RESPONSE LETTER

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Multiplatform analysis of upper-air haze visibility in downtown Beijing

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We deeply appreciate the reviewer for his/her careful reviews of this paper.

RC1. *I can't find the scientific significance and academic value of this article. Why study Up-Vis ïij´L0.1,0.3,0.5kmïijL'ïij§The authors have not pointed out the differences of Up-Vis at the three altitudes, nor have they studied the differences between them and the horizontal visibility on the ground. What is the purpose of using Up-Vis at three high altitudes? There are many detailed studies focusing on the relationship between visibility, relative humidity and other meteorological elements and PM2.5. The study method and conclusions of this article are too simple and general comparing with the related works.*

Response:

As we've known, the haze thickness (HT) is defined as the altitude where the upper air visibility (Up-Vis) is about 5 km (Han et al., 2016). This demonstrates the parameter of Up-Vis is key for obtaining the variation of HT. It is shown in Fig. 6 that the HT changes from 0.3 km to 0.6 km on haze days. So the Up-Vis at the altitudes of 0.1 km, 0.3 km, and 0.5 km are studied to characterize the HT. In addition, the Up-Vis at other altitudes can also be selected to study the characteristics of HT, as shown in Fig. R1. In Fig. R1, the similar phenomenon can be found compared with the results of Fig. 6. But considering the standard appearance of graphics, only three typical altitudes are shown in the paper.

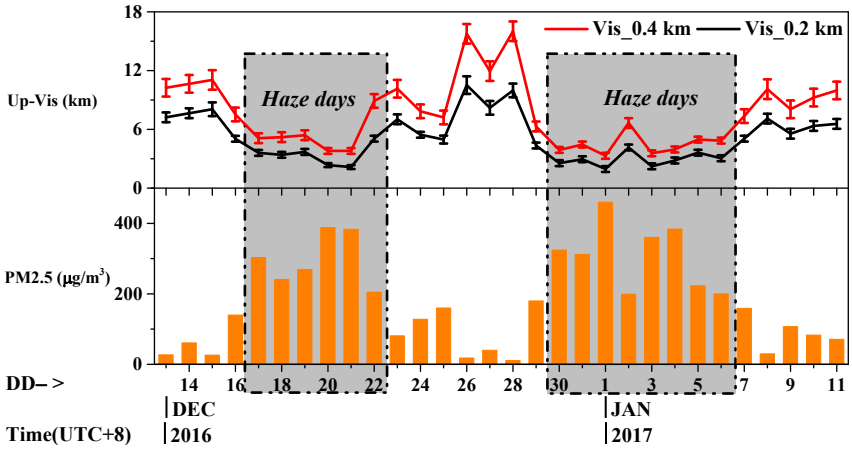

Figure R1: Daily variation of upper air visibility during successive haze episodes in the northwest of downtown Beijing.

According to the research of Tang et al. (2015), the atmospheric boundary layer (ABL) represents the atmospheric diffusion capacity in vertical direction, the aerosol optical thickness (AOT) directly reflects the particle concentration at a certain vertical distance, and the HT represents the main region of high concentration particles. The Up-Vis, the horizontal visibility at different altitudes, represents the horizontal particle concentration at a certain altitude. Therefore, the Up-Vis characterizes the horizontal haze situations at different altitudes; the ABL, AOT and HT characterize the vertical haze situation from different perspectives. And the correlation between vertical haze parameter (ABL, AOT and HT) and horizontal haze parameter (Up-Vis) characterizes the two-dimensional haze situations. Through comparing hourly variations of PM2.5 mass concentration and Up-Vis at different altitudes in certain period, the influence of vertical transport of pollutants on variation of haze parameters could be revealed indirectly. And according to the variation characteristics of Up-Vis and its correlation with vertical haze parameters (ABL, AOT and HT), the haze phenomenon in two dimensions can be analyzed, which provides more insights into haze phenomenon.

