

Authors' Response to Referees' Comments

Anonymous Reviewer #1:

Interactive comment on “The climatology of planetary boundary layer height in China derived from radiosonde and reanalysis data” by Jianping Guo et al.

The manuscript reports climatology of planetary boundary layer (PBL) height in China from sounding observations and a reanalysis data, and explores the relationship between PBL height and meteorological factors such as surface pressure, wind speed, atmospheric instability, etc. As this study represents the first effort to compile the historical records of sounding-based PBL climatology in China, the results in this paper and future exploration of the data are crucial for understanding the regional climate changes in East Asia. I recommend accepting the manuscript by ACP after the authors address some minor comments below.

Response: We are quite grateful to referee #1 for his/her positive comments on our work, which are quite constructive and helpful. All these comments and concerns raised by the referee have been explicitly considered and incorporated into this revision. For clarity purpose, here we have listed the reviewers' comments in plain font, followed by our responses in italics.

1) Can the authors provide the related equations that estimate BLH using the bulk Ri method?

Response: Per your suggestion, the following descriptions with regard to the physical meaning in Equation (1) were added in the revised manuscript:

“Note that the Ri is dimensionless, and has nothing to do with the intensity of turbulence, but it can tell whether the turbulence exists or not. Previous theoretical and laboratory studies (e.g., Stull, 1988) suggested that when Ri is smaller than the critical value (~ 0.25), the laminar flow becomes unstable. Thus, the lowest level z at

which interpolated R_i crosses the critical value of 0.25 is referred to as BLH in this study, similar to the criteria used by Seidel et al. (2012).”

2) Page 9, line 15-20. The authors stated that PBL height is higher in spring than that in summer and they attributed it to the stronger near-surface wind spring. To me, such a seasonal difference of PBL is only obvious at 2000 BJT, not for 0800 BJT, according to Fig. 5. So my question is if the wind only differs at 2000 BJT between spring and summer? An additional plot may help to elucidate it.

Response: The development of PBL is primarily determined by the buoyancy and mechanical forcing (Stull 1988). The strengths of buoyancy and mechanical forcing are relevant to the near-surface thermal stability and wind speed, respectively. Either strong near-surface wind speed or weak stability favors the development of PBL. To better address your concerns, we made the following plots (Figs. R1-R4). The near-surface wind speed in spring is stronger than that of summer at both 0800 and 2000 BJT at most sites (Figs. R1-R2).

At 0800 BJT, although the near-surface wind speed in spring is stronger than that in summer (Fig.R1), the near-surface stability is also stronger than that of summer, especially for the eastern China (Fig. R3). Due to these contrary influences of mechanical forcing and stability, at 0800 BJT the BLH of spring is not generally higher than that of summer.

At 2000 BJT, the near-surface wind speed of spring is stronger than that of summer (Fig. R2), and the near-surface thermal stabilities of these two seasons are comparable (Fig. R4). Thus, at 2000 BJT the BLH of spring is generally higher than that of summer. As a result, further discussions have been added in revised Section 4.2.

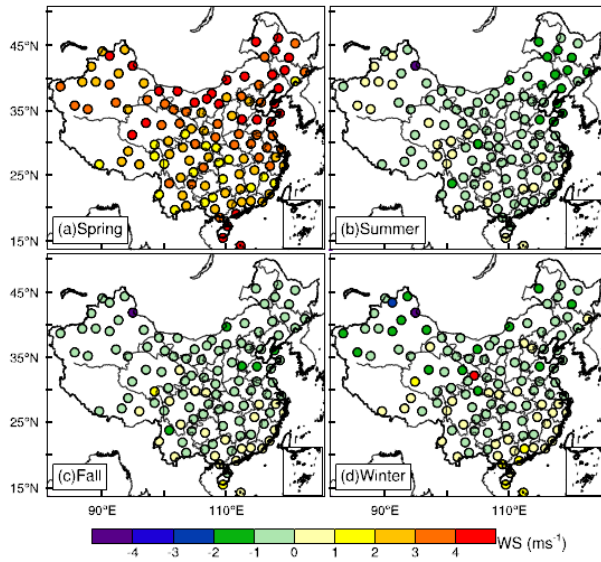


Figure R1. Spatial distribution of near-surface wind speed (a) in spring at 0800 BJT, and the wind speed difference (subtracted from that of spring) in (b) summer, (c) fall, and (d) winter. The seasonally averaged near-surface wind speed was obtained from the CMA soundings by averaging the observations below 100 m AGL.

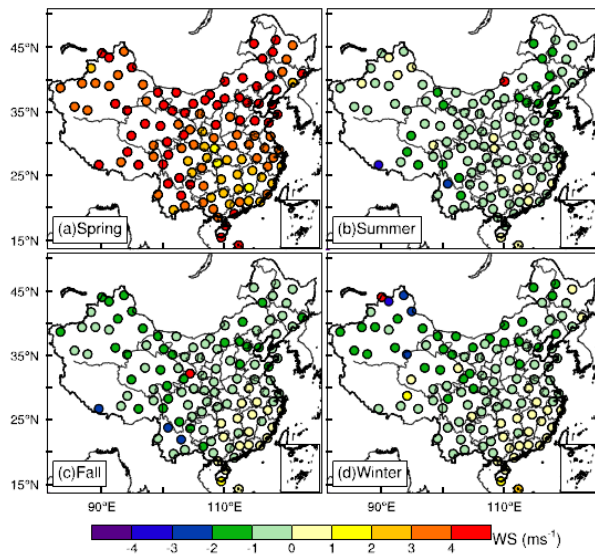


Figure R2. Similar as Fig.R1, but for the spatial distribution of near-surface wind speed at 2000 BJT.

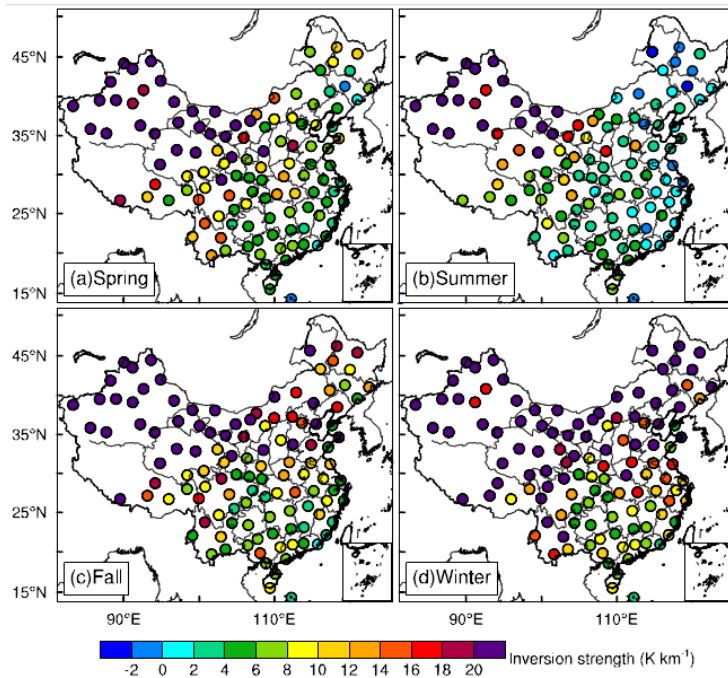


Figure R3. Spatial distribution of near-surface inversion strength (vertical potential temperature gradient between 10 m and 100 m AGL) at 0800 BJT in (a) spring, (b) summer, (c) Fall, (d) Winter.

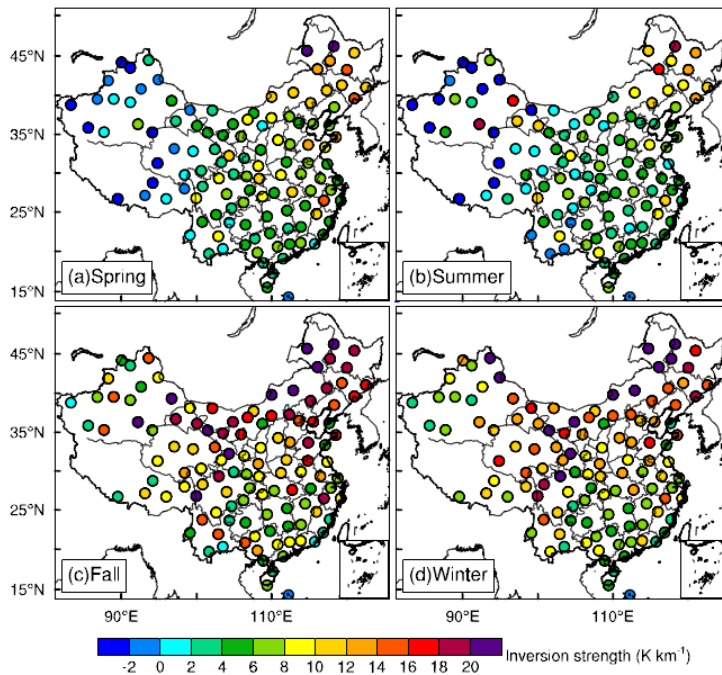


Fig.R4. Similar as Fig.R3, but for the spatial distribution of inversion strength at 2000 BJT.

3) Fig. 7. Tibet Plateau shows the highest PBL height in winter. Why?

Response: As the reviewer pointed out, at 0800 BJT (~0600 LST) the highest ERA-BLH over the northern Tibet Plateau (TP) region occurs in winter, which may be caused by the strongest near-surface wind in winter over the region (Fig. R5), which was based on reanalysis data.

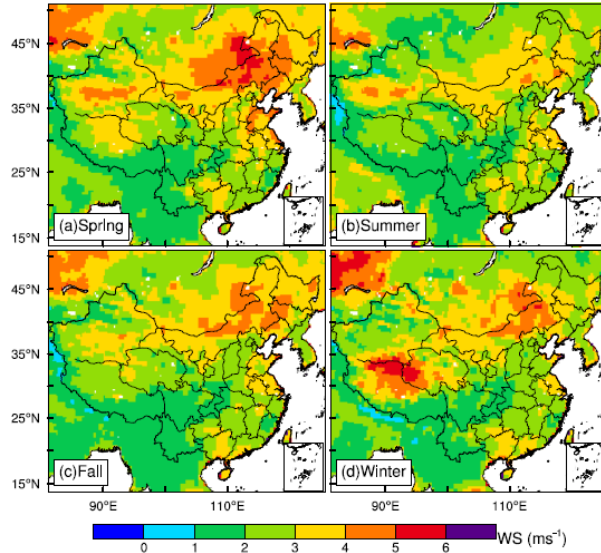


Figure R5. Spatial distribution of seasonally averaged 10-m wind speed in (a) spring, (b) summer, (c) fall, (d) winter derived from ERA-Interim reanalysis from January 2011 to July 2015.

