Characteristics of urban boundary layer in heavy haze process based on Beijing 325m tower data

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ABSTRACT
Beijing experienced serious haze pollution from 24 November 2015 to 2 December 2015. To investigate the planetary boundary layer characteristics, especially turbulence characteristics, the authors analyzed the wind, temperature, humidity, and turbulence characteristics during heavy polluted weather using the observational data of the 325-m meteorological tower in Beijing. The results indicate that the pollution was mainly caused by the easterly and southerly winds. There were negative correlations between wind speed, turbulent kinetic energy, friction velocity, and the PM$_{2.5}$ concentration. During clean days, the wind speed greatly enhanced with height; however, during the period of heavy pollution, the wind speed changed a little from the near-surface layer to the top of the tower. In contrast, the spatial variability of TKE from the near-surface layer to the upper layer was not so obvious. The heavy haze pollution in this study was often characterized by the emergence of an inversion layer; therefore, the diurnal variation of the boundary layer temperature was very small. At the time of serious pollution, the relative humidity was near 100%. The diurnal variations of sensible heat flux and water vapor flux were significantly reduced when severe pollution occurred.

1. Introduction
With the rapid development of China’s economy and the acceleration of urbanization, the intensity of air pollutant emissions is also increasing (Chan and Yao 2007; Guo et al. 2010; Zhao et al. 2012; Huang et al. 2014). High concentrations of relatively long-lived gaseous pollutants come with wind directions from the southwest, southeast, and northeast, with very high frequencies (Xu et al. 2011). High emissions of anthropogenic contaminants can accumulate rapidly in adverse weather conditions, especially low wind and stable and high humidity environments, and further form serious regional pollution in a short time (Wei et al. 2017). Mixed atmospheric pollution cloud can affect weather processes, such as air temperature and rainfall (Ding et al. 2013). Absorbing aerosol can also change the sensible heat flux and latent heat flux through the process of radiation, thus affecting the boundary layer process (Huang et al. 2016); plus, there are obvious seasonal variations of aerosol species, which are related to different meteorological conditions and air pollution sources (Zhang et al. 2013).

In recent years, seriously polluted weather (haze) has occurred frequently in the Beijing–Tianjin–Hebei region of China; the measured mass concentration of fine particles (PM$_{2.5}$) often exceeds the warning line (Lin, Pan, and Zhang 2013; Tang et al. 2016). In the winter of 2012/13, the hourly average PM$_{2.5}$ concentration in Beijing was mostly over 200 μg m$^{-3}$, and the maximum value exceeded 600 μg m$^{-3}$ during the observation period (Quan et al. 2014). In winter, the atmosphere of Beijing has become one of the worst polluted in the...
country and beyond (Wen et al. 2016). Because of haze weather, reduced visibility of the atmosphere endangers people’s lives via traffic safety (Luan et al. 2018), and adversely affects human health (Chen, Zhao, and Kan 2013).

Since air pollution is mainly determined by two factors—namely, the pollution source and meteorological conditions—it is important to study the meteorological conditions in which severe air pollution occurs (Liu and Chan 2002; Sun et al. 2013; Tang et al. 2018). Also, since the source of pollution is almost always in the atmospheric boundary layer (1–2 km from the ground), the meteorological conditions of the boundary layer are more important in providing meaningful scientific references for revealing the formation mechanisms of haze pollution and for controlling and forecasting haze pollution (Schichtel et al. 2001; Liu and Chan 2002). After pollutants are discharged in the boundary layer, they undergo physical and chemical transformations and dry and wet deposition processes, and are then transported farther by advection and turbulent diffusion.

There has been a considerable amount of boundary layer research in terms of air pollution, including observational analyses and numerical simulations (Yang, Dong, and Liu 2011; Sun et al. 2013; Zheng and Zhao 2017). As a result, understanding the mechanisms of contaminant generation, transport and transformation in the atmospheric boundary layer, and studies of the interaction between haze and the boundary layer, are hot topics. However, few studies on the boundary layer structure under heavily polluted weather conditions have been conducted. Existing observations and analyses have concentrated mainly on the near-ground level; the use of observational data from meteorological towers is very rare. Moreover, the variation in turbulence characteristics among different heights during pollution is unknown.

