Response to comments by referee 1

We would like to thank you for your comments and helpful suggestions. We revised our manuscript according to these comments and suggestions.

Specific comments:

The paper deals with the determination of the MLH over Beijing during more than 3 years from ceilometer measurements and its correlation with pollution classes (clear days, slight, light, medium and heavy haze). Most of the paper is devoted to a meteorologically based discussion why the correlations are as they are. This is certainly a positive feature of the paper as often just statements are given without any critical scrutiny. The authors consider a variety of parameters derived from different measurements (e.g., meteorological tower), so the discussion is quite elaborated. However, the readability is often very difficult because a separation of very long sections into different paragraphs is missing, information is only put into words where a table would be helpful, and often it is difficult to follow because the expressions are not clear but unnecessarily complex or in bad English. Consequently, it is sometimes hard to check the validity of the authors' conclusions.

Thus, I strongly recommend to make the text more concise, to clarify statements, to delete redundancies and to improve its consistency. And ask a native speaker or a professional office for improving the language. If this is provided (implying major revisions) the paper can be foreseen for publication. A few suggestions and technical comments (in chronological order, not ordered in terms of importance) for improvements are made below, but it is not possible to review/amend every single expression or sentence.

Responses：

Thank you for your kindly comments and suggestions. We are sorry for the bad presentation in our manuscript. In the revised version of our manuscript, several long paragraphs were separated into some small parts or rephrased concisely. We deleted some redundancies and adjusted the sequences of the sentences to make the manuscript more fluent. Afterwards, a native speaker polished our manuscript to make the language better for the reader.

Specific comments：

Question 1

(28251,7):

"The height to which the atmospheric mixing layer extends is the mixing layer height (MLH)". This sentence is more or less trivial and does not help to explain

Response 1

Thank you for your suggestions. We have deleted this sentence.

Question 2

• (28251,11):

"gradients" →"concentration"
Response 2
Thank you for your suggestions. We have fixed it.

Question 3
• (28251,22):
"1000 m": is this really true, this value seems to be extremely large
Response 3
Thank you for your suggestion. We are sorry for the misunderstanding. We have deleted “to 1000m” in the revised manuscript.

Question 4
• (28251,23):
"...even the hourly observations...": which data set is meant here? Or should it be something like "even if hourly observations would be available they would not provide a sufficient temporal resolution"? Please clarify.
Response 4
Thank you for your suggestion. We have revised it as follows.
When solar radiation increases in the morning, the growth rate of the MLH reaches hundreds of metres per hour and convection develops quickly; even if hourly observations were available, they could not provide sufficient temporal resolution of MLH evolution (Seibert et al., 2000).

Question 5
• (28251,24):
I would not mention airborne measurements because they cannot provide routine measurements. They can only be used for case studies.
Response 5
Thank you for your suggestion. Absolutely airborne measurement is not a routine measurement for the mixing layer height. However, as for the introduction, I think we should show the reader all the measurements to observe the mixing layer height.

Question 6
(28252,4):
"light intensity detection and ranging": delete "intensity"
Response 6
Thank you for your suggestion. We have deleted all the acronyms because the names of the measurements are well known.

Question 7
• (28252,5):
for consistency reasons replace "Doppler radar" by "radar" and explain the acronym. Or do not explain all acronyms (sodar, lidar and radar are well known)!
Response 7

Thank you for your suggestion. We have deleted all the acronyms because the names of the measurements are well known.

Question 8
• (28252,7):
delete "variations in"
Response 8
Thank you for your suggestion. We have fixed it.

Question 9
• (28252,14):
"visible light band": many lidars operate in the UV and NIR, i.e. not visible.
Response 9
Thank you for your suggestion. We have deleted this sentence.

Question 10
• (28252, 17):
"Wind radar is easily interfered by clouds, and the observational height is limited under cloudy conditions." This sentence does not fit here (previous and next sentence is on lidar). By the way: the lidar range is also limited in the presence of clouds.
Response 10
Thank you for your suggestion. We have adjusted the sequence of the sentences. By the way, we have revised the sentence about the wind rader as follows.
The lowest detection height of wind radar is normally above 200 m, and the vertical resolution is limited to 50-250 m, factors that make the interpretation of wind radar data not always straightforward (Seibert et al., 2000).

Question 11
• (28252,24):
"...the eye-safe ceilometers..." This is a feature of all ceilometers, not only of Vaisala-ceilometers. This sentence must be more general, you can cite the AMT paper (Earlinet special issue) on the benefit of ceilometers.
Rersponse 11
Thank you for your suggestion. We have deleted “Vaisala”. We really thank you for your suggestion of the AMT paper, and we have read these carefully and added some references here and elsewhere.

Question 12
• (28253,11):
"...and the atmospheric stratification is stable..." Is this in contrast to the findings on (28255,24) where the authors find "only" 540 out of 800 cases to be stable?
Response 12
Because we acquired a lot of data during 8:00 and 20:00 LT but less data during 14:00 LT, the number of samples in stable condition is much more than that in convective

conditions. In this section, the atmospheric stratification is stable during heavy pollution episodes. In order to clarify this sentence, we have revised as follows.
Previous studies of Beijing have indicated that visibility declines dramatically when the concentration of particles increases; the weather conditions typically include high relative humidity (RH), stable atmospheric stratification, and low wind speed (WS) with a southern flow (Ding et al., 2005; Liu et al., 2014; Zhang et al., 2015).