From Figs. 4-6, it is shown that the Up-Vis at the three altitudes have different variation ranges. The Figs. 7a shows the different correlation between the Up-Vis at the three altitudes and PM2.5 mass concentration. Figure 8 indicates the impact of vertical transport of pollutants on variation of haze parameters by analyzing the delayed variations of Up-Vis between high altitude and low altitude. Figure 9 reveals the correlation between horizontal haze parameter (Up-Vis at the three altitudes) and

vertical haze parameters (ABL, AOT and HT). And Table 1 shows the statistical gradient of Up-Vis at different altitudes changing with the vertical haze parameters. Moreover, Table 2 displays the variation of Up-Vis at the three altitudes under different haze levels. Besides, the paper also indicates the minimum values of Up-Vis at the three altitudes are about 1.5 km, 2.5 km, and 4.2 km respectively on haze days, as shown in Lines 7-8 on Page 7. Therefore, the paper not only shows the numerical differences in Up-Vis at the three altitudes qualitatively and quantitatively, but also shows the different correlation between Up-Vis and vertical haze parameters (ABL, AOT and HT).

Atmospheric visibility basically includes horizontal visibility, slant range visibility and vertical visibility (Hey, 2015). The upper air visibility (Up-Vis) is defined as the horizontal visibility at different altitudes which is detailed in Page 4. The Up-Vis at different altitudes is regarded as the horizontal visibility above the ground, and the horizontal visibility usually indicates the horizontal visibility near the ground.

Until now, many studies on the visibility and its correlation with meteorological elements have been carried out to indicate the importance of visibility to air pollution studies (Yang et al., 2013; Sun et al., 2016; Wu et al., 2012; Bäumer et al., 2008; Pantazis et al., 2017). But these researches focus on the horizontal visibility and the slant range visibility rather than the upper air visibility. According to the obtained variation characteristics of Up-Vis, the influence mechanism of meteorological parameters to Up-Vis, and its correlation with vertical haze parameters (ABL, AOT and HT), the variation of Up-Vis would be significant to obtain the variation of haze thickness, and the haze phenomenon in two dimensions could be recognized, which provides more insights into haze phenomenon.

To be more scientific, we have changed the sentence “However, less focus was attached to the characteristics of upper air visibility (Up-Vis).” into “<u>However, the above research mainly focused on the horizontal visibility near the ground, and less focus was attached to the characteristics of upper-air visibility (Up-Vis). Moreover, the research has been hardly found to report the two-dimensional haze characteristics.</u>” (see Lines 14-16 on **Page 2**).

To well demonstrate the two-dimensional haze characteristics, the sentence "In addition, a higher atmospheric boundary layer improves upper air visibility." has been changed into "In addition, the two-dimensional haze characteristics could be studied by analyzing the correlation between vertical haze parameters (atmospheric boundary layer, haze thickness and aerosol optical thickness) and horizontal haze parameter (upper-air visibility)." (see Lines 12-14 on **Page 1**). The sentence "(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;" has been changed into "(2) reveal the impact of the vertical transport of PM2.5 (particulate matter with a diameter less than 2.5 μm) mass concentration on Up-Vis and investigate the two-dimensional haze phenomenon based on the correlation between vertical haze parameter (ABL, AOT and haze thickness) and horizontal haze parameter (Up-Vis);" (see Lines 23-25 on **Page 2**). We have added the sentence "Besides, AOT is classified as vertical haze parameter because of its representative significance to pollutant concentration at a certain vertical distance." to classify the parameter of AOT (see Lines 19-20 on **Page 3**). The sentence "The Up-Vis is defined as the horizontal visibility at different altitudes." has been changed into "The Up-Vis is defined as the horizontal visibility at different altitudes, which is classified as horizontal haze parameter." (see Line 4 on **Page 4**). We have added the sentence "Therefore, HT reflects the main region of high concentration pollutions and can be classified as vertical haze parameter." to classify the parameter of HT (see Lines 13-14 on **Page 4**). The sentence "Tang et al. (2015) indicated the ABL represents the atmospheric diffusion capacity in vertical direction, so it can be classified as the vertical haze parameter." has been added to classify the parameter of ABL (see Lines 20-21 on **Page 4**). And the sentence "Therefore, a higher ABL has a positive influence on atmospheric visibility; and a lower HT or smaller AOT would enhance atmospheric visibility." has been changed into "The table 1 shows the statistical gradient of Up-Vis at different altitudes changing with the vertical haze parameters. It is obvious that the Up-Vis at altitude of 0.3 km changed faster than that at altitudes of 0.1 km and 0.5 km. Therefore, through the analysis of the correlation between vertical haze parameters (ABL, HT and AOT) and horizontal haze parameter (Up-Vis), the haze characteristics could be well investigated in two dimensions." (see Lines 11-14 on **Page 10**). The added table was shown in table R1 (see Table 1 on **Page 11**). We have changed the sentence "A higher ABL or lower HT as well as smaller AOT have a positive influence on the atmospheric visibility." into

