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# Multiplatform analysis of upper air haze visibility in downtown Beijing

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**Abstract.** The vertical features of upper air visibility in the northwest of downtown Beijing was studied by using a multiplatform analysis during haze episodes near the 2017 New Year's Day. Through the multiplatform data analysis in hourly and daily variation, the upper air visibility follows the opposite trend against the PM2.5 mass concentration. The upper air visibility on non-haze days was about 3-5 times higher than that on haze days. The strong correlation between PM2.5 mass concentration and haze parameters shows the effect of spatial transport of particles on haze parameters. In addition, a higher atmospheric boundary layer improves upper air visibility. The characteristics of multi-parameters have been analysed and concluded for different haze levels.

## 1 Introduction

Due to increasing anthropogenic emissions resulting from China's rapid economy growth and urbanization, haze pollution has been a common problem in East Asia, especially China (Han et al., 2016;Guan et al., 2017;Liu et al., 2013). During the past two decades, scientists have carried out many experiments to explain the formation and evolution mechanism of haze (Gao, 2008;Tao et al., 2014;Wu et al., 2010;Wu et al., 2012;Xin et al., 2014;Zhao et al., 2017). According to researches of Wu et al. (2010) and Gao (2008), the annual average haze days have shown a marked increase in years before 2006 in China. To characterize the haze phenomena, it is important to understand the haze parameters determined by aerosol optical properties. It is known that visibility mainly reflects the information of horizontal extinction near the surface and can be considered a good indicator of haze pollution (Sun et al., 2016;Yang et al., 2013). According to researches of Wu et al. (2012), the visibility on sunny days in 543 stations in China were analysed and the results indicated the annual mean visibility on sunny days is higher in Northwest China and lower in Southeast China, which is similar to the distribution of aerosol optical thickness (AOT). The visibility impairment is attributed to the scattering and absorption of the particulate and gaseous pollutants in the atmosphere (Mishra and Kulshrestha, 2016;Song et al., 2003;Yang et al., 2007).

The height of the atmospheric boundary layer (ABL) is an important parameter to study the remote sensing of particulate matters near the ground, which has the closest relationship with human activities and the ecological environment (Dong et al., 2017;Stull, 2012). It could also adjust due to surface effect within one hour (Chen et al., 2016;Wu et al., 2013;Zhang et al.,

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2013). The dense haze layer can evidently alter regional radiation and the hydrological cycle. Then the near-surface visibility will be further impaired due to radiative feedback (Gao et al., 2015;Qian et al., 2009). Tao et al. (2014) presented the formation and variation of thick haze layers are mostly associated with regional transport and moist airflows. Moreover, many researchers have reported the importance of AOT to visibility (Alexandrov et al., 2016;Bäumer et al., 2008;Dong et al., 2017;Li et al., 2007;Xin et al., 2014). Through observing the deterioration process of air quality in Germany, Bäumer et al. (2008) found that a distinct decreasing trend in visibility was accompanied by a significant increase in AOT. So far, many researches have been conducted to study the effect of different haze parameters on visibility. However, less focus was attached to the characteristics of upper air visibility. Therefore, further studies are necessary to analyse these characteristics.

In this paper, the vertical characteristic of upper air visibility and potential correlation with various haze parameters were investigated in the northwest of downtown Beijing during a haze episode near 2017 New Year's Day. The research was conducted by using the ground-based Raman-Mie LiDAR, meteorological ground-based observation equipment, and the ground-based remote sensing aerosol robotic network (AERONET). This paper aims to (1) present the hourly and daily variation of haze parameters during haze episode in the northwest of downtown Beijing; (2) reveal the impact of PM2.5 (particulate matter with a diameter less than 2.5 μm) mass concentration and haze parameters on upper air visibility; (3) understand the classification standard of haze levels, proposed by World Meteorological Organization (WMO), based on the multi-parameter analysis.

## 2 Methodology

### 2.1 Sites description

Figure 1 shows the geographic coordinates of multiplatform sites, including one ground-based LiDAR detecting site (denoted as star), three air quality monitoring sites (denoted as circle) and four AERONET sites (denoted as upper triangle). The ground-based Raman-Mie LiDAR site is located at the LiDAR Lab of Beijing Institute of Technology in Beijing, China. The detected pure rotational Raman and elastic returns are used for obtaining the vertical characteristic of aerosols. The selected three air quality monitoring sites around the LiDAR site include Xizhimen north site, Wanliu and Guanyuan site. The PM2.5 mass concentration is one of the data types to be monitored. The data collected from four AERONET sites, including Beijing site, Beijing_RADI site, Beijing_PKU site and Beijing_CAMS site, are used to acquire the AOT value in LiDAR site by using statistical calculation. The distances between the LiDAR site and other sites range from 2.63km to 7.59km.