Question 13
(28253,22):
The citations "He and Mao, 2005; Yang et al., 2005;..." should be moved to line 20: after "during heavy pollution periods". At the present position it might be confusing.
Response 13
Thank you for your suggestion. We have fixed it.

Response 14
• (28254,1):
"variation characteristics" → "temporal development"
Response 14
Thank you for your suggestion. We have fixed it.

Question 15
• (28254,1):
"3 years"? In the previous sentence it was "3 years and 5 months" (whereas "July of 2009 to December of 2012" is 3 years and 6 months)
Response 15
Exactly, the observation started from 15th July 2009 and ended on 16th December 2012. If we calculated the observation period using the number of days, it should be 3 years and 5 months. However, we think you are right. We should use 3 years and 6 months in order to eliminate the misunderstanding.

Question 16
• (28254,19):
39.97: Give all geographical coordinates with 3 or 4 decimal places
Response 16
Thank you for your suggestion. We have fixed it.

Question 17
• (28254,22):
"...attenuated backscatter coefficient profile of atmospheric aerosols..." This is not exactly true as water vapor absorption occurs (there are similar expressions elsewhere in the paper).
Response 17
Thank you for your suggestion. The attenuated backscattering coefficient is not the

same as aerosol concentrations, which is influenced by the water vapor absorption (Wiegner et al., 2014). Therefore, we have revised this mistake in proper words in the manuscript according to your suggestions. The revisions mainly include removing the word “aerosol” and adding some descriptions about the observed deviations due to water vapor absorption.

Question 18
• (28255,5):
How is radiation measured by "ultrasonic anemometers"? Use clear descriptions!
Response 18
I am sorry for our mistakes. I have added some sentences to clarify the mistakes. Please see as follows.
The thermodynamic parameters (sensible heat, latent heat, friction velocity, etc.) and the total (285-2800 nm) and net (0.2-100 μm) radiation during the same period were observed using ultrasonic anemometers (CSAT3, Campbell Scientific, USA), a pyranometer (CM11, Kipp & Zonen, Netherlands) and a net radiometer (NR Lite2, Kipp & Zonen), respectively. All of these data were obtained on the meteorological tower at a height of 280 m and processed with a resolution of 30 min. A detailed description is provided by Hu et al. (2012) and Song and Wang (2012).

Question 19
• (28255,8):
PM2.5 and PM10 were measured at the ground?
Response 19
Yes, the observations of particles were setup on the ground. We have added some descriptions about the observations as follows.
To identify the sand-dust crossing, the ratio of $PM_{2.5}$ and PM_{10} was used as an index. If there was no sand-dust crossing, the ratio of $PM_{2.5}$ to PM_{10} might almost exceed 50% (Liu et al., 2014). A sudden decrease in the ratio to 30 % or lower and PM_{10} concentration higher than 500 μg m^{-3} usually indicate a sand-dust crossing. The ground observations of $PM_{2.5}$ and PM_{10} during the same period were made by the ambient particulate monitor (RP1400a, Thermo Fisher Scientific, USA). The data were acquired at a time resolution of 5 min and processed with a resolution of 60 min. A detailed description is provided by Liu et al. (2014).

Question 20
• (28255,26):
"...visibility at station..." How is this measured? How accurate are these numbers? It would help to have this information as it is of importance for subsequent sections of the paper.
Response 20
Thank you for your suggestion. The visibility was measured in ZBAA site using the

visibility sensor (PWD12, Vaisala, Finland) with an accuracy of ±10%.

Question 21
(28255,27):
"...of Wyoming Engineering University (http://weather.uwyo.edu)." Give a more precise URL and name of the institution. Maybe it can be added to the acknowledgements.
Response 21
Thank you for your suggestion. We have revised as follows.
Visibility at station ZBAA, which was obtained from the Department of Atmospheric Science, College of Engineering, University of Wyoming (http://weather.uwyo.edu/surface/meteorogram/), was measured by a visibility sensor (PWD12, Vaisala, Finland) with an accuracy of ±10%.

Question 22
• (28256,3):
"is relatively long and" can be deleted.
Response 22
Thank you for your suggestion. We have fixed it.

Question 23
• (28256,7):
"...backscatter coefficient profile of atmospheric particles". delete: "of atmospheric particles"
Response 23
Thank you for your suggestion. We have fixed it.

Question 24
• (28256,9):
"...we use the gradient method": It should be outlined whether the Vaisala firmware is used or own retrievals have been developed. Especially in the latter case the retrieval should be explained in 2–3 sentences. What is the lowermost level, where the MLH can be detected? Is an overlap correction applied?
Response 24
Thank you for your suggestion. We have added some explanations according to your suggestion as follows.
Time averaging is dependent on the current signal noise; the intervals vary from 14 to 52 min for the CL31. Height averaging intervals range from 80 m at ground level to 360 m at 1600 m height and beyond. Additional features of this algorithm, which is used in the Vaisala software product BL-VIEW, are cloud and precipitation filtering and outlier removal.

Question 25
• (28256,13):

"...spatial and temporal averaging...": give typical values.
Response 25
Thank you for your suggestion. We have revised it, please see the response 24.