"The correlation between vertical haze parameters (ABL, AOT and HT) and horizontal haze parameter (Up-Vis) can help investigate the two-dimensional characteristics of haze phenomenon." (see Lines 17-19 on **Page 12**).

Table R1: Statistical gradient of Up-Vis with different vertical haze parameters at different altitudes.

Vertical haze parameters	Vis_0.1 km	Vis_0.3 km	Vis_0.5 km
ABL	4.801	6.246	6.101
HT	2.275	3.674	2.787
AOT	1.108	1.365	1.111

RC2. Major comments:

The scientific significance of this study is not clear enough to me. Why the authors investigate the relationship between haze parameters and upper air visibility? How important of the upper air visibility and the results of this study on the understanding of haze phenomena? Thus, I'd suggest giving more description on this.

The data analysis and discussion are very shallow and on the surface, and thus more studies and deep discussions should be made to make the study original enough. Furthermore, I was left wondering to what new understanding we are able to take away from the study.

Response:

The aerosol extinction coefficient can be retrieved from the ground-based LiDAR data, and is used to get the upper-air visibility (Up-Vis) at certain altitude, the aerosol optical thickness (AOT) at a certain vertical distance and the height of atmospheric boundary layer (ABL). As we've known, the haze thickness (HT) is defined as the altitude where the Up-Vis is about 5 km (Han et al., 2016). Moreover, according to the research of Tang et al. (2015), the ABL represents the atmospheric diffusion capacity in vertical direction, the AOT directly reflects the particle concentration at a certain vertical distance, and the HT represents the main region of high concentration particles. The Up-Vis, the horizontal visibility at different altitudes, represents the horizontal particle concentration at a certain altitude. Therefore, the Up-Vis characterizes the horizontal haze situations at different altitudes; the ABL, AOT and HT characterize the vertical haze situations from different perspectives. And

the correlation between vertical haze parameter (ABL, AOT and HT) and horizontal haze parameter (Up-Vis) characterizes the two-dimensional haze situations.

Through comparing hourly variations of PM2.5 mass concentration and Up-Vis at different altitudes in a certain period, the influence of pollutants' vertical transport on variation of haze parameters could be revealed indirectly. And according to the variation characteristics of Up-Vis and its correlation with vertical haze parameters (ABL, AOT and HT), the haze phenomenon in two dimensions would be recognized, which provides more insights into haze phenomenon.

To be more scientific, the term "haze parameter", including ABL, AOT and HT, has changed into the term "vertical haze parameter (ABL, AOT and HT)". We have changed the sentence "However, less focus was attached to the characteristics of upper air visibility (Up-Vis)." into "However, the above research mainly focused on the horizontal visibility near the ground, and less focus was attached to the characteristics of upper-air visibility (Up-Vis). Moreover, the research has been hardly found to report the two-dimensional haze characteristics." (see Lines 14-16 on **Page 2**). And we have added the sentence "The close connection with AERONET's statistical results demonstrates that the retrieved aerosol extinction coefficient is reliable and believable." to indicate the retrieved aerosol extinction coefficient is reliable (see Lines 9-10 on **Page 12**). Finally, to demonstrate the influence of meteorological elements on haze, the sentence "The higher relative humidity would aggravate the haze characteristics owing to the enhanced photochemical transformation of secondary aerosols. On the contrary, the strong north wind would accelerate the diffusion of pollutants due to the topographic feature of Beijing." has been added (see Lines 12-14 on **Page 12**).