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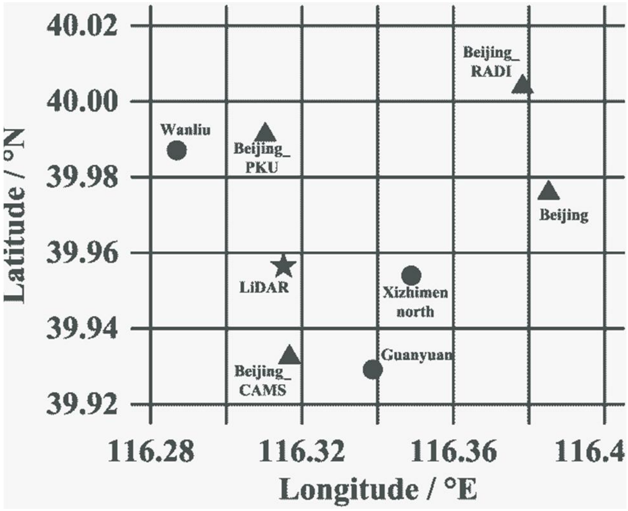


**Figure 1: Geographic coordinate of ground-based LiDAR site (star), air quality monitoring sites (circle) and AERONET sites (upper triangle).**

### 2.2 Data analysis method

To obtain the PM and AOT values in the ground-based LiDAR site accurately and reliably, three air quality sites and four AERONET sites in Fig. 1 are selected for collecting data. According to the distance information between the LiDAR site and the selected sites, the PM and AOT values at the LiDAR site are calculated with the following statistical equation:

$$PM = \sum_{i=1}^{n} G_i PM_i \quad (\sum_{i=1}^{n} G_i = 1,\ n = 3), \tag{1}$$

$$AOT = \sum_{i=1}^{m} Q_i AOT_i \quad (\sum_{i=1}^{m} Q_i = 1,\ m = 4), \tag{2}$$

$PM_i$ represents the PM value of the selected three air quality sites supplied by the Beijing Municipal Environmental Monitoring Centre (BJMEMC); $AOT_i$ describes the AOT value of the four AERONET sites; $G_i$ and $Q_i$ denote the normalized weight function which is inversely proportional to the distance between LiDAR site and the selected sites. As shown in Fig. 2, it is believed that the AOT value deduced from ground-based LiDAR data is reasonable and reliable due to the excellent Pearson correlation coefficient (+0.87) and R2 value (0.75).

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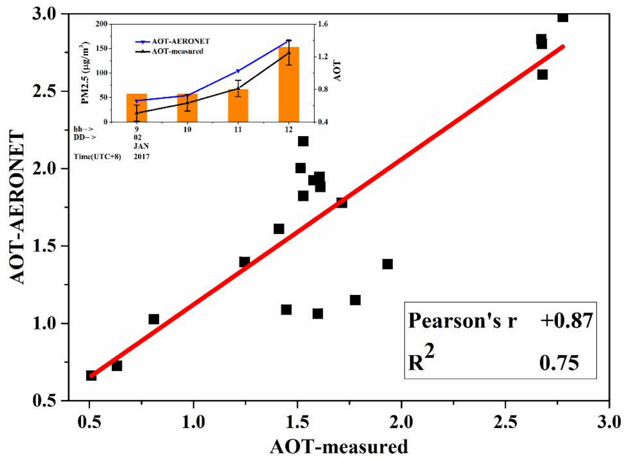


**Figure 2: Correlation of the AOT values deduced from AERONET sites and ground-based LiDAR data. The inserted chart gives the changes of PM2.5 mass concentration and AOT values at the ground-based LiDAR site on January 2, 2017.**

The upper air visibility (Up-Vis) is defined as the horizontal visibility at different altitudes. According to the Koschmieder's formula (Larson and Cass, 1989;Lee and Shang, 2016), the Up-Vis at a certain altitude is calculated with the following equation:

$$V(z) = -{}^{\ln A}/_{b_{ext}(z)}, \tag{3}$$

where $A$ is the limiting contrast threshold for the average human observer, with the common value of 0.02 (Middleton, 1957). $b_{ext}$ is the total extinction coefficient. According to the research of Song et al. (2003), the visibility impairment mainly depends on the light scattering extinction by particles in $b_{ext}$.

