Dear reviewer,

Thank you very much for your comment on our paper, we think it is really very valuable and it helps us a lot.

In particular, as the first author, I am currently a Ph.D. student. I have really learned a lot of boundary layer knowledge from your comments. I would like to express my respect and heartfelt thanks to you !

Based on your review comments, we have added some calculations, redrawn some of the figuers, and responded to your comments one by one in the attachment, and adopted all your suggestions. Specifically:

1) Complement all recommended references.
2) Added MODIS satellite cloud image.
3) Corrected the representation of the height of the radiosonde detection boundary layer. As you said, the maximum temperature gradient method we obtained should be the residual layer top height.
4) Recalculating and drawing with high-resolution radiosonde, giving the wind profile of the low-level jet during heavy pollution. As you pointed out, we should use the jet height (or low-level wind extreme) as the boundary layer height. The value of the boundary height has also been corrected. The drawing is shown in Figure 6.
5) Increased the daily variation of the surface wind field in Beijing and the discussion of the removal of pollutants by cold air.
6) Respond to all major and minor comments you have given.

We sent the revised paper as an attachment, and we are continuing to modify it.

Thank you very much !

Yours sincerely,

Yu Shi (first author)

Fei Hu (corresponding author)

- **Response to the Major comments**

(a) Thank you for the valuable comments of the reviewers. The height we calculated based on the maximum temperature gradient should indeed be the residual layer top. We added the literature to the text and gave a discussion and text modification.

(b) According to the opinions of the reviewers, this maximum wind value can only be applied in the case of low-level jet structure, so we reanalyzed all the wind profiles of this process, and selected the profiles that have obvious “nose” structure or have reached the standard of low-level jet, so as to determine the PBL heights under this kind of wind profile. Here, we give the wind profiles of December 15, 17, 19 and 21 (Figure all are local station time). Although some cases did not meet the LLJ standard at some moments, it also had obvious “nose” structure. Below the height of the low level wind maximum is where affected by the ground friction, it can be concluded that the height of the low level wind extreme value at this time is the boundary layer height. The wind profiler radar can output the atmospheric refractive index structure parameter and determine the height of the boundary layer based on it. It is difficult to detect the stable boundary layer height because of the weak turbulence, so the boundary layer height based on refractive index structure parameter is mostly used in the convective boundary layer (for reference). However, atmospheric refractive index structure parameter was not used in this paper. Instead, wind profiles detected by WPR were used in this paper we, therefore, we still keep the results of wind profiler radar data, and gives the analysis results of the wind structure from low to high levels during the period of urban heavy pollution period.