To well demonstrate the two-dimensional haze characteristics, the sentence "In addition, a higher atmospheric boundary layer improves upper air visibility." has been changed into "In addition, the two-dimensional haze characteristics could be studied by analyzing the correlation between vertical haze parameters (atmospheric boundary layer, haze thickness and aerosol optical thickness) and horizontal haze parameter (upper-air visibility)." (see Lines 12-14 on **Page 1**). The sentence "(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;" has been changed into "(2) reveal the impact of the vertical transport of PM2.5 (particulate matter with a diameter

less than 2.5 μm) mass concentration on Up-Vis and investigate the two-dimensional haze phenomenon based on the correlation between vertical haze parameter (ABL, AOT and haze thickness) and horizontal haze parameter (Up-Vis);" (see Lines 23-25 on **Page 2**). We have added the sentence "Besides, AOT is classified as vertical haze parameter because of its representative significance to pollutant concentration at a certain vertical distance." to classify the parameter of AOT (see Lines 19-20 on **Page 3**). The sentence "The Up-Vis is defined as the horizontal visibility at different altitudes." has been changed into "The Up-Vis is defined as the horizontal visibility at different altitudes, which is classified as horizontal haze parameter." (see Line 4 on **Page 4**). We have added the sentence "Therefore, HT reflects the main region of high concentration pollutions and can be classified as vertical haze parameter." to classify the parameter of HT (see Lines 13-14 on **Page 4**). The sentence "Tang et al. (2015) indicated the ABL represents the atmospheric diffusion capacity in vertical direction, so it can be classified as the vertical haze parameter." has been added to classify the parameter of ABL (see Lines 20-21 on **Page 4**). And the sentence "Therefore, a higher ABL has a positive influence on atmospheric visibility; and a lower HT or smaller AOT would enhance atmospheric visibility." has been changed into "The table 1 shows the statistical gradient of Up-Vis at different altitudes changing with the vertical haze parameters. It is obvious that the Up-Vis at altitude of 0.3 km changed faster than that at altitudes of 0.1 km and 0.5 km. Therefore, through the analysis of the correlation between vertical haze parameters (ABL, HT and AOT) and horizontal haze parameter (Up-Vis), the haze characteristics could be well investigated in two dimensions." (see Lines 11-14 on **Page 10**). The added table was shown in table R2 (see Table 1 on **Page 11**). We have changed the sentence "A higher ABL or lower HT as well as smaller AOT have a positive influence on the atmospheric visibility." into "The correlation between vertical haze parameters (ABL, AOT and HT) and horizontal haze parameter (Up-Vis) can help investigate the two-dimensional characteristics of haze phenomenon." (see Lines 17-19 on **Page 12**).

Table R2: Statistical gradient of Up-Vis with different vertical haze parameters at different altitudes.

Vertical haze parameters	Vis_0.1 km	Vis_0.3 km	Vis_0.5 km
ABL	4.801	6.246	6.101
HT	2.275	3.674	2.787
AOT	1.108	1.365	1.111

To describe the impact of near-ground particle concentration on haze parameters, we have added and changed some sentences as below: (1) added the sentence "In Fig. 7a, with the decreasing of PM2.5 mass concentration, the Up-Vis at the altitude of 0.1 km gradually increases, but the Up-Vis at the altitudes of 0.3 km and 0.5 km increases much faster as shown in the inserted table." (see Lines 8-9 on **Page 8**). (2) changed the sentence "Therefore, the spatial transport of pollutants has a significant effect on haze parameters." into "Therefore, the near-ground pollutant concentration has a significant influence on haze parameters, so the haze could be alleviated by controlling pollutant concentrations near the ground." (see Lines 14-15 on **Page 8**). (3) inserted the table about statistical gradient of Up-Vis at different altitudes as shown in Fig. R2 and added the sentence "The inserted table in Fig. 7a denotes the statistical gradient of Up-Vis at different altitudes." (see Line 4 on **Page 9**). (4) changed the sentence "A strong correlation between PM2.5 mass concentration and haze parameters shows the effect of spatial transport of particles on haze parameters." into "Moreover, a strong correlation between PM2.5 mass concentration and haze parameters shows an obvious influence of near-ground particle concentration on haze parameters, so the haze phenomenon could be alleviated by controlling pollutant concentrations near the ground." (see Lines 14-16 on **Page 12**).