According to the observation and forecasting level of haze (QX/T 113-2010) and the requirements for human health (Jarraud, 2008), when the Up-Vis at a certain altitude is equal to about 5km based on Eq. (3), the haze thickness (HT) can be defined as the value of this altitude.

The height of ABL is affected by the underlying surface, and can be retrieved by detecting the rapid drop-off in extinction or backscatter coefficient between the free troposphere and the mixing layer as shown in the following equation (Flamant et al., 1997):

$$h_{ABL} = \max\left|\frac{\partial \alpha_a(z)}{\partial z}\right|, \tag{4}$$

where $\alpha_a(z)$ is the aerosol extinction coefficient (AEC) which is dependent on aerosol concentration, laser emission wavelength, and the detection altitude (Ji et al., 2017).

## 3 Results and discussion

Figure 3 shows the space-time diagram of AEC by analysing the detected data from ground-based LiDAR during two successive haze episodes in the northwest of downtown Beijing. Figure 3a shows the height of the haze layer (denoted as high extinction area) increased to the maximum value at 5:00 p.m. on December 20, 2016, afterwards, the haze almost dissipates at 3:00 a.m. on December 22, 2016. A thicker haze layer of about 0.6km could be generally observed as shown in Fig. 3b. Therefore, the haze parameters would alter with the hourly and daily changes of haze level, which will be described in details in the sections below. Section 3.1 denotes the hourly changes of multiplatform data, section 3.2 shows the daily variation of multiplatform data, and section 3.3 presents the relationship between multiple parameters.

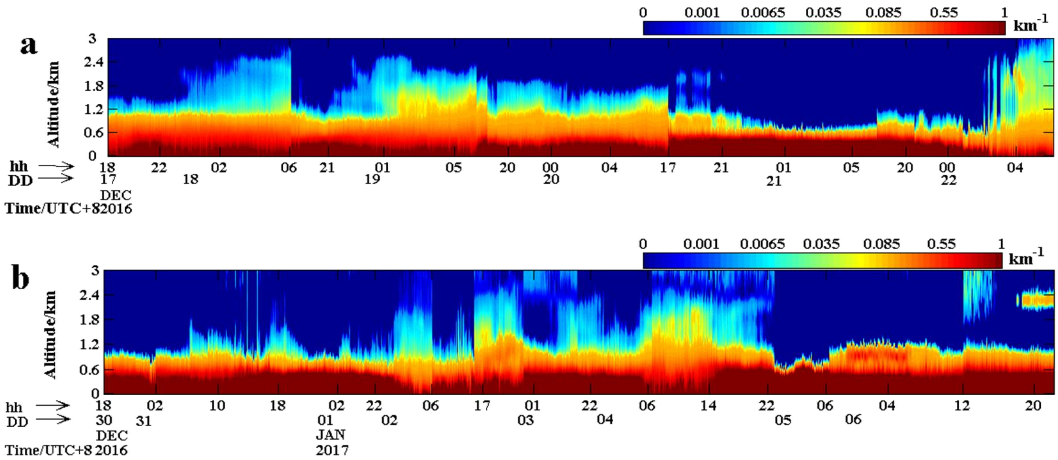


**Figure 3: Space-time diagram of AEC in the northwest of downtown Beijing during two haze episodes near 2017 New Year's Day.**

### 3.1 Hourly variation of multiplatform data

Figure 4 plots the hourly variation of haze parameters and meteorological elements during the first haze episode shown in Fig. 3a. The meteorological elements include PM2.5 mass concentration supplied by BJMEMC, RH, temperature, WD, and WS supplied by China Meteorological Administration (CMA). It is shown that the maximum Up-Vis (about 7.1 km, 12.4 km, and 15 km at the altitudes of 0.1 km, 0.3 km and 0.5 km, respectively) and the maximum ABL height (about 0.9 km) were obtained at 6:00 a.m. on December 22, 2016, where the variation trend is in contrast to the PM2.5 mass concentration. However, the peak and valley values of HT and AOT, respectively occurred at 9:00 p.m. on December 21, 2016 and at 6:00 a.m. on December 22, 2016, following the same trend as the PM2.5 mass concentration. Influenced by the effects of relative humidity (RH), the high RH enhanced the photochemical transformation of secondary aerosols that leads to a higher concentration of fine mode particles, which exacerbates the atmospheric elements, for example, impairment of Up-Vis, turbulence in ABL, and increase in HT and AOT (Hennigan et al., 2008). According to the topographic feature of Beijing, the strong north wind can accelerate the diffusion of pollutants that gradually reduce the haze pollution after December 22, 2016. Moreover, the error bars indicate data uncertainty, which may originate from the fluctuation of signals by the natural variability of the atmosphere and the inaccurate calibration parameter of the inversion method.

