Authors' Response to Referees' Comments

Anonymous Referee #1:

Comments on "Planetary boundary layer height from CALIOP compared to radiosonde over China"

General Comments

The planetary boundary layer height (PBLH) is an important length scale in weather, climate and air pollution models. The CALIOP-derived PBLHs can construct the PBLH climatology on a global scale. The problem is that the validity of CALIOP-derived PBLH should be examined and the uncertainties of CALIOP-derived PBLH should be known. In this paper, the authors compared the CALIOP-derived PBLH to the radiosonde-derived PBLH in China. The results suggest that they agree very well. The authors also analyzed the difference in the PBLHs derived from the two methods, and showed the spatial distribution of deviations. The results in this paper can help to understand the applicability of CALIOP-derived PBLH in China, and provide the basic information for further investigations. However, some details of the dataset should be further specified, and the English writing should be further improved. Therefore, I recommend the manuscript for publication in ACP, pending minor revisions.

Response：We are very grateful to referee #1 for his/her positive comments on our work, which are quite constructive and helpful. All of these comments 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 author declare that the method of Sawyer and Li (2013) was used in this study (in page 6 line 9-10). I suggest that the authors should give a concise introduction of this method, so that the readers can understand how the PBLH is derived from CALIOP in this paper rather than the cited paper. Is this method also applied to the radiosonde data to derive the PBLH? Because the measurement time is almost at noon, the potential temperature profile should exhibit the typical structure of convective BL. Thus the method of maximum potential temperature gradient is suitable for determining the PBLH. Why not use the maximum gradient method? The authors should explain the reason.

Response：Per your kind suggestions, we gave an concise introduction of this method of Sawyer and Li (2013) in section 2.1 of this revision by adding the following sentences:

"By combining wavelet covariance and iterative curve-fitting, Sawyer and Li (2013) developed a novel algorithm (hereafter called SL2013), which can be applied to robustly derive PBLHs from both radiosonde and lidar measurements due to the fact that prior knowledge of instrument properties and atmospheric conditions has been considered. The measurement time of our study is almost at noon, the potential temperature profile more often than not exhibit the typical structure of convective BL. However, due to the potential uncertainties caused by the sensitivity of vertical resolution, and the wide range of sounding time (local time) at different sites across China, SL2013 tends to exhibit advantages over the method of maximum potential temperature gradient. This is most likely because SL2013 is flexible and simple enough for automatic analyses of long-term sounding data at multiple sites, and is able to compensate for noisy signals and low vertical resolution in the soundings. Therefore, SL2013 has been applied to extract PBLHs from radiosonde observations."

2. The derived PBLH should be the height above the ground. However, shown in Fig. 2, the derived PBLH is above the sea level. Is the terrain height derived from CALIPSO or obtained from other data source? The authors should specify this issue. As shown in Fig. 2, the terrain surface is not very clear in some places.

Response: We totally agree with you, so we redrew Fig.2 (i.e., Fig.R1 as below). In the figure caption, we described PBLHs as altitude above ground level. The terrain height is directly extracted from CALIOP. Meanwhile, we added in Fig.2 a gray line to better indicate the terrain height clearly.

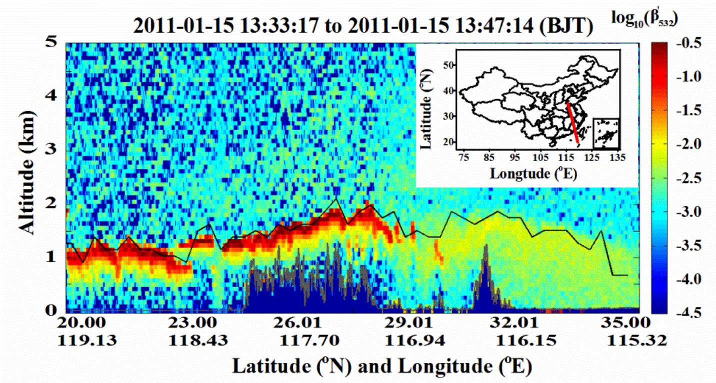

Fig. R1. Curtain plot of attenuated backscatter coefficient as observed from CALIOP aboard CALIPSO on 15 January 2011. The black line indicates the derived PBLH (above ground level) and the grey line immediately on top of the blue region represents the terrain surface (directly from CALIOP data). The red line in the inlet map corresponds to the ground track of CALIOP/CALIPSO over southeastern China.

3. In page 9 lines 3-4, the authors state "Note that over regions where BL is not convective the retrieved values are not representative of the PBLH (Liu and Liang, 2010)". Also in this section (Section 2.3), the authors describe the method how to eliminate the effects of clouds on the CALIOP-derived PBLH. In other words, the CALIOP data in clear days are used to derive the PBLH, and the BL should be convective. Moreover, the passing time of CALIPSO is 13:30 BJT. Thus

it can be expected that the PBLH at this times not very low. However, Table 1 shows that the minimum PBLHs in different seasons are 0.2-0.4 km. I think these values are unbelievable. On the other hand, Table 1 shows that the maximum PBLHs in different seasons are 4-6 km with the largest value in winter. I think these values are also unbelievable. It is likely that uncertainties are introduced in the CALIOP-derived PBLH. Then the problem, to what extent the CALIOP-derived PBLH over China is reasonable, arises. I suggest the author discuss this problem and provide additional information about the statistics of the CALIOP-derived PBLH. For example, by setting the reasonable range of PBLH based on the up-to-date knowledge, the percentage of the derived PBLHs that are in this range can be calculated and compared.

Response：Thanks for pointing this out. Due to the increasingly polluted atmosphere in China, more stable boundary layers have been frequently observed (e.g., Quan et al., 2013; Gao et al. 2015; Miao et al, 2016). This will inevitably lead to retrieved PBLH values that are not representative of the actual PBLH (Liu and Liang, 2010), even though all the CALIOP data are from 1330 LT overpasses. Also, the large uncertainties are most likely due to the algorithm itself used in extracting CALIOP-derived PBLH. To avoid confusion caused by original Table 1, we added the following description in order to provide more information concerning the statistics of CALIOP-derived PBLH in section 3.2:

"As shown in Table 1, we noticed that the maximum PBLHs can reach up to 5-6 km, especially in winter. Therefore, we set the CALIOP-retrieved PBLHs to be within 0.25 and 3km, which seems as a reasonable height range for the midday PBL, highly consistent with the processing methods by McGrath-Spangler (2012). Statistics showed that only 2.1% of all data higher than 3km and 8.8% lower than 0.25km, which have been excluded for further analyses".

Reference:

Gao, Y, Zhang, M, Liu, Z, Wang, L, Wang, P, Xia, X, Tao, M, Zhu, L.: Modeling the feedback between aerosol and meteorological variables in the atmospheric boundary layer during a severe fog–haze event over the North China Plain. Atmos. Chem. Phys., 15(8): 4279–4295, doi: 10.5194/acp-15-4279-2015, 2015.

Liu, S., Liang, X.-Z.: Observed diurnal cycle climatology of planetary boundary layer height. J. Clim., 23, 21, 5790-5809, doi:10.1175/2010jcli3552.1, 2010.

Miao, Y., Liu, S., Zheng, Y., Wang, S.: Modeling the feedback between aerosol and boundary layer processes: a case study in Beijing, China. Environ. Sci. Pollut. Res., 23(4): 3342–3357, doi: 10.1007/s11356-015-5562-8, 2016.

McGrath-Spangler, E.L., Denning, A.S.: Estimates of North American summertime planetary boundary layer depths derived from space-borne lidar. J. Geophys. Res.--Atmos., 117, 2012.

Quan, J., Gao, Y., Zhang, Q., et al.: Evolution of planetary boundary layer under different weather conditions, and its impact on aerosol concentrations. Particuology. 11(1): 34–40, doi: 10.1016/j.partic.2012.04.005, 2013.

4. For the title of Table 1, "seasonal mean" is not accurate. I think, the maximum PBLH, as well as the minimum PBLH, is not the seasonal mean. Maybe "Statistics of the CALIOP-derived PBLH in different seasons" is more accurate. "Standard deviation PBLH" should be "Standard deviation of PBLH". Moreover, the authors should tell the readers how to determine/calculate the values in the table. Is the maximum/minimum PBLH determined as the maximum/minimum value of one grid in the duration or as the average of the maximum/minimum values at every grid in China? Is the standard deviation calculated at every grid and then averaged in China or calculated directly using all the data?

