Authors' Response to Referees' Comments

Anonymous Reviewer #3

It is well known that air pollution is directly associated with atmospheric boundary layer height (BLH). The daytime convective boundary layer (CBL) develops in the synoptic background. Thus the synoptic conditions affect the BLH and consequently air pollution. In this paper, the authors divided the summertime synoptic conditions in Beijing area into seven typical patterns and analyzed the BLH and air pollution level in different synoptic patterns. The results suggest that, the positive synoptic conditions promote CBL development, and higher BLH leads to light air pollution, whereas the adverse synoptic conditions suppress CBL development, and lower BLH leads to heavy air pollution. The authors provided some details about how the special synoptic conditions influence the BLH, and proposed a possible mechanism to explain the reason. The results in this paper can help to understand the impact of synoptic conditions on air pollution. However, some statements and discussion are not convincing, and the English writing should be further improved. Therefore, my recommendation is publication in ACP after major revisions.

First of all, we appreciate the reviewer's comments and suggestions. In response to the reviewer's comments, we have made thorough revisions to the manuscript. Listed below are our responses and the corresponding changes made to the manuscript according to suggestions given by the reviewer. Each comment (in black) is listed, followed by our responses (in blue).

Specific Comments

1. For Eq. (1), presence of u* in the right hand side is an error. If the authors used this formula to calculate the BLH, the results are incorrect.

This was a typo for Eq. (1), which has been corrected in the revised manuscript.

2. This study emphasizes that heavy air pollution is caused by low BLH. But the

authors did not provide solid evidences. In Fig. 3b, the results show that the diurnal variation of 1 h-bin averaged PM2.5 concentration is not significant, but the difference in BLH between 14:00 and 08:00 (or 20:00) is very larger. In addition, even for the situation at 14:00, Fig. 4b shows that the correlation coefficient between PM2.5 concentration and BLH is relatively low. Then the problem arises. What is the major reason for the formation of heavy air pollution in Beijing in summertime, reduction of BLH or transportation of pollutant? In my opinion, discussing the impact of BLH on air pollution level is based on the premise that the air pollution is caused by local emissions. The above mentioned results suggest it may be not the case. If the air pollution is caused by transportation of pollutant, the low BLH may be the result rather than the reason of heavy air pollution. Therefore, the authors should be cautious when discussing the relationship between BLH and air pollution level, and state their results more reasonably.

We totally agree with the reviewer, the BLH is just one of the meteorological factors modulating aerosol pollution. In the revised manuscript, the relationships between BLH and aerosol pollution were rewritten to make the explanation more reasonably. In addition, either horizontal transport of pollutants or aerosol-PBL feedback plays important roles in modulating the air quality under different synoptic conditions. Therefore, the relevant discussions were added on Page 13 and Page 17 in the revised manuscript.

3.1 For the results in Fig. 8, I do not know how the authors obtained the correlation coefficients. This figure shows that the correlation coefficient between PM2.5 concentration and BLH is -0.97 (the absolute value is very close to 1.0). In page 12 line 7, the authors said 'the BLH is the most crucial factor related to aerosol pollution level under different synoptic conditions'. But Fig. 4b shows that the correlation coefficient is very low (the absolute value is smaller than 0.4). I cannot understand such a large difference between the two results. The authors should explain why.

The correlation coefficients in Fig.8 were calculated based on the mean values for each synoptic type. For example, the correlation of BLH and $PM_{2.5}$ concentration was calculated using the seven pairs of BLH and $PM_{2.5}$ concentration. In contrast, the correlation coefficients in Fig.4 were directly calculated using daily averaged $PM_{2.5}$ concentration and its concomitant BLH. In the revised manuscript, such information was added on the caption of Fig. 8.

3.2 Secondly, Fig. 8 shows a high positive correlation between PM2.5 concentration and BLH and a high negative correlation between PM2.5 concentration and CLD. These results imply that the lower BLH is highly related to the larger cloud cover. It is know that the daytime CBL is driven by surface heating. The large cloud cover reduces radiation arriving the surface and then the surface sensible heat flux. This may be the reason for the lower BLH in cloudy days. But the authors only emphasize the effect of capping inversion (they propose a mechanism about this as illustrated in Fig. 13).

We totally agree with the reviewer that the effect of cloudiness cannot be ignored in modulating the BLH, which should not be de-emphasized. In addition to the cloudiness, the cool/warm advections associated with different synoptic patterns may also affect the PBL structure. In the revised manuscript, to better understand the effects of cool/warm advections on PBL structure, several idealized numerical experiments were conducted.