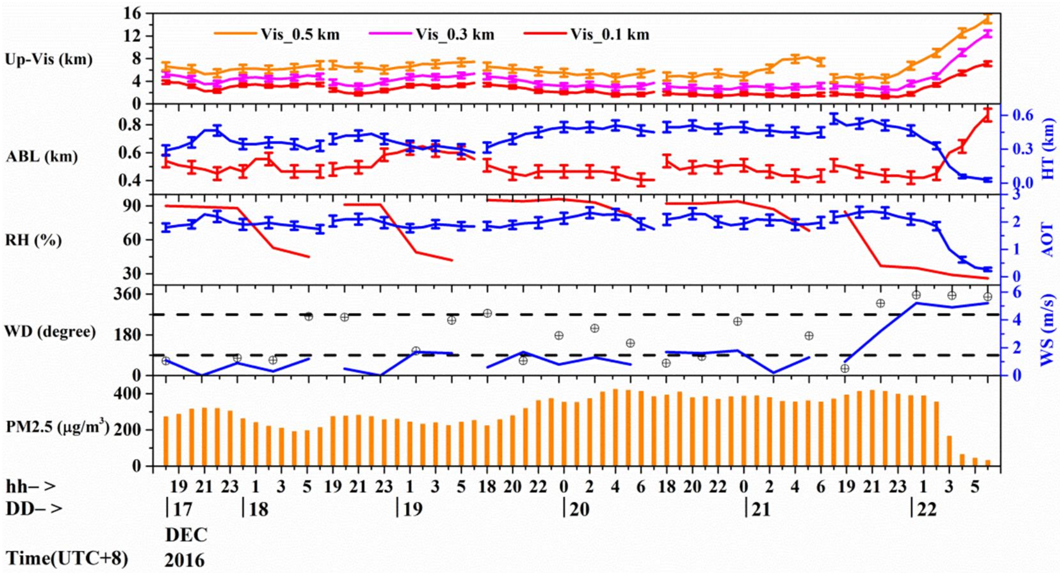


**Figure 4: Hourly variation of multiplatform data between December 17, 2016 and December 22, 2016 in the northwest of downtown Beijing.**

Similar results can be found in the other haze episode shown in Fig. 5. The Up-Vis and ABL has a negative correlation with the tendency of PM2.5 mass concentration. The Up-Vis reached peak values of about 5 km, 9.3 km, and 13.6 km at the altitudes of 0.1 km, 0.3 km, and 0.5 km, respectively in the daytime on January 2, 2017, where the Up-Vis corresponded to the PM2.5 mass concentration of 58μg/m$^3$ and a smaller RH of 55%. On the contrary, the maximum HT and AOT of about 0.8 km and about 3.6 was detected at 2:00 a.m. on January 4, 2017, which corresponded to the PM2.5 mass concentration of 561μg/m$^3$ and a larger RH of 97%. In addition, the continuous moderate pollution after January 5, 2017 can be attributed to the strong north wind with a maximum wind speed of 3 m/s in the night-time of January 4, 2017 and the weak south wind with a mean wind speed of about 1.3 m/s on January 6, 2017 (Han et al., 2016;Zhao et al., 2013). A higher PM2.5 mass concentration led to the increase in AOT, which was accompanied by the decrease in Up-Vis, as derived by Dong et al. (2017) from a combination of the Moderate-Resolution Imaging Spectroradiometer (MODIS) and the Multi-angle Imaging SpectroRadiometer (MISR) across Guanzhong Plain. Additionally, the error bars indicate data uncertainty, which may originate from the fluctuation of signals caused by the natural variability of the atmosphere and the inaccurate calibration parameter of the inversion method.