Response：Per your suggestions, we clarified the issues pointed out by you and modified the caption of Table 1 as follows:

"Table 1. Statistics of the CALIOP-derived PBLH in different seasons during the period 2011 - 2014. The mean PBLHs for all the grids are firstly calculated in China,

then the maximum and minimum values of PBLHs are determined by sorting all the mean values. Meanwhile, the mean and standard deviation values of PBLH are determined as the average of mean values at every grid in China."

5. Following above question, Fig. 8 shows that the CALIOP-derived PBLH ranges from 1.2 km to 2.4km. But the statistics in Table 1 show that the CALIOP-derived PBLH varies in a very large range. How many data are not considered in Fig. 8? The authors should specify this issue in the text or in the figure caption.

Response: Thanks for pointing this out. We attempt to clarify as follows:

In Table 1, all PBLHs derived from CALIOP at every grid across China during the period from 2011 to 2014, which exhibit large variation ranging from 0.15km to 6.13km. However, all the cases with PBLHs greater than 3km or less than 0.25km are viewed as unreliable, which are then removed for further analyses in Fig.8. We have to make sure that PBLHs be extracted simultaneously from both radiosonde and CALIOP observations, leading to less valid collocated data pairs. Moreover, the calculated averaged CALIOP-derived PBLH tends to become more concentrated due to the collocation scheme of the radiosonde measurements and CALIOP, as evidenced in Fig.8. As a consequence, in the caption of Fig. 8, we added the following sentence: "Note that the statistic results are only limited to the samples with collocated CALIOP- and radiosonde-derived PBLHs."

6. The authors declare in the abstract "The CALIOP observations belonging to Scenario 2 were found to be better for comparison with radiosonde-derived PBLH, owing to smaller difference between them". Similar statements are found in the conclusion section. However, Fig. 7 shows that the mean difference for Scenario 3 is the smallest. What is the solid evidence for this conclusion?

Response：In order to find more solid evidence to support the argument, we added to the revised manuscript one new figure (Figure 8, i.e., Figure R2 here), which shows the calculated 5th, 25th, 50th, 75th and 95th percentile values of PBLHs derived from

CALIOP and radiosonde for each scenario. As such, to get a comprehensive understanding of the differences existing among various scenarios, the following texts have been added to section 3.4:

"As indicated in Figure 8, Scenario 2 witnesses the least difference of 0.08km between the CALIOP- and radiosonde-median PBLH values in contrast to larger differences of 0.24km and 0.12km for Scenario 1 and Scenario 3, respectively. In addition, the PBLH differences in terms of 25th and 75th percentile values for Scenario 2 are much more indiscernible, as compared with those for other two scenarios. This implies that Scenario 2 gains more advantages over other two scenarios due to the smaller difference between CALIOP- and radiosonde-derived PBLHs."

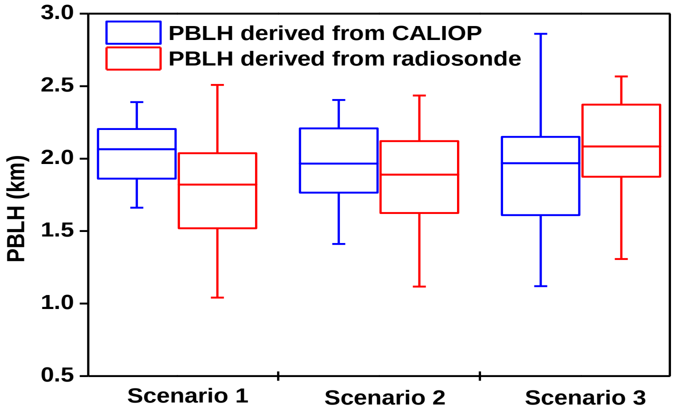

Fig. R2. Box-and-whisker plot showing the 5th, 25th, 50th, 75 th and 95th percentile values of PBLH derived from CALIOP (in blue) and radiosonde (in red) for each scenario. Note that only 1400 BJT radiosonde are used to make comparison with afternoon CALIOP-derived PBLHs.

Technical Corrections

(1) The grammatical errors should be corrected (Just some are listed here. The author should thoroughly check for simple typos and grammatical errors). For example,

Page 2 line 1, “for comparison with” should be “in comparison with”.

Page 2 line 2, “at early summer afternoon” should be “in early summer afternoon”.

Page 3 line 20, “the fact the number” should be “the fact that the number”.

Page 4 line 22, “are” should be “is”.

Page 6 line 9, “this methods” should be “this method”.

Page 8 line 7, “in combination with and” should be “in combination with”.

Response: Except for the typos as you pointed out here, other grammatical errors have been corrected in this revision.

(2) Fig. 2, at the top of this figure the times “05:33:17” and “05:47:14” should be the local times “13:33:17” and “13:47:14”.

Response：Per your kind suggestions, the time at the top of Fig.2 has been changed to the local times, i.e., “13:33:17 (BJT)” and “13:47:14 (BJT)”.

(3) Fig. 7, the value of mean difference between the CALIOP-and radiosonde-derived PBLHs in each panel (0.17km, 0.22km, 0.17km and 0.15km respectively). But the figure shows that the difference for a single site is either positive or negative (denoted by different colours). How to calculate the mean value, directly or by the absolute values? I guess by absolute values. Therefore the absolute value sign should be added to ΔPBLH.

Response：We appreciate you pointing it out. You are right, the difference of PBLH was supposed to denote absolute value. Therefore, it has been changed to “$|\Delta PBLH|$” *in Fig. 7.*

Anonymous Reviewer #2:

Comments on "Planetary boundary layer height from CALIOP compared to radiosonde over China"

The planetary boundary layer height (PBLH) is an important parameter for the weather and climate study, as well as atmospheric pollution study. This study tries to obtain global PBLH based on CALIPSO satellite observations, and carried out an intercomparison study with those from radiosondes and lidars here. The results suggest that they agree reasonably well in China regions. This is a valuable contribution to the science community to better understand the potential applicability of CALIPSO observations to obtain PBLH. However, this paper does need some improvement as detailed below, particularly regarding to the English writing. I would recommend the manuscript for publication in ACP, pending minor revisions.

Response：We are quite grateful to referee #2 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.

Main Comments

1. The English writing strongly need improve. The paper descriptions could be more concise and accurate.

Response：Per your kind suggestions, we have improved the English writing, both grammatically and scientifically. Meanwhile, the descriptions have been revised to be as concise and accurate as possible in this revised manuscript.

2. One key role of this study as the author expressed is "The PBLH retrieval from CALIOP is expected to complement the ground-based site measurement due to its large spatial coverage". However, I think the pass of CALIPSO satellite over a specific location is limited. May you please provide more information about the CALIPSO passed regions?

Response：We agree with the reviewer that the pass of CALIPSO satellite over a specific location is temporally limited (especially in the capability of charactering diurnal variation of PBL). As shown in Figure 1, during one CALIPSO revisit cycle (16 days), there are about 42 ground tracks in China for the daytime ascending overpasses (1330 LT). And the neighboring ground tracks of CALIPSO are in the intervals of approximately 100-150 km, depending on latitudes. To make the description more accurate, in the introduction section, we added "From the climatological point of view" just before "the PBLH retrieval from CALIOP is expected to complement the ground-based site measurement due to its large spatial coverage."

3. Section 2.1, I would like to know the uncertainties in the PBLHs obtained from radiosondes, which is very important since the authors are using them to evaluate those from CALIOP.

Response: The uncertainties associated with PBLH obtained from radiosonde come from (1) the estimation methods of PBLH, which are generally referred to structural uncertainty (Seidel et al., 2010). To our knowledge, the method (Sawyer and Li, 2013) we used here is one of the most advanced algorithms, in which prior knowledge of instrument properties and atmospheric conditions has been adequately taken into account; (2) the extreme adverse weather, which is also an important influential *factor. For instance, the PBL as deep convective cloud occurs will collapse, leading to an extremely large value; (3) the failed launch of weather balloon. All of these uncertainties have been reflected in this revision.*

Reference:

Seidel, D.J., Ao, C.O., Li, K.: Estimating climatological planetary boundary layer heights from radiosonde observations: Comparison of methods and uncertainty analysis. J. Geophys. Res. - Atmos. 115, 2010.

4. Section 2.2, what is the uncertainties of PBLHs from lidars, and what are the extra uncertainties caused by the selection of compare region size?

Response：In our points of view, the uncertainties of PBLHs from lidars largely come from the contamination caused by boundary layer cloud, along with the heavy haze which always leads to strong signal attenuation.

Moreover, the temporal window utilized to take averages centered at the observation time of ground-based lidar may be a factor influencing the PBLH uncertainty. To just name a few, the thorough analysis by Hennemuth and Lammert (2006) indicated that 10-min window leads to an average bias of 150 m as compared with 1-h window. All of these uncertainties have been discussed in detail and reflected in the last paragraph in section 2.2 of this revised manuscript.

