Ambient TSP concentration and dustfall variation in Urumqi, China

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Abstract: Total suspended particulate (TSP, particle diameters $\leq 100 \mu\text{m}$) was the dominant air pollutant and significantly influenced local air quality. In this paper, we investigated the interannual and seasonal variations of TSP and dustfall of the atmosphere over Urumqi, the capital city of Xinjiang Uygur autonomous region, northwestern China, basing on environmental monitoring records and meteorological data from 1986–2012. The results showed that during the study period, annual average TSP concentration decreased from 716 to 260 $\mu\text{g}/\text{m}^3$, with an average level of 422.9 $\mu\text{g}/\text{m}^3$, while dustfall intensity reduced from 350.4 to 166.6 $\text{t}/(\text{km}^2\cdot\text{a})$, with an average level of 259 $\text{t}/(\text{km}^2\cdot\text{a})$. Over 50% of the annual pollution days were induced mainly by TSP. Spring and winter had relatively higher dustfall intensities, and dense traffic and residential areas had the highest dustfall intensities in the Urumqi metropolitan area. With an annual average precipitation of less than 300 mm, atmospheric particulates in Urumqi could be hardly removed through wet deposition. During spring and summertime prevailing winds from northwest and northeast could carry aeolian dust particles from sandy deserts to Urumqi. Aeolian dusts from deserts would remain to be a priority regarding air pollution control in arid oasis cities.

Keywords: total suspended particle; dust deposition; desert; atmospheric environment

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Airborne dust is a notable contributor to air pollution in northern China and has significant impacts on the environment in eastern Asia (Husar, 2001; Xuan et al., 2002). Over the past few decades, the emission, transportation and deposition of dust have received increasing attention (Derbyshire et al., 1998; Sassen, 2002; Uno et al., 2009; Groll, 2013). Numerous reports have suggested that dust from central Asia has caused dust deposition in Korea, Japan, USA and across the northern Pacific, as well as traces in ice and snow cores in Greenland (Prospero et al., 1989;

Leinen et al., 1994; Yu et al., 2012). One of the main dust sources in Asia is the Taklamakan Desert located in Xinjiang Uygur autonomous region, northwestern China (Okada and Kai, 2012).

When winds are sufficiently strong in deserts, dust particles are entrained by wind shear at the surface and transported by advection and turbulent diffusion. Finally, they are deposited through dry and wet removal processes (Shao, 2000). This cycle has a significant impact on the atmosphere. Mineral aerosols associated with trace elements are carried by strong winds, and

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then deposited to populated regions, resulting in reduced visibility and substantially contributing to air pollution. Currently, major oasis cities in northwestern China, such as Urumqi, are undergoing rapid development due to urbanization and population growth (Chen et al., 2009; Mamtimin and Meixner, 2011; Wang et al., 2012). For the past several decades, Urumqi has suffered from heavy dust haze (Li et al., 2006), and it is vulnerable to natural dust emissions from the arid and semi-arid desert areas of Xinjiang.

Recently, some studies have been carried out analyzing the chemical pollution and mineral dust components in the atmosphere above Urumqi. It was reported that the average $\text{PM}_{2.5}$ (particle diameter $\leq 2.5 \mu\text{m}$) and TSP (particle diameter $\leq 100 \mu\text{m}$) concentrations in the winter of 2007 were 187 and 385 mg/m^3 with maxima of 487 and $1,313 \text{ mg/m}^3$, respectively. These levels were 12 times higher than the U.S. EPA standard for $\text{PM}_{2.5}$, and three times higher than China's National Ambient Air Quality Standard for TSP (Li et al., 2008). According to the observations by Mamtimin and Meixner (2011), monthly mean PM_{10} (particle diameter $\leq 10 \mu\text{m}$) concentrations in Urumqi from 2000–2006 were between 150 and $240 \mu\text{g/m}^3$. Dong et al. (2011) studied the physicochemical characteristics of mineral dust particles in the precipitation of the Urumqi River Valley and indicated that aerosol dust in the precipitation was very sensitive to the seasonal change of the regional atmospheric environments in central Asia. However, the research on a long-term influence of TSP and dustfall variations specifically for the atmospheric environment over the dry, populated city of Urumqi is still scarce and inadequate. A study on the impact of dust aerosols that improves the understanding of how ambient TSP and dustfall influence the oasis atmosphere is critical to local residents because it could lead to significant improvements in urban air quality.

In this paper, we systematically investigated the impacts of ambient TSP and dustfall on the atmosphere through a long-term time series and statistical analyses basing on data from environmental monitoring stations and observations over the past three decades. Furthermore, the changes in seasonal precipita-

tion and wind frequency as well as their possible associations with TSP and dustfall in Urumqi were also discussed.