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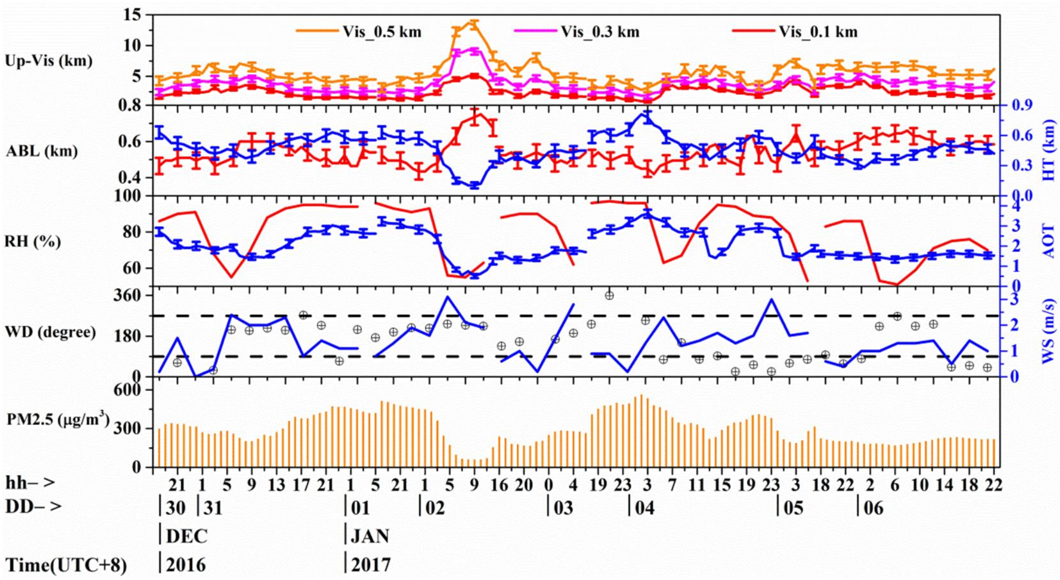


**Figure 5: Hourly variation of multiplatform data between December 30, 2016 and January 6, 2017 in the northwest of downtown Beijing.**

### 3.2 Daily variation of multiplatform data

To compare and analyse the difference of haze parameters on haze days and non-haze days, Fig. 6 presents the daily variation of Up-Vis, ABL, HT, and AOT with the meteorological elements. The following phenomena are concluded from Fig. 6: (1) the minimum Up-Vis values were about 1.5 km, 2.5 km, and 4.2 km at the altitudes of 0.1 km, 0.3 km, and 0.5 km, respectively. The Up-Vis on non-haze days was about 3-5 times higher than that on haze days. (2) The height of ABL was about 0.5 km on haze days, and ranged from 0.6 km to 0.9 km on non-haze days. (3) The trends that contradicted to the Up-Vis and ABL could be found in the results of HT and AOT. By combining meteorological elements, a lower Up-Vis and higher HT can be measured when PM2.5 and RH values were higher and the wind blew from the south. Moreover, when the prevailing wind came from the north and the RH value decreased, the diffusion of pollutants was accelerated, which improved the air quality and enhanced the Up-Vis. A high RH may favour the local contribution of humidity-related physicochemical processing in haze pollution, so the Up-Vis decreased on haze days, which is similar to the research from Tang et al. (2015). In addition, the error bars indicate data uncertainty, which may originate from the fluctuation of signals caused by the natural variability of the atmosphere and the inaccurate calibration parameter of the inversion method.

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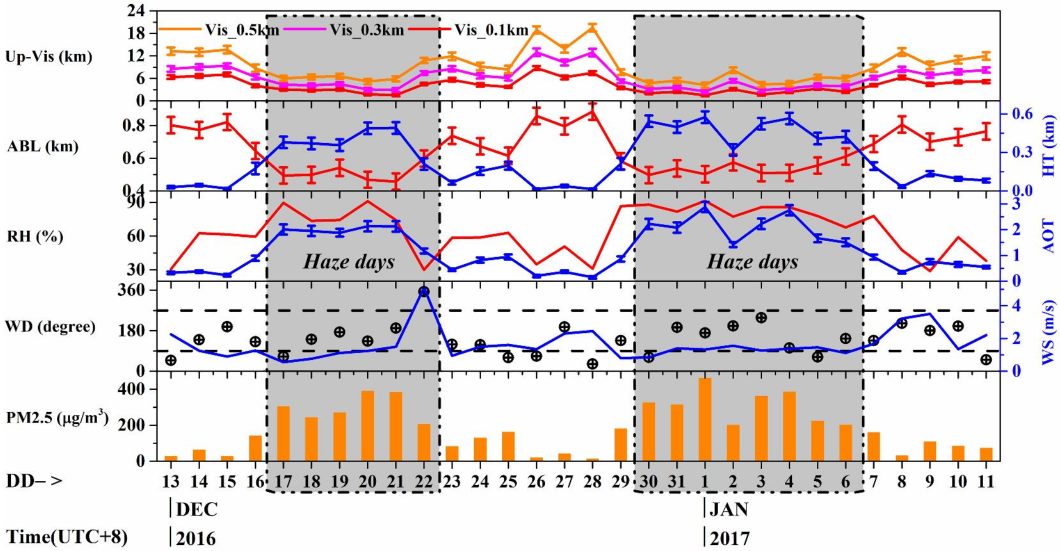

