect is more significant for smaller particles.

Surface wind speed is negatively correlated with the concentrations of all four kinds of particles in summer, autumn and winter (except for TSP in summer). Due to gravity, fine particles can be diffused and transported by wind more easily than coarse particles, as shown in Table 3. However, it is particularly noteworthy that springtime wind speed is negatively correlated with $PM_{2.5}$ and $PM_{1.0}$ concentrations, but positively correlated with TSP and PM_{10}

Table 3
Correlation coefficient between logarithms of PM concentration and local surface meteorological elements.

	Surface wind speed	Horizontal visibility	Relative humidity
Spring			
$Log_{10}TSP$	0.118[b]	−0.291[a]	−0.429[a]
$Log_{10}PM_{10}$	0.099[b]	−0.401[a]	−0.312[a]
$Log_{10}PM_{2.5}$	−0.081[c]	−0.614[a]	0.037
$Log_{10}PM_{1.0}$	−0.159[a]	−0.600[a]	0.132[a]
Summer			
$Log_{10}TSP$	0.028	−0.315[a]	−0.002
$Log_{10}PM_{10}$	−0.074[c]	−0.476[a]	0.198[a]
$Log_{10}PM_{2.5}$	−0.243[a]	−0.697[a]	0.551[a]
$Log_{10}PM_{1.0}$	−0.258[a]	−0.685[a]	0.567[a]
Autumn			
$Log_{10}TSP$	−0.036	−0.166[a]	−0.241[a]
$Log_{10}PM_{10}$	−0.103[b]	−0.340[a]	−0.089[c]
$Log_{10}PM_{2.5}$	−0.217[a]	−0.630[a]	0.192[a]
$Log_{10}PM_{1.0}$	−0.231[a]	−0.644[a]	0.195[a]
Winter			
$Log_{10}TSP$	−0.191[a]	−0.474[a]	−0.206[a]
$Log_{10}PM_{10}$	−0.227[a]	−0.572[a]	−0.104[c]
$Log_{10}PM_{2.5}$	−0.293[a]	−0.734[a]	0.127[b]
$Log_{10}PM_{1.0}$	−0.309[a]	−0.738[a]	0.156[a]

[a] Correlation is significant at the 0.001 level (2-tailed *t*-test).
[b] Correlation is significant at the 0.01 level (2-tailed *t*-test).
[c] Correlation is significant at the 0.05 level (2-tailed *t*-test).

(or $PM_{>10}$ and $PM_{2.5-10}$) concentrations. This reflects an important phenomenon in Lanzhou which is different from the situation of other cities, that is, the rise of wind speed in spring is generally associated with weather processes of dust-storm. While strong wind rapidly diffuses fine particles (mainly from local emissions) and thus reduces their concentration, it also brings a large amount of dust (mainly coarse particles) from upstream regions to Lanzhou. Besides, strong wind can also aggravate sand-dust pollution due to local dust blowing in Lanzhou. As a result of both, TSP and PM_{10} concentrations increase greatly.

4. Conclusions and discussion

Based on our work, the following conclusions can be made:

(1) The annual distribution of the monthly average concentrations of coarse particles (TSP and PM_{10}) in Lanzhou in 2005 is bimodal, with the highest peak in April and the second highest in December. However, the annual distribution of fine particle ($PM_{2.5}$ and $PM_{1.0}$) concentrations is unimodal, with the maximum value occurring in December. The difference in the behavior between coarse and fine particles indicates that dust events in spring contributed more to coarse than to fine particles in Lanzhou. This conclusion is supported by the fact that springtime wind speed in Lanzhou is correlated positively with TSP and PM_{10} concentrations, but negatively with $PM_{2.5}$ and $PM_{1.0}$ concentrations because the wind diffusion reduces the concentration of local fine particles (from local emission).

(2) Under normal conditions (without dust intrusions), the diurnal pattern of coarse particle concentrations in April in Lanzhou has a bimodal distribution, with one peak in the forenoon and another in the evening. However, the average diurnal pattern of coarse particles during dust intrusions in the same month has a trimodal distribution. The occurrence of the afternoon peak is due to dust intrusions.

(3) In general, the highest concentration peaks of the diurnal variations for TSP, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ occur at about the same time. However, there are obvious differences in the occurrence time of minimum concentrations among different kinds of PM, that is, the minima generally occur in the early morning for coarse particles and before dark for fine particles. This is due to the fact that coarse and fine particles diffuse differently in the atmospheric boundary layer because of their difference in mass. The concentration of fine particles mainly depends on the atmospheric diffusion conditions, while that of coarse particles mainly depends on emission from local sources.

(4) For the same kind of particles, the seasonal differences in the diurnal variation of PM concentration are also visible. The highest peaks of the four kinds of PM all occur earlier in spring and summer than in autumn and winter. This is closely related to the factors such as local sunrise time, atmospheric stratification situation in the boundary layer and human activities.

(5) The effects of various meteorological elements on PM concentrations are remarkably different and show clear seasonal variations. Of all the meteorological elements studied, horizontal visibility, relative humidity and surface wind speed correlate particularly well with PM concentrations.

Finally, it must be pointed out that the effects of different weather processes and their relevant meteorological elements on PM concentrations should be different. In order to fully understand this problem, the behavior of PM concentrations during certain typical weather processes will be studied in the future.

Acknowledgments

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