Question 26
• (28256,19):
"convective state": delete "state"
Response 26
Thank you for your suggestion. We have fixed it.

Question 27
• (28256,21):
"variations" → "profiles"
Response 27
Thank you for your suggestion. We have fixed it.

Question 28
• (28257,8):
"and the results were evaluated." I believe that can be deleted too.
Response 28
Thank you for your suggestion. We have fixed it.

Question 29
(28257,11):
delete "of atmospheric particles"
Response 29
Thank you for your suggestion. We have fixed it.

Question 30
• (28257,3): Section 3.1
If a "verification" shall be provided it must be defined what is considered as "truth". It seems that the radio soundings are used as reference. This should be clearly stated. Another important aspect is that it is not clear what the "error" of the ceilometer data is (backscatter profile? MLH-determination?, relative error? Absolute error?...). This must be clarified at different places of the manuscript.
Response 30
Thank you for your suggestion. We used radiosondes as reference as you said. The error introduced in the manuscript is absolute error, and we have clarified it in the revised manuscript. We have revised the manuscript according to your suggestion as follows.
Previous studies with ceilometers did not resolve issues concerning the applicability of ceilometers in Chinese areas with high aerosol concentrations. According to the methods described in Sect. 2.1.2, 260 and 540 effective observation samples were obtained for the stable and convective states,

respectively. The MLH data acquired by meteorological radiosondes and by ceilometer were compared for the two types of weather conditions (Fig. 2). Using the MLH calculated from the radiosondes as a reference, the results showed that the MLH observed by the ceilometer was overestimated or underestimated in a portion of the samples.

Question 31
• (28257,10):
The whole sentence starting with "Because the ceilometer determines..." is not clear. What is the measurement error? How is it determined? This has to be explained in Section 2.2.1. Give a reason why the error increases when the concentration is low?
Response 31
Thank you for your suggestion. We have revised it as follows.
Because the ceilometer determines the MLH by measuring the attenuated backscatter profile, if the concentration of atmospheric particles is relatively low, it will be difficult to determine the MLH based on a sudden change in the backscatter profile, and use of this method will lead to a higher absolute error (AE) of the measured MLH (Eresmaa et al., 2006; Munoz and Undurraga, 2010). When taking the visibility into account, we found that the underestimations of the observed MLH always occurred when visibility was good. However, there were still a number of samples that had low AE under conditions of good visibility (Fig. 2). Consequently, clear days with good visibility are not the main reason for underestimation of the observed MLH.

Question 32
• (28257,14):
"An analysis...". The sentence is not clear at all, must be re-phrased. If "visibility" is introduced here: where does this information comes from? What is "high" and "low" visibility? How is it measured? What is its accuracy?
Response 32
Thank you for your suggestion. We have rephrased this paragraph. Please refer to response 31.
As for the visibility, please see the response 20.

Question 33
• (28257,19):
"...predict underestimations". See remark to (28257,3). What is the reference?
Response 33
Thank you for your suggestion. We have rephrased this paragraph, please see the response 31.

Question 34
• (28257,22):
A bi-level structure (two layers are meant?) could be better seen if the attenuated

backscatter profile is added to Fig. 2b.

Response 34

Thank you for your suggestion. A bi-level structure is meant two layers, but the two layers structure can only be observed by the radiosondes. We cannot acquire the two layers structure because of the sand-dust crossing. This is the main reason that the overestimations of the MLH during sand-dust crossing. In order to clarify this question, we used the calculated backscatter gradients to explain this overestimation, and rewrite this paragraph as follows.

With respect to overestimations of the ceilometer results, we may take the meteorological radiosonde at 14:00 LT on 29 December 2009 as an example (Fig. 5). The MLH is determined at approximately 1100 m, where the virtual potential temperature and the WS begin to increase; the ozone concentration is transported from the background area, where ozone is present at approximately 40 ppbv. However, the ceilometer recorded a higher MLH at approximately 1600 m, where there was a sudden change in the backscatter gradient. When we measured the $PM_{2.5}/PM_{10}$ ratio at this moment, we found that the ratio was only 0.15, a clear characteristic of a sand-dust crossing. Due to the large number of dust particles, the aerosol concentrations became uniform below 1600 m. This led to a sudden change in the backscattering gradient at 1600 m and made it difficult to identify the real MLH at 1100 m; thus, an erroneously high MLH was determined. This result shows that sand-dust crossing is the main reason for the overestimations (Figs. 2 and 5).

Question 35

• (28258,26):

What is the "variation rate"?

Response 35

Thank you for your suggestion. We have deleted “the variation rate”.

Question 36

• (28258,28):

It is not clear to which data points in Fig.2 the PM2.5/PM10 labels belong to. This must be clear, maybe by giving only the numbers without "PM2.5/PM10".

Response 36

Thank you for your suggestion. We have fixed it in Figure 2.

Question 37

• (28259,5ff):

Do I understand correctly what has been done? The authors identify cases, where the MLH from the ceilometer strongly differs from the radio sounding (under- and overestimates). These cases (and as a consequence specific meteorological conditions as e.g. cold air masses and dust occurrence) are excluded from the further investigation. An alternative approach would have been to try to correct the MLH from the ceilometer to consider an unbiased data set of meteorological situations. I recommend to revise the whole paragraph to make absolutely clear what have been done.