**Figure 6: Daily variation of multiplatform data during successive haze episodes in the northwest of downtown Beijing.**

### 3.3 Correlation between Up-Vis, ABL, HT, AOT, and PM2.5 mass concentration

As shown in Fig. 7, the correlation between PM2.5 mass concentration and haze parameters has been established to describe the effect of spatial transport of particles on haze parameters in the northwest of downtown Beijing. Figure 7a and 7b plot the exponential reduction of the ABL and Up-Vis values when PM2.5 mass concentration increased, with $R^2$ values at about 0.73 (mean value of 0.76, 0.81, and 0.62) and 0.62, respectively. The exponential correlation between ABL height and PM2.5 mass concentration is similar to the studies of Zhao et al. (2017). From Fig. 7c and 7d, it can be observed that the HT and AOT values increased linearly with the growing PM2.5 mass concentration, with the $R^2$ values at 0.75 and 0.84, respectively. With the accumulation of pollutants, the aerosol column concentration and the PM2.5 mass concentration would increase, which aggravates the light scattering and absorption. Therefore, the spatial transport of pollutants has a significant effect on haze parameters.

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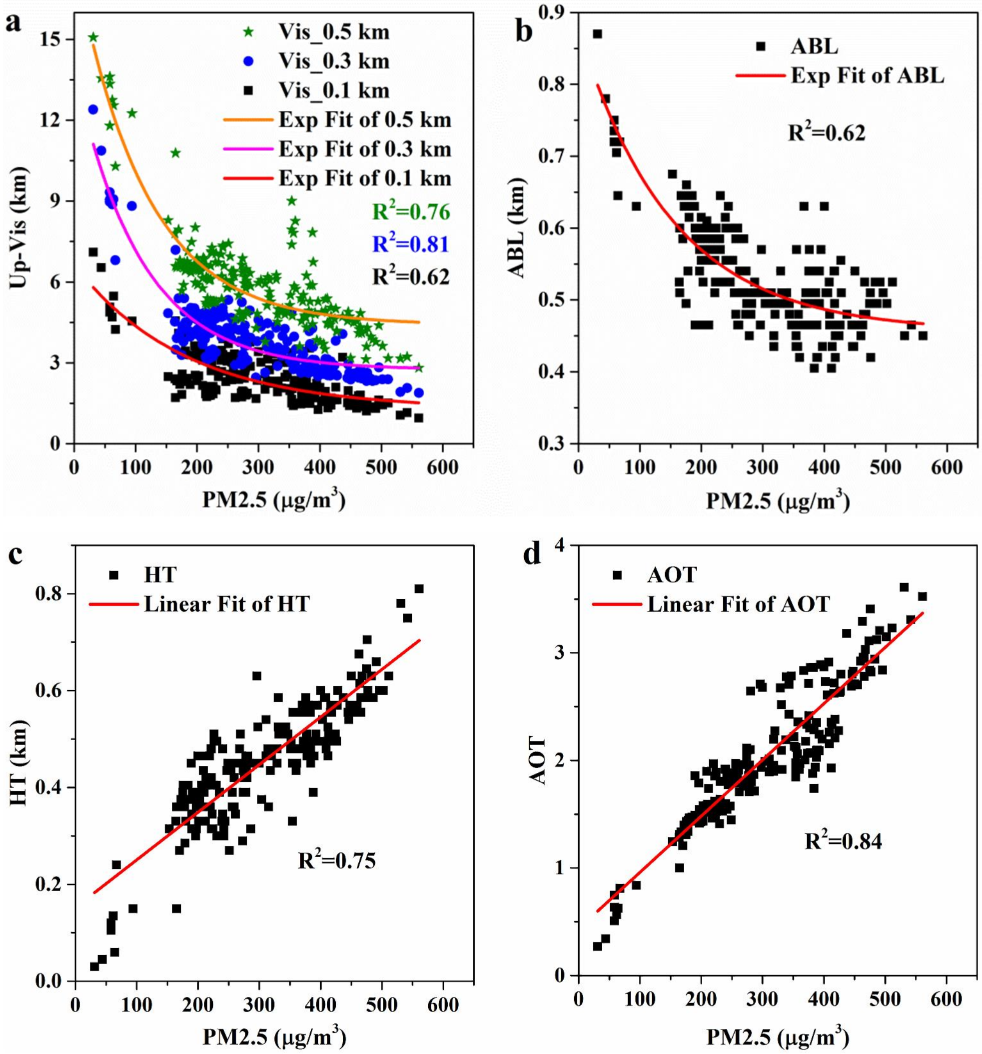