To make the intercomparison more robust, a circle with a radius of 75 km centered at ground site was chosen to obtain averaged PBLH from CALIOP. As such, at least 100 samples around each radiosonde site can be used for the estimation of PBLH from CALIOP, given the 5km resolution along CALIPSO track.

Reference:

Hennemuth B, Lammert A. Determination of the atmospheric boundary layer height from radiosonde and lidar backscatter [J]. Boundary-Layer Meteorology, 2006, 120(1): 181-200.

5. Section 3.1, this is a comparison. If you would like to say ‘evaluation”, you need assume the accuracy of ground-based lidar-derived PBLH with at least clear uncertainty information.

Response：Per your kind suggestion, "evaluation" has been changed to "comparison".

6. Section 3.2, I would suggest you add the climatology of PBLH from the radiosonde profiles over China and compare this with your results from CALIPSO observations. This could let us know how reliable of your CALIPSO-derived PBLHs.

Response：Per your suggestion, the climatology of PBLH from the radiosonde profiles over China was added, as shown in Fig. R3 (i.e., Figure S2 in the supplementary material). Note that only the radiosonde-derived PBLH climatology at 1400 BJT in summertime is and should be used for comparison with CALIOP-derived PBLHs. In order to let the readers better know the reliability of CALIOP-derived PBLHs, the following description was added in the first paragraph of section 3.4:

"In terms of the spatial differences of PBLHs, both CALIOP retrievals (Figure 4b) and radiosonde observations (Figure S2) show that large PBLH values tend to occur at Tibetan Plateau, southwestern China, and northern China in early summer afternoon. This is likely indicative of good agreement between CALIOP- and radiosonde-derived PBLH retrievals"

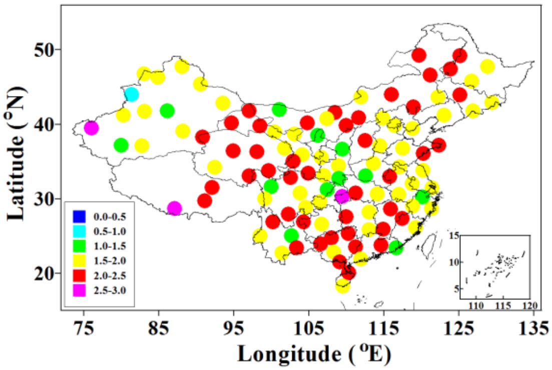

Fig. R3. Spatial distribution of climatological PBLHs derived from radiosonde at 1400 BJT in summer (June-July-August, JJA) during the period from 2011 to 2014.

Specific Comments:

Page1

（1） Line 12: The description could be more concise: the accurate estimation of planetary boundary layer height (PBLH) …. The PBLH retrieved from …"

Response：Amended as suggested.

（2） Line 17: ground-based and satellite-based or ground-based and spaceborne.

Response：Amended as suggested.

（3） Line 17-18, for r=0.59 or 0.65, could we say "good agreement"?

Response：The sentence has been revised to "Comparison between PBLHs from ground- and satellite-based lidars leads to a correlation coefficient of 0.59 in Beijing and 0.65 in Jinhua, respectively."

（4） Line 19, ‘during 2011 to 2014’ -> ‘for the period from 2011 to 2014’

Response：Amended as suggested.

（5） Line 19, lower values

Response：Amended as suggested.

（6） What is the uncertainty for PBLH from radiosonde observations? What are the factors that could result in the differences in PBLH between satellite-and ground-based observations, and their contributions?

Response：Please see our response to main comment #3.

Page2

（7） Line 17, how do you arrange the order of references?

Response：We rearranged the order of references to chronological order by year of publication, which shows as follows: “(Medeiros et al., 2005; Hong et al., 2006; Zhang et al., 2007; Hu et al., 2010).”

（8） Line 18-20, the sentence have grammar error with 2 verbs.

Response： The sentence you pointed out has been revised as follows:

“The depth (or height) of PBL, which determines the vertical extent of turbulent mixing and convection activity within it, is a key length…”

Page 3

(9) line 1-3, why is it required 4-8 times for IOP experiment?

Response：Generally speaking, 4-8 times are required during IOP experiment to better capture the diurnal variation in the thermodynamic and dynamic conditions of atmosphere.

(10) line 4, how accurate of the PBL height is it for the measurements from radiosondes?

Response：Please see our response to question 3 for more detail.

(12) line 12-13, what do you mean with (Amiridis et al.) in these lines? Reference?

Response：It means reference. Therefore, we added a reference "(Seibert, 2000)" here.

Page 4

(13) line 13-15, what do you mean for this sentence: "large seasonal and diurnal variations in PBLHs were observed between the different methods applied to radiosonde, ground-based lidar, CALIOP observations over one site in South Africa"

Response：It has been changed to "large seasonal and diurnal variations in PBLHs were observed, most likely due to the different methods utilized to…"

(14) what do you mean for "large scale land-based observations"?

Response：We clarified it by changing it to "large scale ground-based radiosonde observations" in this revision.

(15) how reliable for the ground-based lidar observation of PBLH?

Response：Please see the response to main comment # 5 for more details.

Page 5

(16) line 14, times -> time

Response：Amended as suggested.

(17) line 15, why call the summer as flood season? It might be wet season, but not good as flood season?

Response: "flood season" has been changed to "wet season".

(18) line 16, what do you mean for "severe weather forecasting"?

Response：The sentence has been changed to "CMA required the soundings to be launched three to four times a day in summer (the wet season), i.e., 0200 BJT, 0800 BJT, 1400 BJT, and 2000 BJT to seamless monitor the vertical structure of atmosphere, and thus to better serve the high-impact weather forecasting."

(19) line 16-19, 'owe to ..., ... therefore..."?

Response: "therefore" was removed .

Page 6

(20) line 9, What are you comparing to regarding "a good agreement"?

Response：We rewrote the sentence as follows:

"By combining the methods of wavelet covariance and iterative curve-fitting (Steyn et al., 2009), Sawyer and Li (2013) developed a novel algorithm (hereafter called SL2013), which can be applied to robustly derive PBLHs from both radiosonde and lidar measurements due to the fact that prior knowledge of instrument properties and atmospheric conditions has been adequately considered."

(21)line 9, 'this methods of ... was ...'?

Response:"methods" has been changed to "method".

Page 7

(22) line 6, 'the algorithm in Zhang et al. (2015) are applied on ..."-> "the algorithm developed by Zhang et al. (2015) are applied to ..."

Response：Amended as suggested.

(23) line 7, what kind of profiles are you talking about? lidar profiles?

Response：We are referring to CALIOP profiles.

(24) line 8-9, why do you choose the area with radius of 75 km?

Response：See our response to main comment #3, please.

(25) line 10-13, what are the data volume fraction for these cases?

Response：Overall, the data volume fraction is roughly 87.7 %. To better describe the ground-based lidar data, we added Figure R4 (i.e., Figure S1 in the supplementary material). The related description was added to the end of section 2.2.

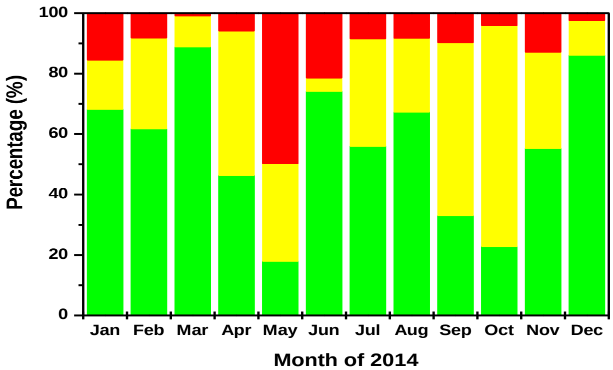

Fig. R4. Statistics showing the fractional volumes (in percent) of lidar measurement at Beijing during the whole year of 2014 stratified by no observation (in red), without PBLH retrievals due to weather conditions (in yellow), and with PBLH retrievals (in green).

(26) line 17-19, please correct the sentences, such as "It measures attenuated backscatter coefficients at resolutions of 1/3 km in the horizontal and 30 m in the vertical at the visible wavelength ..."

Response：The sentences have been changed to ''It measures attenuated backscatter coefficients at a resolution of 1/3 km in the horizontal at the visible wavelength (532 nm) and near-infrared wavelength

(1064 nm), and its vertical resolution varies with altitude (h): 30m from ground up to h = 8.2 km, 60m from h = 8.2 km to 20.2 km, and 180m from h = 20.2 km to 30.1 km (Winker et al.,2009; Huang et al.,2015)"

Page 8

(27) line 7, " in combination with and …"?