Response 37

Thank you for your suggestion. You are right. We have revised this paragraph as follows.

For underestimations, the meteorological data were used to eliminate the periods when cold air passed with a sudden change in temperature and WS. For overestimations, we referred to the sand-dust weather almanac to identify the sand-dust days (CMA, 2012, 2013, 2014, 2015). If there was no sand-dust crossing, the ratio of $PM_{2.5}$ to PM_{10} might almost exceed 50% (Liu et al., 2014). A sudden decrease in the ratio to 30% or lower usually indicates a sand-dust crossing. Using this principal, the exact times of sand-dust starting and ending were determined as the times at which the ratio of $PM_{2.5}$ to PM_{10} suddenly decreased or increased, respectively. Finally, the data obtained during the sand-dust periods were eliminated. After the screening process, the post-elimination ceilometer data and meteorological radiosondes are strongly correlated, with a correlation coefficient greater than 0.9, demonstrating the effectiveness of the elimination method (Fig. 6). Consequently, the elimination results are good. This method replaces the time-consuming method of filtering the data manually and is of great practical value for future measurements of MLH with ceilometers.

Question 38

• (28259,10):

"sand-dust weather almanac": What is this?

Response 38

The sand-dust weather almanac is like a statistic yearbook published every year. The main contents are the records of the sand-dust, which includes the time period, area and intensity of the sand-dust. In order to clarify this problem, we added the references in the revised manuscript.

Question 39

• (28259,15):

delete "and manipulability" (I don't know, what is meant)

Response 39

Thank you for your suggestion. We have fixed it.

Question 40

• (28259,22):

What is meant by "high-quality..."?

Response 40

Because of the problems of the communication between CL31 and the data receiver, the data of CL31 was always interrupted during July to October 2009. The data from December 2009 to November 2012 were continuously observed. Therefore, the data during this period were selected to do the analysis.

Question 41
• (28259,24 and 26):
"effectiveness of the data" → "availability..."
Response 41
Thank you for your suggestion. We have fixed it.

Question 42
• (28259,26 – 28260,5):
Are these correlations an independent result or a consequence of the filtering process described in the previous section?
Response 42
The results were a consequence of the filtering process described in the previous section.

Question 43
• (28260,8):
"The monthly average maximum for the daily minimum MLH": is this the "maximum of the monthly average of the daily minimum"?
Response 43
Thank you for your suggestion. We have fixed it.

Question 44
• (28260,16):
What are "platform periods"?
Response 44
Thank you for your suggestion. We have added some explanations about the platform and transition periods as follows.
As shown in Fig. 7b, two platform periods (from March to August and from October to January) and two transitional periods (February and September) occur for the monthly average MLH. The MLH is similar from October to January at approximately 500 m, and it is similar from March to August at approximately 700 m. February and September are the two transitional months and have values of approximately 600 m.

Question 45
• (28260,17):
Here, MLH are rounded and numbers like 600 m, 700 m are given. This does not fit to numbers like 351 m given previously; later (28264) heights are even given with one decimal place (this is nonsense with respect to any meteorological application). Please give all numbers in a consistent way. It would be worthwhile to add the variability of each height (each number is an average over almost 100 values [3 years, 31 days]).

What about the inter-annual change of the monthly means?
Response 45
Thank you for your suggestion. We are sorry for the misunderstandings. The numbers like 600 and 700m are not exact numbers like the other numbers. We just want to show the reader the MLH are consistent from March to August. In order to eliminate the misunderstanding, we have added "approximately" before these numbers.
Thank you for your suggestion about the variability of each MLH. We have added the variability in the revised manuscript.
From the figure as follows, you can see the inter-annual change of the monthly mean. It is very similar in different years, and no inter-annual trend can be found. Therefore, we used the averaged seasonal variation to do the analysis.

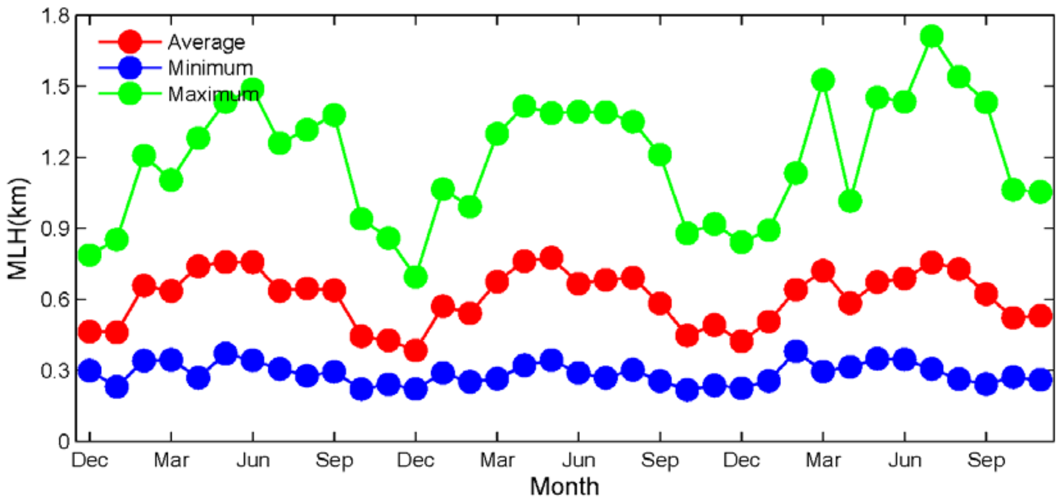


Figure S2 Monthly variations of MLH from December 2009 to November 2012 in Beijing.

