Observation of nocturnal low-level wind shear and particulate matter in urban Beijing using a Doppler wind lidar

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\section*{ABSTRACT}
A field experiment of nocturnal mountain wind and corresponding particulate matter (PM) evolution under weak synoptic forcing at five sites within urban Beijing was conducted using a moving Doppler wind lidar and a fixed tower. Clear wind shear and zero-horizontal-wind zones at 40–320 m above the ground with a delay of 1.5 h were found at two sites between 20 km from north to south urban Beijing. The wind speed and height of the low-level jet at the north urban Beijing site were greater than those at the east urban Beijing site. The average horizontal distribution of low-level PM at 240 m was similar to the ground-level PM at night. The PM\textsubscript{2.5} (aerodynamic diameter ≤2.5 μm) accumulation center showed no abrupt changes with a shift in wind direction until the northerly wind jet arrived.

\section*{1. Introduction}
The mountain-plain wind and corresponding particle matter (PM) evolution around Beijing under weak synoptic forcing began to be observed in the 1980s, and the related mesoscale weather systems, streamline field, and vertical distributions of the mountain-plain wind (low-level jet (LLJ), wind direction shift) have been summarized in several studies (Liu, Li, and Li 1983; Li and Shu 2008; Dou, Wang, and Miao 2014; Ye et al. 2016; Chen et al. 2017). The mountain-plain wind system can be modulated by urban heat island (UHI) circulation, with wind convergence occurring from suburban to urban centers due to mountain wind at night (Zhu et al. 1982; Wang et al. 2008; Miao et al. 2009, 2015; Hu et al. 2013; Dou, Wang, and Miao 2014). High PM concentrations mostly accumulate in wind convergence zones and are caused by terrain- and city-induced circulation (Zhu et al. 1982; Ren et al. 2004). PM concentrations at low levels have also been found to increase during the day-to-night transition (1–3 h) of wind direction, and then decrease when the northerly wind (mountain wind) at low-level heights replaces the southerly wind (Chen et al. 2015, 2017).

Measurement of wind and PM profiles commonly requires the use of a tower or tethered balloon equipped with wind, air temperature, and PM sensors that provide direct accurate measurement and easy deployment. For example, the spatial structure of topography-driven flows over the complex urban terrain of Urumqi was studied with five 100-m meteorological towers (Jin et al. 2016). However, the tower is restricted by height limitations, and the tethered balloon is limited by its low frequency. Remote sensing methods using Doppler radar, sodar, and lidar have also been used to measure wind profiles. However, the noise of sodar and the blind area of radar limit their applications in urban environments. Wind lidar, which presents a portable volume and low noise/radiation, has seen increased use in recent urban wind and pollution studies (Xia, Wang, and Min 2011; Chen et al. 2017;
Huang et al. 2017), particularly because the high-frequency data afforded by this technology can be used to characterize low-level wind structures in detail. In addition, moving wind-profile measurements by Doppler lidar have generally been based on slow-moving ship-borne platforms (Pichugina et al. 2012; Aichert et al. 2015), rather than road vehicles in urban areas.

While previous studies have described the features of the evolution of mountain-plain wind and related PM, these works mainly used 1-h average ground observations, a single variable (wind or PM) measurement from towers or tethered balloons, or high-frequency vertical profiles only at one site. Thus, the detailed 3D characteristics of vertical/low-level wind and PM evolution during nocturnal mountain wind periods are lacking, especially when characterizing the high-frequency vertical profiles of both wind and PM in urban areas.

The present study focuses on low-level wind and PM in urban Beijing during the stable nighttime period. A site-by-site observation experiment within the urban area was conducted to measure wind profiles, and a comparison of measurements between the tower and lidar was performed to determine the evolution of wind profiles. The characteristics of low-level PM concentrations at four sites and the relationship between corresponding 10-m wind and ground PM$_{2.5}$ (aerodynamic diameter ≤2.5 μm) measurements were also analyzed.