Response：It has been changed to "in combination with.." .

(28) line 8-9, "This is because that …", You do not need to explain since you have said for "cloud screening"

Response：The redundant sentence you pointed out has been removed according to your kind suggestion.

(29) line 9-11, please indicate the advantage of your choosing method.

Response：Just following "..be inferred (McGrath-Spangler and Denning, 2012, 2013)." The following sentence was added: "However, either maximum variance algorithm or Haar wavelet technique has its weakness due to the strong dependence on the chosen strategy in the threshold values."

(30) line 11, there are two periods.

Response：One redundant period was removed.

(30) line 9-16, please tell readers the uncertainties or the uncertainty-influential factors for this determination method.

Response：We added the sentence as follows: "However, either maximum variance algorithm or Haar wavelet technique has its weakness due to the strong dependence on the chosen strategy in the threshold values."

(31) line 16-19, this is redundant since you have mentioned the 75 km earlier. Also, why do you select 75 km, not 50 or 25 km?

Response：These redundant sentences have been removed, and the following paragraph was added to the end of 2nd paragraph in section 2.2:

"Due to the neighboring ground tracks of CALIPSO at approximately 100-150 km longitudinal interval over China, a 75km-radius circle centered at each ground-based lidar site has been determined for its spatial matchup with CALIOP, so has the matchup of radiosonde site with CALIOP."

Page 9

(32) line 1, what do you mean “valid” here? For the overpasses, are there invalid ones? I do not understand.

Response：“valid” means without cloud. Therefore, we modified the sentence to “The CALIPSO measurements were retained for PBLH retrievals at grid points where the number of valid (i.e., without cloud)…”

(33) line 4, How do you determine if the BL is convective or not?

Response：Our method utilized in PBLH retrieval (see our response to general comment #1 by reviewer #1 for details) does not rely on whether the BL is convective or not, and thus the sentence was deleted in this revision.

(34) line 5-10, you just gave one case to show the good agreement between two algorithms (even17 profiles averaged within a 5 km region). This is not enough to conclude that “the combined algorithms are reliable”.

Response: The sentence of "indicating that the combined algorithms is reliable " was deleted in this revision.

(35) line 10, ‘is’ ->’are’

Response：Amended as suggested.

(36) line 13,are you sure your comparison study is “a first attempt”?

Response：We deleted “a first attempt” and revised the sentence to “In order to make the intercomparison more reliable between CALIOP- and radiosonde-derived PBLHs…”.

(37) line 15-16, how do you exclude the cases with cloud cover? In other words, how do you get the cloud coverage?

Response：The cases were manually determined whether they were contaminated or not, based on the meteorological data from the neighboring weather station.

(38)line 17, “shows that”? I believe it should be just “shows”

Response：You are right, and thus "that" was deleted as suggested.

(39) line 17-21, for so limited data samples, how reliable are the comparison results?

Response：We rewrote these sentences as below:

"Due to the samples being still limited, we cannot be quite sure to argue that the CALIOP-derived PBLHs are reliable enough. Further evaluation studies are warranted in the future as long as more ground-based lidar observations are available. However, the correlation coefficients obtained here are similar to those reported at SACOL site of northwestern China (e.g., Liu et al., 2015)."

Page 10

(40) line 1-2, the correlation coefficients are low, why do you say ‘show a good agreement’?

Response：“which shows a good agreement” was deleted.

(41) line 11-13, the variability in winter (0.4 km) is larger than that in summer (0.31 km), why do you say the lowest PBLH variability occurs in winter?

Response：Per your suggestion, the "variability" has been removed, and the sentence has been changed to "the lowest PBLH values occur in winter".

(42) line 13, “were occurred” -> “occur’

Response：Amended as suggested.

(43) line 14-15, please modify the description to make it more concise.

Response：We modified the sentence as follows:

“...when the development of PBL is typically suppressed due to the less solar radiation received at the surface. In contrast, the more intense solar radiation reaching the surface in summer favors the development of PBL (Stull et al., 1988).”

(44) line 19, ‘was’ -> ‘were’

Response：Amended as suggested.

(45) line 21, ‘may be suppressed by aerosol radiative effects and aerosol-wind interactions(Xia et al., 2007; Yang et al., 2016)’

Yang, X., C. Zhao, J. Guo, Y. Wang, 2016, JGR: intensification of air pollution associated with its feedback with surface solar radiation and winds in Beijing，

Response：Amended as suggested.

Page 11

(46) line 2, ‘had been’ -> “have been”

Response：Amended as suggested.

(47)line 5-7, this information has been described two times earlier. I would suggest a more detailed description for only one time.

Response：We can not agree with the reviewer any more, so we deleted it in the first paragraph of section 3.3, and more detailed description concerning the matchup scheme between radiosonde and CALIOP was added in section 2.3.

(48)line 7-9, this also seems redundant.

Response：It has been deleted as suggested.

(49) line 14, delete "On the other hand,"

Response：Deleted.

(50)line 16, 'can be' -> 'are'

Response：Amended as suggested.

Page 12

(51) line 8, what do you mean for "basically"?

Response："basically" has been revised to "mostly".

(52) line 11-12, could you give me a little more explanation? I do not understand the logic here.

Response：We have revised the sentences as follows:

"..The more northward the radiosonde sites, the greater number of the CALIPSO overpasses over the same circle of 75 km radius. Therefore, the distinct discrepancy in geographic distributions of radiosonde sites belonging to Scenarios 1 and 3 are most likely due to the latitude differences…"

(53) line 16-17, "the PBLHs at all the 113 radiosonde sites have been successfully derived" and "so have the CALIOP-derived PBLHs" seem the same meaning to me.

Response：We have revised the sentence to "Using the algorithms as detailed in Section 2, the PBLHs at all the 113 radiosonde sites have been successfully derived from radiosonde and CALIOP."

(54) line 18-20, there is no verb in this sentence. Also, I do not understand what difference are you talking about? Do you mean “the difference of PBLH derived from CALIOP and from radiosonde”?

Response：You are right, and thus we revised the sentence to: “..the differences of PBLHs at every radiosonde sites (Figure 1) from CALIOP measurements at 1330 LT minus those from radiosonde observations at 1400 BJT in the summertime (June-July-August) during the period of 2011-2014 are calculated...”

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(55) line 1-2, I believe you are talking that PBLH exhibit negative values, not sites exhibit negative values. Please correct the description.

Response：Per your kind suggestion, we changed the sentence to “As shown in Figure 7(a), the PBLH differences over most of the radiosonde sites ..”

(56) line 7-10, I believe the two sentences are expressing the same meanings, please delete one.

Response：Per your kind suggestion, we deleted “Note that we cannot totally rule out other factors that may also contribute to the east-west gradient.”

(57) line 12-15, please modify it to make it concise.

Response: It has been shortened as “…Overall, the radiosonde-derived PBLHs tend to be overestimate compared with CALIOP-derived PBLHs due to the majority of radiosonde sites…”

(58) line 19, occurrence frequency for what?

Response：Occurrence frequency for the number of radiosonde sites

Page 15 (59) line 8, ‘are’ -> ‘is’

Response：Amended as suggested.

Planetary boundary layer height from CALIOP compared to radiosonde over China

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Abstract. The accurate estimation of planetary boundary layer height (PBLH)boundary layer height is key to air quality prediction, weather forecast and so on. The planetary boundary layer height PBLH(PBLH) retrieval from CALIOP is expected to complement the ground-based site measurement due to its large spatial coverage. To such end, we estimated PBLHs are estimated from CALIOP, using the combination of Haar wavelet and maximum variance techniques, which was are then validated against PBLHs from ground-based lidar at Beijing and Jinhua. Comparison –between PBLHs from ground-based and satellite-based lidars shows good agreement with leads to a correlation coefficient of

0.59 in Beijing and 0.65 in Jinhua. Also, ~~.~~ t~~T~~he PBLH climatology from CALIOP and radiosonde are~~was~~ compiled over China during~~for~~ the period from 2011 to 2014~~during 2011 to 2014~~. Maximum CALIOP-derived PBLH can be~~was~~ seen in summer as compared to lower values in other seasons. ~~Prior to intercomparisons between CALIOP- and radiosonde-derived PBLHs, t~~Three matchup scenarios a~~we~~re proposed according to the position of each radiosonde site relative to its closest CALIPSO ground tracks. For each scenario, intercomparisons were performed between CALIOP- and radiosonde-derived PBLHs, and ~~. The CALIOP observations belonging to~~ Scenario 2 i~~w~~s ~~ere~~ found to be better ~~for~~ in ~~comparison with radiosonde-derived PBLH~~, owing to smaller difference between them. ~~The PBLHs at~~ ~~i~~In early summer afternoon ~~range from 1.6 km to 2.0 km, accounting for~~ over 70% of the total radiosonde sites have PBLH values ranging from 1.6 km to 2.0 km. Overall, CALIOP-derived PBLHs seem to be well consistent with radiosonde-derived PBLHs. To our knowledge, this study is the first intercomparison study of PBLH over large scale using the radiosonde network of China, shedding important light on the data quality of initial CALIOP-derived PBLH results.

