Air Particulate Pollution in Ulaanbaatar, Mongolia:
Variation in Atmospheric Conditions from Autumn to Winter

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Abstract

Ulaanbaatar, the capital city of Mongolia, is subject to high levels of atmospheric pollution during the winter, which severely affects the health of the exposed population. Using lidar and ground level meteorological observations, we studied the temporal variation of the PM₂.₅ and the structure of the atmospheric boundary layer (ABL) during the 2010 heating season. The concentration of PM₂.₅ increased after the air temperatures sharply decreased during two cold waves occurring 8–10 and 21–25 October. The surface air temperatures first dropped below 0°C because of the cold wave beginning on 10 October, which prompted the households in the ger (traditional Mongolian dwelling) districts to start combusting coal for heating, resulting in increased PM₂.₅ concentrations. Meanwhile, the maximum ABL height continuously decreased from summer to winter and dropped below 800 m after the second cold wave, when the weather was influenced by a Siberian high. The stable atmospheric conditions and surface inversion layer in winter resulted in low wind velocities (< 2 m s⁻¹), especially at night. Consequently, because of both the meteorological and topographical conditions, air pollutants remained at the urban surface level, which resulted in high concentrations of PM₂.₅ in winter.

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1. Introduction

Ulaanbaatar, the capital city of Mongolia, has been experiencing sustained growth since the 1990s, and this development has caused a number of social and environmental problems. One of the most serious problems is atmospheric pollution in winter, the other one is traffic congestion in the urban areas of Ulaanbaatar.

The emission sources of particulate matter (PM) in Ulaanbaatar are not complicated. Coal combustion is the main source of heat in Ulaanbaatar, and the emitted particles and dusts from such are the primary PM sources. Other sources of PM include fine particles from vehicle exhausts and floating soil dusts disturbed by passing vehicles along roads, especially unpaved roads (Guttikunda 2007). In recent years, the number and total surface area of ger districts in Ulaanbaatar have increased (Oyunchimeg and Tsolmon 2007). In 2007, 62,000 tons of fine PM emissions in Ulaanbaatar included 62,000 tons of fine PM emissions in 2010 (Guttikunda et al. 2013). Because of the heavy use of coal in the ger districts, Ulaanbaatar has become one of the most polluted cities in the world.

Although air particulate pollution has been receiving wide attention in recent years worldwide (Zhang et al. 2006; Zhang et al. 2010; Wang et al. 2010), Ulaanbaatar has several characteristics that differ from those of other cities. As shown in Fig. 1a, Ulaanbaatar is located in a basin surrounded by mountains, and its high latitude leads to longer and colder winters than most other global capital cities. Such topographical and geographical factors provide suitable conditions for the formation of inversion layers in winter. When an inversion layer persists, air pollutants emitted at the ground level cannot escape easily, resulting in severe pollution. Unfortunately, among previous studies regarding air pollution in Ulaanbaatar, none has mentioned the seasonal variation of urban atmospheric boundary layer (ABL) structure, and only a few have used lidar (light detection and ranging) to measure air particulate pollutants (Nishikawa et al. 2011).

A typical air pollution event occurred in Ulaanbaatar in October 2010. In this study, we investigated the temporal and spatial distributions of PM₂.₅ and the structure of the ABL during the heating season in Ulaanbaatar by analyzing lidar and surface meteorological data. By discussing the characteristics of PM₂.₅, the wind patterns, and the ABL structure, our results may provide some useful scientific support for lidar measurement of both ABL variations and air particulate pollution, with the aim of aiding in the amelioration of urban air particulate pollution in Ulaanbaatar.

2. Data and methods

2.1 Lidar and surface meteorological data for Ulaanbaatar

The lidar system in Ulaanbaatar has been operational since September 2007 and is part of the Asian lidar network (Sugimoto et al. 2009). It consists of two-wavelength Mie-scattering lidar (532 nm and 1064 nm) with depolarization ratio measurements of 532 nm. Measurements are taken automatically, and the 5-minute averaged lidar profiles are recorded every 15 minutes in continuous observation mode. The lidar in Ulaanbaatar (106.90E 47.92N; 1320 mASL) is located in the building of the National Agency for Meteorology and Environment Monitoring of Mongolia (NAMEM) (Fig. 1b). Observations taken less than 120 m above the surface were not used because the accuracy of the retrieved data in the lower atmosphere is unknown (Shimizu et al. 2010).