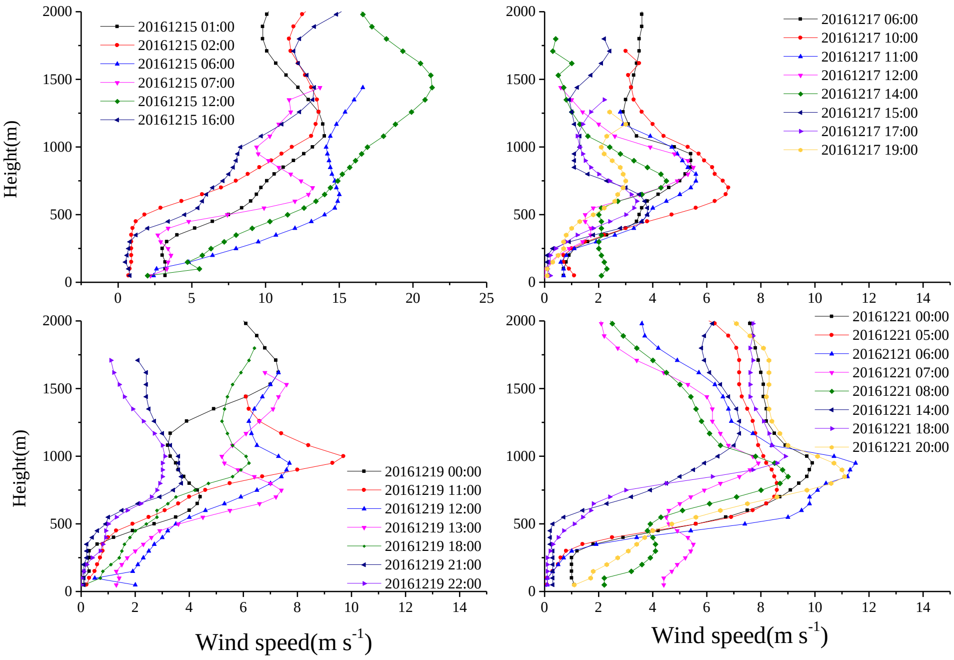


Figure Wind profiles of December 15、17、19 and 21

(c) This study could benefit from a discussion of the synoptic and mesoscale meteorology. Based on Fig. 2, it looks like there were cold fronts (strong NW winds) on both 12/15 and 12/22 which advected pollutants away and resulted in air quality. Between the fronts, the PM2.5 slowly increased as the air was stagnant (weak and variables winds in between) and pollutants emitted locally likely slowly built up. The wind direction also seems to be cyclical every day, perhaps this is in response to a local mountain-valley circulation around Beijing? This warrants more investigation. It appears that these factors, namely the stagnant air, dominate over the PBL processes in resulting in the poor air quality.

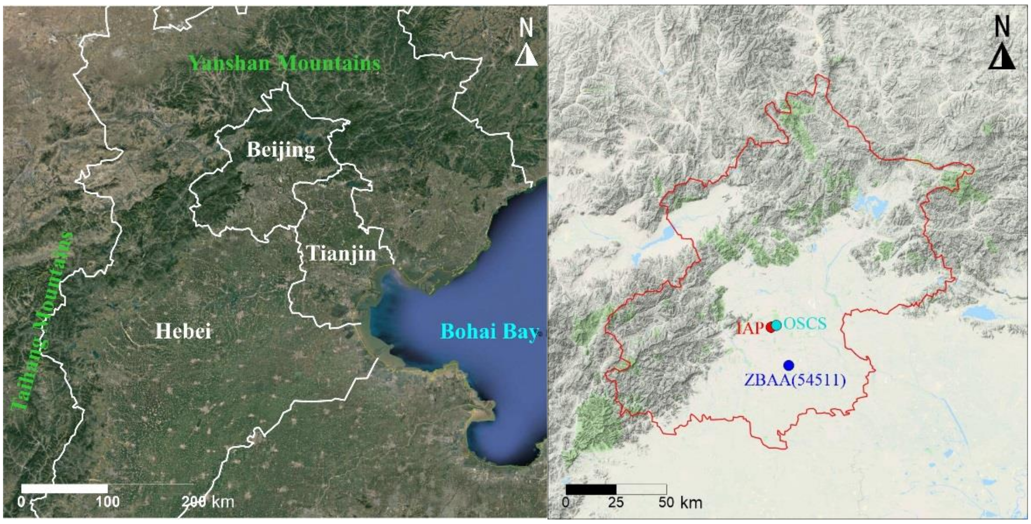
(d) While the authors provide numerous references early in the manuscript, there is little-to-no discussion of how the key findings and results compare to previous studies.For example, how does this haze episode compare to other poor air quality case studies in Beijing and other areas, considering both meteorology and boundary-layer processes? The authors should relate the hygroscopic growth to that observed in other studies (there are many). There have also been many other studies comparing lidar PBL heights with those from radiosonde and/or wind profilers, mainly focused on the convective boundary-layer where the top of the boundary-layer is clearly defined.These studies should be related to as well.

- **Response to the Major comments**

a) P. 1 line 13: ‘Tubrulent activities were great inhibited during haze pollution’. This must be rephrased, as the evidence in the paper does not support this statement. It is unclear if the haze suppresses turbulence, or if weak turbulence results in poorer air quality. Indeed, whether the turbulence affects pollutants or pollutants affects turbulence, the evidence in this paper is not very clear. This sentence has been changed to “Turbulence and pollutant concentration are closely related during haze pollution”.

b) P. 2, line 8: ‘Please define all the acronyms, such as for URBAN, MIAGE, and SURF (similarly to how COST was defined and spelled out)’. The explanation of these abbreviations nouns is added in the text.

c) We have redrawn this figure to make it more standard. First, the topographic map of Beijing and its surrounding areas have been added, and some important details have been added to the map, and the scale has been added. As shown in the Figure1, we marked the mountains, bays and other topography around Beijing, and marked the observation data during this period. In figure(), the east of Beijing is the Bohai Bay, so generally the easterly wind will bring water vapor to the Beijing area, which can help to explain some characteristics.



