Response to the reviews of the manuscript

"Statistical Analysis of Relationship between Lidar-Derived Planetary Boundary Layer Height and Relevant Atmospheric Variables in the Semi-Arid Region in Northwest China"

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I. Response to the editor's comments

Following the review of Research Article titled "Statistical Analysis of Relationship between Lidar-Derived Boundary Layer Height and Relevant Atmospheric Variables in the Semi-Arid Region in Northwest China" by Ruijun Dang, Hong Li, Zhiguo Liu and Yi Yang, I recommend that it should be revised taking into account the changes requested by the reviewer(s), particularly:

1. Improve the writing and better literature review to address "This study is scientifically not new, and it is not clear with its originality and novelty" by reviewer 1 and many other issues.

2. Discussion of boundary layer structure in terms of temperature profiles (by reviewer 2, or radiosonde by reviewer 1)

Note that in this case, carefully and appropriately addressing the reviewers' comment is extremely critical for the editor to re-consider the manuscript for publication.

Response: Thank you very much for your time and effort. The manuscript has been modified carefully and seriously in the light of the reviewer's comments. We have answered every question referred to in the reviewer's comments.

II. Reviewer #1(comments to Author):

General comment:

This manuscript presents a study of statistical relationship between lidar-derived boundary layer height and atmospheric variables in Northwest China. This study is scientifically not new, and it is not clear with its originality and novelty. Hence, I recommend a major revision before publication.

Response: The reviewer gave the authors very helpful suggestions and comments that are a big help to the authors to revise this manuscript. The authors have modified this manuscript according to these very useful suggestions.

Specific comment:

(1) The development of BLH is modulated by the synoptic forcing, land surface energy balance (sensible heat flux), wind shear, and cloud mask. All these factors need to be analyzed to understand the development of BLH.

Response： The study mainly analyze the statistical correlation between atmospheric variables and BLH from 10:00 to 18:00 (Beijing Time)(convective boundary layer) in cloudless sunny days for the purpose of assimilation of BLH, so did not take the modulation of the synoptic forcing and cloud mask to the development of BLH into consideration. For wind shear, we only have wind speed data at 1, 2, 4, 8, 16, 32 m and wind direction at 8 m from micrometeorological tower, the limitation of data and quality problem make it difficult to analyze the influence of wind shear to the BLH. Because we mainly count up the statistical correlation between BLH and conventional atmospheric variables using the direct traditional observations, so for land surface energy balance, we analyzed radiation variables and surface temperature replacing the sensible heat flux when surface sensible heat flux has to be computed. We have

appended that the aim of analyzing the statistical correlation between atmospheric variables and BLH in the study is to provide service for BLH assimilation in the numerical model (see the revised version of manuscript, Lines 110 to121).

(2) The BLH is usually calculated by using the radiosonde measurements. Are there any differences between the radiosonde-BLH and lidar-derived BLH?

Response: We can only explain that compared with radiosonde, lidar can provide long-term continuous observations in theory (as described in section 1), but we can't do the work to find out the differences between the radiosonde-BLH and lidar-derived BLH because of the lack of radiosonde data to get radiosonde-BLH and it is not emphases in this study.

(3) The synoptic forcing and surface conditions (both heat flux and surface characteristics) in different season can be different, it is better to analyze the BLH in each season, and give some discussion about the seasonal variation of BL and land surface processes. Besides, the diurnal development of BLH in different season can be different.

Response： We selected cloudless sunny days to do the work so didn't take the synoptic forcing into consideration. For seasonal variation of BL and land surface processes, we mainly discussed in the part of cases analysis (section 4) through the daily variation of variables and BLH on four typical cases, which obviously show the seasonal difference with significant contrast (see the revised manuscript, Section 4).

(4) Some reanalysis dataset can also be used to understand the seasonal variation of synoptic forcing, land surface processes and BL development in Northwest China.

Response: There is no doubt that the reanalysis dataset can be used to understand the seasonal variation of land surface processes and BL development in Northwest China, but it is not key point of the researching on this paper. It will be meaningful to adjust the initial conditions of variables contributing to BLH with assimilating BLH. For the BLH assimilation in the numerical model, we should master which variables well correlate with the BLH and how far the influence radius of variables is in the horizontal and vertical directions. So the focus of study is to find out the statistical correlation between BLH and conventional atmospheric variables according to the direct traditional observations at SACOL to provide basis and support for the assimilation of BLH in northwest China.

(5) To verify the statistical results and analyze the roles played by atmospheric variables and land surface processes in the development of BLH, the typical case in different season can be investigated by using numerical simulations, and then give some discussion about the possible physical mechanisms behind these statistical results (i.e. the vertical dependence of BLH on air temperature).