4) Fig. 13. How about the correlations based on monthly mean data for each month other than the annual cycles? Meanwhile, the plot needs to be stretched vertically.

Response: Per your suggestion, we compared the monthly mean values of CMA-BLH with the four meteorological parameters, including surface pressure, 10-m wind speed, near-surface temperature, and lower tropospheric stability (Figs. R6 and R7). Although the correlation coefficients for a specific site are different (Fig.R6), the correlations (Fig. R7) on the whole are generally similar to those of annual cycles (Fig. 13 in the revised manuscript). Namely, the BLH is positively correlated with the near-surface wind speed and temperature, and anti-correlated with the lower tropospheric stability and surface pressure.

By the way, Fig. 13 you pointed out has been stretched vertically, and relevant modifications have been added in the revised Section 4.4.

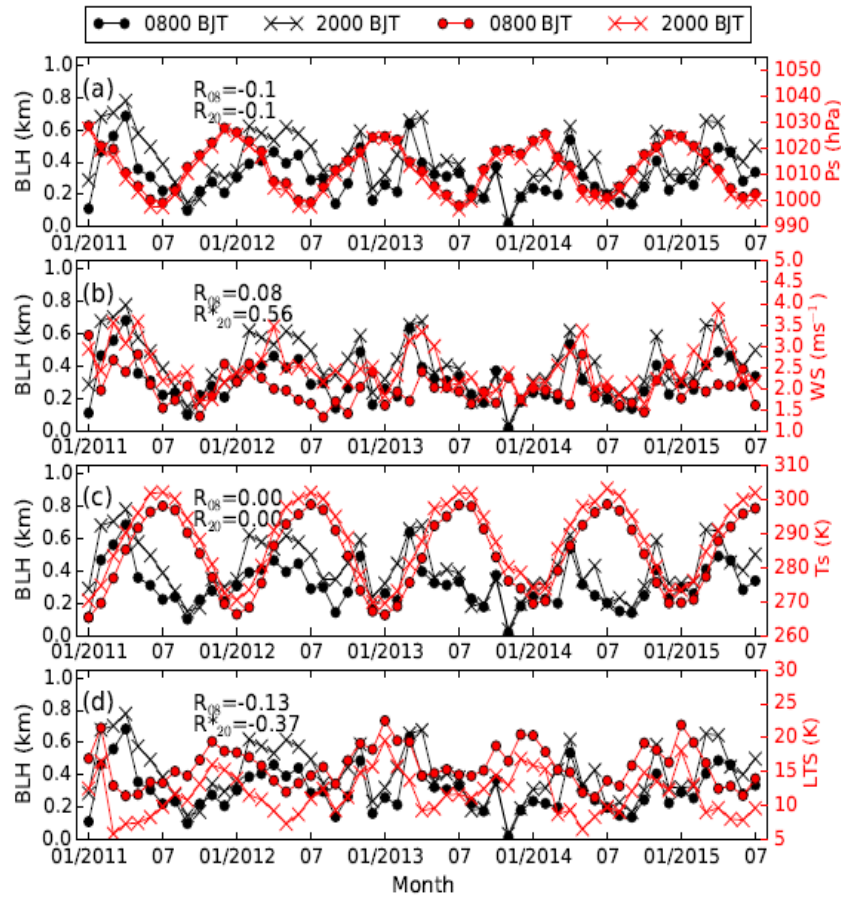


Figure R6. Monthly mean of CMA-BLH at Beijing (39.8°N , 116.47°E) from January 2011 to July 2015 at 0800 BJT (dot symbols) and 2000 BJT (x symbols), respectively, as superimposed by the counterparts of meteorological parameters, including (a) surface pressure (P_s), (b) 10-m wind speed (WS), (c) near-surface temperature (T_s), and (d) Lower Tropospheric Stability (LTS). The correlation coefficients at 0800 (R_{08}) and 2000 BJT (R_{20}) between of CMA-BLH and meteorological parameters are given in each panel as well, and the star superscripts indicate the values that are statistically significant ($p < 0.05$).

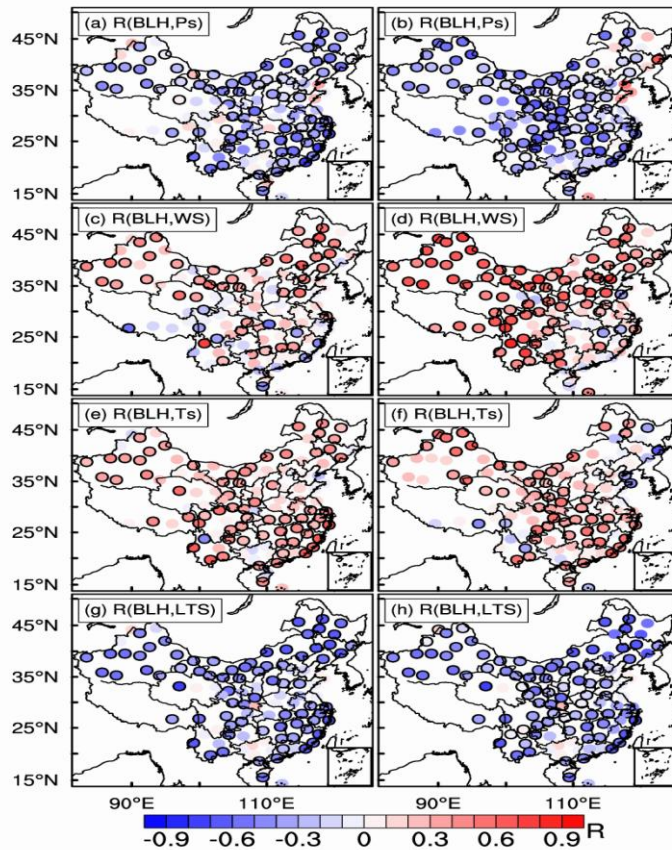


Figure R7. Correlations (R) between monthly mean values (from January 2011 to July 2015) of CMA-BLH and (a, b) surface pressure (P_s), (c, d) 10-m wind speed, (e, f) near-surface temperature (T_s), (g, h) Lower Tropospheric Stability (LTS), at (left) 0800 and (right) 2000 BJT. Symbols outlined in black indicate values that are statistically significant ($p < 0.05$)

5) The interference between PBL height and atmospheric aerosol concentrations were widely discusses by previous studies [Y. Wang et al., Atmos. Env., 2013; R. Zhang et al., Chem. Rev., 2015], especially over China [A. Ding et al., GRL, 2016]. Those discussions are worthy in the introduction part to emphasize the importance of the PBL record in the air pollution research

Response: Per your suggestion, the references have been added in the introduction section to highlight the importance of these studies.

Anonymous Reviewer #2:

This paper investigates the planetary boundary layer height over many regions in China on a seasonal and diurnal basis. It shows the non-uniformity of the BLH over the country and uses high-resolution radiosonde observations and reanalysis data. Overall this is a good study and fits the scope of ACP and suggestions for revisions have been provided in a supplemental PDF.

Response: We are quite grateful to referee #2 for his/her positive comments on our manuscript, which are pretty constructive and valuable. Because all these suggestions for revisions raised by the referee are almost all grammar errors or typos, which have been explicitly considered and incorporated into this revision, we will not list here the response one-by-one to each comment or suggestion.

Anonymous Reviewer #3:

Guo et al. present a well written manuscript that reports on a comprehensive investigation of the planetary boundary layer height (BLH) in China using fine-resolution sounding observations and reanalysis data from January 2011 to July 2015. The bulk Richardson number based BLH estimation method is a popular approach and the results are finely analyzed and discussed. The findings are important in understanding air pollution in China. This manuscript should be published after my suggestions below have been satisfactorily addressed.

Response: We are quite grateful to referee #3 for his/her positive comments on our work, which are quite constructive and helpful. All these comments and concerns raised by the referee have been explicitly considered and incorporated into this revision. For clarity purpose, here we have listed the reviewers' comments in plain font, followed by our response in italics.

Specific Comments:

1. The physical meaning of the Richardson number method, turbulent flow becomes laminar flow when $Ri > Rc$ (Stull, 1988), should be included in the manuscript in a proper way. $Rc = 0.25$ is the critical value of the bulk Richardson number.

Response: The following paragraph was added in the method section of this revised manuscript to better describe the physical meaning of the bulk Ri method:

“Note that the Ri is dimensionless, and itself says nothing about the intensity of turbulence, but it can tell whether the turbulence exists or not; theoretical and laboratory research suggest that when Ri is smaller than the critical value (~0.25), the laminar flow becomes unstable (Stull, 1988). Thus, the lowest level z at which interpolated Ri crosses the critical value of 0.25 is referred to as BLH in this study, similar to the study of Seidel et al. (2012).”

2. Which map projection is used in the manuscript (Figs. 1, 7-10, 13)?

Response: The map project we used is the Lambert-conformal conic projection.

3. Page 5, Line 10: “121operational” → “121 operational”.

Response: Amended as suggested.

4. Page 6, Line 10: “0.7 degree” → “0.75 degree”?

Response: Amended as suggested.

5. Page 7, Line 7: Add latitude, longitude and altitude for Beijing site.

Response: “(116.47°E, 39.80°N, 32m a.s.l.)” has been added for Beijing site.

6. Page 8, Line 4: “Figures 2” → “Figure 2”.

Response: Amended as suggested.

7. Page 10, Lines 16-17: “due to the solar radiation in eastern China is stronger than that of western regions” → “due to stronger solar radiation in eastern China than that of western regions”.

Response: Corrected.

8. Page 14, Line 17: It is not appropriate to write “As the first attempt to obtain climatology of BLHs in China” because Liu et al. (2015) have already done research on BLH over China using CALIPSO and ERA-Interim reanalysis data.

Response: Per your suggestion, it has been revised to “As the first effort to compile the climatological sounding-based BLHs in China...”. Meanwhile, Liu et al., 2015 has been cited in the section of Introduction.

9. Page 16, Line 17: “Reference” → “References”.

Response: Amended as suggested.

10. Page 31, Fig. 10: ERA-BLH and CMA-BLH don't agree well at 0200 BJT, why?

Response: To our knowledge, the soundings at 0200 BJT were launched occasionally in summer in attempt to capture the major severe storms taking place in China, and consequently a total of 1,578 profiles were collected and used for this study. As shown in Fig. R8, most stations have less than 30 of sounding profiles. Due to this sampling limitation, the seasonally averaged CMA-BLH at 0200 BJT don't agree well with ERA-BLH. Therefore, to reflect this issue, the original Fig. 10 was replaced by Fig. R8 in the revised manuscript, in which only the stations have more than 30 soundings are plotted.