**Figure 7: Scatter plot of PM2.5 mass concentration and haze parameters of Up-Vis, ABL, HT, and AOT in the northwest of downtown Beijing.**

The ABL height is an important parameter to analyse the dynamic effect of air pollution (Wu et al., 2013). HT or AOT directly reflects the pollutant concentrations. The correlations between ABL, HT, AOT, and Up-Vis are plotted in Fig. 8. And Fig. 8a shows a positive exponential correlation between ABL and Up-Vis, with $R^2$ values of 0.44, 0.58, and 0.46 at the altitudes of 0.1 km, 0.3 km, and 0.5km, respectively. Tang et al. (2015) indicated the ABL can represent the atmospheric diffusion capacity in vertical direction, so the increase in Up-Vis was accompanied by the increase in ABL. However, when the HT or AOT values increased, the Up-Vis would decrease exponentially as shown in Fig. 8b and 8c. Compared with the studies of Dong et al. (2017), the similar anticorrelation can be inferred between visibility and AOT. And the exponential changes in Up-Vis and AOT or HT could be attributed to the rapid accumulation of aerosol particles near the surface.

Therefore, a higher ABL has a positive influence on atmospheric visibility; and a lower HT or smaller AOT would enhance atmospheric visibility.

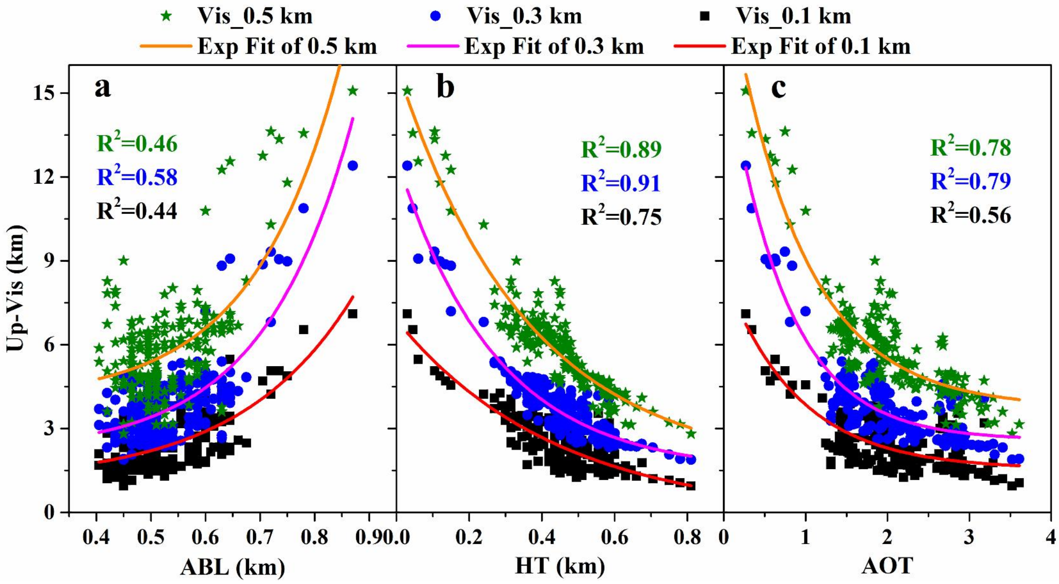


**Figure 8: Scatter plot of Up-Vis and haze parameters of ABL, HT, and AOT in the northwest of downtown Beijing.**

According to the observation and forecasting levels of haze supplied by CMA, the forecasting levels of haze are divided into four levels: slight pollution, mild pollution, moderate pollution and severe pollution (CMA, 2010). Table 1 provides the standard range of horizontal visibility on the surface (H-Vis) for different haze levels. When slight pollution occurred with the H-Vis of 5-10 km, the corresponding PM2.5 mass concentration is less than 60±20μg/m$^3$, the Up-Vis at the altitudes of 0.1 km, 0.3 km, and 0.5 km is larger than 6.5±0.3 km, 9±0.5 km, and 14±1 km, respectively, and the ABL is higher than 0.8±0.03 km. When mild pollution occurred with the H-Vis of 3-5 km, the minimum Up-Vis decreased to 3.8±0.2 km, 5.1±0.2 km, and 7.2±0.3 km at the altitudes of 0.1 km, 0.3 km, and 0.5 km, respectively. While the ABL would also decline, with the minimum value of 0.57±0.03 km. However, the AOT would increase from 0.4±0.05 to 1.5±0.1. When the H-Vis value is between 2 km and 3 km, the haze level is classified as moderate pollution. The PM2.5 mass concentration changes from 150±30μg/m$^3$ to 300±40μg/m$^3$. The Up-Vis would decrease from the minimum value of mild pollution to 2.6±0.1 km, 3.7±0.2 km, and 