The surface data for Ulaanbaatar is collected by two aerosol monitors (E-Sampler Aerosol Monitor, Met One Instruments, Rowlett, TX, USA) placed on the roof of the NAMHEM building. They measure the PM₁₀ and PM₂.₅, wind speed and direction, and visibility hourly.

Previous studies have proved that lidar measurement of ABL height is as accurate as radiosonde measurement and allows for easier long-term continuous measurement (Cohn and Angevine 2000; Tomasi and Perrone 2005). Meanwhile, compared with the method using the gradient of attenuated backscattering coefficient, the wavelet covariance transform method, which will be discussed in Section 2.2, is less influenced by the signal-to-noise ratio (Baars et al. 2008) and is considered applicable for determining the ABL height in a meteorological condition with seasonal variations of climate and aerosol concentration.

2.2 Method to determine maximum ABL heights

We defined the height of the cloud base by the gradient of the attenuated backscattering coefficient exceeding 4 × 10⁻⁵/m/sr per meter, and the attenuated backscattering coefficient that first exceeded 5 × 10⁻⁶/m/sr. Profiles containing clouds were excluded...
before calculating the ABL heights. For details of the method for defining the cloud base height, please refer to Sugimoto et al. (2009).

To determine the ABL height on sunny days, a wavelet covariance defined by Gamage and Hagelberg (1993) using the Haar function was employed,

$$ W_f(a,b) = a^{-1} \int_{z_0}^{z_b} f(z) h \left( \frac{z-b}{a} \right) dz, $$

where $z$ is the altitude; $z_a$ and $z_b$ are the highest and lowest altitudes in the lidar backscatter profile, respectively; $f(z)$ is the lidar backscatter profile as a function of altitude; $a$ is the spatial extent, or dilation of the function; $b$ is the translation that shows the location at which the Haar function is centered; and $a^{-1}$ is the normalization factor.

For every lidar profile between 10:00 and 18:00 (Local Standard Time, LST), for altitude 150 m to 3 km, we normalized the value of measured attenuated backscatter coefficient from 0 to 1, as Fig. 2a shows. Then, we took the wavelet covariance between the normalized attenuated backscatter coefficient and the Haar function, and the altitude on which the wavelet covariance firstly showed the maximum value that exceeded the threshold 0.15 was defined as the ABL height of each profile. The profile of the wavelet covariance is shown in Fig. 2b.

Finally, the maximum ABL height among the profiles between 10:00 and 18:00 (LST) was defined as the daily maximum ABL height.

Because the proper value of the threshold varies both by season and by hour, we tested the lidar profiles with threshold values from 0.05 to 0.2, and the value of 0.15 was found to be sufficient to identify the diurnal ABL height in Ulaanbaatar’s winter. If the threshold condition is not fulfilled, the algorithm will not provide an ABL height to the profile.

3. Results

3.1 Weather in October 2010

The Asia-Pacific surface weather charts from October 2010 are shown in Fig. 3. On 4 October, the isobars around Ulaanbaatar were still loose, and neither closed high- nor low-pressure systems dominated the surrounding area (Fig. 3a). However, a Siberian high travelled eastward across Ulaanbaatar, causing the surface air temperature to decrease rapidly. On 9–10 October, the Siberian high covered Ulaanbaatar and the surrounding area (Figs. 3b and 3c). The temperature decreased again with the eastward transit of a second stronger Siberian high between 22 and 25 October (Figs. 3d, 3e, and 3f). This high signaled the arrival of winter in Ulaanbaatar. We can clearly see that the isobars in Figs. 3d, 3e, and 3f are closer together than those in Figs. 3a and 3b are, indicating that there was heavy snow on these days, especially during the night.