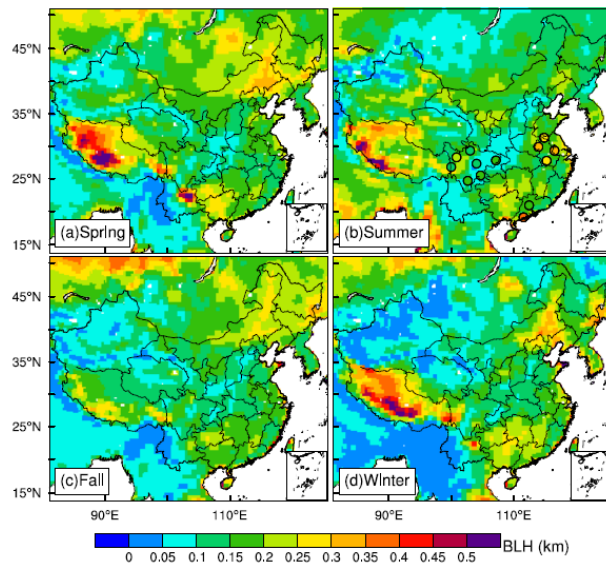


Figure R8. Spatial distributions of the seasonal mean of ERA-BLH (color shaded) and CMA-BLH (color dots) at 0200 BJT in (a) spring, (b) summer, (c) fall, and (d) winter. Note that only the stations have more than 30 soundings are plotted in (b).

References

- Liu, J., Huang, J., Chen, B., Zhou, T., Yan, H., Jin, H., Huang, Z., and Zhang, B.: Comparisons of PBL heights derived from CALIPSO and ECMWF reanalysis data over China, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 153, 102-112, doi:<http://dx.doi.org/10.1016/j.jqsrt.2014.10.011>, 2015.
- Stull, R. B.: *An Introduction to Boundary Layer Meteorology*, edited by R. B. Stull, Springer 5 Netherlands, Dordrecht, 1988.

The climatology of planetary boundary layer height in China derived from radiosonde and reanalysis data

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[#] [These authors contributed equally to this work.](#)

15 **Abstract.** The important roles of planetary boundary layer (PBL) in climate, weather and air quality have long been recognized, but little ~~has been~~ known about the PBL climatology in China. Using the fine-resolution sounding observations made across China and ~~a~~ reanalysis data, we conducted a comprehensive investigation of the PBL in China from January 2011 to July 2015. The boundary layer height (BLH) is found to be generally higher in spring and summer than that in fall and winter. The comparison of seasonally averaged BLH derived from observations and reanalysis shows good agreement. The BLH derived from three- or four-times-daily soundings in summer tends to peak in the

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early afternoon, and the diurnal amplitude of BLH is higher in the northern and western sub-regions of China than other sub-regions. The meteorological influence on the annual cycle of BLH ~~isare~~ investigated as well, showing that BLH at most sounding sites is negatively associated with the surface pressure and lower tropospheric stability, but positively associated with the near-surface wind speed and temperature. This indicates that meteorology plays a significant role in the PBL processes. Overall, the key findings obtained from this study lay a solid foundation for us to gain a deep insight into the fundamentals of PBL in China, which helps ~~to~~ understand the roles of PBL playing in the air pollution, weather and climate of China.

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1. Introduction

The planetary boundary layer (PBL), the lowest layer of troposphere, is directly influenced by the Earth's surface, at a response timescale of about an hour or less (Garratt, 1994; Stull, 1988). The accurate parameterization scheme with regard to how the PBL evolves is critical to prediction of weather, climate and air quality, which heavily relies on the high resolution observations of atmospheric profiles (Hu et al., 2010; Wood, 2012; Xie et al., 2012). Through the PBL, the exchanges of momentum, water, heat and air pollutants take place between the Earth's surface and the free troposphere. To characterize the structure of PBL, the concept of boundary layer height (BLH) is commonly used (Seibert, 2000; Seidel et al., 2010), since the BLH determines the vertical extent of turbulent mixing, vertical diffusion, and convective transport within PBL.

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The development of PBL is dominated by ~~the~~ complex surface forcings, including sensible heat flux, frictional drag, evaporation, transpiration, and terrain induced flow modification (Stull, 1988). As a result, the BLH is quite variable both in time and space. During a diurnal cycle, the BLH is typically shallow (a few hundred meters) at night due to the strong near-surface stability, and the PBL can be well developed and reach several kilometers in the afternoon.

Traditionally, the BLH is diagnosed using the height-resolved observations of temperature, humidity, and wind from radiosondes (Seibert, 2000; Seidel et al., 2010). The vertical resolution of these profiles are not sufficient to estimate BLH, since most soundings only provide a few records below 500 hPa (Liu and Liang, 2010). Partly due to the lack of fine-resolution soundings, there have been rather limited investigations of the BLH climatology over specific locations and regions using atmospheric sounding data (Liu and Liang, 2010; Norton and Hoidale, 1976; Seidel et al., 2012).

In addition to the traditional radionsonde-based BLH algorithms, other methods relying on new data sources such as ground-based lidar (Hennemuth and Lammert, 2006; Sawyer and Li, 2013), sodar (Beyrich, 1997), ceilometer (Eresmaa et al., 2006), aircraft sounding (Dai et al., 2014), and space-borne lidar (Chan and Wood, 2013; [Liu et al., 2015](#); Zhang et al., 2016) have been put forward to determine the PBL structure and its processes. However, the multiple types of observations tend to reveal different aspects of the PBL characteristics, due to the differing atmospheric variables used, leading to inevitable BLH differences (Seidel et al., 2012). Besides, even for a single data source, the use of different methods to estimate BLH could yield a wide range of results (Seidel et al., 2010). If the same approach is applied to different types of measurements, such disagreements will be lowered (Sawyer and Li,

2013). Therefore, it is better to employ a consistent method to a single type of observation to construct the BLH climatology.

The BLH climatology has been highly sought in the PBL community, pioneered by the research of Holzworth (1964), who used early radiosonde data to study BLH over the U.S., followed by the work of the U.S. Environmental Protection Agency Air Quality Modeling Group, who makes the U.S. mixing height data product publicly accessed (available at <http://www.epa.gov/scram001/mixingheightdata.htm>), but it only limited to the 1980s and thereafter. By extending the radiosonde data, new aspects of the BLH climatology over typical regions have been further investigated, producing a much clearer regional picture of BLH (Liu and Liang 2010; Seidel et al. 2010; Sawyer and Li, 2013). A recent climatological BLH studies (Seidel et al. 2012) gained new insight into the diurnal and seasonal variations of BLH over the continental United States and Europe by combining the radiosonde observations, a reanalysis, and two climate models.

There ~~we~~ are a host of ~~literatures-studies~~ (e.g., Zhang et al., 2014; Tang et al., 2016) ~~that~~ attempted to elucidate BLH characteristics in China, but most of them are limited to a specific place, let alone the BLH climatologies across China. They did not give much information of PBL over China, in part due to the lack of high-resolution observations in China priori to 2011. After then, the radiosonde data have been acquired at a much higher vertical resolution (1 second resolution) across China by the China Meteorological Administration (CMA), rendering a unique opportunity to study the PBL features across China.

—Using a consistent method and a traditional data source, radiosonde observations, BLH climatologies are presented in this study—~~from~~ the three and a half years of (from January 2011 to July 2015) sounding data acquired by the CMA sounding network, in conjunction with a modern reanalysis data product, are used to investigate the PBL climatology in China. To our knowledge, this is the first ~~sounding observation~~-based nation-wide PBL climatology in China. It provides us a unique opportunity to explore the relationship between PBL structure and other meteorological parameters in China.

The main goals of this study are to investigate the BLH climatology in China, and to use it to explore the potential influence of meteorology on the climatological BLHs. [This study of BLH climatology has important implications for better understanding the physical mechanisms, seasonal variation, and spatial distribution of severe air pollution in China \(Zhang et al., 2015a, 2015b\), since the PBL structure and processes play important roles in modulating the air quality \(Guo et al., 2009; Hu et al., 2014; Miao et al., 2015; Lee et al., 2015\). Meanwhile, during the haze events the presence of aerosol can also modify the PBL meteorology and exacerbate pollution \(Wang et al., 2013; Quan et al., 2013; Ding et al., 2016; Miao et al., 2016\).](#)

[The remainder of this paper is organized as follows.](#) Section 2 describes the data and method used, followed by the uncertainty analysis for the BLH retrievals in section 3. Section 4 presents the climatology of BLH in China, as well as the associations with atmospheric variables. Finally, the key findings are summarized in section 5.

2. Data and methods

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The radiosonde network of L-band sounding system dated back to 2002 when the China Meteorological Administration (CMA) began upgrading its radiosonde system. As of the beginning of 2011, deployment of the L-band sounding systems have been expanded to 120+ operational radiosonde stations (Figure 1). The GTS1 digital electronic radiosonde, one of key components of the L-band sounding system, is now widely used in operational radiosonde stations in China, providing fine-resolution profiles of temperature, pressure, relative humidity, wind speed and direction twice a day at 0000 (0800) and 1200 UTC (2000 BJT) (Figure 2).

Previous intercomparison studies (e.g., Bian et al., 2011) indicate that the two types of radiosondes, i.e., Vaisala RS80 and GTS1, agree very well in the profile measurements in the troposphere (including PBL), albeit the large biases in the upper atmospheric levels. Therefore, the data from radiosondes of GTS1 are good enough to derive BLH for the superior performance in PBL.

The sounding data collected from January 1, 2011 to July 31, 2015 are used here to obtain the BLH at widely scattered radiosonde network across China. In total, we have made use of 391,552 profiles across China, including 1,578 profiles at 0200 BJT, 190,027 profiles at 0800 BJT, 10,313 profiles at 1400 BJT, and 189,634 profiles at 2000 BJT. In summer (the monsoon season), up to two additional soundings are launched occasionally at 0600 UTC (1400 BJT) and 1800 UTC (0200 BJT) during certain intensive observing periods at selected stations. The fine-resolution sounding observations provide essential information to investigate the diurnal structure of PBL.

In addition to the CMA sounding observations, the simultaneous profiling data of temperature and wind from ERA-Interim reanalysis (Dee et al., 2011) are also used to derive BLH in this study. The

ERA-Interim reanalysis assimilates a variety of measurements, including radiosonde observations at highly discrete levels (the so-called standard sounding levels), into weather prediction models in a physically consistent manner. The horizontal resolution of ERA-Interim reanalysis is 0.75 degree. In the vertical, there are 60 layers using hybrid coordinates that extend from the surface to the top of 0.1 hPa level, with 21 layers between the surface and 5 km above ground level (AGL). The vertical resolution is about 20 m near the surface, and gradually decreases to about 200 m at 900 hPa level and 500 m at 500 hPa level.