Question 46
• (28260,26):
The "total radiation flux" should be defined: is total referring to the spectral range?
Response 46
Thank you for your suggestion. The total radiation flux was observed by CM11 (Kipp & zonen, Delft, Netherlands). The spectral range was 285-2800nm. We have added some description in the methodology section about this.

Question 47
• (28260,29):
"has determined seasonal variations in the MLH, because more data were eliminated for winter and spring,..."'. If this is true, the evaluation is somewhat questionable because the results should not depend on the sampling but on meteorological conditions. Please comment on this.
Question 48
• (28261,2):
"... winter and spring seasons are likely underestimated." This conclusion should be

explained in a convincing way.
Question 49
• (28261,3):
"To avoid the influence of data elimination on the study, ...". This is certainly a good idea (see comment on 28260,29), but it is not clear how the determination of the correlation with the sensible heat helps. By the way: if the sensible heat is determined at several heights, it should be clarified here, which heights are meant.
Response 47, 48 and 49
I am sorry for the misunderstanding. We have revised this paragraph as follows.
Other researchers have suggested that the seasonal variation in MLH may be related to radiation flux (Kamp and McKendry, 2010; Munoz and Undurraga, 2010), but our study was entirely consistent. As shown in Fig. 7b, although spring had a significantly higher total radiation flux than summer, the MLH in spring is equal to that in summer. This is because more data were eliminated for winter and spring, especially for weather with dry wind and relatively high MLH. Thus, using the monthly mean of MLH is not a good method by which to analyse the reasons for MLH variations.
To gain a better understanding of the reasons for the MLH variations, we use the daily mean instead of the monthly mean to do the analysis. As the simple framework in which we can analyse the MLH variations in Beijing, we consider the thermodynamic model of the mixing layer growth (Stull, 1988), as follows:

$$\frac{\partial z_i}{\partial t} = \frac{\overline{w'\theta'_s} - \overline{w'\theta'_{z_i}}}{\gamma z_i} \qquad (6)$$

where z_i is the MLH (m), t is the time (s), θ_s is the virtual potential temperature near the ground (K), θ_z is the virtual potential temperature in the top of the mixing layer (K), and γ is the lapse rate of the virtual potential temperature (K m^{-1}). Suppose the heat from the ground is the only way to warm the mixing layer and the heat flux at height z_i is zero, then the MLH is related to $\overline{w'\theta'_s}$. Considering that Q_H is defined as equation (1), MLH is correspondingly related to Q_H. Therefore, the relationship between daily changes in the Q_H at 280 m and MLH was analysed. The results showed that the average Q_H and MLH from 12:00 to 17:00 LT were well correlated, with a correlation coefficient of 0.65. Because net radiation (Q*) should be balanced by the Q_H, Q_E, and soil heat flux (Q_G) given as follows (Stull, 1988):

$$Q^* = Q_H + Q_{HE} + Q_G \qquad (7)$$

the strong correlation between the Q_H and MLH proves the dominant role of radiation in the variation of MLH (Fig.~8). This proves the dominant role of radiation in variation of MLH (Fig. 8).

Question 50
• (28261,16)
Why are only spring and summer discussed. What about the other seasons?
Response 50
The daily MLH range is 728, 828, 562, and 407m for spring, summer, autumn and

winter, respectively. The relatively low ranges in autumn and winter have obvious relationship with the low radiation flux. But it should be noted that summer has the lower radiation with a larger daily range than spring. Therefore, our study will emphasize on the reasons for the differences of the daily MLH ranges in summer and spring. By the way, we added the diurnal variations of winter and autumn in the supplement materials.

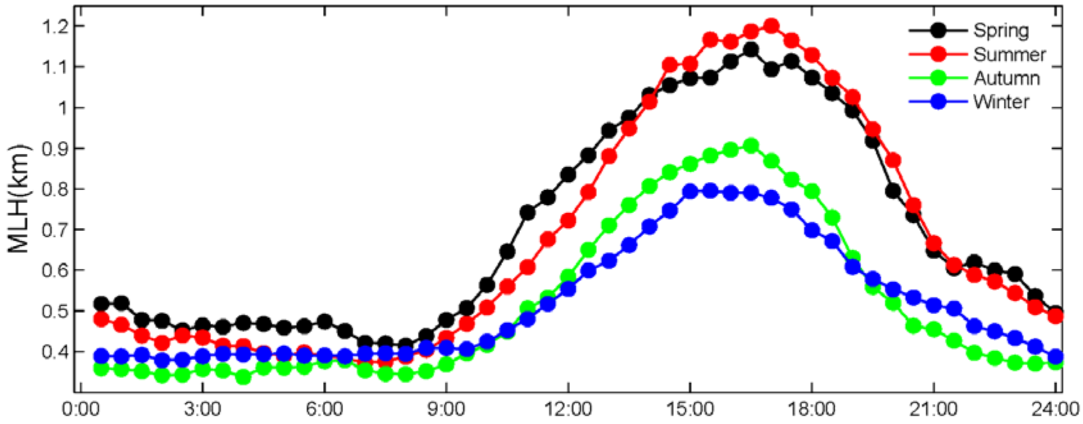


Figure 2 Diurnal variations of MLH in different seasons in Beijing

Question 51

• (28261,21)

"..only reaches 102 m/h..": is the difference to 114 m/h really significant? It seems to be within the error margins. Please discuss briefly.