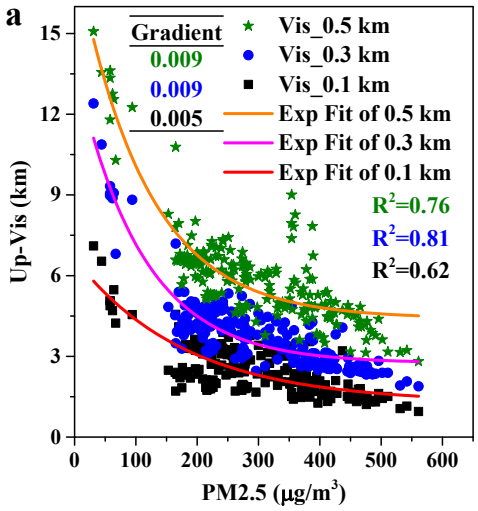

Figure R2: Scatter plot of PM2.5 mass concentration and Up-Vis in the northwest of downtown Beijing. The inserted table denotes the statistical gradient of Up-Vis at different altitudes.

RC2. Minor comments:

P1, Abstract: it is better to give the periods of the haze episodes, and which altitude of the upper air and what the haze parameters refer to here.

Response:

We have added the periods of the haze episodes, the altitude of the upper-air visibility and the detailed haze parameters in the Abstract. To be more scientific, the sentence of "The vertical features of upper air visibility in the northwest…near the 2017 New Year's Day" has changed into "The features of upper-air visibility at altitudes of 0.1km, 0.3km and 0.5km and the two-dimensional haze characteristics in the northwest of downtown Beijing were studied by using a multiplatform analysis during haze episodes between December 17th, 2016 and January 6th, 2017." (see Lines 7-9 on **Page 1**). And we have changed the sentence "The strong correlation between PM2.5 mass concentration and haze parameters shows the effect of spatial transport of particles on haze parameters." into "The vertical transport of pollutants can be inferred from the delayed variation of upper-air visibility between high altitude and low altitude." (see Lines 11-12 on **Page 1**).

P1, L19: "the haze days have shown a marked increase in years before 2006." How about the years after 2006? Is it after 2006 here?

Response:

We have changed the sentence "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." into "According to research of Chen and Wang, the annual haze days in North China were relatively few in the 1960s, but increased sharply in the 1970s and have remained stable to the present through the analysis of long-term variation during the period of 1960-2012 (Chen and Wang, 2015)." to add the description about the variation of haze days after 2006 (see Lines 20-23 on **Page 1**).

P3, 2.2: please give the short description on how to get the AOD from lidar measurements, how about the uncertainties?

Response:

Aerosol optical thickness (AOT) can be defined as the extinction of monochromatic light due to the presence of aerosols in the atmosphere. Based on the lidar equation, the aerosol extinction coefficient was retrieved by some robust inversion methods. Then the AOT can be retrieved by the integration of aerosol extinction coefficient over a certain vertical distance. Owing to the signal-to-noise ratio difference caused by the natural variability of the atmosphere and the calibration and estimation errors caused by the robust inversion methods, the retrieved AOT would cause some errors according to the error propagation theory. To be more scientific, we have added the sentence "AOT is defined as the extinction of monochromatic light due to the presence of aerosols in the atmosphere, and can be retrieved by the integration of aerosol extinction coefficient over a certain vertical distance." to describe the AOT (see Lines 9-10 on **Page 2**).