3.2 Air pollution episodes

In October 2010, two occasions occurred when the temperature declined rapidly because of cold waves, on 8 and 21 October. The present study was divided into the following three periods: 1–10 October for period A, 11–21 October for period B, and 22–31 October for period C. Figure 4a shows the temporal variations in the daily averaged air temperature and PM$_{2.5}$ concentration during period A. Between 8 and 10 October, the air temperature rapidly declined to $-0.5^\circ$C, and the PM$_{2.5}$ concentration increased to 47 μg/m$^3$ on 11 October. For 11–18 October, the air temperature varied between 0–2.5$^\circ$C, and the PM$_{2.5}$ concentration fluctuated between 36–55 μg/m$^3$. Because of drizzle and rain showers on 18–19 October, the PM$_{2.5}$ concentration fell to 23 μg/m$^3$ on 19 October. During period C, the air temperature never exceeded 0$^\circ$C because of the second cold wave, and the PM$_{2.5}$ concentration rose to 80 μg/m$^3$ on 29 October. The PM$_{2.5}$ was negatively correlated with air temperature. Unlike period
A, an increasing concentration of PM$_{2.5}$ was clearly detected by the lidar in periods B and C. As shown in the red frame in Fig. 4b, the attenuated backscattering coefficient at the 0−500 m level increased to over $2 \times 10^{-5}$/m/sr after 10 October. Figure 4c shows the daily averaged vertical integration of the attenuated backscattering coefficient at 1064 nm, which was calculated from 150 m to the ABL height. The profiles with clouds were excluded before calculation. The integration reflects the variation of PM$_{2.5}$ concentration very well, especially for the days when PM$_{2.5}$ rapidly increased, such as 11, 16, and 21 October. Figure 4d shows the variation of the daily maximum ABL height. Although there were several days for which we could not determine the maximum ABL height because of continuous cloudy, rainy, or snowy weather in the daytime, a clear decreasing trend can be seen throughout the month. Figure 4e shows the diurnal visibility, which was averaged from the hourly data from 10:00 to 18:00. Compared with Fig. 4a, we find negative correlation between PM$_{2.5}$ concentration and diurnal visibility, especially in period C.

3.3 Diurnal variation of ABL

Figures 5a, 5b, and 5c shows the time-height cross-sections of the total attenuated backscattering coefficients measured at 1064 nm on 4, 14, and 28 October, over periods A, B, and C. There was relatively clear development structure of the ABL on 4 October, and the attenuated backscattering coefficient at the surface was mostly below $1 \times 10^{-7}$/m/sr.

The diurnal convective mixed layer was still seen in 14 October. In Fig. 5b, the low ABL height and the residual layer after
18:00 still existed and are almost the same as those in Fig. 5a, but the surface attenuated backscatter coefficient was much higher (over $1.5 \times 10^{-5}/\text{m/sr}$) both during the day (07:00−10:00) and at night (18:00−24:00). This high value of the attenuated backscatter at the surface indicated increased PM$_{2.5}$ emissions, especially between 8:00 and 11:00, which corresponds to rush hour traffic and the cold nighttime temperatures after 19:00.

Finally, Fig. 5c shows that, on 28 October, the development of the ABL was quite different than it was during the previous two periods, although it was a clear and sunny day. Because of the Siberian high and the air temperatures falling below the freezing point (−2.6°C), the atmosphere became so stable that the daily maximum ABL height did not exceed 1000 m. Furthermore, compared with 14 October, the surface attenuated backscatter coefficient on 28 October was very high (over $2 \times 10^{-5}/\text{m/sr}$) throughout the day, peaking between 01:00 and 07:00. This shows that the PM$_{2.5}$ concentration was greatest during period C (Fig. 5a). The stable atmospheric conditions contributed to the high PM$_{2.5}$ concentration, which we will discuss in Section 4.

4. Discussion

After the middle of October 2010, the values of PM$_{2.5}$ began to exceed the 24-hour average standard of 50 μg/m$^3$ (Jugder et al. 2013). The average PM$_{2.5}$ value in our study was approximately seven to eight times larger than the WHO air quality guideline value of 10 μg/m$^3$ (Krzyzanowski and Cohen 2008).

As well as increased emissions, meteorological and geographical factors also affect the air quality in Ulaanbaatar. Figure 6 shows a clear negative relationship between the daily averaged PM$_{2.5}$ concentration and the daily maximum ABL height for 28 sunny days chosen from 10 October 2010 to 31 January 2011. During this period, the air temperature was low enough (below 0°C) that continuous emission of air pollutants existed, and both the air temperature and the daily maximum ABL height continued...
to decrease. Generally, cities located at high latitudes, such as Ulaanbaatar, experience much colder and longer nights in winter than do cities located at low or middle latitudes. Therefore, the stable nocturnal boundary layer is much thicker, and the diurnal convective mixed layer is shallower. These meteorological conditions lead to a persistent and stable boundary layer throughout the year, with a capping inversion layer (Oyunchimeg and Tsolmon 2011; Nishikawa et al. 2011, 2015).