1. Introduction

The planetary boundary layer (PBL), the lowest layer of troposphere closest to the surface, is directly influenced by the presence of the Earth's surface, and responds to surface forcings (e.g. sensible heat flux, mechanical drag) on a timescale of about an hour or less (Stull, 1988). The terrestrial PBL is extremely complex, given the nonlinearity and complexity of convective and turbulent processes occurred within PBL. The PBL processes play significant roles in modulating the exchange of momentum, heat, moisture, gases, and aerosols between the Earth's surface and the free troposphere (Hu et al., 2010, 2014; Miao et al., 2015). Therefore, ~~,~~ a growing consensus has been reached on the role

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there is general agreement that understanding and predicting weather, climate and air quality depend on accurate characterization of boundary layer processes and its structures have being played in greatly advancing our capabilities in understanding and predicting weather, climate and air quality (Hu et al., 2010; Hong et al., 2006; Medeiros et al., 2005; Hong et al., 2006; Zhang et al., 2007; Hu et al., 2010; Medeiros et al., 2005).

The depth (or height) of PBL height (PBLH), which determines the vertical extent of turbulent mixing and convection activity within it, is a key length scale in weather, climate, and air quality models. to parameterize Tthe accurate prediction of vertical diffusion, cloud formation, and pollutant deposition in turn relies on the reliable parameterization of PBL (Hu et al., 2006; Seibert 2000; Xie et al., 2012). The PBL height (PBLH) typically varies from less than one hundred meters to several thousand meters (Hennemuth and Lammert, 2006). The most common PBLHs are derived from radiosonde soundings of temperature, humidity, and so on. The balloons are required to be launched twice a daydaily for the purpose of operational weather forecast, or 4-8 times per dayily from the perspective of scientific research during intensive observation period (Seibert, 2000; Liu and Liang, 2010). Although the radiosonde can provide height-resolved temperature and humidity profiles for accurate estimation of PBLH, which is independent of cloud cover conditions, it is still too sparse to detect the PBL evolution over large spatial scale, and thus can-not adequately serve the PBL research on global or even regional scales (Sawyer and Li, 2013). With the limited available radiosonde observations (mostly from the Unite States and Europe), Seidel et al. (2010; 2012) constructed a general picture of PBLH climatology on a global scale,. Hhowever, partly for the lack of observation in China, they did not give much detailed information of PBL over China, in part due to the lack of high-resolution observations in China. In 2011, a land-based radiosonde network across China was has been successfully deployed by the China Meteorological Administration (CMA), which provides a unique opportunity to fill in the gap left.

In addition to the land-based radiosone observations, the lidars that allow the measurement of aerosol or trace gas ~~profiles,~~profiles ~~also~~ can be used to study PBL structure (Seibert, 2000~~ref~~). It is well known that aerosol concentrations vary significantly with height, which not only affects the detection of boundary layer, but also may be a large source of uncertainty particularly for satellite-based aerosol retrievals using wavelength of ultraviolet (UV) (e.g., Torres et al., 1998, 2013; Huang et al., 2015). Turning to the measurements of active remote sensing instruments, such as Cloud Aerosol LIdar with Orthogonal Polarization (CALIOP) aboard Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) (Winker et al., 2007), aerosols can be detected and used as tracers of PBL dynamics. This is most likely due to the fact that the number of aerosol particles in the PBL is often greater than that ~~above~~ in the free troposphere (Leventidou et al., 2013). Mor~~e~~ore~~st~~ importantly, unlike the radiosonde measurement that only provides a “snapshot” of PBL profile at a fixed site (Seibert et al., 2010), the spaceborne lidar can obtain PBL variation over large area of interest, especially over remote regions (Jordan et al., 2010; Zhang et al., 2015).

The overpass time of CALIOP/CALIPSO is around 1330 Local Time (LT), which is almost coincident with the atmospheric sounding observations around 1400 Beijing Time (BJT) operated by CMA in the summer. In the late morning and afternoon time, when the convective boundary layer is well established, ~~the top of convective boundary layer is often clearly characterized by the~~ strong gradient of aerosol particles can often be seen at the top of convective boundary layer, and thus~~content,~~ the lidar~~-~~detected PBLH is generally ~~close to~~ in good agreement with the radiosonde-derived PBLH ~~(Hennemuth)~~ (Garratt, 1994; Seibert, 2000; Hennemuth and Lammert, 2006). Therefore, at the time of

CALIOP overpasses (1330 LT), ~~its detection~~it seems suitable for~~ed~~ ~~to~~ determining~~e~~ the convective boundary layer height.

As one of the first attempts to validate the CALIOP-derived PBLHs, Kim et al. (2008) carried out the intercomparison studies between PBLHs from radiosondes and CALIOP measurements, showing high consistence between them. Among others, Ho et al. (2015) compared the marine boundary layer heights from CALIOP profiles with those from radiosonde soundings. On the other hand, large biases of the seasonal and diurnal variations in PBLHs were observed~~ between~~, most likely due to the different methods ~~applied~~ utilized to radiosonde, ground-based lidar, CALIOP observations over one site in South Africa (Korhonen et al., 2014). Although CALIOP possesses the ability to derive PBLHs over large and remote regions on a regular basis, these comparison studies ~~were~~ only involved ~~in~~ one or a few sites, and a comprehensive evaluation of CALIOP-derived PBLH with large scale land~~ground~~-based radiosonde observations ~~is~~ remains ~~still~~ lacking~~missing~~. In this study, the long-term CALIOP-derived PBLH over China will be validated and assessed by ~~using~~ means of the measurements of land-based radiosonde network of CMA.

~~To some extent~~From the climatological point of view, ~~The~~ the PBLH retrieval from CALIOP is expected to complement the ground-based site measurement due to its ~~large~~ ~~regular~~large spatial coverage. The main objective of this study ~~are~~is twofold: ~~is, therefore, to use nearly collocated ground-based lidar observations~~ (1) to ~~quantify~~ construct ~~the~~ a climatological ~~uncertainty of the~~ CALIOP-derived PBLH dataset; (2)~~ and~~ to ~~further~~ quantify the discrepancies between CALIOP-derived and radiasonde-derived PBLHs. The remainder of this paper proceeds as follows: the data and methods used are described in Section 2. Section 3 reports the ~~evaluation~~ comparison results of CALIOP-derived PBLH using ground-based lidar measurements. ~~, and~~ T~~t~~he spatial and temporal distribution pattern of

CALIOP-derived PBLH~~ from CALIOP~~ is presented as well. Moreover, intercomparisons between PBLHs derived from CALIOP and radiosonde measurements will be performed. Last, a brief summary is given in Section 4.

2. Data and methods

2.1 Radiosonde observations and their processing

The radiosonde measures once per second, acquiring detailed vertical profiles of temperature, pressure, relative humidity, wind speed and wind direction over a given weather station~~, with a vertical resolution of 10 m~~. The sounding balloons~~es~~ are operationally launched twice a day at fixed time~~s~~, i.e. 0800 BJT and 2000 BJT, throughout all the radiosonde sites shown in Figure 1. Fortunately,~~ it~~ ~~is required by~~ CMA required the soundings to be launched three to~~ increased to~~ four times a day in summer (the ~~flood~~ wet season), i.e., 0200 BJT, 0800 BJT, 1400 BJT, and 2000 BJT to ~~better~~ seamless monitor the vertical structure of atmosphere, and thus~~serve the~~ to better serve the high-impact ~~the severe~~ weather forecasting~~ nowcasting can be more accurate~~ ~~forecasting~~. Owinge to our focus on the convective PBL in the daytime, the ~~added~~ 1400 BJT soundings in summer ~~therefore~~ allow us to determine PBLHs over ~~all~~ most weather sites throughout China, which are used for comparison analysis~~ring~~ with CALIOP-derived PBLH~~s, which is~~ being typically available at 1330 LT.