P4, figure 2: Only one day's data is used to validate the lidar retrieved AOD, is it because only one day retrieval available?

Response:

Figure 2 shows the correlation of AOT values deduced from AERONET sites and ground-based LiDAR data. By comparing the data of the deduced AOTs, there are 20 sets of matching data, as shown in Fig. R3. To display how AOT values deduced from AERONET sites and ground-based LiDAR data alter along with the changes of PM2.5 mass concentration, the results in one day are selected to demonstrate the variation, as shown in the inserted chart of Fig. R3. The inserted chart indicates the AOT values increase with the increasing of PM2.5 mass concentration through analyzing the data in this day. By combining all the matching data, a higher correlation between AOT values deduced from AERONET data and that retrieved from ground-based LiDAR data can be obtained, which demonstrates the AOT values (that is to say the aerosol extinction coefficient) retrieved from ground-based LiDAR data is reasonable and reliable. To be more scientific, we have added the number of matching samples into the figure (see **Figure** 2 on **Page 4**).

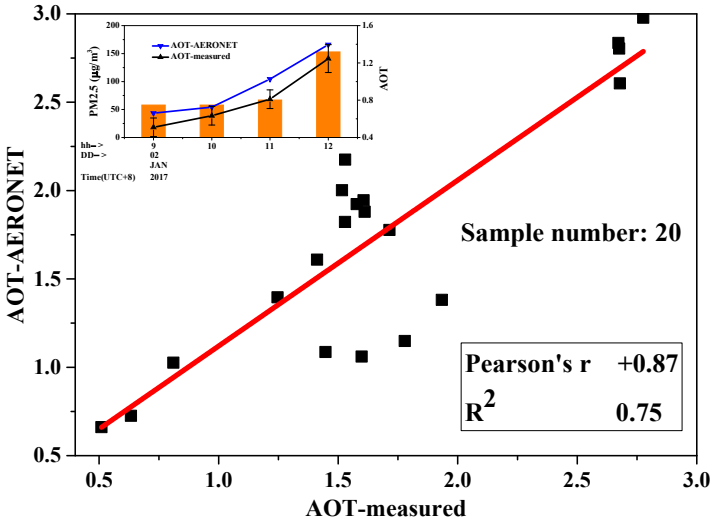

Figure R3: Correlation of the AOT values deduced from AERONET sites and ground-based LiDAR data. The inserted chart gives the changes of PM2.5 mass concentration and AOT values at the ground-based LiDAR site on January 2, 2017.

P4, figure3: The AEC determined from lidar is only for cloud-free conditions or all conditions?

Response:

The aerosol extinction coefficient (AEC) obtained from LiDAR data can be used for analyzing all conditions including the atmospheric characteristics below more than 10 km. Owing to the severe extinction caused by the existing haze, the detection altitude may not reach the position of cloud. Moreover, the haze mainly concentrates within about 1 km. Therefore, the plotted interval of Y-axis in Fig. 3 is below 3 km.

P5, L3: "the haze parameters would alter with the hourly and daily changes of haze level", this result is well known. The figures 3 just give the variation of haze height.

Response:

Thanks for your valuable comment. We have changed the sentence "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." into "Moreover, the variation of some haze parameters would be further obtained by analyzing the two

successive haze episodes, which is detailed in the sections below." (see Lines 6-7 on **Page 5**).

P7, L7: on haze day or non-haze day?

Response:

To be more clear, we have added the description of the region for haze days. As shown in Lines 6-7 on **Page 7**, we have added the sentence "The haze days are shown in the areas highlighted in grey in Fig. 6.".

P8, L11: I do not see the results of "the spatial transport of pollutants has a significant effect on haze parameters" can be concluded from the above description.

Response:

Thanks for your valuable comment. We have changed the term "spatial transport" into "vertical transport" and added the figure 8 to further describe the vertical transport of pollutants as shown in Fig. R4. Moreover, the descriptions about the vertical transport of pollutants have been added.