2. Measurements, instrumentation, and data

The 325-m meteorological tower (39°58′N, 116°22′E; 49 m above sea level) is located in urban Beijing (denoted as ‘Tower’ in Figure 1), measuring wind profiles (15 levels) from 8 to 320 m based on 010C cup anemometers and 020C wind vanes (Metone, U.S.A.).

A Doppler wind lidar called ‘Windcube-8’ (Leosphere, France) was deployed. Windcube-8 can measure wind profiles from 40 to 320 m based on computations of radial wind speed measurements along four cardinal geographical directions separated by 90°. It can also perform measurements of wind speed and direction up to 10 heights depending on the environmental and weather conditions, such as aerosol backscatter, turbulence, humidity, and precipitation, producing a time series at each height every 1.1 s. More details of the Windcube principle can be found in Table 1 and Aitken, Rhodes, and Lundquist (2012). The 10-min averaged wind measurements between Windcube-8 and the tower show high correlation (Chen et al. 2017). PM$_1$ (aerodynamic diameter ≤1 μm) mass concentrations can also be estimated by the carrier-to-noise ratio (CNR) of Windcube-8 (Chen et al. 2017).

According to the study by Jacobson et al. (2015) on the main urban area of Beijing, the sixth ring road of Beijing can be considered the approximate boundary of the urban area, so the sites for moving observations were mainly located within the sixth ring road of Beijing. An observation experiment within the urban area was conducted on the night of 1 February 2015 and dawn of the next day using a van to carry the lidar to four moving observation points (M1–M4, Figure 1). Wind profile measurements were taken for at least 20 min at these points. The distances between M1 and M2, between M2 and M3, and between M3 and M4 are 13.8, 14.6, and 18.8 km, respectively. Tower wind measurements were used as a reference to describe differences in wind profiles in the city.

Hourly ground PM$_{2.5}$ measurements by the Beijing Municipal Environmental Monitoring Center (http://zx.bjmemc.com.cn/) were applied to show the horizontal distribution of PM$_{2.5}$. The hourly 10-m wind measurements by the automatic weather station in Beijing run by the China Meteorological Administration were also used to present the mountain-wind evolution.

3. Results and discussion

During this event, the Beijing area was located in the rear of surface high pressure and controlled by weak synoptic forcing. This weather condition was favorable for local
circulation development. Also, the temperature profile measured by radiosonde at the Beijing meteorological station shows that the height of the inversion layer increased from 50 to 300 m during 2000–0800 LST (local standard time) above ground level.

Figure 2 shows the wind profile measured at the tower site. To better highlight the structure of the wind shear layer, four types of horizontal wind direction are plotted. The blue color denotes the wind direction within 292.5°–360° and 0°–67.5° (northerly wind), whereas the yellow color denotes 112.5°–247.5° (southerly wind), and the other two colors denote the transition between the northerly and southerly winds. Early in the morning of 2 February 2015 at the tower site, the diurnal wind was a typical mountain-plain wind characterized by light wind and weak vertical shear during the evening transition period from the southerly to the northerly direction and LLJ in the morning (Figure 2). Figure 3 shows the wind profile measured by Windcube-8 at four moving observation sites (M1–M4) around Beijing. A comparison of tower and moving Windcube-8 wind measurements is shown in Figures 2 and 3.

During the evening transition, the southerly wind speed at 200–320 m at M2 (0115–0135 LST) was lower than that at the other three sites, i.e. at M1 (0000–0200 LST), M3 (0215–0325 LST), and the tower site, thereby suggesting that the southerly wind at 200–320 m in western and central urban Beijing during the transition is lower than that.

![Figure 2](image1.png)

**Figure 2.** Horizontal winds measured at the 325-m meteorological tower.
Notes: WS, horizontal wind speed; WD, wind direction (where 292.5°–360° and 0°–67.5° is 0–1 (northerly wind) and 112.5°–247.5° is 2–3 (southerly wind)); AGL, above ground level.