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As summarized in Seidel et al. (2010), there are seven commonly used methods to derive PBLHs ~~using~~ based on the profiles of temperature, potential temperature, virtual potential temperature, relative humidity, specific humidity, and refractivity. The traditional approach encountered in the textbooks (e.g., Oke, 1988; Sorbjan, 1989; Garratt, 1992) typically defines PBLH as the pressure level where the maximum vertical gradient of potential temperature occurs, indicative of a transition from a convectively less stable region below to a more stable region above. Recently, a more sophisticated method (Brooks, 2003; Davis et al., 2000) involves the wavelet covariance transform. In contrast, t~~T~~he algorithm of wavelet covariance transform was first proposed by Gamage and Hagelberg (1993) as a way to detect step changes in a signal.

~~Combining the methods of wavelet covariance transform and simulated annealing (Steyn et al., 2009),~~ By combining the methods of wavelet covariance and iterative curve-fitting (Steyn et al., 2009), Sawyer and Li (2013) developed a novel algorithm (hereafter called SL2013), which can be applied to robustly derive PBLHs from both radiosonde and lidar measurements due to the fact that prior knowledge of instrument properties and atmospheric conditions has been adequately considered. The measurement time of our study is almost at noon, the potential temperature profile more often than not exhibit the typical structure of convective BL. However, due to the potential uncertainties caused by the sensitivity of vertical resolution, and the wide range of sounding time (in LT) at different sites across China, SL2013 tends to exhibit advantages over the method of maximum potential temperature gradient. This is most likely because SL2013 is flexible and simple enough for automatic analyses of long-term sounding data at multiple sites, and is able to compensate for noisy signals and low vertical resolution in the soundings. Therefore, SL2013 has been applied to extract PBLHs from radiosonde observations. However, bear in mind that the extreme adverse weather, which is also an important influential factor, will inevitably exert large uncertainties on the retrieved PBLH. For instance, the PBL as deep convective cloud occurs will collapse, leading to an extremely large value. These cases will be excluded for further comparison analysis with CALIOP-derived PBLHs. ~~developed a novel algorithm to derive~~

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~~PBLH from both radiosonde and lidar measurements, showing the regression R2 values are above 0.5 and the systematic error is lowa good agreement. This method is combined two methods for PBL depth detection (wavelet covariance and iterative curve fitting) are combined and applied to long-term time series of radiosonde profiles. It is a robust mothed for ground-based observation extracting PBLH, because that prior knowledge of instrument properties and atmospheric conditions has been considered. As such, this methods of Sawyer and Li (2013) was used in this study.~~

~~—~~T~~As shown in Figure 1, t~~he sounding observations of 113 radiosonde sites (black dots in Figure 1) during the period 2011-2014 are then used to calculate PBLHs~~, and~~, ~~as well as~~ and perform ~~-~~comparison analysis~~ed~~ with the CALIOP-derived PBLHs as well.

2.2 Ground-based lidar observations

Ground-based lidar observations from two sites~~,~~ (i.e., Beijing and Jinhua)~~,~~ ~~were~~ have been~~also~~ used to evaluate the PBLHs retrieved from CALIOP. The site of Beijing (40.00°N, 116.38°E) is located on the campus of ~~at~~ the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, where the CE370 micro-pulse Lidar (made by CIMEL of France) was deployed during the period of January 1, 2014 to December 31, 2014. The profiles of aerosol backscatter coefficient obtained from~~using~~ CE370 have a vertical ~~spatial~~ resolution of 15 m. The laser transmitter system is reported to have a diameter of 20cm, which is used to expand laser beam through a refracting telescope.

The other ground-based lidar was deployed ~~–~~on the campus of ~~at~~ Zhejiang Normal University of Jinhua (29.0°N, 119.5°E), ~~in the urban area of Jinhua.~~ Zhejiang Province. The altitude of this site is 71m above sea level. Jinhua~~ is~~, located in the Yangtze River Delta of East China, underwent~~going~~

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increasingly deterioratedpolluted air quality due to the rapid economic development in recent years (Guo et al., 2011; Wang et al., 2015).

The ground-based lidar deployed at Jinhua are similar to CALIOP with two orthogonally polarized channels at 532 nm and one channel at 1064 nm. The algorithms developed by Zhang et al. (2015) arehas been applied to in Zhang et al. (2015) are applied on the profiles of ground-based lidars deployed at Beijing and Jinhua, respectively. To be more specific, only the segment of CALIOP profiles of CALIPSO corresponding to segments of of CALIPSO groundits ground track within a circle of 75km radius centered at the abovementioned two ground-based lidar sites are included in the PBLH retrievals. Due to the neighboringneighbouring ground tracks of CALIPSO at approximately 100-150 km longitudinal interval over China, a 75km-–radius circle centered at each ground-based lidar site has beenwas determined for its matchup with CALIOP, so has the matchup of radiosonde site with CALIOP.

The lidar observations has beenare scheduled shut off (1)paused during midday in summer to preventotect the optics from harms caused by intense sunlight, (2) during maintenance period of lidar, or (3) during the time period when lidar cannot normally work, leading to unwanted breaks of PBLH lidar observations. detections.Meanwhile, The other unfavorable weather conditions, including (e.g. rains, heavy haze episodes, among others, generally lead to unreliable PBLH retrievals). Overall, the data volume fraction is roughly 87.7 % for Beijing site. can also cause the unwanted breaks in the lidar observations.

The lidar measurements with PBLH detection differ largely by month. A total of 133 hours are obtained in May, as compared with 661 hours in March (Figure S1). Given the unreliable PBLH retrievals under some unfavourable conditions as described above, the annual average of the data is reduced to 64%, similar to 72% over Jinhua site.

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2.3 CALIOP observations and their processing

The CALIOP onboard the CALIPSO platform (flying as part of the A-Train satellite constellation since April 2006) is a three-channel elastic backscatter lidar, which is optimized for aerosol and cloud profiling. It measures attenuated backscatter coefficients at a resolutions of 1/3 km in the horizontal ~~and 30 m in the vertical~~ at the visible wavelength (532 nm) and near-infrared wavelength (1064 nm), and its vertical resolution varies with altitude (h): 30m from ground up to h = 8.2 km, 60m from h = 8.2 km to 20.2 km, and 180m from h = 20.2 km to 30.1 km ~~in low and middle troposphere, along with polarized backscatter in the visible channel~~(Winker et al., 2009; Huang et al., 2015). All satellites of the A-train constellation are in a 705-km sun-synchronous polar orbit between 82 °N and 82 °S with a 16-day repetition cycle, with a nominal ascending node equatorial crossing time of 1330 (0130) local day (night) time (Liu et al., 2009; Winker et al., 2007; Winker et al., 2003). As shown in Figure 1, red lines represent the ground tracks over China for the daytime overpasses of CALIPSO (in ascending mode), while blue lines ground tracks for nighttime overpasses of CALIPSO (in descending mode). The neighboring ground track is at a longitudinal interval of approximately 150-km, varying with latitudes.

The PBLH is predominantly estimated from the CALIOP Level 1 product: the total attenuated backscatter coefficient, in combination with ~~and~~ Level 2 product of cloud layer products (1/3 km in the horizontal) for cloud screening. ~~This is because that all the PBLH retrievals are limited to cloud free scenes. According to the summary of~~Resembling the methods utilizsed to derive PBLHs proposed by ~~in~~ Jordan et al. (2010), we relyied on the maximum variance algorithm to derive PBLHs from CALIOP

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attenuated backscatter coefficient profiles at wavelength of 532 nm, in combination with the Haar wavelet technique.. The maximum variance algorithm is originated from the ideas proposed by Melfi et al. (1985) and heavily relies on the existence of a strong aerosols concentration gradient at the top of the PBL, which can be detected by examiningcorresponds to the levels where the maximum standard deviation occurs of lidar backscatter. This method has been widely used to derive PBLHs from CALIOP so that the global seasonal variations can be inferred (McGrath-Spangler and Denning, 2012, 2013). However, either maximum variance algorithm or Haar wavelet technique has its weakness due to the strong dependence on the chosen strategy in the threshold values. To make the comparison of radiosonde-derived PBLHs with between radiosonde and CALIOP-derived PBLHs more reliable and robust, the combined algorithm has been applied on the corresponding profiles of CALIOP according to the matchup scheme described in section 2.2.. Due to the neighboringneighbouring ground tracks of CALIPSO at approximately 100-150 km longitudinal interval over China, a 75km radius circle centered at each radiosonde site has beenwas determined for the matchup of CALIOP and radiosonde site. corresponding to segments of CALIPSO ground track within a circle of 75km radius centered at each radiosonde siteof CALIOP. All the comparisons are limited to daytime measurements due to the nature of convective boundary layer, unless noted otherwise.