1 Study area

Urumqi ($42^\circ 45' 32''$ – $44^\circ 08' 00''$ N, $86^\circ 37' 33''$ – $88^\circ 58' 24''$ E), which is located in northwestern China, is the capital city of Xinjiang Uygur autonomous region. It is flanked by the Gurbantunggut Desert in Junggar Basin to the north and rest on the northern foothills of the eastern Tianshan Mountains (Fig. 1). The city was built along a river valley near Bogda Mountain which boasts an elevation of 5,545 m asl. The regional climate is semi-arid, with an annual average precipitation of about 300 mm and annual average wind velocity of approximately 2.5 m/s. In 1998, Urumqi was assessed as one of the ten worst polluted cities in the world in terms of air pollution (Mamtimin and Meixner, 2007) and its total population has rapidly increased from 1.20×10^6 in 1981 to 2.43×10^6 in 2010 (Urumqi Municipal Bureau of Statistics, 2013).

2 Materials and methods

The TSP and dustfall data were collected from 12 environmental monitoring stations in the Urumqi metropolitan area (Fig. 2). Airborne TSP samples were taken by an air sampler with fine fiberglass films at 1.5 m above the ground. Daily TSP concentration data were obtained by the arithmetic mean of at least four measurements, and the sampling time for every measurement lasted longer than an hour. TSP concentration was expressed in mg/m^3 as the mass of particulate matter per unit volume of atmosphere (MEP, 1995). Dustfall was determined by the gravimetric method at monthly intervals. Dust samples were collected with cylindric glass vessels (three replicates) filled with glycol ($\text{C}_2\text{H}_6\text{O}_2$), at 10 ± 1 m above ground. The glass vessel is 15 cm in diameter and 30 cm in depth. All the dust samples were oven-dried at 105°C , and then weighed. Dustfall intensity was expressed as the mass of dust settled naturally per unit area over a certain unit time, in $\text{t}/(\text{km}^2 \cdot \text{a})$ (MEP, 1994).

The daily API (Air Pollution Index) data were obtained from statistics published by the Ministry of Environmental Protection of China (<http://datacenter>).

Fig. 1 Location of the study area (Urumqi) and its surrounding desert environment

Fig. 2 Distribution of environmental monitoring stations in the Urumqi metropolitan area

mep.gov.cn). The meteorological data, including precipitation, wind speed, wind direction, etc., were collected from the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn>). The desert distribution dataset was provided by the Environ-

mental and Ecological Science Data Center for Western China sponsored by the National Natural Science Foundation of China (<http://westdc.westgis.ac.cn>). In this paper, the percentages of particle pollution days per year and per month were used to quantify the im-

pect of TSP pollution on the atmospheric environment in Urumqi.

3 Results and discussion

3.1 TSP concentration and dustfall intensity

Urumqi is in the middle of two dust sources: the Taklamakan Desert and the Gurbantunggut Desert, from which dust particles are easily transported by the wind. Figure 3 depicts the changes in annual average TSP concentration and dustfall intensity in Urumqi from 1986 to 2012. The annual TSP concentration changed within a range of roughly 300–700 $\mu\text{g}/\text{m}^3$, with a maximum of 716 $\mu\text{g}/\text{m}^3$ in 1990 and a minimum of 260 $\mu\text{g}/\text{m}^3$ in 2005. In the late 1980s, 1990s and 2000s, the annual average TSP concentrations were 541, 464 and 338 $\mu\text{g}/\text{m}^3$, respectively. During the same period, the annual average dustfall intensity in Urumqi decreased from 350 to 167 $\text{t}/(\text{km}^2\cdot\text{a})$. In the 1980s, 1990s and 2000s, the annual average dustfall intensity was 276, 306 and 222 $\text{t}/(\text{km}^2\cdot\text{a})$, respectively. It can be seen clearly that the atmospheric environment with

regard to dust pollution has improved since 1986 and a jointly decreasing trend was observed between dustfall intensity and TSP concentration. Generally, the average annual concentrations of TSP have degraded in three stages: 1986–1990, 1991–2001 and 2002–2012. The dustfall intensity dropped abruptly in 2002 after remaining stable for several years. At the end of 2012, the average annual TSP concentration and dustfall intensity in Urumqi decreased by more than 20% and 25%, respectively. This atmospheric improvement might be attributed to two main factors: One is that the local government created and enforced an energy conservation policy beginning in the later 1990s, funded extensively by the ‘Blue Sky’ project. Massive conversion from coal to natural gas consumption was implemented, which achieved significant progresses in air pollution control (Xinjiang Department of Environmental Protection, 2012). Another factor was due to a decrease in the frequency of dust storm outbreaks in the arid and semi-arid desert areas of Xinjiang during the past several decades (Details are discussed in Section 3.2).