Response 51

Thank you for your suggestion. The daily MLH range is 728, 828, 562, and 407m for spring, summer, autumn and winter, respectively. It is a significant difference between spring and summer for the daily range. After calculating the growth rate of MLH for each day, we do the T tests between the growth rate in spring and summer and find that the differences in the growth rates are significant ($P<0.05$).

Question 52

• (28261,22)

Here, the findings are discussed in terms of time (hours), previously four stages are introduced. It seems to be more consistent to use these terms here again.

Response 52

Thank you for your suggestion. Although the four stages are the same with that introduced before, the mountain-valley winds intersect the fast development stage into two parts. From 9:00 to 12:00 LT, the mountainous winds dominate Beijing, while the valley winds dominate Beijing after 12:00 LT. In order to interpret the influence of the mountain-plain winds, more precise stages should be pull-in.

Question 53

• (28261, 24):

"...convex variation characteristics...": there should be a better description, the present

text is not clear.
Question 54
• (28263, 5–6):
".. the air space from near surface to 300 m...": should be re-phrased, maybe just "troposphere below 300 m".
Question 55
• (28263, 18):
"...concave-down curvature...": there should be a better description.
Response 53, 54 and 55
Thank you for your suggestion. As shown in Fig. 9c, the mountainous winds are emerged at 02:00 LT during night near the ground, and then the influence of mountainous winds extend in the vertical direction. At 08:00 LT, troposphere below 300m is dominated by the mountainous winds.
In order to make this section clearer, we revised this section thoroughly as follows.
Although the daily average MLH is similar in spring and summer, the diurnal cycle exhibits obvious differences (Fig. 9a). At night-time in spring, the MLH is high and almost constant, whereas at night-time in summer, the MLH shows a gradual decreasing trend. After sunrise and before 12:00 LT, the rate of increase in the MLH is relatively high in spring, reaching 114 m/h, whereas the rate in summer is relatively low, 102 m/h. Between 12:00 and 14:00 LT in spring, the rate of increase in the MLH is 119 m/h, whereas in summer the rate of increase is significantly enhanced, reaching 165 m/h. These changes reflect the convex and concave characteristics during the development stage of the MLH in spring and summer, respectively.
According to the description in Sect. 3.2, variations in the MLH should exhibit a good linear relationship with the amount of radiation. Thus, the higher daily MLH range with lower radiation in summer is difficult to explain, suggesting that there are other reasons for this phenomenon. The development of MLH is mainly related to the turbulent energy and the production of the turbulent energy is closely related to two components: the heat flux caused by radiation ($\frac{g}{\theta_v}\overline{w'\theta_v'}$) and the momentum flux generated by wind shear ($-\overline{u'w'}\frac{\partial\bar{u}}{\partial z}$) (Stull, 1988). Because the seasonal variation in heat flux is difficult to explain according to the aforementioned criteria, we analysed the seasonal variations of the horizontal wind vector.
To avoid the impact of near-surface buildings on the wind measurements, we selected the wind vector at 100 m on the Beijing tower. Figure 9b shows that there is obvious seasonal variation of the wind vector in Beijing. Winter is dominated by a northwest wind, and spring typically exhibits a northwest wind in the morning and a southwest wind in the afternoon. What matters most is the alternation between the mountainous winds that begin at 03:00 LT at night and the plain winds at 12:00 LT in the afternoon that begins to occur in summer. In September, the circulation of mountainous plain winds starts to weaken, and this circulation disappears in November.

Beijing is affected by the Siberian High in winter and spring; at these times, a strong prevailing northwest wind with dry air mass always occurs. However, the northward lift and westward intrusion of a subtropical high in summer causes the southern moist air mass with small WS to arrive and dominate. Because Beijing is located west of the Taihang Mountains and south of the Yanshan Mountains (Fig. 1), without the passage of large- or medium-scale meteorological systems in the summer, the local mountainous plain winds are superimposed on the southern air flow, and these two systems jointly affect the meteorological characteristics of the North China Plain.

With the surface cooling that occurs at night in summer, the cold air near the surface forms a shallow down-sliding flow from the northeast to the southwest; this is called the downslope wind or cold drainage flow. The cold air flows into the plain and accumulates in a cold pool, increasing the thickness of the inversion layer, and the thickness of the mixing layer gradually decreases. After sunrise, the radiation increases; the MLH increases rapidly under the impact of thermal buoyancy lift, and this type of cold drainage flow is maintained until 12:00 LT. After 12:00 LT, the plain wind from the southwest gradually dominates and is maintained until approximately 03:00 LT in the morning of the next day. According to Fig. 9c, from 03:00 LT to 12:00 LT in summer, the troposphere below 300 m gradually cools from low to high due to the cold drainage flow in the northeast direction, and the MLH exhibits a gradually decreasing trend from 03:00 to 06:00 LT. However, this trend does not occur in spring (Fig. 9a). Similarly, between 09:00 and 12:00 LT in summer, the cold drainage flow suppresses the development of the MLH with a low growth rate; in spring, without this inhibitory effect, the growth rate of the MLH is high. After 12:00 LT in summer, the southerly plain wind causes the growth rate to increase between 12:00 and 14:00 LT.