Similar to the methods used by Seidel et al. (2012) to investigate the characteristics of BLH climatology in the United States and Europe, the bulk Richardson number (Ri) method (Vogelezang and Holtslag, 1996) was taken to simultaneously estimate the BLH from CMA soundings and ERA-Interim data. The Ri method has been proved to be one of the best methods for BLH climatology analysis, since it is suitable for both stable and convective boundary layers and can be applied to large amount of radiosonde and reanalysis data (Seidel et al., 2012). Ri is defined as the ratio of turbulence associated with buoyancy to that induced by mechanical shear, which is expressed as

$$Ri(z) = \frac{(g/\theta_{vs})(\theta_{vz}-\theta_{vs})(z-z_s)}{(u_z-u_s)^2+(v_z-u_s)^2+(bu_*^2)} \quad (1)$$

where z denotes height above ground, s the surface, g the acceleration due to gravity, θ_v virtual potential temperature, u and v are the component of wind speed, and u_* the surface friction velocity. u_* can be ignored here due to the much smaller magnitude compared with bulk wind shear term in the denominator (Vogelezang and Holtslag, 1996). [Similar to the study of Seidel et al. \(2012\), the lowest](#)

level z at which interpolated Ri crosses the critical value of 0.25, is referred to as BLH. Note that the Ri is dimensionless, and itself says nothing to do with about the intensity of turbulence, but it can tell determine whether the turbulence exists or not. Previous theoretical and laboratory studies research (e.g., Stull, 1988) suggested that when Ri is smaller than the critical value (~ 0.25), the laminar flow becomes unstable. (Stull, 1988). Thus, the lowest level z at which interpolated Ri crosses the critical value of 0.25 is referred to as BLH in this study, similar to the study criteria used by of Seidel et al. (2012). A case in point for the BLH derived from sounding profiles in Beijing (116.47°E, 39.80°N, 32m a.s.l.) is presented in Figure Fig. 2. For purposes of simplicity and clarity, the BLHs derived from CMA soundings and ERA-Interim reanalysis are referred to as CMA-BLH and ERA-BLH hereafter, respectively. Unless noted otherwise, all the values of BLH are presented with reference to the height above ground level, rather than that above sea level, to rule out the impact of topographic variation.

For the intercomparison between ERA-BLH and CMA-BLH, all profiles from reanalysis have been sampled at 9 grid points centered at the radiosonde locations. Meanwhile, the ERA-Interim reanalysis data were sampled at 0000 (0800), 0600 (1400), 1200 (2000), and 1800 UTC (0200 BJT) to match the radiosonde observation times. Using instantaneous BLH estimates from the radiosondes and ERA-Interim, we computed seasonal-averaged (DJF, MAM, JJA, and SON) 5th, 25th, 50th, 75th, and 95th percentile BLH values for each station or grid point investigated, separately for 0200, 0800, 1400, and 2000 BJT.

3. Uncertainty analysis

Since the selection of critical Ri may bring uncertainty to the estimated BLH from the bulk Ri method as shown in Eq. (1), one case study has been carried out based on the 2000 BJT 03 August 2012 radiosonde observation at Beijing site. The BLHs for differing critical values of 0.2, 0.25, and 0.3 were then derived in attempt to quantify the uncertainties. As illustrated in ~~Figure~~^{Fig.s} 2, the difference among the BLHs computed using different critical Ri can be hardly recognized, although the BLH of Ri = 0.3 seems slightly higher.

In the spirit of overall evaluation of the ensemble BLH estimations, scatter plots have been made to show CMA-BLHs computed using 0.2 and 0.25 as critical Ri, versus using 0.25 and 0.3 as critical Ri. As expected, the CMA-BLHs of Ri = 0.3 (0.2) are generally higher (lower) than those of Ri = 0.25, however, the CMA-BLH based on various Ri is significantly correlated with each other ($R = 0.99$). Figures 3c-~~and~~3d present the uncertainties as a function of BLHs (Ri = 0.25). It is found that the 50th and 75th percentile values of the absolute uncertainties are < 0.05 km and < 0.1 km, respectively; and the 50th and 75th percentile values of the associated relative uncertainties are both $< 5\%$ for BLH (Ri = 0.25) > 2 km, and $< 15\%$ for BLH (Ri = 0.25) < 2 km. As such, the uncertainty caused by the selection of critical value is quite small.

4. Results and discussion

This section presents the basic BLH climatologies from the CMA radiosondes and ERA-Interim, including seasonal and diurnal variations. Intercomparisons of climatological results from radiosonde

observations with the ERA-Interim are made to better elucidate the BLH characteristics in China. Finally we will explore the potential influences of meteorology on the observed annual cycle of BLH.

4.1 Overall climatological pattern

5 | Figures 4a-4b present the frequency distributions of CMA-BLH at 0800 and 2000 BJT. At 0800 BJT, almost all the CMA-BLHs are lower than 1 km, with a mean value of merely 0.19 km. The CMA-BLHs at 0800 BJT are typically lower than those at 2000 BJT.

10 | The frequency distributions of summertime CMA-BLH at four observed times (0200, 0800, 1400, and 2000 BJT) are also illustrated in Figures 4c-4d. During a diurnal cycle, the CMA-BLH peaks in the afternoon (1400 BJT), with a mean value of 1.25 km. After sunset, the daytime convective boundary layer undergoes a transition into the nocturnal stable boundary layer. The soundings of 2000 BJT provide information about the transition state, and the soundings of 0200 BJT capture the nocturnal boundary layer. In the next morning (around 0800 BJT), after sunrise the PBL experiences another transition to the convective boundary layer.

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4.2 Seasonal variation of CMA-BLH and ERA-BLH and their intercomparison

Since only the soundings of 0800 and 2000 BJT are launched conventionally, the seasonal variation of BLH is mainly investigated at these two moments (Figure 5). At 2000 BJT, the CMA-BLH generally follows a downward trend from spring to winter (Figure 5b), that is, spring > summer >

fall > winter. The climatologically strongest near-surface wind speed [in most of China](#) in spring (Guo et al., 2011; Zhao et al., 2009) and the intense solar radiation in summer (Miao et al., 2012, 2015), which favor the development of boundary layer during these two seasons. In spring, the mean value of CMA-BLH is ~0.71 km, which is slightly higher than that of summer (~0.65 km) [but can occasionally exceeds](#) 2 km (95th percentile value) in spring and summer.

In contrast, in fall and winter, the mean values of CMA-BLH are merely ~0.32 km, which are significantly lower than those of spring and summer. Such a huge difference of the seasonally averaged CMA-BLH between the warm seasons (spring and summer) and cold seasons (fall and winter) at 2000 BJT is well captured by the ERA-BLHs, although the ERA-BLHs tend to underestimate the springtime BLHs, and overestimate that of summer ([FigureFig. 5b](#)). The scatter plots of seasonally averaged CMA-BLHs and ERA-BLHs ([FigureFig. 6](#)), demonstrate the close correspondence between these two kinds of BLH, and give confidence that the seasonally averaged ERA-BLHs can be used as an alternative when the CMA soundings are unavailable. [It is interesting to note that at 0800 BJT the CMA-BLH of spring is not generally higher than that of summer although the near-surface wind speed is stronger in spring for both 0800 BJT and 2000 BJT \(Figs. S1-S2 in Supplement\); This-which is most likely due to caused by the stronger near-surface stability in spring \(Fig. S3\), which-that to some extent inhibits the development of PBL-\(Figure S1\).](#)

In terms of the spatial distributions of BLHs, there exists solar radiance difference received at various stations or grid points across China due to the large spatial range. For a sounding observation at a given

time (e.g., 0200, 0800, 1400, 2000 BJT), zonal evolution of BLHs have to be considered from the perspective of actual solar radiance received at the given area.

The spatial distributions of seasonally averaged CMA-BLHs and ERA-BLHs at 0800 BJT are presented in [Figure 7](#). At 0800 BJT, due to [the stronger](#) solar radiation in eastern China than that of western regions, higher BLHs can be distinctly seen over the eastern regions ([Figure 7](#)). This BLH spatial pattern is more prominent in spring and summer than in fall and winter ([Figures 7a-b](#)). Comparing with the BLHs at 2000 BJT, it is found that the BLHs of 0800 BJT are generally lower ([Figures 4a and 5](#)), and the seasonal variation of BLH is weaker. Despite these differences, the BLHs of 0800 BJT show a similar seasonal variation, that is, higher BLHs are in spring and summer. [It is also interesting to note that the highest ERA-BLH at 0800 BJT over the Northern Tibet Plateau \(TP\) region is in winter \(Figure 7\), which may be caused by the strongest near-surface wind over the Northern TP region \(Figure S42\). Since there is no available sounding observation in the northern TP region, the seasonal variation of ERA-BLH in this region cannot be characterized in this study, which needs further field campaign validation.](#)

As illustrated in [Figure 8](#), both CMA-BLHs and ERA-BLHs at 2000 BJT demonstrate a strong east-to-west BLH gradient in the warm seasons (spring and summer), with higher BLHs over the western China ([Figures 8a-b](#)). The BLH spatial pattern may be caused by the different solar radiation in the west (stronger radiation at an earlier Local Sidereal Time) and east of China at 2000 BJT.

In fall, it is interestingly to note that the east-to-west gradient of BLH is less prominent (FigureFig. 8c). Likewise, the BLHs during winter in most regions of China are less than 0.3 km, except for the Tibet Plateau, in which the BLHs can exceed ~0.5 km at 2000 BJT.

Since the soundings of 0200 and 1400 BJT are only launched in summer, the seasonal variation of BLH at these two moments cannot be investigated by using the CMA-BLH alone. Therefore, the seasonal variations of BLH at 0200 and 1400 BJT are roughly evaluated by using the seasonally averaged ERA-BLHs. It is found that at 1400 BJT the ERA-BLHs in spring and summer are higher than those of fall and winter (FigureFig. 9). At 0200 BJT, most plain regions of China are covered by a relatively shallow boundary layer, without significant seasonal variation (FigureFig. 10).

4.3 Diurnal variation of BLH

In summer, four times per day (i.e. 0200, 0800, 1400, and 2000 BJT) soundings are available at most of the radiosonde sites, which allows us to investigate the summertime diurnal variation of BLH (FigureFig. 11a).