Response: As described in several questions above, the focus of study is to find out the statistical correlation between BLH and conventional atmospheric variables according to the traditional observations to provide basis and support for the assimilation of BLH, not using numerical simulations. For the possible physical mechanisms behind the statistical results we discussed in detail in section 3 and section 4 (see the revised manuscript, Sections 3 to 4).

(6) What is the feedback between the BLH development and surface variables? For example, as the BL grows, the momentum from the free troposphere can be

transported to the BL, which may play a role in modulating the near-surface wind speed.

Response: After sunrise, ground surface absorbs solar radiation and heat flux is transported upward, the boundary layer begins to develop. With the increasing of absorbing solar radiation of surface, free convective turbulence starts to develop, the upper air begins to be warmer because of the upward transportation of heat flux, and meanwhile the momentum from the free troposphere is transported to the BL which speeds up the lower air, so there exits feedback between BLH development and the momentum. But for thermal variables such as surface temperature, nearer the ground, the value is bigger, and the heat flux is transported upward always, so it is almost impossible for thermal variables to be transported downward and maybe unnecessary to consider the feedback between the BLH development and surface thermal variables. Besides, although downward transportation of the momentum speeds up the lower air, in the study wind speed and direction were not taken into consideration.

III. Reviewer #2(comments to Author):

General comment:

In this paper, the authors investigated the correlation of Planetary Boundary Layer (PBL) height (BLH) and some atmospheric variables near land surface or within the PBL, taking advantages of the lidar data and other observations. The results provide some insight into using the surface meteorological and radiation variables to indicate the variation trend of BLH. However, how the meteorological conditions relate to BLH need some further studies to get this paper published.

Response: Thanks a lot for your time and effort. We have modified the manuscript according to your very useful suggestions and have done some further studies.

Major comments:

(1) As this paper mainly focus on the BLH and related meteorological variables, it's necessary to add some brief review on the definition of BLH and the main physical processes impacting BLH.

Response: We have added some brief reviews on the definition of BLH in the revised manuscript. Please see them in Section 1: The boundary layer height (BLH) is of major relevance in boundary layer research as a key parameter characterizing the structure of the boundary layer, and because of its effect on pollutant dispersion. The height and structure of boundary layer is closely related to the distribution of air temperature and atmospheric stability. Under clear conditions when atmosphere is in neutral or unstable, BLH is more or less identical with the mixed layer height (MLH), which is defined as the height up to the bottom of the inversion layer that prevents the thermally driven turbulent vertical mixing process. So the gradients of conservative variables such as potential temperature, specific humidity and the concentration of aerosol particle are often regarded as suitable signs to identify the height of mixed layer (also BLH) (Lines 66 to 74).

(2) The curve fitting method is critical for data processing in this paper, butthe author failed to describe this method in more details For example, the definitions of several terms have not been presented: what does 'r' denote in the definition of the idealized backscatter profile? (Does it represent height above the ground level?) What does 'EZT' represent?

Response:

$$B(r) = \frac{(B_m + B_u)}{2} - \frac{(B_m - B_u)}{2}\,\mathrm{erf}\left(\frac{r - Z_m}{S}\right), \qquad (1)$$

$$B(z) = \frac{(B_m + B_u)}{2} - \frac{(B_m - B_u)}{2}\,\mathrm{erf}\left(\frac{z - Z_m}{S}\right), \qquad (2)$$

Use the second equation to replace the first one in the old version of the manuscript. Where Z represents height above the ground level; S is a variable relating to the thickness of the entrainment zone layer EZT: $EZT = 2.77 \times S$.

(See the revised manuscript, Lines 158 to 163)

(3) Observations from many meteorological instruments were used in this manuscript. It's important to point out the accuracy or observation error of each measured meteorological quantity, as well as the quality control process applied for these quantities and backscattering signal from the lidar. Meanwhile,the estimated error of the BLH determined by the curve fitting method needed to be documented.

Response: Yes, we have appended sentences about quality control in the revised manuscript. For all the conventional atmospheric variables, after basic quality control process, observations from meteorological instruments with a relatively high accuracy were selected. The micro-pulse lidar (MPL-4) in SACOL has been a number of the Micro-Pulse Lidar Network (MPLnet) [2] lidars, observations follow the uniform rules of MPL-net. Meanwhile, for lidar data, a series of correction have been done such as background correction, overlap correction and range correction [3] (Lines 148 to 153).