In summary, the mountainous wind in summer causes the mixing layer to decline gradually at night; this also suppresses the development of the mixing layer before noon, and the prevalence of plain winds after noon causes the mixing layer to increase rapidly. Therefore, compared to spring, the regional circulation in summer produces a concave-down variation in the rapid development stage of the MLH in summer.

Question 56
• (28265, Eq. 1):
Every symbol must be defined.
Response 56
Thank you for your suggestion. We have added other equations and add the explanations of each symbol in the revised manuscript.

Question 57
• (28264-28265):
All numbers listed here should be summarized in a table for the different visibility

classes. This table should also include the definition of the classes (name, v-range). Then, it would be much easier to follow the arguments of the authors because the text is better to read. As a consequence the whole text can be rephrased to be absolutely concise. Don't use MLH with decimal places! Check if there is no confusion between "slight haze" and "light haze".

Response 57

Thank you for your suggestion. We have summarized a table to make this section clear and concise. Slight haze is a condition better than light haze, the corresponding visibility are 5km≤Vis<10km and 3km≤Vis<5km for slight and light haze, respectively (CMA, 2010).

Table 2 Statistics of thermos/dynamic parameters according to different visibility

	Clear day Vis≥10km	Slight haze 5km≤Vis<10km	Light haze 3km≤Vis<5km	Medium haze 2km≤Vis<3km	Heavy haze Vis<2km
WS(m/s)	3.8	2.5	2.1	2.0	1.8
RH(%)	43.3	63.1	73.4	79.6	86.4
MLH(m)	664	671	586	430	320
Q^*(W/m^2)	77.6	74.6	63.9	53.6	32.8
Q_E(W/m^2)	18.7	19.9	21.5	18.8	19.8
Q_H(W/m^2)	20.4	19.7	15.2	12.8	7.8
$\bar{e}$(m^2/s^2)	0.99	0.64	0.56	0.52	0.46
u_*(m/s)	0.45	0.32	0.28	0.26	0.23
BT(m^2/s^3)	0.67	0.64	0.49	0.39	0.24
ST(m^2/s^3)	1.02	0.66	0.37	0.26	0.23

WS: wind speed; RH: relative humidity; Q^*: net radiation; Q_E: latent heat; Q_H: sensible heat; $\bar{e}$: TKE per unit mass; u_*: friction velocity; BT: buoyancy term of the TKE; ST: shear term of the TKE.

We have also rewritten this paragraph as follows.

To analyse variations in the thermal dynamic parameters inside atmospheric mixing layers under different degrees of pollution, visibility was used as a reference. WS, RH, Q_H, Q_E, u_*, and TKE at 280 m were obtained under different visibility conditions (Tab. 2 and Fig. 10). Clear days were defined as days when the visibility is ≥10 km, and slight, light, medium, and heavy haze pollution corresponded with 5 km≤visibility<10 km, 3≤visibility<5 km, 2 km≤visibility<3 km and visibility<2 km, respectively (CMA, 2010). On clear days with atmospheric visibility ≥10 km, RH was the lowest, with an average of 43.3%, and Q_H, u_* and TKE were the highest, averaging 20.4 W m^{-2}, 0.45 m s^{-1}, and 0.99 m^2 s^{-2}, respectively. The MLH was 664 m on average, and the maximum in the afternoon reached 1145 m. Compared with clear days, during light haze pollution the RH significantly increased to 63.1%, and the u_* and TKE significantly declined to 0.32 m s^{-1} and 0.64 m^2 s^{-2}, respectively, with a reduction of approximately 30%; the Q_H and MLH were 19.7 W m^{-2} and 671 m, respectively, without any significant changes. With the pollution aggravated, the RH continued to increase; during light, medium, and heavy haze it reached 73.4,

79.6, and 86.4%, respectively. The u_* and the TKE remained almost constant, and the Q_H and the MLH showed a declining trend. The measured values under light, medium, and heavy haze were as follows: u_* was 0.28, 0.26, and 0.23 m s^{-1}, respectively; TKE was 0.56, 0.52, and 0.46 m^2 s^{-2}, respectively; Q_H was 15.2, 12.8, and 7.8 W m^{-2}, respectively; and the MLH was 586, 430, and 320 m, respectively.

Question 58
• (28266, 25):
"...exhibit a conflicted state." That is meant?
Response 58
Thank you for your suggestion. We have revised it as follows.
However, although the atmospheric diffusion capability is much better in spring and summer and the VC in summer can be 1.7 times higher than in autumn and winter, the visibility is lowest (~9 km) and the PM2.5 concentration is highest (~85 μg m^{-3}) in summer (Fig. 12a). By focusing on visibility≥10 km and visibility<10 km separately, we find that the frequency of haze occurrence is highest (up to 73%) in summer, whereas it is approximately 40% in other seasons (Fig. 12b). Therefore, strong diffusion capability cannot explain the occurrence of heavy pollution in summer.