With the intense solar radiation in summer, the boundary layer is more fully developed during the daytime. At 1400 BJT, more than half of the seasonally averaged CMA-BLHs are higher than 1 km (c.f., FigureFigs. 9b and 11a). Both the CMA-BLH and ERA-BLH demonstrate a south-to-north gradient of BLH, with higher BLH over the dry northern regions (FigureFig. 9b), implying that the hydrologic

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factors such as humidity, in addition to solar radiation, may play a role in modulating the spatial distribution of daytime BLH (Seidel et al., 2012).

After sunset, the convective boundary layer undergoes a transition to the nocturnal stable boundary layer. Since the LST is earlier in the west of China than the east (15° longitude is equivalent to a one-hour change in time), the evening transition of boundary layer structure is well manifested by the east-to-west gradient of BLH at 2000 BJT (FigureFig. 8b), although the effects of elevation on the spatial distribution of BLH cannot be ignored. During the nighttime, the BLH is less than 0.3 km over most China (Figures. 10b and 11a). Comparing the BLH at 0200 BJT with that of 1400 BJT, it is found that diurnal amplitude of BLH is stronger in the north and west of China.

Similar to the spatial distribution of BLH at 2000 BJT, the BLH at 0800 BJT demonstrates the transition from nocturnal boundary layer to convective boundary layer (FigureFig. 7b), characterized by a west-to-east BLH gradient.

With the ground-based cloud cover observations obtained simultaneously at the same sounding sites, the effects of cloud cover on the diurnal evolution of BLH in summer are investigated as well. As illustrated in FigureFig. 11b, during the daytime the development of PBL is typically suppressed due to the less solar radiation received at the surface under cloudy condition. As a result, at 1400 BJT, the 25th, 50th and 75th percentile values of BLHs decrease by around 0.3 km. And the higher mean and 75th percentile values of BLHs under clear condition also could also be observed at 2000 BJT and 0200 BJT, which may be relevant to the larger heat storage of land surface. In contrast, a slightly thicker boundary

layer could be formed in the early morning under cloudy conditions, which may be caused by the stronger atmospheric counter radiation processes.

Using the ERA-BLH as an alternative, the diurnal variations of BLH in the other three seasons are presented in the supplementary materials (Figures S531-S753). It is found that the diurnal variation of BLH in spring (Figure S531) is comparable to that of summer, while the diurnal variation of BLH in fall (Figure S642) is less prominent. In winter (Figure S753), due to the weak solar radiation, the development of BLH over the plains of eastern China is severely suppressed, leading to the weakest diurnal variation of BLH during the four seasons over the plains regions.

4.4 Association of BLHs with related meteorological variables

As a preliminary effort to explore the potential influence of meteorology on the observed annual cycle of BLH, we turned to ground-based weather observations and soundings that are simultaneously obtained from sites shown in Figure 1. In particular, the association of CMA-BLH with four other atmospheric variables was evaluated using correlation analyses, including surface pressure, 10-m wind speed, near-surface temperature, and lower tropospheric stability (LTS). The LTS is defined as the difference in potential temperature between 700 hPa and the surface pressure (Slingo, 1987), which can be used to describe the thermodynamical state of the lower troposphere (Guo et al., 2016).

For instance, Figure 12 compares the annual cycles of CMA-BLH with these four meteorological variables in Beijing. The annual cycles of CMA-BLHs at 0800 and 2000 BJT are quite similar. In other

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words, both CMA-BLHs peak in May, and reach the minimum in October. The annual cycle of CMA-BLH is anti-correlated with the annual cycle of surface pressure (~~Figure~~Fig. 12a), implying that the seasonal shift of large-scale high/low pressure systems can suppress/facilitate the development of boundary layer through the associated large-scale ~~de~~ascending motion (Liu et al., 2013; Medeiros et al., 2005). The annual cycle of BLH is positively correlated with the annual cycle of near-surface wind speed and temperature (~~Figures.~~ 12b-12c). In addition, the annual cycle of CMA-BLH is anti-correlated with the variation of LTS (~~Figure~~Fig. 12d). Comparing with the near-surface temperature, the variation of LTS is in closer correspondence to the annual cycle of BLH.

Extending this analysis to the full set of radiosonde stations analyzed, Figure 13 presents the correlations among these variables at 0800 and 2000 BJT. ~~Overall, results obtained at~~The most sites in China are consistent with ~~the results those at~~ from Beijing. ~~Specially~~In particular, the annual cycle of CMA-BLHs is anti-correlated with the variation of surface pressure and LTS (~~Figures.~~ 13a, 13b, 13g, and 13h), and positively correlated with near-surface wind speed and temperature (~~Figure~~Figs. 13c-13f). Generally, the correlations are closer at 2000 BJT, ~~a~~. ~~And~~ the correlations are weaker ~~at~~in some sites close to the southern coasts and the east of Tibet Plateau, probably due to the modulation of local geographical effects (Stull, 1988). The positive/negative correlations derived from the annual cycle of CMA-BLHs and these four meteorological parameters, can also be obtained based on the monthly mean values of CMA-BLHs and meteorological parameters (Figures. S86 and S-S97).

5. Concluding remarks

As the first ~~attempt effort to obtain~~ obtain compile the climatology of icala sounding-based BLH climatologys in China, we have made an extensive use of sounding data from the L-band radiosonde network operated and maintained by CMA from January 2011 to July 2015. The CMA-BLHs were also compared with coincident ERA-BLHs using the same bulk Richardson number method.

The mapping of BLH for the first 41 months of new-generation radiosonde network provides considerable insight into the large-scale spatio-temporal variations of boundary layer characteristics across China with continuous radiosonde data studied to date. Previously unknown facts about the boundary layer across whole China were first discovered. A complex pattern of the boundary layer has been revealed, exhibiting strong geographical, diurnal, and seasonal variations, corroborated by BLHs derived from ERA-Interim. There are substantial influences by elevated terrain features and major land-water boundaries. The association of BLH with solar radiation is a compelling relationship when examining the results for the first 4 years of operation of radiosonde network.

The sounding observations at 0800 and 2000 BJT show that the BLH of spring and summer is generally higher than that of fall and winter. This annual cycle of BLH at most sites is found to be anti-correlated with the annual cycle of surface pressure and LTS, and positively correlated with the near-surface wind speed and temperature. These correlations are stronger at 2000 BJT.

At 2000 BJT, the spatial distribution of CMA-BLH exhibits a pronounced east-west gradient of BLH, and a reversed BLH gradient is presented at 0800 BJT. These spatial patterns of BLH in the early evening and early morning are likely caused by the differing magnitudes ofent solar radiation in the

west (at an earlier Local Sidereal Time) and east of China. The comparison of seasonally averaged CMA-BLH and ERA-BLH at 0800 and 2000 BJT shows good agreement. The seasonal, and spatial variation of CMA-BLH at these two observation times are generally well reproduced by ERA-Interim reanalysis, although the ERA-Interim reanalysis tends to overestimate the BLH in spring and underestimate the BLH in summer.

The climatological diurnal cycle of BLH, revealed by the four-times-daily sounding in summer, shows that BLH peaks in the afternoon and diurnal amplitude of BLH is higher in the north and west of China. Comparing with other seasons, it is found that the diurnal variation of BLH is typically stronger in spring and summer than in fall and winter.

The climatological features of BLH in China revealed here have important implications for better understanding the formation mechanism of aerosol pollution, cloud and even extreme precipitation in China. In the near future, other algorithms for deriving BLH merit a more comprehensive test based on the radiosonde network of China, apart from further scrutiny for the sources of uncertainty with regard to the data and methods applied in this study.

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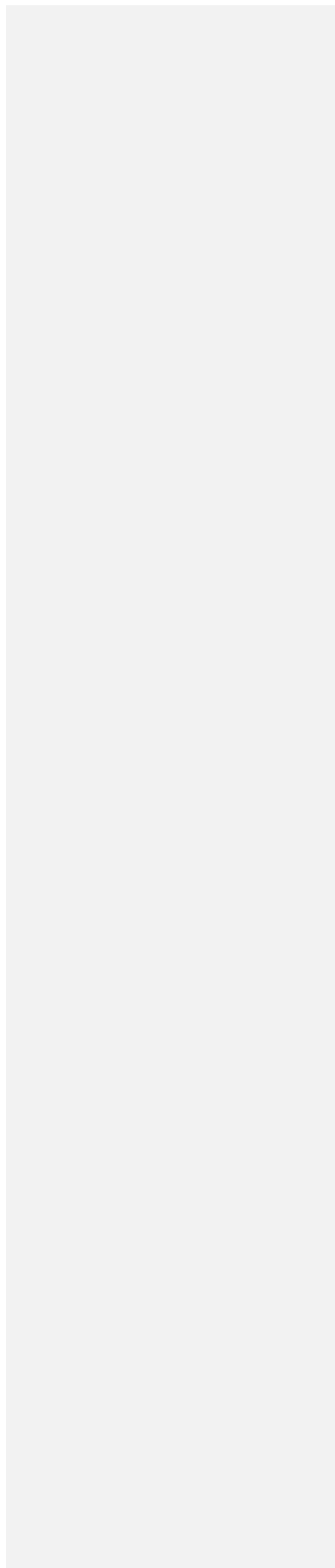
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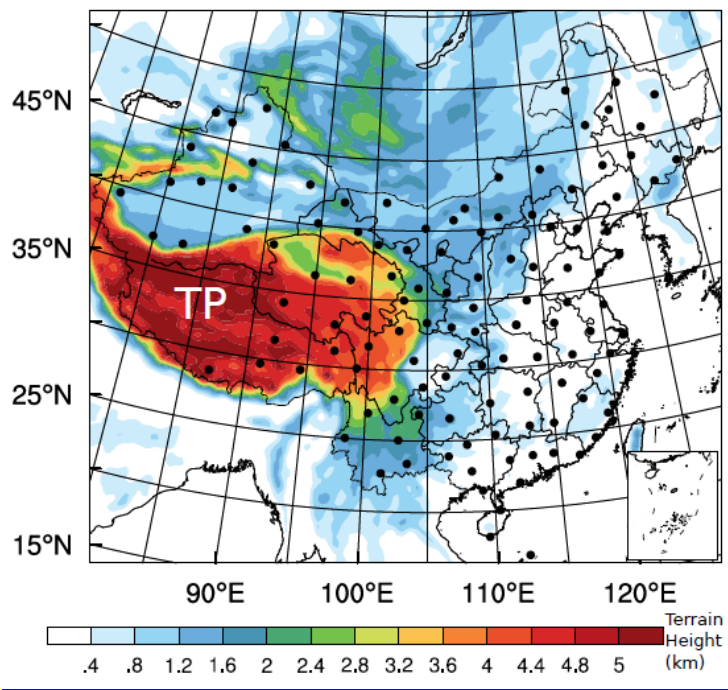
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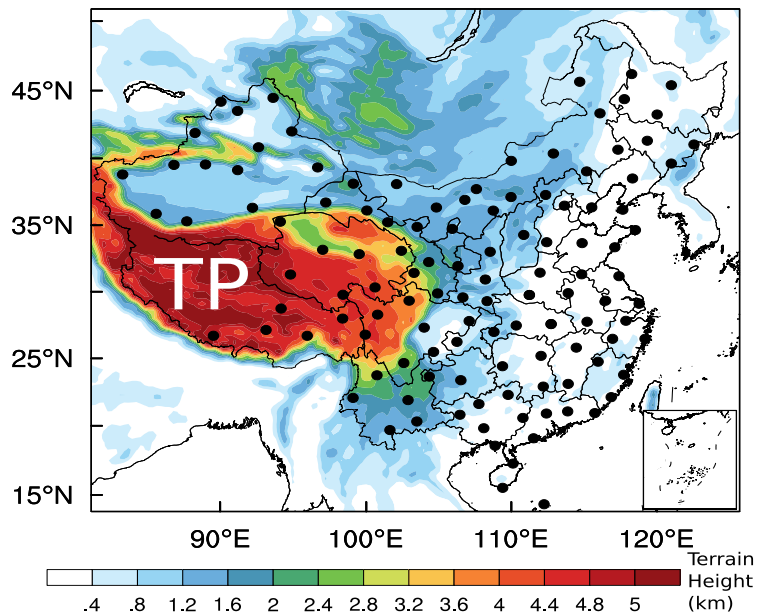