Fig. 3 Changes in annual average TSP concentration and dustfall intensity in Urumqi from 1986 to 2012

The basic background information for environmental monitoring stations in the Urumqi metropolitan area as well as the average annual dustfall intensity from 1986 to 2012 for each station were listed in

Table 1. The comparison of the 12 stations revealed higher dustfall intensities in dense traffic and residential areas. Dustfall intensity showed a high degree of spatial variability, which ranged from 127.9 $\text{t}/(\text{km}^2\cdot\text{a})$

in Sigong to 374.5 t/(km²·a) in Shoufeisuo. The dustfall intensity at the edge of the metropolitan area was around 200 t/(km²·a) except for Sigong in the north. Stations with the heaviest dust deposition were Shoufeisuo and Tiezhao, which were respectively located in a dense traffic area and residential center. The average annual dustfall intensity from 1986 to 2012 in Urumqi city amounted to 259 t/(km²·a). Generally, it's assumed that particle pollution was mainly attributed to locally sourced aerosols generated by automobile vehicles or domestic combustion combined with natural sources like desert dust (Yang and Chen, 2002;

Bogo et al., 2003; Liang et al., 2008; Wang et al., 2010).

The distribution of seasonal dustfall intensity was useful to assess possible pollution sources and identify periods most prone to dust pollution. Figure 4 indicates that dustfall intensity in Urumqi was highest in spring (March-April-May, or MAM), followed by winter (December-January-February, or DJF) and autumn (September-October-November, or SON), with summer (June-July-August, or JJA) being lowest. Moreover, there was no apparent distinction in the dust deposition in autumn by comparison with winter.

Table 1 The environmental monitoring stations used in this study

No.	Station name	District	Function zone	Dustfall intensity (t/(km ² ·a))
1	Shoufeisuo	Tianshan	Dense traffic area	374.5
2	Beimen	Tianshan	Dense traffic area	305.8
3	Jiancezhan	Sayibak	Dense traffic area	291.1
4	Tiezhao	Xinshi	Residential area	324.9
5	Changjianglu	Sayibak	Dense traffic area	241.2
6	Baoshe	Sayibak	Commercial area	219.7
7	Huagongchang	Shuimogou	Industrial area	256.1
8	Qixiangju	Tianshan	Residential area	253.0
9	Nanmen	Tianshan	Residential area	261.9
10	Qifang	Shuimogou	Industrial area	235.9
11	Sanxiangjiao	Xinshi	Industrial area	216.2
12	Sigong	Xinshi	City outskirts	127.9
Total average				259.0

Note: dustfall intensities were calculated with annual averages from 1986 to 2012.

Fig. 4 Seasonal distribution of dustfall intensity at 12 monitoring stations in Urumqi from 1986 to 2012

In the spring, the main sources of dust in Urumqi were from neighboring farmlands and deserts (Li et al., 2008). The particulates generated by automobiles and secondary blowing dust might be additional factors affecting the dust intensity and distribution in Urumqi (Li et al., 2008; Li et al., 2010).

3.2 Influence of TSP on air quality

In China, most northern cities suffer seasonal dust haze and dust storms. The dust pollution not only damages human health, but also changes regional radiative forces and surface albedo (IPCC, 2007). In March 2000, the Chinese government launched an air quality monitoring network in major Chinese cities. Figure 5 depicts daily air quality levels in Urumqi from 2001 to 2012. It shows that the primary source of air pollution in Urumqi was TSP for all seasons. Heavy TSP pollution significantly affected the atmosphere of Urumqi. The most severe air pollution events happened primarily in spring and winter which are with the worst air quality of the year. On the whole, TSP pollution in spring has apparently decreased since 2002. Over the past three decades, the frequency of dust storms had decreased substantially in northern China (China Meteorological Administration, 2010). Therefore, the TSP pollution mitigation in spring might be attributed to a reduction in dust storm frequency in Xinjiang in the late 20th century (He et al., 2003; Wei et al., 2004; Amina and Dilinuer, 2011). Summer showed the best air quality among the four seasons, with an average daily API of less than 100, which ranked within excellent air quality (0–50) or slight TSP pollution (51–100) on the Chinese API scale. In autumn, the weather gradually becomes cold and windy, and the air quality is relatively good compared to that of the frigid winter season. Below-freezing winters in northwestern China, especially Urumqi, require substantial heating for homes. A widespread temperature inversion occurs in the city throughout the winter (Mamtimin and Meixner, 2011). Therefore, air pollution could be trapped beneath the inversion for long periods, which is likely the cause of high TSP levels in the atmosphere (Fig. 5).