Question 59
• (28267, 17):
"Previous studies..." Give citations!
Response 59
Thank you for your suggestion. We have fixed it.

Question 60
• (28268, 14):
"...and the critical threshold is 80 %." Where is this statement coming from? Is it a definition/estimate of the authors?
Response 60
I am sorry for the misunderstanding. We do the analysis of the correlation between MLH and visibility and find the correlation shows a sudden change when the RH is beyond 80% (Table S1), so 80% is used as the threshold for the RH. In order to clarify this question, we have rewritten this paragraph as follows.
Table S1 Correlation coefficients (R) between the MLH and visibility according to different RH

	RH≤40	40<RH≤50	50<RH≤60	60<RH≤70	70<RH≤80	80<RH≤90	RH>90
R	0.15	0.04	0.01	0.09	0.41	0.70	0.77

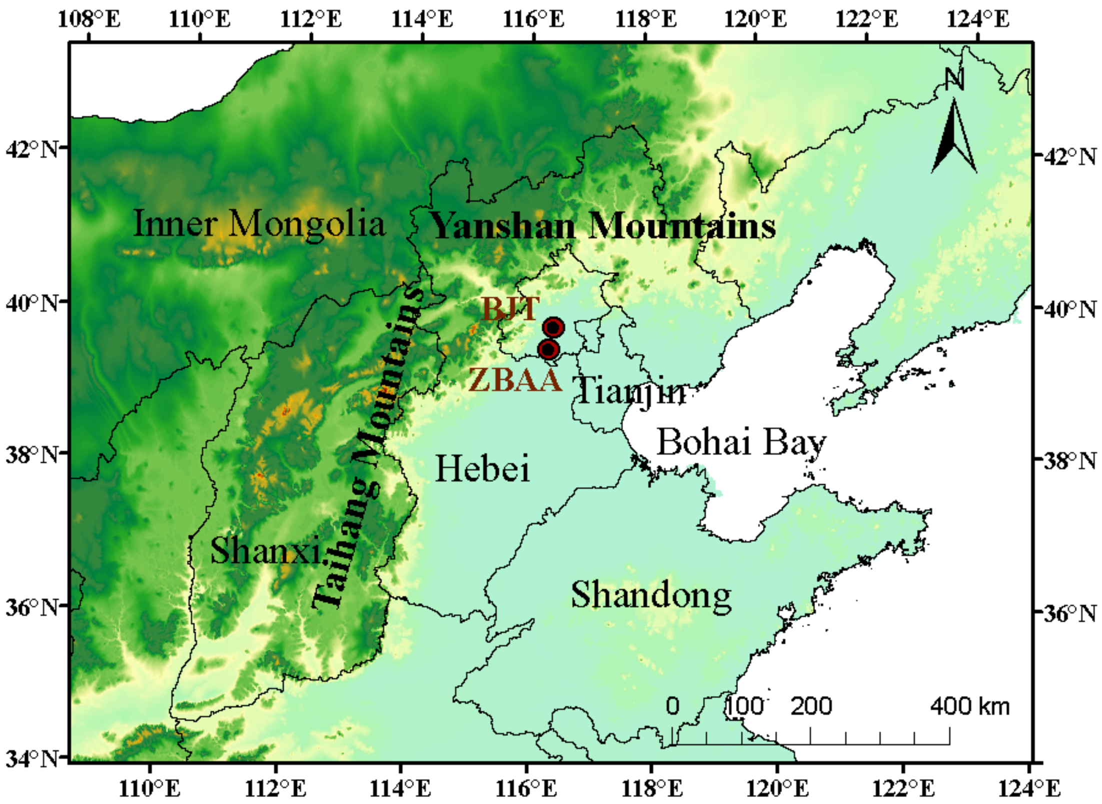
Question 61
• (28268, 17):
"We found that the..." I don’t understand this and the next sentence? Is the order of visibilities and names (10 km does not correspond to heavy haze) correct?
Please clarify!
Response 61
Thank you for your suggestion. We have added a table according to your suggestion in question 57. In that table, the different degrees of air pollution are clarified in detail. In addition, the sequence of the degrees of air pollution is not the same with the context, which may induce the reader misunderstanding. Therefore, we revised this paragraph. Please see response 60.

Question 62
• (28269, 16):
"exhibits the feature": please re-phrase
Response 62
Thank you for your suggestion. We have fixed it.

Question 63
• (28269, 17):
"variation in the MLH": please re-phrase
Response 63
Thank you for your suggestion. We have fixed it.

Question 64
• (28270, 1):
"slight haze": should be light haze?
Response 64
Thank you for your suggestion. We have clarified the degrees of the haze, please see the response 57.

Question 65
• Fig. 1
A scale would be helpful
Response 65
Thank you for your suggestion. We have revised the map as follows.



Question 66

• Fig. 10

"visibility levels": levels can be omitted.

Response 66

Thank you for your suggestion. We have fixed it.

Question 67

• all Figs.

whenever possible include a x/y-grid

Response 67

Thank you for your suggestion. We have added the grid in Figs. 2, 3, 4, 6, 8 and 11.

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