In the idealized experiments, the simulation region was set as the same studied region shown in Fig. 1, with a horizontal grid spacing of 0.1° (~11 km). In the vertical dimension, 48 layers were set from the surface to 100-hPa level, with 21 layers between the surface and 2 km above ground level (AGL). To isolate the effects of synoptic forcing (e.g. warm/cold advection) from cloudiness, the microphysics and cumulus schemes were turned off in the idealized simulations. Similar approaches have been used by De Wekker (2008) to investigate the suppression of BLH near a mountain, and by Pu and Dickinson (2014) to investigate the dynamics of Low-Level Jet over the Great Plains.

In the revised manuscript, the description of numerical experiments were added on Page 10 to 11. And the relevant results and discussions were added on Page 15 to

16.

3.3 Thirdly, results in this figure suggest that the wind direction plays an important role in the formation of air pollution. High air pollution level is associated with south wind, implying that the pollutants may come from the cities south of Beijing. In this situation the lower BLH may be caused by the enhanced air pollution. However, the authors' analyses give me a strong feeling that the reduced BLH leads to heavy air pollution. So my question is how to interpret the results in Fig. 8. The authors should provide us a "clear picture".

As the anti-correlated relationship illustrate in Fig. 4 and Fig. 8, the reduced BLH may be one factor modulating the pollution level, however, the horizontal transport of pollutants should not be de-emphasized as the reviewer suggested. In the revised manuscript, we try to provide a more "clear picture" about the relationships between meteorological factors/processes (i.e., BLH, horizontal transportation, aerosol-PBL feedback) and pollution. The relevant discussions were added on Page 13 to 14.

4. Page 13, line 1-2 'Among the seven identified synoptic patterns, the strongest near-surface could advection is associated with Type 1 (Fig. 11a), leading to the coldest PBL at 1400 BJT (Fig. 9a)', and line 5-6 'Types 2, 4, 5 and 6 also show cold advection toward Beijing but it is less prominent (Figs. 11b and 11d-f)'. I am not sure if the PT anomaly is caused by cold advection. Large cloud cover may also reduce PT in the boundary layer. The PT anomaly in Type 2 is similar to that in Type 1, and the other conditions in the two types are almost the same: the same CLD, no warm advection above CBL top. Why Type 1 has a negative BLH anomaly but Type 2 has a positive BLH anomaly? Moreover, the BLH in Type 1 is slightly lower than the seasonal average while the BLH in Type 2 is slightly higher than the seasonal average (as shown in Fig. 6a), and the BLH difference in the two types is merely about 200 m. Why such a small difference in BLH can introduce large difference in $PM_{2.5}$ concentration (one is 101 μg m-3, another is 67μg m-3)? I guess, transportation of high concentration pollutants may contribute to heavy air pollution in Type1, because

Type 1 has south wind whereas Type 2 has east wind.

We agree with the reviewer, the large difference of $PM_{2.5}$ concentration between Type 1 and Type 2 may be primarily caused by the different horizontal transport of pollutants. The relevant discussions were added on Page 13 in the revised manuscript.

Besides, to understand the impacts of cool/warm advection on PBL structure, several idealized simulations were conducted to isolate the impacts of advection from other factors, such as the cloudiness and aerosol-PBL feedback. As the simulated cross section of PT shown in Fig. 11, the cold/warm advection could play a role in modulating the PBL structure in Beijing. The relevant discussions were added on Page 15-16 in the revised manuscript.

5. For Fig. 11, I do not think the PT anomaly and the wind field can match very well. Fig. 11d shows an elevated negative PT-anomaly area, stretching from the right to the left. But the wind direction is form the left to the right together with a downward component. Actually, Fig. 6a shows that the boundary layer wind blows towards northeast (with a relatively small west component). It means that the flow passing Beijing does not come from Bohai or Yellow Sea (the same evidence can be found in Fig. 10d). Also, Fig. 11e shows an isolated maximum negative PT-anomaly area over Beijing. If this negative PT-anomaly area is caused by cold advection, the magnitude of PT-anomaly in the right area should be larger than, or at least the same as, that in this area. I mean the maximum negative PT-anomaly area should stretch to the right side of picture, as shown in Figs. 11a&b or Fig. 11f. Can the isolated maximum negative PT-anomaly area over land be regarded as the result of cold advection from sea? In my opinion, the isolated maximum negative PT-anomaly area over Beijing implies a local cooling. So, my question is, can the negative PT-anomaly be interpreted as the result of cold advection from sea? I think the authors should discuss this issue cautiously.

We agree with the reviewer, the development of PBL can be extremely complex, influencing by the cloudiness, warm/cold advection, and aerosols at the same time. And the resolution of FNL reanalysis may be not enough to study the PBL structure/process. Thus, in the revised manuscript, seven idealized numerical experiments were conducted to understand the effects of cold/warm advection on PBL structure, in which the effects of cloudiness were isolated through turning off relevant parameterization schemes. The relevant discussions were added on Page 15-16 in the revised manuscript.