![Figure 3](image2.png)

**Figure 3.** Horizontal winds measured by Windcube-8 at the four moving observation sites (M1–M4).
Notes: WS, horizontal wind speed; WD, wind direction (where 292.5°–360° and 0°–67.5° is 0–1 (northerly wind) and 112.5°–247.5° is 2–3 (southerly wind)); AGL, above ground level.
and 26 urban sites (Figure 4; the same sites as selected by Dou and Miao (2017)). The UHI intensity of this event was in southern and northern urban Beijing. In addition, the southerly wind at 200–320 m at M3 was larger than that at the tower site, thus suggesting that north urban Beijing experiences larger drag effects due to buildings than south urban Beijing. After the evening transition, the LLJ wind speed in the northern area (the tower site) was larger than that in the eastern area (M4) at 0400–0600 LST; the northern LLJ height (200 m) at the tower site was also higher than that at M4 (150 m).

A zero horizontal-wind-speed zone was found along the wind direction shear line from 40 to 320 m at M3 and the tower site during the evening transition, and the timing of the wind shift at the tower site (0030–0200 LST) was earlier than that at M3 (0200–0330 LST). Only wind direction shear below and above 150 m was found at M1 and M2; at M4, the whole layer was controlled by a northerly wind. Both M1 and M2 did not show whole wind direction shear from 40 to 320 m, possibly because of the short and late observational time applied in these areas.

The above results imply that the mountain-plain wind originates from the north and moves to the south. Besides, M2, which yielded the lowest southerly speed measurements at 200–320 m, is located in the low-speed ground-wind region between the second and third ring roads because of its high surface roughness, as pointed out by Dou, Wang, and Miao (2014). To discuss the impact of the UHI effect on the mountain-plain wind, the diurnal UHI intensity of the Beijing area during this event was calculated based on average 2-m temperature from 8 rural sites and 26 urban sites (the same as the sites selected by Dou and Miao (2017) and marked in (a)) and 2-m temperature difference between a mountain and a nearby plain rural site (blue line in (b); site locations and their altitude of sea level (units: m) are marked in (a)) from 1200 to 1100 LST (local standard time) 1 and 2 February 2015.

Figure 4. Diurnal UHI (urban heat island) intensity (black line in (b)) based on average 2-m temperature from 8 rural sites and 26 urban sites (the same as the sites selected by Dou and Miao (2017) and marked in (a)) and 2-m temperature difference between a mountain and a nearby plain rural site (blue line in (b); site locations and their altitude of sea level (units: m) are marked in (a)) from 1200 to 1100 LST (local standard time) 1 and 2 February 2015.

Figure 5. The 240-m average CNR (carrier-to-noise ratio) observations at the 325-m meteorological tower and four moving observation sites (M1–M4) over different periods (marked in blue) and PM$_{2.5}$ average mass concentrations observed at Beijing environmental monitoring sites from 2100 to 0800 LST (local standard time) 1 and 2 February 2015 (marked by black numbers). Those sites with PM$_{2.5}$ > 150 μg m$^{-3}$ are marked in red, while those with ≤150 μg m$^{-3}$ are marked in green; the 2nd to 6th ring roads are marked by the black lines.

and 26 urban sites (Figure 4; the same sites as selected by Dou and Miao (2017)). The UHI intensity of this event was
strong at night, and higher than the average UHI intensity in winter calculated by Dou and Miao (2017) (~5.5 °C vs. ~3.5 °C). It was colder at a mountain site at night than a nearby plain rural site (Figure 4). The impact of UHI on northerly mountain-plain wind speed in north Beijing was an increase due to their same wind direction, while the UHI impact on the northerly wind speed during this event may have been stronger than the winter average reported by Dou and Miao (2017) due to its higher UHI intensity.

As the variability of PM concentrations at a certain height above the ground can be captured by Windcube-8-observed CNRs (Chen et al. 2017), average CNRs at 240 m were used to describe PM variability. The average periods and related CNRs at M1–M4 and the tower are marked in Figure 5. The PM in central and eastern Beijing (M2 and M4) was higher than that at the other sites. A similar horizontal PM pattern characterized by a high-value zone maintained in central and eastern Beijing was found in the PM$_{2.5}$ monitoring sites (Figure 5); this finding suggests that the average horizontal distribution of ground and 240-m PM in half a day was similar under this low wind speed condition.