(a) (b)

Figure 1 (a) Local topography of Beijing and its surrounding areas, (b) The location of the observation sites, red circle: IAP(Lidar, 325mtower, WPR), blue circle: WMO radiosonde observation station (ZBAA), cyan circle: pollution observation station (OSCS) about 2km in the north-east of the IAP. Beijing is a densely populated city with an area of about 396 square kilometers

d) Thank you very much for your comments, and we are very sorry for this carelessness. We have modified this mistake.

e) We have listed out six types of pollutants here and modified it in the paper.

f) We have adopted the comment by reviewer, and have moved the definition to the discussion of Table 1.

g) Thank you for your help with the modification explanation of the temperature and RH diurnal variation characteristics due to the heavy pollution. We have added the MODIS cloud figures in this paper, and further analysis of satellite cloud images during this period shows that this pollution process was indeed accompanied by fog, but due to the high concentration of pollutants, it was basically a mixed state of fog and haze. As shown in the figure3, pollution has formed in the south-central part of Hebei province on the 15 December 2016, and then spread over the whole Beijing-Tianjin-Hebei area on the 18 December. Stratiform clouds appeared in the surrounding areas of Beijing on the 21 December. Because of the high concentration of pollutants ($PM_{2.5}$ approaching 400 μg m^{-3}), haze was basically mixed in the Beijing area. During the day, pollutants scatter more solar radiation and the ground receives less solar radiation which leads to the suppression of diurnal variation of temperature and relative humidity observed on the ground.

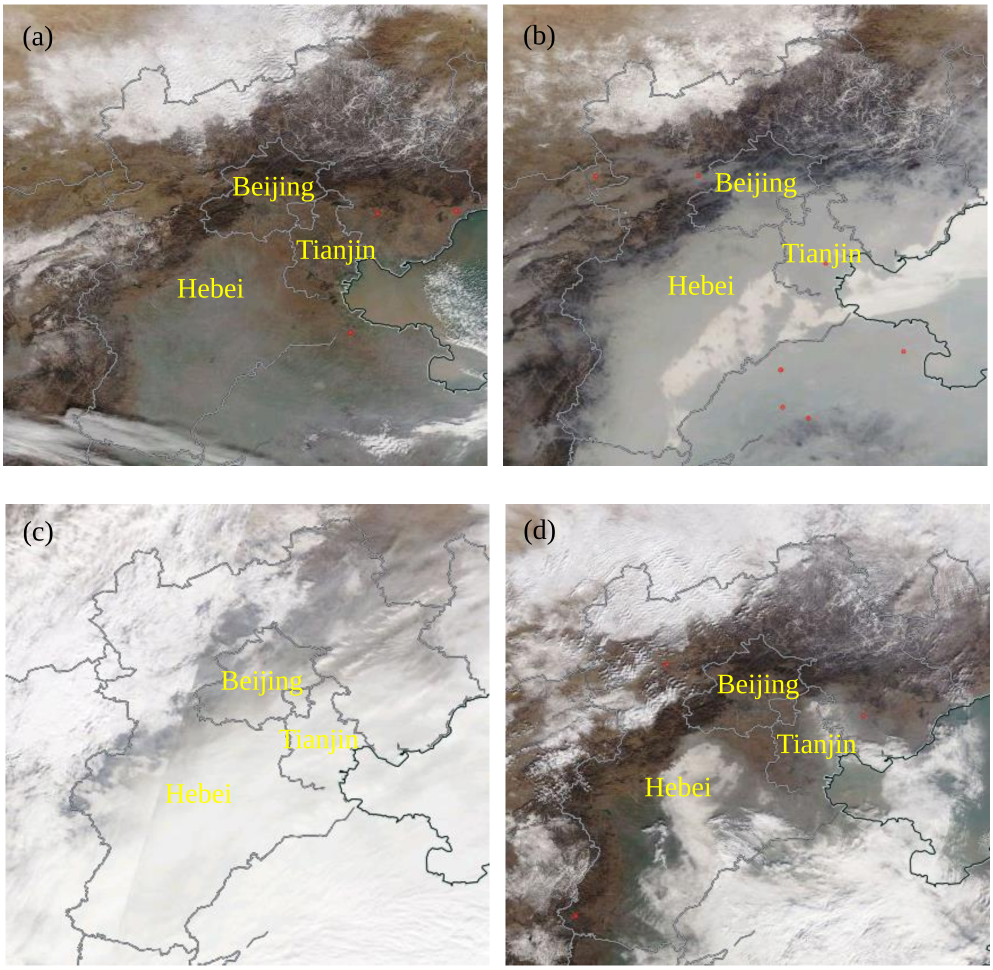


Figure 2. MODIS image of Beijing-Tian-Hebei area from 14-23 December 2016. (a)15 December 2016, (b)18 December 2016, (c)21 December 2016, (d)22 December 2016

h) Because relative humidity is dependent on temperature, so that this paper compared relative humidity on the condition of the same temperature. Ground observation data shows that the temperature at 00:00 17 December and 00:00 20 December were all -4℃, but the relative humidity at 00:00 20 December was 100%, far more than it at 00:00 17 December(74%).Since the temperature was the same, we infer that there was an increase in water vapor at 00:00 20 December.