For curve fitting method, what should be considered is that the change of B_m (the mean backscatter in the mixed layer) greatly influences the effect of fitting [4] which may leads to the estimated error of the BLH. Furthermore, the technique can only detect boundary layer structures when the aerosols play as targets or tracers for lidar backscatter, but on the whole, the curve fitting method owns the ability to detect the

mixed layer depth and EZT even in very difficult cases and has the robustness not found in other methods [5] (Lines 165 to 169).

In the paper, according to Figure 2, the difference between the height at which the signal reduced fastest and the BLH retrieved with the curve fitting method is small and the corresponding times are fairly consistent, which supports the choice of the curve fitting method for retrieving BLH on sunny days.

(4)In terms of data selection, 42 'cloudless sunny days with good atmospheric visibility' are chosen for this manuscript, but the author failed to provide the specific criterion for the selection. For example, how is the cloud cover determined or how is the 'clear day' specified? Does the criterion come from surface observations or examining the vertical and temporal distribution of lidar signals?

Response: Yes, we have appended the sentence describing specific criterion for the cloudless sunny days in the revised manuscript. The days that are non-precipitation, without thunderstorm and no cloud or total-cloud covers is less than 20 percent all day were defined as cloudless sunny days and selected to do the work. Then the days with a clear structure of backscatter signals of lidar and complete observations of atmospheric variables were chosen as 42 ideal cases for the study (see the revised manuscript, Lines 126 to 128).

(5) The correlations in Table 2 were derived for daily mean variables, including both convective boundary layer and nocturnal boundary layer. The structures and formation mechanisms of the convective and nocturnal boundary layer are different, especially that the nocturnal boundary layer is largely influenced by the mechanical

forcing (wind shear). Therefore, the BLH of both boundary layers should be discussed separately and should not be averaged together.

Response： Yes, however, In this article, we only focus on the correlations between relevant atmospheric variables and boundary layer height during 10:00 and 18:00on 42 days shown in Table 2, which shows the statistical correlations between the averages of atmospheric variables and boundary layer height from 10:00 to 18:00, not derived for daily mean variables, that is to say that nocturnal boundary layer was not included.

(6)In the analysis of the correlation between different atmospheric variables and BLH with a time lag, the lag was chosen as 1, 2, and 3 hours. The BLH was selected every 30 min, and the amount of data was quite limited. The same instrument of lidar (MPL-4) was used by Wang et al. (2012, and its temporal resolution is 1 min. It could be better if the authors can use the lidar data with a higher temporal resolution than 30 min, with a shorter time lag (e.g. 1min), in order to derive a more precise time lag corresponding to the highest correlation. Wang, Z., Cao, X., Zhang, L., Notholt, J., Zhou, B., Liu, R., and Zhang, B.: Lidar measurement of planetary boundary layer height and comparison with microwave profiling radiometer observation, Atmos. Meas. Tech., 5, 1965-1972, doi:10.5194/amt-5-1965-2012, 2012.

Response： Yes, the temporal resolution of the micro-pulse lidar (MPL-4) is 1 min, so we can get the BLH with the resolution of 1 min, but the temporal resolution of all atmospheric variables is 30 min, so we have to select the BLH of every 30 min to analyze the correlations between BLH and the different variables, which leads to the limitation of the data. Besides, considering variability of the boundary layer height and quality control of lidar data, often use averages over time.

(7)In the analysis of correlations between BLH and air temperature at different heights, the correlation was analyzed for different observation time. Technically, the structure of convective boundary layer is closely related to the structure of air temperature profile. In other term, the BLH can be estimated according to the air temperature profile. Therefore, the analysis should take the vertical profile (structure) of air temperature into consideration, not only considering the correlation at each single level. In addition, the layer above the BLH height is usually not impacted by the surface forcing. Thus it is necessary to explain the mechanism resulting in the relatively high correlation between BLH and air temperature in the mid layer of the atmosphere in the afternoon.

Response： We analyzed the correlations between BLH and air temperature below 5 km, the vertical spatial resolution of air temperature providing by Radiometrics profiling radiometer (TP/WVP-3000) is 100 m below 1 km and 250 m above 1 km. which can represent temperature profile to some extent. Besides, through air temperature profile, we mainly wanted to know change rule of the statistical correlation between air temperature and BLH in the vertical direction, so we consider the correlation at each single level.

Thermal forcing is the driving force for the development of mixing layer in daytime (10:00-18:00), but only small amount of solar radiation is absorbed by air in the boundary layer, most (about 90%) are delivered to the surface, then the surface varies responding to the solar radiation changes and forces the changes of boundary layer through turbulent transport, so it is suitable that correlations between BLH and air temperature is strongest at surface and decreases with height [1]. Besides, for the whole troposphere, the ground surface is the main heat source, the air temperature in

the free atmosphere also changes with the surface variation, that is, variation of solar radiation, so there is relatively high correlation between BLH and air temperature even at 5 km in the afternoon (14:00) [6] (see the revised manuscript, Lines 246 to 257).