In this study, the boundary layer and turbulence characteristics under heavily polluted weather conditions were studied by using the data of the 325-m meteorological tower in Beijing during a severe haze pollution from 24 November 2015 to 2 December 2015. The statistical characteristics of wind speed, wind direction, temperature and humidity are given and analyzed, compared with the corresponding PM$_{2.5}$ pollution monitoring data; plus, we compare some turbulence characteristics of the canopy layer and upper layer. The aim of this paper is to understand the structure of the urban boundary layer under heavy pollution conditions, and to provide reference for understanding the mechanism of heavy pollution and improving the parameterization of air pollution in numerical models.

2. Observational instruments and data

Beijing, as the capital of China, is the center of politics, the economy and culture. The topography of Beijing is high in the northwest and low in the southeast, which is unfavorable for pollution to diffuse. The meteorological tower of the Institute of Atmospheric Physics, Chinese Academy Sciences, built in August 1979, is 49 m above sea level, 325 m high, and is located (39°58’N, 116°22’E) between the Beijing North Third Ring Road and North Fourth Ring Road. A total of 15 observation platforms (at 8, 15, 32, 47, 65, 80, 100, 120, 140, 160, 180, 200, 240, 280, and 320 m) are set up on the tower, with wind speed (010C, MetOne, USA), wind direction (020C, MetOne, USA), temperature (HC2-S3, Rotronic, Switzerland) and humidity (HC2-S3, Rotronic, Switzerland) observation instruments mounted on each platform. Moreover, seven sets of three-dimensional ultrasonic anemometers (Wind Master, Gill, USA) and water vapor/carbon dioxide analyzers (LI-7500, Licor, USA) are also installed on the tower (at 8, 15, 47, 80, 140, 200 and 280 m). All turbulence data sampling frequencies are 10 Hz. In order to obtain effective statistical averages of atmospheric turbulence data, researchers generally use 10–60 min as the averaging time (Kmail and Finigan 1994; Wood et al. 2010). In this paper, the averaging time period is 20 min. A detailed description of the meteorological tower can be found in Al-Jiboori and Hu (2005), and on the website http://view.iap.ac.cn:8080/imageview/.

Data used in this paper also include the air quality level index (AQI) and other related air pollution data from online publicly released data. We selected the data of a very serious haze event, from 24 November 2015 to 2 December 2015, as the object of this study. The time used in this paper is local station time (LST). Table 1 exhibits the daily average data of six major air pollutants in Beijing during the heavy pollution of this time. The reason for the choice of this period is that Beijing’s air quality had gone from good conditions to heavy pollution, and then returned to good conditions, which was a complete occurrence, development and dissipation of a haze process. Within this selected five-day period of serious pollution, the middle of 29 November was the key to the red alert problem. According to ‘Technical Specification for Air Quality Index (HJ 633–2012)’ red alert means that air pollution index reaches above 300 and lasts for more than three days. Due to the initial prediction of air quality after noon on 29 November, the heavy pollution process was divided into two parts, and thus did not meet the conditions of red
alert warning. However, in fact, the pollution situation on this day has been underestimated.

3. Results and discussion

3.1 The analysis of wind, temperature, and humidity

In order to understand the pollution process comprehensively, we analyzed the vertical profiles of temperature, wind speed and wind direction as shown in Figure 1. Two typical times 12:00 (noon) and 02:00 (night) have been chosen to represent day and night. In addition, we also chose one figure at 21:00 to strengthen the analysis. According to Stull (1988), the calculation method of the potential temperature is as follows:

$$\theta = T + \gamma_d z,$$

where $\gamma_d$ is dry adiabatic temperature lapse rate and equals to 0.00975 K m$^{-1}$, $T$ is air temperature and $z$ is the measurement height. 0° represents north wind. On 25 November, the air quality was good. At 12:00 (Figure 1(a)), the high-altitude wind speed was about 5 m s$^{-1}$, and the potential temperature profile displayed that the stability of different heights of the boundary layer was different. But on the whole, the temperature difference between the high and low layers was not very large, and it was basically a neutral layer. At 02:00 26 November (Figure 1(b)), from the city canopy to the high level, the northwest wind was dominant. The wind speed had increased significantly compared to the day, and the maximum wind speed was about 12 m s$^{-1}$. Under the effect of strong wind, the change in potential temperature varied little with height, and it was still characterized by a neutral boundary layer. Prior to 28 November, the air quality had been polluted for two days, and the wind profile at 12:00 (Figure 1(c)) showed the main northeast wind was about 2 m s$^{-1}$, which indicated statically stable weather. Furthermore, the temperature had increased compared to 25 November at this time. At night (Figure 1(d)), the main flow of the atmospheric boundary layer was the southeast wind, which provided abundant water vapor for the hygroscopic growth of aerosol particles in the Beijing area, although the wind speed was low. The temperature of the planetary boundary layer (PBL) changed little compared with the daytime. It can be seen that the thermal insulation effect of the atmosphere was remarkable.

The 29 November was the third day of continuous pollution. The wind direction at 0200 had changed to northwest (Figure 1(e)), but the wind speed observed by the tower was almost no more than 2 m s$^{-1}$. From the distribution of the wind, although the wind direction at noon (Figure 1(f)) was still counterclockwise with height and the wind speed of the high layer had increased to 5 m s$^{-1}$, the low-level wind speed was still maintained at 2 m s$^{-1}$. The potential temperature profile showed that an inversion layer clearly existed at 200 m above the surface. Due to the longwave cooling effect of surface radiation at night (Figure 1(g)), the boundary layer was obviously stable from the surface to about 150 m, and the part over 150 m was the residual layer of the day. The wind was still small and dominated by northeastern wind, whether at 12:00 on 30 November (Figure 1(h)) or 02:00 on 1 December (Figure 1(i)).

On 1 December, the pollution situation was still not optimistic. The wind speed was still below 2 m s$^{-1}$ during the day (Figure 1(j)), and a sporadic northwest wind appeared. At night, the wind speed had increased to some extent (Figure 1(k)). At 1200 LST 2 December (Figure 1(l)), the principal northwest wind increased distinctly, and the maximum wind speed up to almost 15 m s$^{-1}$. In terms of the potential temperature profile, stable stratification still existed at this time. Generally speaking, the low level of the PBL during the pollution process was mainly southerly and easterly winds.

Table 1. Daily average data of six major air pollutants in Beijing during heavy pollution from 24 November to 2 December 2015: PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, and O$_3$ (µg m$^{-3}$), CO (mg m$^{-3}$).

| Date       | Quality level   | AQI index | PM$_{2.5}$ | PM$_{10}$ | NO$_2$ | SO$_2$ | CO    | O$_3$ |
|------------|-----------------|-----------|------------|-----------|--------|--------|-------|-------|
| 2015-11-24 | Good            | 57        | 41         | 30        | 45     | 8      | 0.99  | 23    |
| 2015-11-25 | Good            | 72        | 50         | 34        | 37     | 9      | 1.13  | 26    |
| 2015-11-26 | Good            | 52        | 33         | 43        | 34     | 10     | 0.80  | 38    |
| 2015-11-27 | Heavy polluted  | 232       | 183        | 161       | 84     | 34     | 2.60  | 7     |
| 2015-11-28 | Serious polluted| 303       | 252        | 237       | 99     | 41     | 3.76  | 7     |
| 2015-11-29 | Serious polluted| 291       | 240        | 272       | 102    | 38     | 4.73  | 10    |
| 2015-11-30 | Serious polluted| 364       | 339        | 337       | 121    | 23     | 5.71  | 7     |
| 2015-12-01 | Serious polluted| 478       | 476        | 461       | 136    | 35     | 8.11  | 5     |
| 2015-12-02 | Good            | 36        | 18         | 16        | 17     | 3      | 0.50  | 43    |