Time	Temperature (℃)	RH (%)	Wind speed (m s-1)	Wind direction (degree)	Visibility (km)
2016/12/17 00:00	-4	74	2	350	4
2016/12/20 00:00	-4	100	1	11	0.2

i) Thank you for your comment. We have modified it to “Lidar observed boundary

layer heights”. In addition we have rewritten this paragraph as follows:
“ The most essential definition of the ABL height is the height at which the influence of the earth’s surface on the lower troposphere disappears. This influence applies not only to conventional meteorological elements but also to the turbulence quantities, or even more the substances in the atmosphere such as aerosols, water vapor or nonreactive tracer gases (Seibert et al., 2000). Various pollutants and water vapor in the ABL are much higher than that in the free atmosphere and therefore, there often exists obvious aerosol concentration gradient between the boundary layer and the free atmosphere. Extinction coefficient reflects the scattering degree of aerosol particles to laser in atmosphere, So the PBL height can also be estimated by extinction coefficient gradient. This paper used three popular methods, gradient method (Lidar_gra) (Flamant et al., 1997), standard deviation method (Lidar_std) (Hooper and Eloranta, 1986) and wavelet method (Lidar_wav) (Cohn and Angevine, 2000; Davis et al., 2000; Brooks, 2003) respectively to extract the boundary layer heights from the extinction coefficients. The ABL height determined by Lidar is represented by Hc.The Lidar_gra method is defined by the height of atmosphere where the gradient of the Lidar extinction coefficient reaches its steepest negative value in this article. The standard deviation of extinction coefficient reflects the degree of the dispersion of the Lidar echo signals at different heights. The top of the planetary boundary layer is the intersection of the air in the boundary layer and the free atmosphere, which leads to a strong signal change on the top of the boundary layer. This paper defines the height of the maximum standard deviation of signals as the ABL height. The Lidar_wav method can also be used to detect the abrupt change of signals, so we have used the Haar wavelet and taken the height in which wavelet coefficient is maximum as the height of the ABL height. The purpose of these methods is to find the abrupt change of extinction coefficient at the top of boundary layer, but also have their own limitations.

Generally, the atmospheric boundary layer can be divided into the daytime convective mixing layer and the night stable boundary layer. In the morning the well-mixed convective boundary layer (CBL) is growing and often reaches its maximum height in the early afternoon. In the afternoon the CBL gradually changes into a neutral boundary layer. Figure.3 shows the evolution of the ABL heights measured by Lidar, WPR and radiosonde respectively.”

j) We take the dilation of Haar wavelet as power of 2, i.e. 2^{-2}, 2^{-1}, 2^{1}, 2^{2} ……

k) Why is extension near the surface so small? Mainly because the blind zone of the radar has a thickness of several tens of meters, and the measurement in the near-surface layer is not reliable.

We have stated the time used in this paper is local station time in Section2: Observation sites, instruments and data “The time used in this paper is the local station time and the observational instruments and data are as follows ……”

l) thanks to the reviewer, “transformation zone” should be “transition zone”, and have rewritten this expression into “ the aerosol concentration was low and the extinction coefficient of Lidar displayed no obvious decrease from the ground to the upper height”

m) The reviewer did not give comments under this item

n) Thank you for the comments pointed out by the reviewers, we adopted this discussion in the text.

o) Thanks to the reviewer for pointing out our mistakes, we have modified the value of SBL top and top of the residual layer in the text.

p) Thank the reviewers for their comments. It is indeed our negligence. By giving topographic map(figure1), it can be seen that the east part of Beijing is the Bohai Bay. Generally, the easterly wind, especially the southeast wind, can bring abundant water vapor to Beijing.

q) P.9 line6: According to the reviewer's suggestion, here we have added 3 references: Svenningsson et al. (1992), Chuan (2003) and Pan et al. (2009).

r) We thanked and adopted the reviewers' comments and added a note to the text: “Until about 100m from the ground, another elevated temperature inversion layer appeared, while the top of this decooupled residual layer is at about 700m.”