The weak wind due to the stable atmosphere and terrain (basin) also increased the concentration of air pollutants. We plotted the distribution of the wind and PM$_{2.5}$ from October 2010 to January 2011 in Fig. 7a. For all 2951 hourly observations taken over these 4 months, the wind velocity remained low (< 4 m/s), and over 75% of the observations were < 2 m/s. The concentration of PM$_{2.5}$ increased between October 2010 and January 2011 and was higher when the wind velocity was < 2 m/s. In December 2010 and January 2011, the PM$_{2.5}$ concentration reached extremely high levels (> 600 μg/m$^3$). These PM concentrations place Ulaanbaatar among the most polluted cities in the world (Health Effects Institute 2004, 2010), exceeding the levels of air pollution in Mexico City and Buenos Aires (Gurjara et al. 2008).

The wind direction in Ulaanbaatar during these four months varied greatly. As seen in Fig. 7a, the northwest wind had higher velocity than the other directions did, and the velocity of the northeast wind was lowest. Because the ger districts, which are recognized as the main source of coal combustion, are mainly distributed north of the observation station (Fig. 1b), the PM$_{2.5}$ concentration becomes extremely high (> 400 μg/m$^3$) when the wind blows from the north and north-northeast. Furthermore, we calculated the hourly mean wind velocity (Fig. 7b). Generally, the wind velocity was low in winter. The mean wind velocity at night (19:00–08:00) was much lower (< 1.0 m/s) than the diurnal wind velocity. It has been reported that the PM concentration patterns of Ulaanbaatar vary on a daily basis, with the maximum peaks at midnight and the minimum peaks for a few hours after midday (Mori et al. 2012). The PM concentration has significant negative correlation with the wind velocity pattern, as shown in Fig. 7b.

We suggest that air particulate pollutants are emitted mainly from coal combustion in domestic stoves used for heating, especially during nighttime, and vehicle exhaust and soil dusts disturbed along roads via vehicle passage also make contributions to PM emissions diurnally. The city is surrounded by mountains, which further restrict both the vertical and horizontal dispersion of air particulate pollutants. These meteorological and topographical conditions contribute to the high concentration of PM$_{2.5}$.

In addition to air particulates, chemical constituents such as SO$_2$ and NO$_x$, which could chemically react with the water vapor in the atmosphere, also could affect air pollution levels. It is reported that the main source of SO$_2$ and NO$_x$ emissions in Ulaanbaatar is thermal power plants (TPPs), which account for more than 85% of these emissions (Oyunchimeg and Tsolmon 2011). Three activated TPPs exist in Ulaanbaatar, located west-southwest of the urban area. It is clearly shown in Fig. 7 that winds from the west-southwest have relatively higher velocity, which can affect the concentrations of SO$_2$ and NO$_x$ measured in the city center. Meanwhile, our meteorological data show that, in 2010, the relative humidity in Ulaanbaatar was about 65% to 75% in winter, which was much higher than it was in summer (30% to 40%). This high relative humidity in winter could also enhance the concentrations of SO$_2$ and NO$_x$. Several previous studies have investigated some chemical characteristics in Ulaanbaatar (Nishikawa et al. 2015; Luvsan et al. 2012), but further research is still needed.

5. Conclusion

By analyzing lidar data, surface measurements, and weather charts, we investigated the causes of air pollution in Ulaanbaatar. When the air temperature in Ulaanbaatar first dropped below 0°C, the PM$_{2.5}$ concentration increased and remained at elevated levels throughout the winter. Although there is traffic congestion throughout the year, severe air pollution only occurs during the winter. Therefore, it is mostly caused by the emission of particulate pollutants from coal combustion in the city, especially in the ger districts. During winter, the wind velocity was low, especially at night. After mid-October, because of the persistence of the Siberian high, the maximum height of the ABL was lower than 1 km, and the existence of a surface inversion layer contributed to the increased PM$_{2.5}$ concentration at the ground level. Air pollution in Ulaanbaatar is a complex problem that represents a major threat to public health, and the provision of clean and efficient central heating systems to reduce home heating emissions should be the primary focus of future air pollution control efforts.

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