Figure 1. Spatial distribution of CMA sounding sites (black dots), overlaid over the terrain height (color shaded) of China. The white “TP” indicates the location of Tibet Plateau. [This figure was plotted by using the Lambert-conformal map projection.](#)

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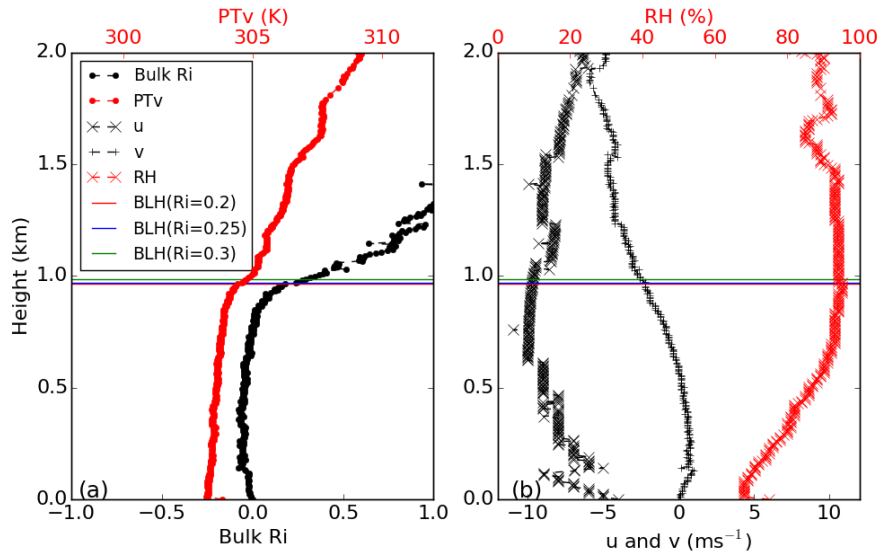


Figure 2. Vertical profile of (a) virtual potential temperature (PTv), bulk Richardson number (Ri), (b) wind speed (U and V), and relative humidity (RH) based on the 2000 BJT 03 August 2012 radiosonde observation at Beijing. The horizontal lines indicate boundary layer heights (BLH) computed using 0.2 (red), 0.25 (blue), and 0.3 (green) as critical bulk Richardson number.

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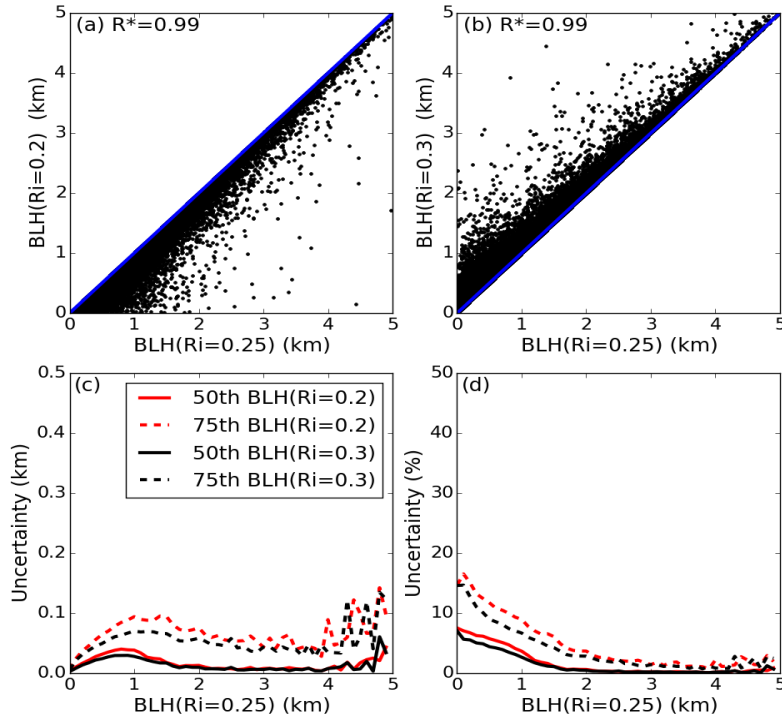


Figure 3. Scatter plots showing (a) CMA-BLHs computed using 0.2 and 0.25 as critical Ri, and (b) CMA-BLHs computed using 0.25 and 0.3 as critical Ri, both of which are based on 391552 soundings across China from January 2011 to July 2015. The 50th and 75th percentile values of (c) absolute uncertainty and (d) relative uncertainty using 0.2 and 0.3 as critical Ri are shown as well. The correlation coefficients (R) are given in the top panels, where the star superscripts indicate that values are statically significantly ($p < 0.05$).

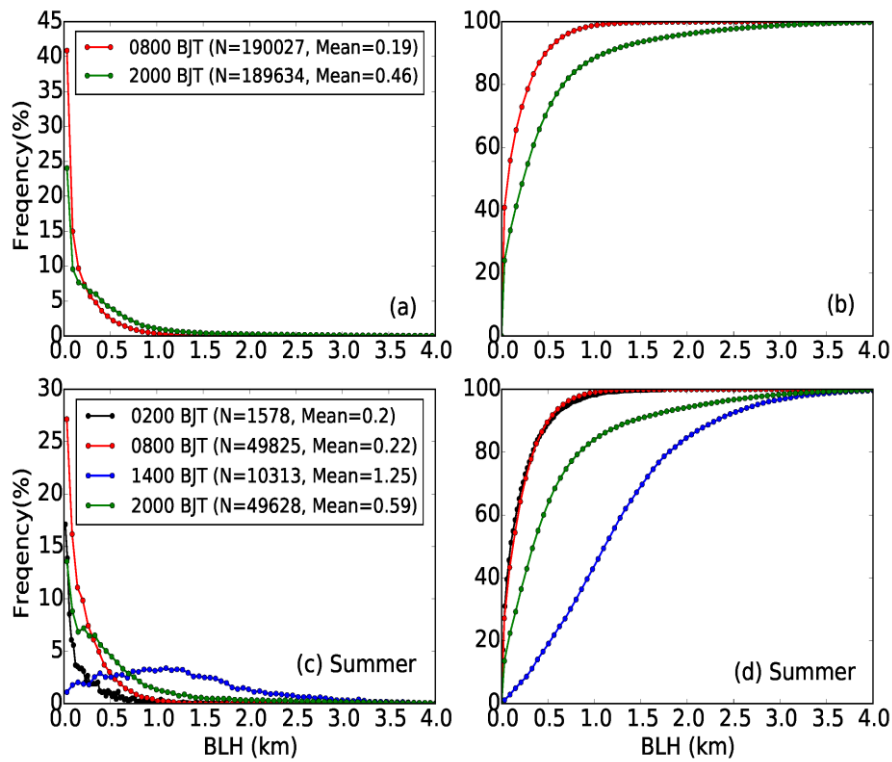


Figure 4. Frequency distribution (left) and cumulative frequency distribution (right) of CMA-BLH at 0200 (in black), 0800 (in red), 1400 (in blue) and 2000 BJT (in green) during (a, b) the whole period and (c, d) the summertime from January 2011 to July 2015. The number of soundings (N) and mean value at each observed time are also

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given. Noted that the soundings at 0200 and 1400 BJT are occasionally launched during certain intensive observation periods in summer.

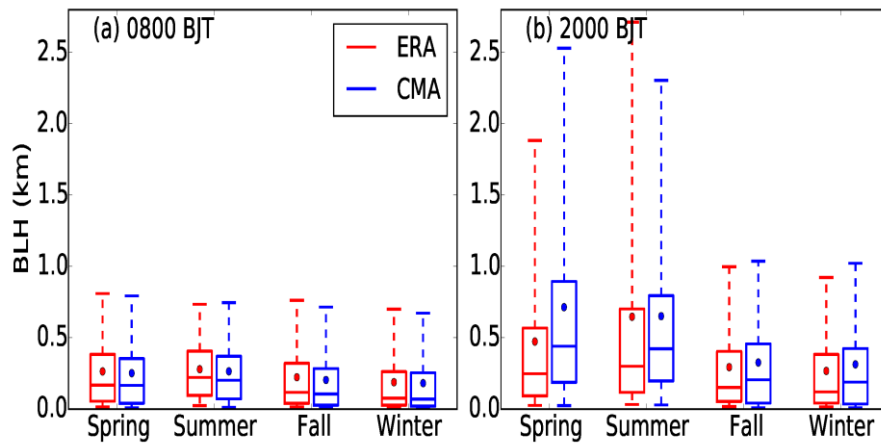


Figure 5. Box-and-whiskers plots showing the 5th, 25th, 50th, 75th, and 95th percentile values of ERA-BLH (in red) and CMA-BLH (in blue) during each season at (a) 0800 BJT and (b) 2000 BJT during the period from January 2011 to July 2015. The dot in the each box indicates the mean value of BLHs. Note that there exists larger uncertainty for the evening BLH climatologies in (b).