Due to the most likely blocking and attenuation caused by optically thin or thick clouds, we have to perform the cloud-screen procedures prior to the algorithm mentioned above operating on the CALIPSO level 1 profile data. The CALIPSO measurements data were retained for PBLH retrievals at grid points where the number of valid (i.e., without cloud) CALIPSO overpasses (means without cloud) exceeded 15% of the total number of overpasses. As such, we can minimize the effect of clouds on the retrieved PBLHs to a certain degree. Meanwhile, to improve the signal-to-noise ratio (SNR) for better PBLH retrievals, roughly 15 CALIOP profiles with 333-m resolution along track have to be resampled to one 5-km resolution profile for all CALIOP observations. Note that over regions where BL is not convective the retrieved values are not representative of the PBLH (Liu and Liang, 2010).

As a good case in point for a better view of the results derived using the above algorithms, the CALIOP-derived PBLHs (indicated by the black line) on 15 January 2011 over southeastern China is shown in Figure 2. To improve the signal-to-noise ratio (SNR) to derive the boundary layer top, 17 profiles at 333-m resolution along track were resampled to one 5-km resolution profile. By visual interpretation, we can see that the derived-PBLHs PBL tops are just located accurately aton the boundary levels where aerosol backscatter signals changes abruptly, indicating that the combined algorithms is are reliable.

3. Results and discussion

3.1 Evaluation Comparison of CALIOP-derived PBLH against ground-based lidar-derived PBLH

As a first attempt toIn order to perform make the intercomparison more reliable between CALIOP- and radiosonde-derived PBLHs from different sources more stringent,, CALIOP-derived resultsthe former hasve to undergo an evaluation using ground-based lidar, which typically shares the similar techniques. To minimize the influence of cloud on the PBLH determination from lidar, we exclude all the lidar measurements of Beijing and Jinhua with clouds (extracted directly from the meteorological data at neighbouring weather station) cover have been excluded for further analyses.

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Figure 3 shows that tThe scatter plots of are shown in Figure 3 concerning the intercomparison between the ground-based lidar derived PBLHs versus and CALIOP-derived PBLHS over Jinhua

~~(29.1°N, 119.6°E)~~ and Beijing (40.0°N, 116.4°E). Due to the twice-per-month revisit period of CALIPSO satellite, only 17 cases out of 24 at Beijing are selected, in which both CALIOP and ground-based lidar have simultaneous measurements at 1330 LT. And the simultaneous PBLH retrievals~~ has~~ have been carried out for 7 cases out of 12 at Jinhua. For the overall comparison between the PBLHs derived from ground-based lidar and CALIOP, the correlation coefficient through orthogonal regression reaches 0.59 at Beijing and 0.65 at Jinhua, respectively~~, which shows a good agreement~~. Due to the samples being still limited, so we cannot be quite sure to argue that the CALIOP-derived PBLHs are reliable enough. Further evaluation studies are warranted in the future as long as more ground-based lidar observations are available. However, the~~ Similar~~ correlation coefficients obtained here are similar to those~~ between the ground-based lidar and CALIOP derived PBLHs has been~~ reported at SACOL site of northwestern China (e.g., Liu et al., 2015).

3.2 CALIOP-derived PBLH Climatology throughout China

Figure 4 presents the spatial distributions of seasonal mean PBLHs with 0.2°×0.2° resolution derived from CALIPSO afternoon measurements during the period 2011 through 2014. The original 5 km PBLH data have been smoothed and resampled to 20 km resolution to highlight the coherent large-scale structures. It can be clearly seen that the PBLHs over China exhibit large spatial and seasonal variations. On average, both Figure 4 and Table 1 indicate that the highest PBLHs (1.82km $\pm$ 0.31km) were ~~developed~~ seen in summer (June, July and August), mainly ranging from 1.5 to 2.5 km. On the other hand, the lowest PBLH values~~ and variability~~ (1.51km $\pm$ 0.40km) ~~were occurred~~occur in winter (December, January and February~~).~~) when ~~This is most likely due to that t~~the development of PBL ~~is directly~~is typically suppressed due to ~~caused by~~ the less ~~surface thermal~~solar~~ and mechanical forcings~~

radiation received at the surface~~ maybe response for this~~. In contrast, ~~In summer, ~~the more intense solar radiation reaching the surface in summer ~~favors~~favours the development of PBL (Stull et al., 1988). As shown in Table 1, we notice that the maximum PBLHs can reach up to 5-6 km, especially in winter. Therefore, we set the CALIOP-retrieved PBLHs to be within 0.25 and 3km, which seems as a reasonable height range for the midday PBL, highly consistent with the processing methods by McGrath-Spangler (2012). Statistics showed that only 2.1% of all data higher than 3km and 8.8% lower than 0.25km, which have been excluded for further analyses.

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In terms of the discrepancy in spatial distribution of PBLH, the Tibetan Plateau (TP) was characterized by high values, irrespective of the evolution of seasons. Over eastern China, particularly the regions with large population and severe air pollution (Guo et al., 2009; 2011) (e.g. North China Plain, the Yangtze River Delta, and Pearl River Delta), the PBLHs ~~was ~~were higher in spring and summer, but did not show expected large seasonal variation. During the seasons (such as winter) when haze event frequently occurs, ~~the aerosol particles within the development of PBL may~~due to th~~b~~e suppression~~ed~~ by aerosol radiative effects and aerosol-wind interactions (Xia et al., 2007; Yang et al., 2016), ~~and leads to a ~~relatively shallow PBLHs can be apparently seen across most of China, in good agreement with previous findings (e.g., Quan et al., 2013; 6~~Miao et al, 2016; ~~Gao et al. 2015; Miao et al, 2016). This aerosol-rich haze, in combination with lowered PBL, tends to significantly delay the precipitation and its peak (Guo et al., 2016). The spatial distribution of PBLH revealed a tendency for higher PBLH over high elevation regions, consistent with dependence on elevation reported ~~similar distribution ~~in the United States ~~had ~~(~~have been reported by ~~Seidel et al., ~~(~~2012). Such spatial variation of PBLH may be related to the local land surface and hydrological processes (Seidel et al., 2012).

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3.3 Matchup between CALIOP profiles and radiosonde soundings

~~Due to the neighboring ground tracks of CALIPSO at approximately 100-150 km longitudinal interval over China, a 75km radius circle centered at each radiosonde site was determined for the matchup of CALIOP and radiosonde site.~~ As revealed in Section 2.3, we have averaged out the PBLHs derived from the CALIOP profiles ~~were averaged~~, which are then involved in ~~for~~ comparison analysis with the mean PBLHs from radiosonde soundings~~, which correspond to segments of CALIPSO ground track within a 75-km-radius circle centered at each radiosonde site~~. After multiple rounds of iteration through the positions of each radiosonde site over China relative to its closest CALIPSO ground tracks, a total of three scenarios are~~can~~ representative of all the cases, as shown in Figure 5. Scenario 1 denotes the cases with two CALIOP ground tracks, the shortest distance to which each is more than 37.5km from each radiosonde site. In contrast, Scenario 2 represents the cases with one CALIOP ground track, the shortest distance to which is less than 37.5km from each radiosonde site. ~~On the other hand,~~ Scenario 3 is the same as Scenario 2 except for the shortest distance to which is more than 37.5km from radiosonde site.

The details of classification criteria ~~can be~~are summarized in Table 2. Out of the total of 113 radiosonde sites were classified, 64 sites belonged to Scenario 2. That means about 56.6% of all radiosonde sites make a good match with CALIOP profiles for its nearest distance to CALIPSO ground tracks less than 37.5km. By comparison, there are 22 sites (19.5%) attributed to Scenario 1 whereas 27 sites (23.9%) scenario 3.

Figure 6 shows the geographic~~physical~~ distribution concerning the location of radiosonde sites relative to its closest CALIOP ground tracks inside a circle of radius 75 km over China, which are stratified by Scenarios 1, 2, and 3. Owing to the nearest distance to radiosonde site in Scenario 2, profiles in CALIOP observations can be used to better capture the PBL evolution, and thus facilitate the intercomparisons. It happens that the radiosonde sites (56.6%) belonging to Scenarios 2 are uniformly distributed over China, indicating that most of the radiosonde sites in China can be collocated well with afternoon CALIPSO overpass.