6. For Fig. 13, I suggest to remove this schematic map. I think there is no solid evidence to support the so-called "advection mechanism". The authors can add the seasonal mean PT profile in each panel of Fig. 9. By comparing the PT profile in each type with the seasonal mean PT profile, we can know whether the capping inversion is enhanced or weakened in each synoptic pattern. Then the authors can discuss the possible reasons.

The schematic diagram was removed as suggested, and the revised Fig.9 was drawn, in which the PT anomaly (subtracted from the seasonally averaged PT profile in summer) for each synoptic type was added.

For Types 1, 4, and 5, the differential cooling/ warming anomalies within PBL and above it play a role in enhancing the thermal inversion at PBL top, which would suppress the development of PBL. Specifically, the cooling (warming) of Type 1 (4) is stronger (weaker) within PBL than that above it; and for Type 5, the PT anomaly within PBL is negative while that above PBL is positive. In contrast, the PT anomaly of other Types (2, 3, 6, and 7) tend to lower the thermal inversion at PBL top to some extent, favoring the growth of PBL. These PT anomalies and resultant BLHs could be partially responsible to the different pollution level for different synoptic types. In the revised manuscript, the relevant discussions were added on Page 15.

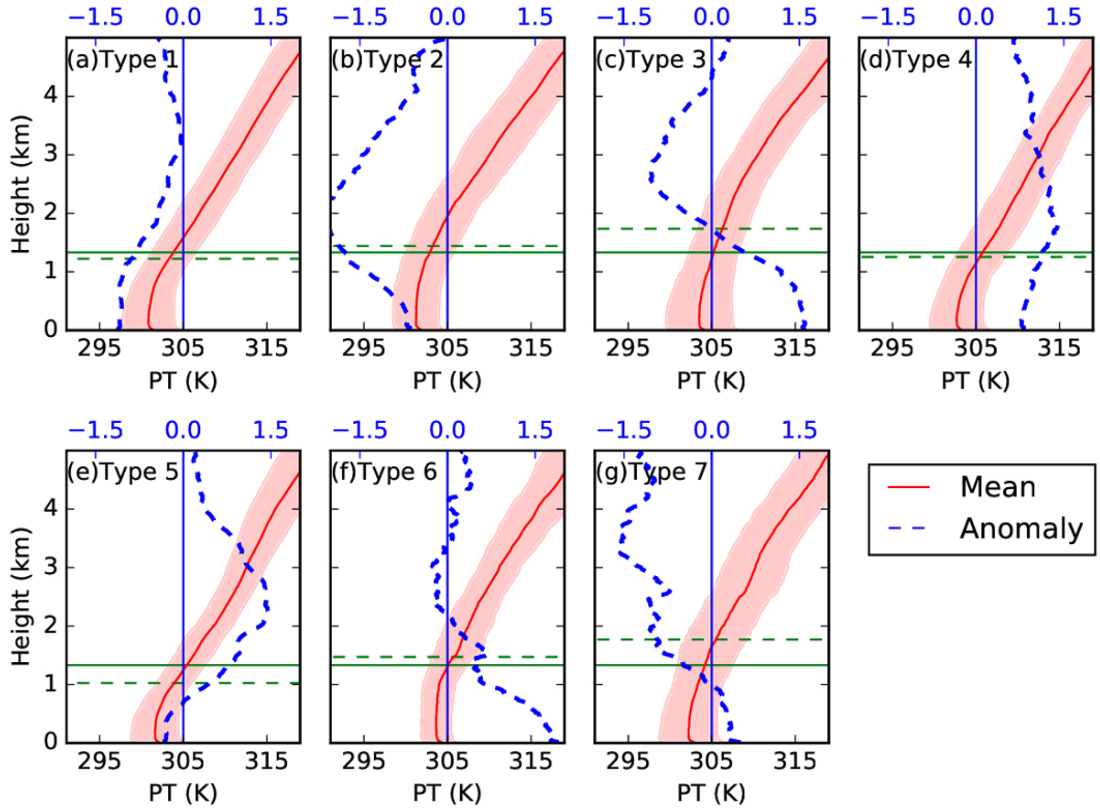

Fig. 9. Vertical profiles of potential temperature (PT) at 1400 BJT associated with the seven types of synoptic pattern derived from soundings (red lines). Solid lines indicate average values and shaded areas show the uncertainty range (the mean ± one standard deviation). Green solid lines represent the summer averaged BLH and green dashed lines represent the average BLH for each synoptic type. The PT anomaly (subtracted from the summer averaged PT profile) for each synoptic type was also given by the blue dash-lines in each panel.

7. For the English wording and writing, I suggest that the authors get a fluent writer/speaker of English to look through the paper.

Per your kind suggestion, a native speaker has been invited to review the manuscript.

References:

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Pu, B. and Dickinson, R. E.: Diurnal spatial variability of Great Plains summer precipitation related to the dynamics of the low-level jet, J. Atmos. Sci., 71, 1807–1817, doi:10.1175/JAS-D-13-0243.1, 2014.