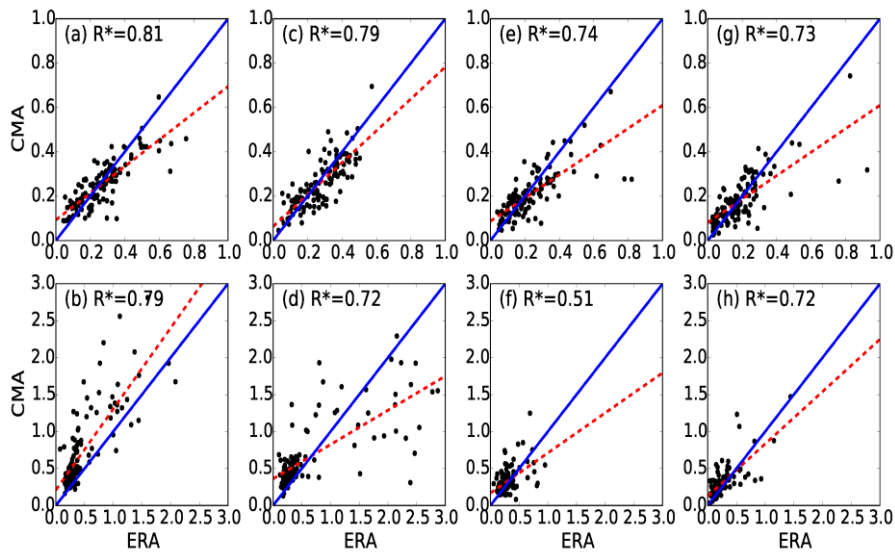


Figure 6. Scatter plots of the seasonally averaged CMA-BLH and ERA-BLH at (top) 0800 and (bottom) 2000 BJT in (a, b) spring, (c, d) summer, (e, f) fall, and (g, h) winter. The correlation coefficients (R) are given in each panel, where the star superscripts indicate that values are statically significantly ($p < 0.05$).

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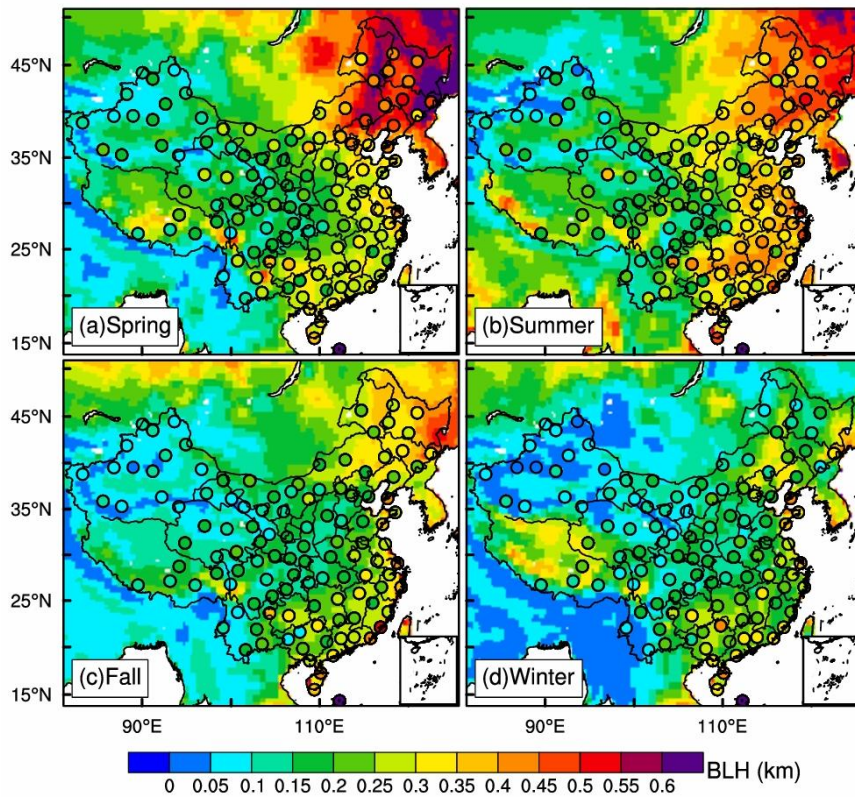


Figure 7. Spatial distributions of the seasonal mean of ERA-BLH (color shaded) and CMA-BLH (color dots) at 0800 BJT in (a) spring, (b) summer, (c) fall, and (d) winter.

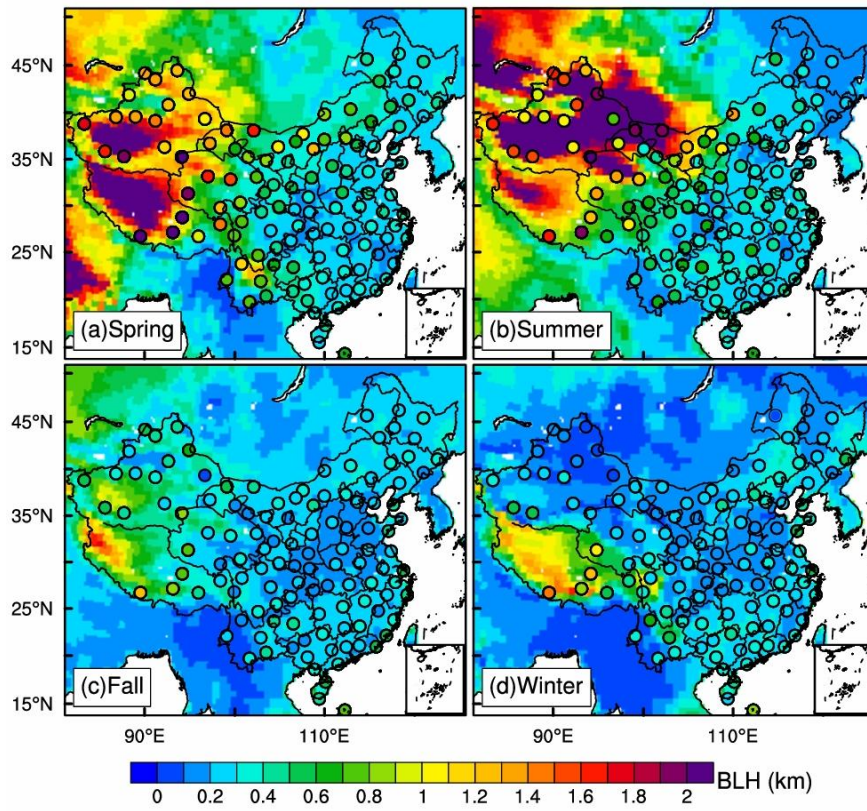


Figure 8. Same as in Figure 7, but for the spatial distribution of BLHs at 2000 BJT.

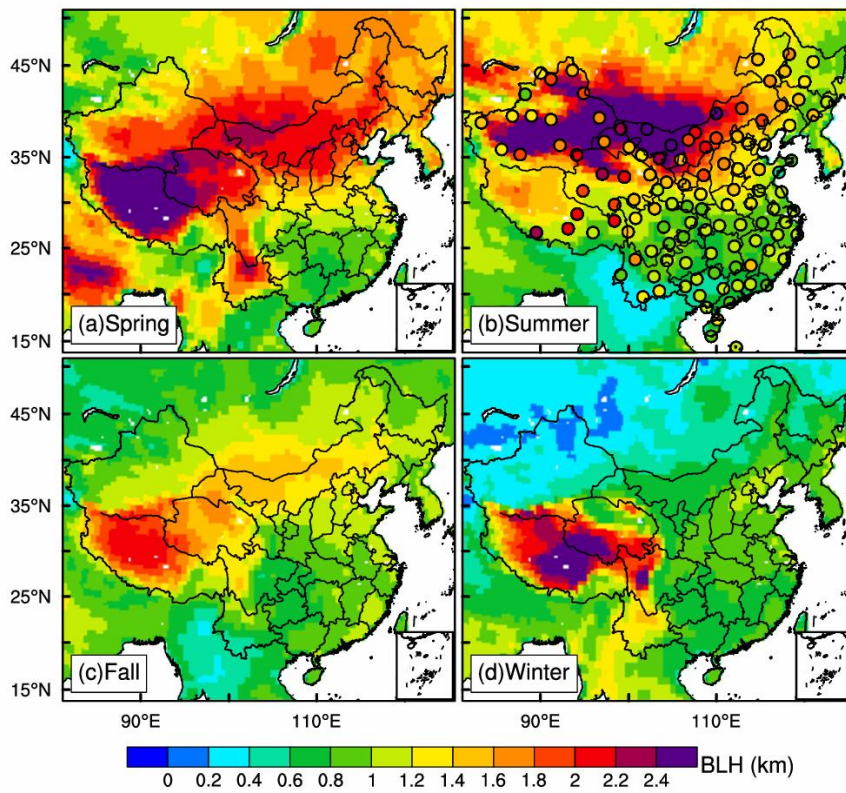
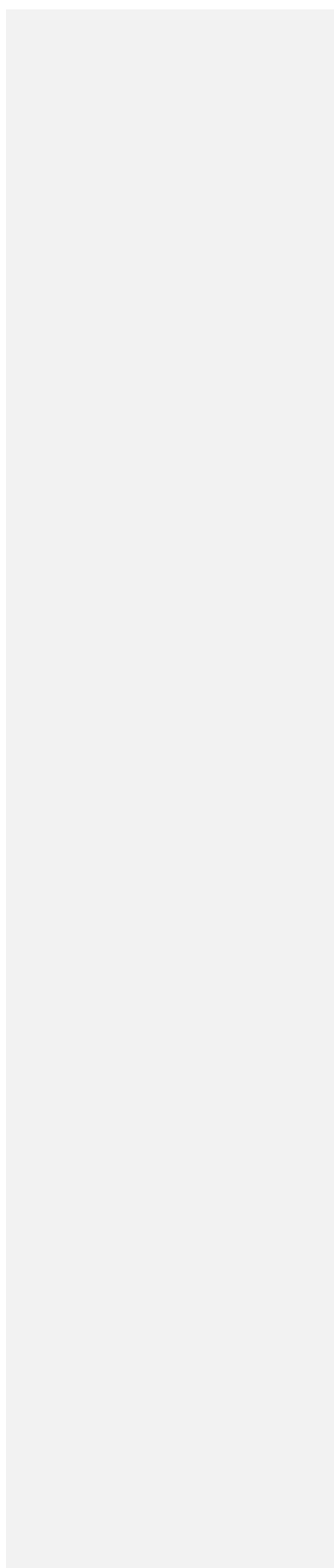
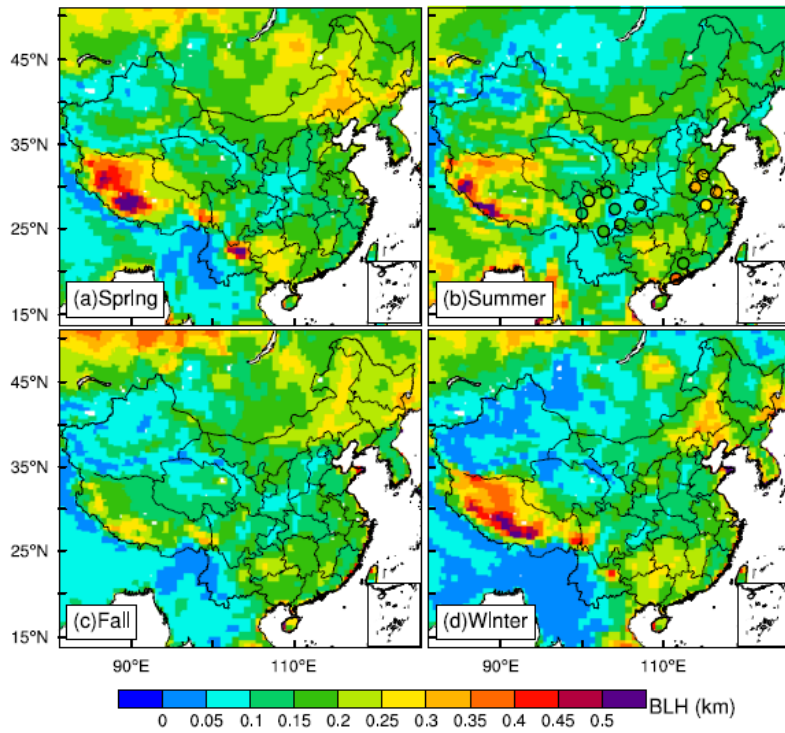