s) P.9 line 11: Initially, because of the low vertical resolution of our radiosonde data. Based on the reviewer's opinion, we used the high vertical resolution radiosonde data and H_theta recalculated was about 380m.

t) We have redrew Figure4 and made sure that the tick marks on the right-most y-axis in panel c) are aligned with the other tick marks. The height is above the ground level, The first sounding data is basically from 30m.

u) P.9 line 13: we have rewritten this sentence and made it clear.

v) According to the reviewer's opinion, considering that this paper is only a case study of one air pollution process, there is not enough evidence to support the sentence “However, when the atmosphere was clean, the aerosol concentration was obviously reduced and the inversion layer was not so significant.”, so we remove this sentence in the text.

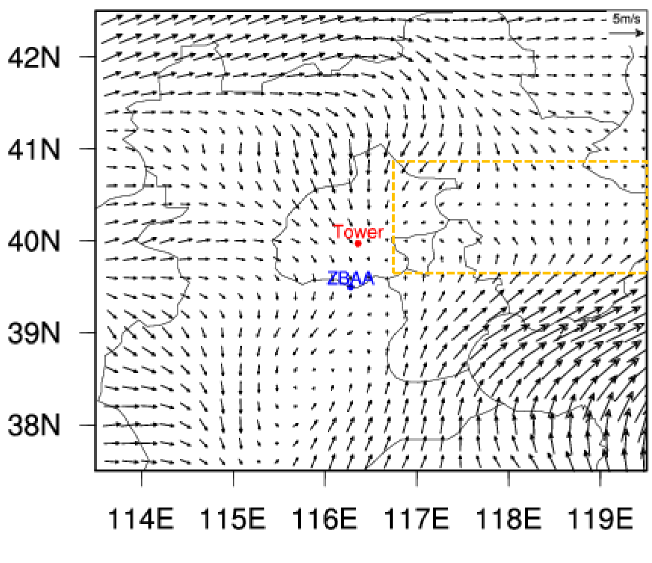
w) P.11 line4: The calculation of friction velocity in Fig. 6 is corrected. Thank you for your reminder. We revised the expression of friction velocity correctly.

x) Based on your comments, we have redrawn these figures to make the wind direction clear, and have deleted the description of w'^3 and added the plots from daytime comparison between clear and pollution day.

At daytime on 21 December 2016, the $PM_{2.5}$ concentration was about 400 μg m^{-3}, the wind speed was small, the turbulent kinetic energy TKE maintained zero value, and the potential temperature observed by the tower during the pollution period was basically neutral stratification. The sensible flux was positive, but The maximum value does not exceed 0.05 Kms^{-1}. At noon on 22 December, when the weather was better, the wind speed was obviously higher. Turbulence kinetic energy still had a maximum at 47m. The influence of urban canopy was greater below 47m. Unlike the polluted day, the sensible heat flux was larger at this time, and the lower layer reached 0.1K m s^{-1}. The tower observation data clearly show that sensible heat flux decreased significant at daytime during haze episode because of the more scattering of solar radiation by particles.

y) Thanks to the reviewer for his valuable comments, wo use the ABL height “heightened slightly”, and added a sentence in the text: “Since the data in this paper is only one case of heavy pollution process, the calculated small differences meybe not statistically different between categories, except compared with ‘good’ air quality.”

z) P.15 line6: Thank the reviewers for their comments. At first, we analyzed the 10m wind field data from FNL reanalysis data. The convergence zone of northeast and southeast winds in the east part of Beijing is shown in the yellow dotted line frame. Later, the 10m wind field data map was not added due to the use of ground observation data and wind profile radar. So, we revised the relevant expression in the paper.



aa) Based on your comment, we have rewritten this sentence to make it clear.

bb) Yes, our high-resolution 7-layer turbulence instrument observation shows that the sensible heat flux on the ground was positive at night during the pollution period. First of all, at night, due to the presence of pollutants and more vapor, the long-wave radiation cooling effect from the ground was inhibited. Furthermore, in a city with large population, such as Beijing, the building heat storage and anthropogenic heat of the city also made it possible that the surface sensible heat flux appeared positive at night.

- **Response to the Editorial corrections**

a) We have modified this paper heavily based on your comments and many details have been rewritten.

b) P.3, line12: We have removed “49m” according the opinion

c) P.3 line 13: Our original intention is that this tower was established in 1979 and has been revised in the paper.