The trends of the PM$_{1}$ levels retrieved at the tower and ground PM$_{2.5}$ monitoring sites at Beijing Olympic Sports Center were analyzed. The ground PM$_{2.5}$ concentration decreased by 25% from 119.3 μg m$^{-3}$ (2100–2300 LST) to 89.7 μg m$^{-3}$ (0600–0800 LST), while the 260 m PM$_{1}$ concentration retrieved using the CNR–PM$_{1}$ fitting line in Chen et al. (2017) similarly decreased by about 23% from 112.7 to 86.2 μg m$^{-3}$ over the same period, thereby suggesting that the retrieved PM$_{1}$ concentrations can at least represent the diurnal trends of the PM under low-wind and wind-shear pollutant events.

Figure 6. The 1-h surface PM$_{2.5}$ mass concentration (gray circles) and 10-m wind (arrows; northerly wind mark in blue; southerly wind marked in red) observed at environmental monitoring sites and by automatic weather stations in urban Beijing.
Figure 6 presents the hourly ground horizontal distribution of PM$_{2.5}$ and 10-m wind during this event. The southerly wind covered most of central Beijing, while some westerly and northerly wind appeared at some stations near the mountain at 2100 LST. The front of the northerly wind reached the northern 4th ring road during 0000–0100 LST, and almost covered the whole of central Beijing at 0300 LST. Two maxima of flows (≥2 m s$^{-1}$) coming from the northwest and northeast impacted central Beijing at 0200–0400 LST and 0400–0700 LST, respectively. A high-value center of ground PM$_{2.5}$ maintained in the southern and eastern area within the 4th ring road from 2100 to 0500 LST. This PM$_{2.5}$ accumulation center did not change immediately with the wind direction shift to northerly at 0300 LST; however, it then moved to the southern area at 0800 LST when the northerly wind jet covered central Beijing. The detailed distribution of hourly PM$_{2.5}$ and 10-m wind during this event shows the nocturnal jet of the local mountain-plain wind can at least impact the center of Beijing (from the northwest to southeast area within the 4th ring road) at the hourly time scale, suggesting that the local mountain-plain wind of Beijing can modulate the PM pollution of urban Beijing, at least over a period of several hours. It should be noted that the reason for the expansion in the area of the PM$_{2.5}$ high-value center in northeast urban Beijing from 0100 to 0500 LST was that this area was possibly located in a convergence zone with continuous southerly winds transporting PM from southern areas.

4. Summary

A site-by-site experimental study within the urban Beijing area was conducted using a van to carry Windcube-8 equipment and measure wind profiles and CNRs at four locations (M1–M4), and comparison of the measurements from the tower and Windcube-8 at M1–M4 in Beijing was made during the stable nighttime period. Our findings are summarized as follows.

In urban Beijing, the mountain-plain wind originated from the northern area and moved towards the southern area, considering that the timing of the wind shift at the tower site was 1.5 h earlier than that at M3. The southerly wind speed at 200–320 m above the ground at M2, where there is higher surface roughness, was lower than that at the tower site. The LLJ wind speed and height in northern urban Beijing were greater than those in eastern urban Beijing (M4). The average horizontal distribution of low-level PM at 240 m was similar to the ground PM at night under this low wind-speed condition. The PM$_{2.5}$ accumulation center did not change immediately with the wind direction shift; however, it then moved to the south when the northerly wind jet covered central Beijing.

The results presented in this paper provide a novel insight into the differences in the characteristics of nocturnal low-level wind and PM for mountain-plain wind featuring wind shear in the urban area of Beijing. An observation with a compact wind lidar, as well as the measurements obtained from the fixed tower, can capture the spatial variability of the mountain-plain wind. This site-by-site observation presents several advantages, such as low cost, rapid, and easy deployment in the urban area, over the fixed tower and tethered balloon network system under nocturnal low-wind conditions. However, limited information on air temperature, humidity, stability, and aerosol levels may hinder efforts to describe in detail the evolution of low-level wind and PM in urban cities with complex terrains. Wind lidar working at a scanning mode is also needed to obtain more detailed 3D wind structure.

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Disclosure statement

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