Figure 6 reflects that the share of average annual TSP pollution days was over 54% from 2001 to 2012, with the exception of 2005, and the monthly share

from April to October was over 90%. The share of annual average TSP pollution days showed an incremental rise in the last six years, staying above 75%. There were considerable variations among seasons with average monthly shares of TSP pollution days ranging from 46% to 98% and dropping sharply in winter compared to relatively high values in spring, summer and autumn (Fig. 6b). This phenomenon of air pollution levels of TSP decreasing in winter (Fig. 5 and Fig. 6b) is attributed to the heating process of coal combustion which produces large amounts of sulfur-containing pollutants (Li et al., 2008). Therefore, the share of average monthly SO₂ pollution days was rising rapidly during cold wintertime. Although the monthly share of TSP was lower in winter than in other seasons, particle pollution still severely affected the atmosphere of Urumqi year-round.

3.3 Factors of influencing TSP and dust deposition

Figure 7 depicts the seasonal change of daily average TSP concentration and precipitation in Urumqi from 2001 to 2012. It showed that daily TSP concentrations changed with seasons. TSP concentrations were higher in spring and winter than in summer and autumn. However, spring is the season in which sand and dust storms occur most frequently in Xinjiang. During these periods, particles with larger diameters are deposited at an increased rate near the edge of deserts through gravitational settling. In contrast, finer particles are transported over longer distances to oasis regions such as Urumqi. During spring and summer, precipitation plays a vital role in removing dust particles since wet deposition removes dust particles floating in the atmosphere more efficiently (Li and Wang, 2007). Urumqi is cold and dry in winter with a mean monthly precipitation of around 12–30 mm and minimum surface temperatures reaching a frigid –28.1– –29.0°C. Annually, heating within the city is available over six months, from 15 October to 15 April (Li et al., 2007). This lengthy period resulted in gross consumption of fossil fuels, and caused a high level of particulate pollution in the late autumn and winter. It's estimated that annual coal consumption in 2010 was 1.6×10^7 tons (Xinjiang Statistical Bureau, 2012). Although snowfall precipitation occasionally occurred throughout the winter and apparently

Fig. 5 Air pollution index (API) and major air pollutants in Urumqi city from 2001 to 2012

Fig. 6 Changes in annual (a) and monthly (b) shares of TSP pollution days from 2001 to 2012

Fig. 7 Seasonal change in average daily TSP concentration and precipitation in Urumqi from 2001 to 2012

improved air quality within 1–2 days (Li and Wang, 2007), a comprehensive reduction of persistent and continuous particulate pollution in the atmosphere is still necessary.

Wind plays an important role in carrying particles over a long distance in arid and semi arid areas (Shao, 2000; Kumar, 2008). The frequency and distribution of maximum wind velocities in Urumqi in spring, summer, autumn and winter from 2001 to 2012 are shown in Fig. 8. Maximum wind velocity of different seasons was mainly originating from the northeast and southwest in winter, northwest and northeast in spring, northwest in summer, and southwest in autumn, respectively. With a mean altitude of about 800 m asl,

Urumqi is surrounded by the Tianshan Mountains with the mountain peak topping over 5,000 m asl in every direction except north, creating a valley wherein the city lies. In winter, air pollution is not easily removed since Urumqi was built along a northeast to southwest river valley with northwest and southwest winds blocked by the Tianshan Mountain Range that houses the valley. Consequently, the air pollution can hover for long periods. Wind direction in spring blows from the north, often carrying sand and dust from the nearby Gurbantunggut Desert, exasperating the effect. This result corresponds to points of view in relative studies (Li et al., 2008; Mamtimin and Meixner, 2011).

Fig. 8 Seasonal frequency and distribution of maximum wind velocity in Urumqi from 2001 to 2012

4 Conclusions

From 1986 to 2012, average annual TSP concentration and dustfall intensity in Urumqi decreased by 63.6% and 52.4%, respectively. Although air quality has been obviously improved and TSP concentration and dustfall intensity decreased accordingly, the atmospheric environment of Urumqi is still affected by airborne particulates. In arid climatic conditions, precipitation plays a limited role in removing airborne particles. Under sand and dust storms, strong winds blow large amounts of aeolian dust particles from desert areas to the metropolitan region. Aeolian dust from arid deserts would remain a dominant contributor to air pollution in oasis cities.

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