(8)Variations of various meteorological quantities and BLH are discussed in this paper. The correlation was examined separately between each variable and BLH. However, some of them are inherently, physically related. The physical relations among the thermal quantities and the parameters relevant to radiation should be considered in the analysis, in order to explain more clearly their correlation with BLH. Meanwhile, it is necessary to take a full consideration of the different variables, and to derive a regression model for the surface observations and the BLH.

Response: The physical relations among the thermal quantities and the parameters relevant to radiation were considered in the analysis in section 3 and section 4.

For deriving a regression model, as mentioned before, the focus of study is to find out the statistical correlation between BLH and conventional atmospheric variables according to the routine observations at SACOL to provide basis and support for the assimilation of BLH, not calculating the BLH according to the variables. So deriving a regression model for the surface observations and the BLH is not involved in the study.

Minor comments:

1) Section 1 (introduction), line 4, ‘turbulent state’-> ‘turbulent status’

Response: Yes. The words “turbulent state” have been changed to “turbulent status”.

2) Section 1 (introduction), line 6, ‘matter’-> ‘substances’

Response: Yes. The word “matter” has been changed to “substances”.

3) In Section 1, it is not precise to say that 'there is no means of measuring the BLH directly', since the BLH is a descriptive variable for the depth of the PBL, but not a physical quantity. It cannot be 'measured', and should only be estimated, or defined according to other atmospheric properties, such as wind speed, air temperature, stability, and turbulent intensity.

Response: Yes, it is not precise to say that 'there is no means of measuring the BLH directly', we have changed the description: "The gradients of conservative variables such as potential temperature, specific humidity and the concentration of aerosol particle are often regarded as suitable signs to identify the height of mixed layer (also BLH)".

4) The notification of 'boundary layer' in the title of this paper and the abstract should be revised into 'planetary boundary layer', to be more precise for the atmospheric condition.

Response: Yes. We have use the words "planetary boundary layer" to replace "boundary layer" in the title and abstract of the paper.

5) Section 1, paragraph 4, 'divided into' –> 'categorized into'

Response: Yes. The words "divided into" have been changed to "categorized into".

6) Section 1, paragraph 4, for land surface processes part, 'including the transfer of solar radiation energy to the surface as heat, heating of the Earth's surface' is poor writing. It's more like 'the absorption of solar radiation by the land surface'. In addition, the land surface processes also include the mechanical process (friction).

Response: Yes. The words "including the transfer of solar radiation energy to the surface as heat, heating of the Earth's surface…" is poor writing, and the mechanical process (friction) should be included, so now the description is "The atmospheric thermal boundary layer is largely governed by land surface processes, including the

absorption of solar radiation by the land surface, transmission of heat energy to the atmosphere and soil and mechanical processes."

7) Section 1, Paragraph 5, 'I investigated' -> 'we investigated'

Response: Yes. The words "I investigated" have been changed to "we investigated".

8) The unit of time should be denoted, such as 'universal time coordinate (UTC)', 'local standard time (LST)', or 'Beijing time (BJT)', etc.

Response: Yes. We have denoted the unit to time (local standard time) in Figure 2 and corresponding place in the paper.

9) Section 4, paragraph 1, 'decreased rapidly' -> 'decreased most rapidly'

Response: Yes. The words "decreased rapidly" have been changed to "decreased most rapidly" in paragraph 1, Section 4.

10) Figures 2 and 3, 'diurnal' -> 'temporal'

Response: Yes. The word "diurnal" has been changed to "temporal" in Figures 2, 3, 4, and 5.

11) Section 4, paragraph 2, there are many kinds of gases with significant absorption of longwave radiation (greenhouse gases), among them are water vapor and carbon dioxide. It is not accurate to list only these two.

Response: Yes. There are many kinds of gases with significant absorption of longwave radiation (greenhouse gases) such as water vapor and carbon dioxide. We have changed the description: "After the longwave radiation is absorbed by greenhouse gases such as water vapor and carbon dioxide, the atmosphere is exothermic…"

12) Section 4, paragraph 4, 'nadir' -> 'minimum'

Response: Yes. The word "nadir" has been changed to "minimum".

13) It’s necessary to clarify the heat flux used in this manuscript is whether sensible heat flux or latent heat flux.

Response: Because we mainly count up the statistical correlation between BLH and conventional atmospheric variables using the direct traditional observations, so for land surface energy balance, we analyzed radiation variables and surface temperature replacing the sensible heat flux in the revised manuscript when surface sensible heat flux has to be computed.

References

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