Note: data source is from http://www.tianqihoubao.com/air/beijing.html.
Figure 1. Vertical profiles of wind speed and potential temperature at 12:00 on (a) 25 November, (c) 28 November, (f) 29 November, (h) 30 November, (i) 1 December, (l) 2 December; at 02:00 on (b) 26 November, (e) 29 November, (g) 30 November, (j) 1 December, and (k) 2 December; and at 21:00 on (d) 28 November 2015.
Figure 1. Continued.
also given. As can be seen from the figure, there was a significant negative correlation between the wind velocity and the concentration of PM$_{2.5}$. That is, when the wind speed was high, the concentration of PM$_{2.5}$ was low, and vice versa. During clean days, the wind varied greatly with height, with a maximum difference of about 10 m s$^{-1}$ (e.g., 26 November). However, the wind velocity changed a little with height, averaging only 2–3 m s$^{-1}$, from the near-surface layer to the upper layer during heavy pollution. At noon on 29 November, the wind speed increased at 280 m, but the time for strong wind to maintain was slightly shorter. The wind speed at 15 m was still less than 2 m s$^{-1}$, which brought difficulties to the prediction of the pollution situation.

To analyze the temporal and spatial distribution of moisture comprehensively, we exhibit the value of the temperature minus the dewpoint temperature ($T - T_d$) during this period in Figure 2(b), where the dewpoint temperature is calculated based on the measurement data from the water vapor/carbon dioxide analyzer. When the degree of contamination was low, the $T - T_d$ from the ground to the high level was mostly greater than zero, indicating that the humidity was also low (e.g., 2 December). The wet growth of particles is an important physical mechanism during haze, and we further examined the RH changes for this reason (Figure 2(c)). The following characteristics can be seen clearly from Figure 2(c): (1) When the degree of pollution was low, the RH was relatively low, such as on 12:00 on 25 November to 12:00 on 26 November, and 2 December; but when the pollution was high, the RH increased significantly, even reaching 100%. (2) When heavy pollution occurred (1 December), the distribution of humidity with height also appeared with a stratification phenomenon. The RH at the height of 32 m from the ground had reached 100%; however, the RH at the height of 32–100 m and the RH at 140–180m were less than 95%; plus, the RH of 100–200 m and 200 m and above were 100% again. Thus, we can see the multilayered structure with the coexistence of fog and haze.

Figure 2. (a) Temporal evolution of wind speed at 15 m (red line; units: m s$^{-1}$), 280 m (green line; units: m s$^{-1}$) and the concentration of PM$_{2.5}$ (blue columns; units: $\mu$g m$^{-3}$) (data source: http://www.stateair.net/web/post/1/5.html). Temporal and spatial distribution variation of (b) $T - T_d$ (units: °C/100 m) and (c) RH (units: %).
3.2 Turbulence characteristics

In order to investigate the effect of turbulence on the PM$_{2.5}$ concentration, we choose turbulence kinetic energy (TKE) and frictional velocity ($u_*$) as an index to reflect the turbulence intensity. The TKE was calculated by TKE = $1/2 (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$, and $u_*$ was calculated by $u_* = [(\overline{u'w'^2})^2 + (\overline{v'w'^2})^2]^{1/4}$. The $u'$, $v'$, and $w'$ are the fluctuations of velocity components of $u$, $v$ and $w$ respectively. Figure 3(a,b) show the relationship between the TKE and $u_*$ of the urban canopy (15 m) and upper layer (280 m) and the PM$_{2.5}$. It can be seen clearly that the TKE had a significant effect on the change in PM$_{2.5}$ concentration. The strong TKE indicates that the diffusion capacity was strong and the corresponding PM$_{2.5}$ concentration was low, and vice versa. The TKE during heavy pollution was basically less than 1 m$^2$ s$^{-2}$. It can also be found that the spatial distribution variation of TKE from the near surface to the upper layer was not so significant, whether heavily polluted or not. This phenomenon, however, is different from the variation in wind velocity with height shown in Figure 2(a), especially at low PM$_{2.5}$ concentrations with good air quality. As shown in Figure 3(b), there was an obvious negative correlation between $u_*$ and PM$_{2.5}$. The $u_*$ at 280 m was slightly larger than that of the canopy during clean weather, and the $u_*$ between the two layers was very close when polluted. The $u_*$ at 15 m was almost less than 1.5 m s$^{-1}$, and when the $u_*$ was more than 0.4 m s$^{-1}$, the degree of pollution would be reduced. We can see that both wind speed and turbulence intensity, whether TKE or $u_*$, both have a good negative correlation with PM$_{2.5}$ concentration, which should be of reference value in the parameterization of pollution patterns or the forecasting of pollution.