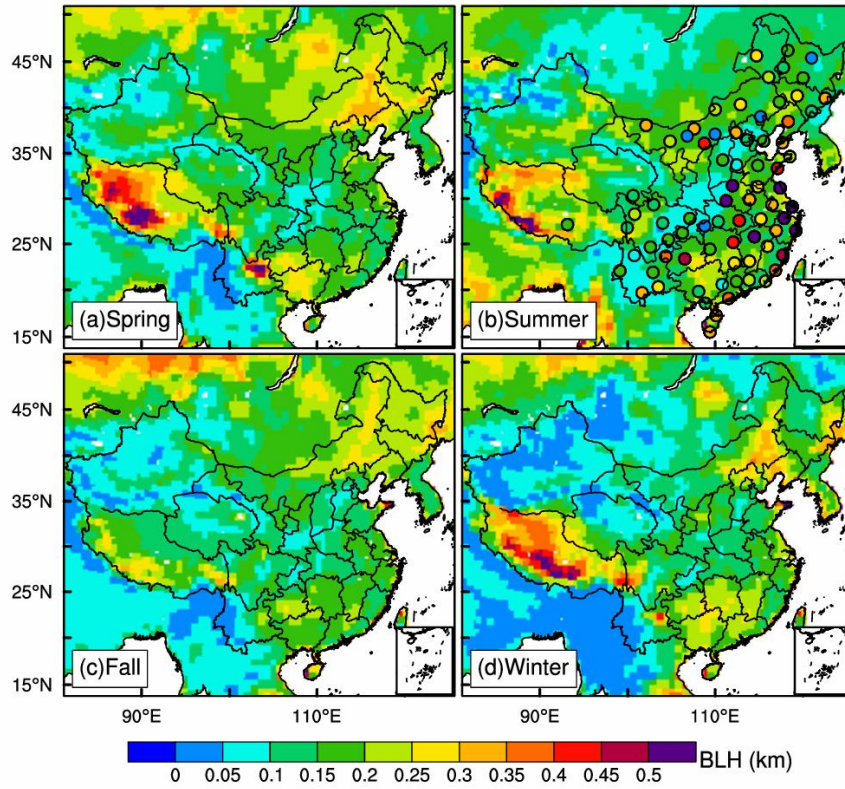
Figure 9. Same as Figure 7, but for the spatial distribution of BLHs at 1400 BJT.

Note that only the stations have more than 30 soundings are plotted in (b).





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Figure 10. Same as in Figure 7, but for the spatial distribution of BLHs at 0200 BJT.

Note that only the stations have more than 30 soundings are plotted in (b).

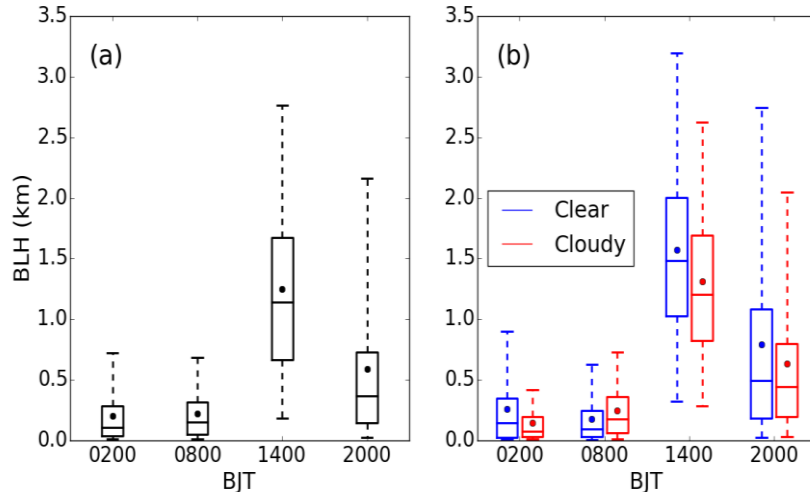


Figure 11. (a) Box-and-whiskers plots showing the 5th, 25th, 50th, 75th, and 95th percentile values of CMA-BLH at 0200, 0800, 1400, and 2000 BJT in summer based on all the summertime soundings in China. (b) Box-and-whiskers plots showing CMA-BLH in summer under clear (total cloud cover $\leq 20\%$, in blue) and cloudy (total cloud cover $\geq 80\%$, in red) conditions. Note that the rainy days are not considered in (b).

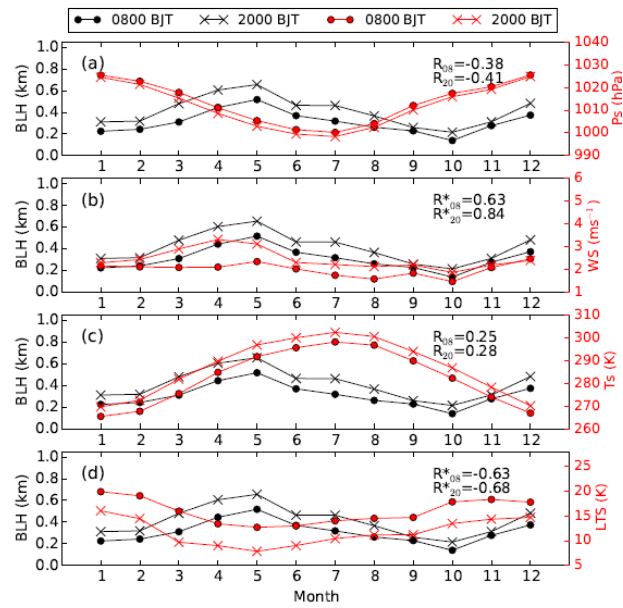
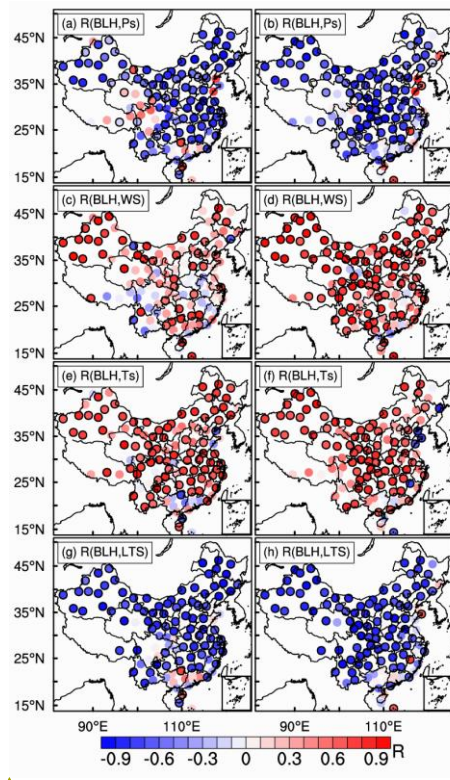


Figure 12. Climatological mean annual cycle of CMA-BLH at Beijing (39.8°N, 116.47°E) at 0800 BJT (dot symbols) and 2000 BJT (x symbols), respectively, as superimposed by the counterparts of meteorological parameters, including (a) surface pressure (Ps), (b) 10-m wind speed (WS), (c) near-surface temperature (Ts), and (d) Lower Tropospheric Stability (LTS). The correlation coefficients at 0800 (R_{08}) and 2000 BJT (R_{20}) between of CMA-BLH and meteorological parameters are given in each panel as well, and the star superscripts indicate the values that are statistically significant ($p < 0.05$).

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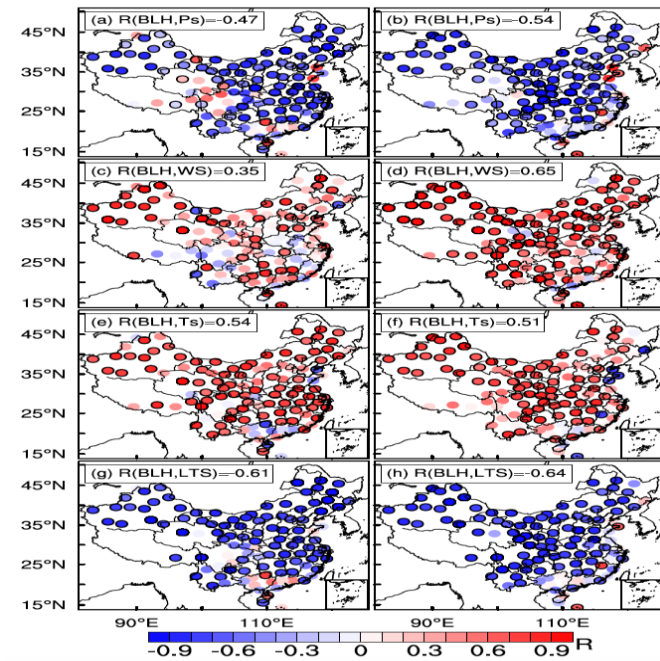


Figure 13. Correlations (R) between mean annual cycles (12 monthly values) of CMA-BLH and (a, b) surface pressure (Ps), (c, d) 10-m wind speed, (e, f) near-surface temperature (Ts), (g, h) Lower Tropospheric Stability (LTS), at 0800 (left panels) and 2000 BJT (right panels). Symbols outlined in

black indicate values that are statistically significant ($p < 0.05$), and the overall mean R is given for each panel as well.

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