5.2±0.2 km at the altitudes of 0.1 km, 0.3 km, and 0.5 km, respectively. Simultaneously, the HT of between 0.3±0.03 km and 0.48±0.03 km could be obtained. Once the H-Vis is lower than 2 km, severe pollution would occur, with the corresponding PM2.5 mass concentration higher than 300±40μg/m$^3$. The Up-Vis would decrease further based on the minimum value of moderate pollution, and the turbulent ABL height could range from 0.42±0.03 km to 0.5±0.03 km. Moreover, the HT and AOT would further increase. Therefore, the obtained variation range of different haze parameters would be helpful for understanding the atmospheric elements of different haze levels through multi-parameter analysis and for serving the haze governance.

**Table 1: Values of Haze parameters and meteorological elements corresponding to the haze levels.**

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| Parameters | | Slight pollution | Mild pollution | Moderate pollution | Severe pollution |
|---|---|---|---|---|---|
| H-Vis (km) | | 5-10 | 3-5 | 2-3 | <2 |
| PM2.5 (μg/m$^3$) | | <60±20 | 60±20-150±30 | 150±30-300±40 | >300±40 |
| | *0.1 km* | *>6.5±0.3* | *3.8±0.2-6.5±0.3* | *2.6±0.1-3.8±0.2* | *<2.6±0.1* |
| *Up-Vis (km)* | *0.3 km* | *>9±0.5* | *5.1±0.2-9±0.5* | *3.7±0.2-5.1±0.2* | *<3.7±0.2* |
| | *0.5 km* | *>14±1* | *7.2±0.3-14±1* | *5.2±0.2-7.2±0.3* | *<5.2±0.2* |
| ABL (km) | | 0.8±0.03-1[a] | 0.57±0.03-0.8±0.03 | 0.5±0.03-0.57±0.03 | 0.42±0.03-0.5±0.03 |
| HT (km) | | ≈0 | <0.3±0.03 | 0.3±0.03-0.48±0.03 | >0.48±0.03 |
| AOT | | <0.4±0.05 | 0.4±0.05-1.5±0.1 | 1.5±0.1-2.1±0.2 | >2.1±0.2 |

[a]: Range of ABL is 0.3-1 km (Garratt, 1994).

## 4 Conclusions

In this study, the traits of upper air visibility were investigated during the haze episode near the 2017 New Year's Day in the northwest of downtown Beijing by using a multiplatform analysis. The main conclusions are as follows:

(1) Compared with the changes of PM2.5 mass concentration, an opposite tendency can be found for Up-Vis by hourly and daily haze analysis. The Up-Vis on non-haze days was about 3-5 times higher than that on haze days.

(2) A strong correlation between PM2.5 mass concentration and haze parameters shows the effect of spatial transport of particles on haze parameters. A higher ABL or lower HT as well as smaller AOT have a positive influence on the atmospheric visibility.

(3) The proposed variation range for different haze parameters would be beneficial to understand the atmospheric condition of different haze levels through multi-parameter analysis and to serve the haze governance.

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