To further study the turbulence characteristics during the heavy pollution period, we utilized the data observed by the 325-m meteorological tower to analyze the evolution of sensible heat flux and water vapor flux in the canopy layer (15 m), surface layer (80 m), and upper layer (280 m). As illustrated in Figure 3(c), we can see that, whether it was a clean day or heavy pollution,
the sensible heat flux had an obvious diurnal variation at 15 m in the canopy layer and at 80 m in the representative surface, and the diurnal variation of pollution days decreased. The temporal evolution difference of sensible heat flux between the lower layer (15 and 80 m) and the upper layer (280 m) on 24–26 November may be due to warm advection, which is a common phenomenon before heavy pollution in Beijing (Zhang et al. 2016; Hao et al. 2018). It is worth noting that, on 1 December, the sensible heat flux was basically maintained at zero, even at noon, and the sensible heat flux of three layers was less than zero in the afternoon, indicating very stable atmospheric stratification at this time. Because of the stable atmospheric stratification, as well as the weak southwest wind (Figure 1(j)), the pollution situation on 1 December was extremely serious. Generally speaking, the sensible heat flux reaches a maximum at noon each day. The temperature of the earth surface increases, due to the gradual absorption of solar shortwave radiation, and the flux is positive from sunrise. During heavy pollution, the increase in aerosol loading leads to a decrease in shortwave solar radiation, and the flux is positive from sunrise. During heavy pollution, the atmosphere from low to high was in a very weak state of turbulence, which made the statistical characteristics of turbulence change little with height. On clean days, the difference in sensible heat flux between the three layers increased and the sensible heat flux at 15 m was relatively small. The diurnal variation of water vapor flux was not so obvious (Figure 3(d)) compared to the sensible heat flux, but we can still see that the water vapor flux was greatly reduced during the pollution period. The reason for this phenomenon is that the turbulence intensity was reduced when the weather was polluted. We can still see that water vapor flux, observed at three layers, was less than the 0.005 g m\(^{-2}\) s\(^{-1}\). In particular, the water vapor flux at 280 m was significantly reduced at noon on 1 December, signifying the downward transfer of water vapor, which would augment the humidity in the lower atmosphere, thus being beneficial to the hygroscopic growth of fine particles.

4. Conclusions

In recent years, pollution in Beijing has occurred frequently. To further understand the PBL characteristics, the statistical characteristics of wind, temperature, and humidity mean fields, and the TKE, \(u_\text{s}\), sensible heat flux, and water vapor flux of turbulence fields, during severe haze pollution from 24 November 2015 to 2 December 2015, were investigated using the observational data of the 325-m meteorological tower in Beijing. By analyzing the temporal and spatial evolution of these parameters, the following primary conclusions were obtained:

1. There was a significant negative correlation between the time series of wind speed and the concentration of PM\(_{2.5}\). During the heavy pollution period, the low wind speed changed little with height from the near surface to the high level, and easterly and southerly wind prevailed.

2. The heavy pollution period was associated with the emergence of an inversion layer, especially from the ground to 120–140 m in height, where the inversion temperature layer appeared more stable. During the haze, the boundary layer had a heat preservation effect; the temperature of the diurnal variation was very small.

3. When the degree of pollution was low, \(T – T_d\) was greater than zero from the ground to the upper air, RH was also slightly lower, but the RH was very high, having reached 100% in some layers during serious pollution.

4. There was also negative correlation between TKE, \(u_\text{s}\), and PM\(_{2.5}\) concentration. Unlike wind speed, the spatial variability of TKE from the near-surface layer to the upper layer was not so great. The diurnal variation of sensible heat flux and water vapor flux were significantly reduced when severe pollution occurred.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Supported by the National Key Research and Development Program of China [grant numbers 2017YFC0209600 and 2016YFC0208802].

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