"As shown in Fig. 8, the vertical transport of particles could be obtained by comparing hourly variations of PM2.5 mass concentration and Up-Vis at different altitudes in certain period. In Fig. 8 (1), as the PM2.5 mass concentration near the ground decreased, the Up-Vis at the altitude of 0.5 km increased three hours later than that at the altitudes of 0.1 km and 03 km. This indicates pollutants might ascend and prevents the improvement of Up-Vis at the altitude of 0.5 km. In Fig. 8 (2), the Up-Vis at the altitude of 0.5 km increased rapidly, while the Up-Vis at the altitudes of 0.1 km and 0.3 km increased slowly four hours later. This demonstrates the delayed diffusion might result from the descent of pollutants. While the descent of pollutants cause that near-ground PM2.5 mass concentration decreased slowly in this period. Therefore, the delayed variations of Up-Vis between high altitude and low altitude indirectly reveal the influence of vertical transport of pollutants on variation of haze parameters." (see Lines 5-13 on **Page 9** and Figure 8 on **Page 10**).

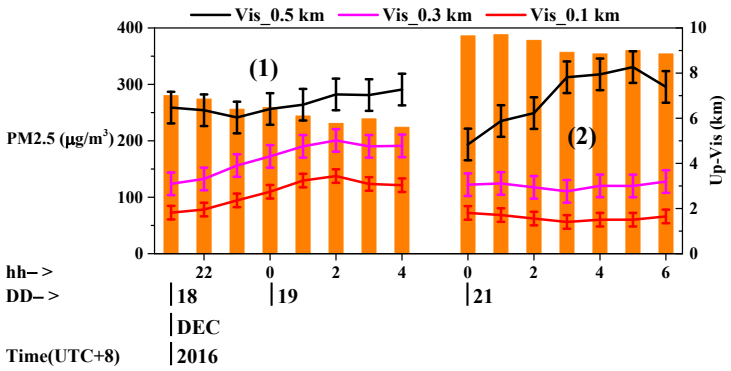

Figure R4: Hourly variation of Up-Vis and PM2.5 mass concentration in certain period.

Finally, the sentence "In addition, the delayed variations of Up-Vis between high altitude and low altitude reveal the vertical transport of pollutants." has been added to conclude the vertical transport of pollutants (see Lines 16-17 on **Page 12**).

Figure 7: please give the number of samples.

Response:

We have changed the sentence "As shown in Fig. 7 … to describe the effect of spatial transport of particles on haze parameters in the northwest of downtown Beijing." into "As shown in Fig. 7, the correlation between PM2.5 mass concentration and haze parameters was established based on the 201 statistical samples in Fig. 4 and 5, which describes the impact of near-ground particle concentration on haze parameters in the northwest of downtown Beijing." (see Lines 4-6 on **Page 8**). The sentence "The ABL height is an important parameter to analyze 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." has changed into "According to the 201 statistical samples mentioned above, the correlations between vertical haze parameters (ABL, HT and AOT) and horizontal haze parameters (Up-Vis) are plotted in Fig. 9 to analyze the two-dimensional characteristic of haze phenomenon." (see Lines 3-5 on **Page 10**).

P10, L5: please give the standard of the four haze levels

Response:

According to the observation and forecasting levels of haze (QX/T 113-2010) supplied by CMA, when the horizontal visibility on the ground is between 5 km and 10 km, the haze level is slight pollution; when the horizontal visibility on the ground is between 3 km and 5 km, the haze level is mild pollution; when the horizontal visibility on the ground is between 2 km and 3 km, the haze level is moderate pollution; when the horizontal visibility on the ground is less than 2 km, the haze level is severe pollution, which is displayed in table R3. To be more scientific, we have changed the sentence "According to the observation and forecasting levels of haze supplied by CMA…" into "According to the observation and forecasting levels of haze (QX/T 113-2010) supplied by CMA…" (see Lines 4-5 on **Page 11**).

Table R3: Standard of the haze levels.

Haze levels	Standard/km
Slight pollution	5-10
Mild pollution	3-5
Moderate pollution	2-3
Severe pollution	<2

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