Interestingly, the radiosonde sites for Scenario 1 are ~~basically~~mostly located in the northern China, as opposed to those for Scenarios 3 in the southern China. The more northward the radiosonde sites, the greater number of the CALIPSO overpasses over the same circle of 75 km radius. Therefore, t~~T~~he distinct discrepancy in geographic distributions of radiosonde sites belonging to Scenarios 1 and 3 are most likely due to the latitude differences. ~~The more northward the radiosonde sites, the~~ ~~greater number of~~~~more frequently the CALIPSO overpasses over the same circle of 75 km radius.~~ More importantly, because the region of interest (China) spans several time zones, the spatial variations of radiosonde-derived PBLHs observed at fixed observation times (1400 BJT) tend to be conflated with diurnal variations, as discussed in the following Section 4.

3.4 Intercomparison between CALIOP- and radiosonde-derived PBLHs

Using the algorithms as detailed in Section 2, the PBLHs at all the 113 radiosonde sites have been successfully derived from radiosonde ~~and CALIOP, so have the CALIOP-derived PBLHs~~ and CALIOP. In terms of the spatial differences of PBLHs, both CALIOP retrievals (Figure 4b) and radiosonde observations (Figure S2) show that large PBLH values tend to occur at Tibetan Plateau, southwestern China, and northern China in early summer afternoon. This is likely indicative of good agreement between CALIOP- and radiosonde-derived PBLH retrievals. Furthermore, ~~On one hand,~~ ~~According to three matchup scenarios for both CALIOP profiles and radiosonde sites described above,~~ the differences of PBLHs at every radiosonde sites (Figure 1) -from CALIOP measurements at 1330 LT minus thos~~e~~~~at~~ from radiosonde observations at 1400 BJT in the summertime (June-July-August) during the period of

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2011-2014 arewere calculated.- In the mean timeOn the other hand,, the differences of PBLHs have to be averaged out for each radiosonde sites again according to three matchup scenarios for both CALIOP profiles and radiosonde sites described in Table 2.

As shown in Figure 7(a), the PBLH differences over most of the radiosonde sites to the east of 110 ººE longitude exhibit negative values, indicating CALIOP-derived PBLHs tend to be underestimated compared with radiosonde-derived PBLHs. In contrast, it is a different story (to be overestimated as compared with radiosonde) for the sites to the west of 110 ººE longitude (the western China), especially in provinces such as Xinjiang, Sichuan and Chongqing. Because observation time for The CALIOP observations corresponds toat roughly 1330 LT in the western China has been compared with -while late afternoon in the east, tthe radiosonde measurements at 1400 BJT which corresponds to 1100-1400 LT differing by longitudes, therefore, the relatively low PBLHs from the radiosondes -in the west China are expected to be in association with weak afternoon convection, leading to relative low PBLHs derived from radiosondes. This in turn leads to overestimated CALIOP-derived PBLHs in the western China. Note that we cannot totally rule out other factors that may also contribute to the east-west gradient. However, there are other aspects neglected to be discussed here, which are likely to be contributed to the discrepancies between the two data sourcesmethods.

We divided aAll sites in Figure 7 (a) are divided into three subgroups according to the matchup scenario described in previous section, sas shown in Figure 7 (b-d). From the perspective of PBLHs over any radiosonde siteOverall, the radiosonde-derived PBLHs tend to be overestimate compared with CALIOP-derived PBLHs tend to be underestimated compared with radiosonde-derived PBLHs, born out by the results in Table 2 and Figure 8 due to the majority of radiosonde the larger percentages of sites (77 of 113 sites, i.e., 68%) showing lower PBLH values. This is also consistent with the results shown in Table 2. As shown in Figures 7b-d, ~~In terms of~~ the average ~~mean~~ biases between CALIOP- and radiosonde-derived PBLHs~~,~~ for Scenario 2, as expected, have ~~s~~ smaller magnitude (0.17 km), as compared with Scenario 1 (with a magnitude of 0.22 km). On the other hand, the smallest ~~mean~~ average bias (0.15 km) i~~wa~~s observed for Scenario 3. More statistics with regard to the biases between CALIOP- and radiosonde-derived PBLHs are illustrated in Figure 8.

As indicated in Figure 8, Scenario 2 witnesses the least difference of 0.08km between the CALIOP- and radiosonde-median PBLH values in contrast to larger differences of 0.24km and 0.12km for Scenario 1 and Scenario 3, respectively. In addition, the PBLH differences in terms of 25th and 75th percentile values for Scenario 2 are much more indiscernible, as compared with those for other two scenarios. This implies that Scenario 2 gains more advantages over other two scenarios due to the smaller difference between CALIOP- and radiosonde-derived PBLHs.

Figure 9~~8~~ shows the ~~occurring~~ frequency of occurrence for the number of radiosonde sites, which~~PBLHs~~ are ~~as~~ stratified by binned radiosonde-derived mean PBLHs (1400 BJ~~L~~T) and CALIOP-derived mean PBLHs (around 1330 LT) over China in the summertime (June-July-August) during the period of 2011-2014. Typically speaking, the PBLHs in~~at~~ early summer afternoon over China range from 1.6 km to 2.0 km, accounting for over 70% of the total radiosonde sites. The pattern in Figure 9~~8~~(c) is more similar to that in Figure 9~~8~~ (a), suggesting that the results from Scenario 2 to some extent are representative of the overall results over all sites. In other words~~As such~~, comparison of the histogram of CALIOP PBLHs to the radiosonde observations indicates that they are in good enough agreement with each other.

4. Conclusions

This study presents initial validation results of space-borne CALIOP-derived PBLHs by comparing with coincidental observations from two ground-based lidars at Beijing (from January 1, 2014 to December 31, 2014) and Jinhua (from June 1, 2013 to December 31, 2013). Results show that the correlation coefficient is about 0.59 in Beijing and 0.65 in Jinhua, respectively. The selected data set represents two different underlying land surfaces, i.e., urban and mountain area, both of which are obtained under cloud-free conditions.

The climatology of seasonal mean PBLHs at 0.2°×0.2° resolution has been constructed, as derived from ~~daytime~~ afternoon CALIPSO measurements during the period 2011 through 2014. The PBLHs over China are found to exhibit large spatial and seasonal variations. ~~On average~~Overall, summer (June, July and August) ~~is~~ tend to have~~characterized by the~~ highest ~~-~~PBLH values, as opposed to the lowest PBLH values occurring in winter (December, January and February). Such seasonal variation of PBLH may be caused by the seasonal variation of solar radiation.

Prior to the comparison analysis between~~ng~~ CALIOP- and radisonde-derived PBLHs~~ with radiosonde~~, three matchup scenarios are proposed according to the position of each radiosonde site over China relative to its closest CALIPSO ground tracks~~,~~. The matchup of each ~~which cover all the collocated data pairs of CALIOP and~~ radiosonde site with its neighbouring CALIPSO ground tracks can be attributed to one the three scenarios. ~~Matchup m~~The spatial distribution of radiosonde sites belonging to ~~aps for~~ Scenario 2 indicates that most of the radiosonde sites in China can be collocated very well with afternoon CALIPSO overpass. ~~As such~~Further intercomparison analyses suggest~~,~~ that ~~the profiles in~~ CALIOP observations belonging to Scenario 2 seem to be better as~~for~~ compared~~ison~~ with radiosonde-derived PBLH, ~~owing~~ due to much smaller difference between them.

Overall, CALIOP-derived PBLHs tend to be underestimated compared with radiosonde-derived PBLHs. On the other hand, more than 70% of the radiosonde sites across China in early summer afternoon have relatively higher ~~the~~ PBLH values ~~at early summer afternoon over China mostly range~~ , which vary from 1.6 km to 2.0 km~~, accounting for over 70% of the total radiosonde sites.~~ . Therefore, CALIOP PBLHs tend ~~seem~~ to agree pretty well with radiosonde-derived PBLHs. Despite the limitation in the presence of clouds, CALIOP has been routinely available for determination of PBLHs and therefore ~~are~~ is a valuable method for long-term climatology analyses. To our knowledge, this study is the first intercomparison study of PBLHs between CALIOP- and radiosonde-derived PBLHs over large scale using the radiosonde network of China, although much detailed regional analyses have not been dealt with, which merit further investigation in the near future.

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Table list:

Table 1. Statistics of the CALIOP-derived PBLH in different seasons during the period 2011 - 2014Descriptions regarding the statistical results of seasonal mean PBLH estimated from CALIOP. The mean PBLHs for all the grids are firstly calculated in China, then the maximum and minimum values of PBLHs are determined by sorting all the mean values. Meanwhile, the mean and

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standard deviation values of PBLH are determined as the average of mean values at every grid in China~~After the mean PBLHs at every grid in China calculated, the maximum/minimum/mean/standard deviation values of the mean PBLHs over China are calculated and showed here.~~

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	Spring	Summer	Autumn	Winter
Maximum PBLH (km)	4.57	4.40	3.60	6.13
Minimum PBLH (km)	0.15	0.38	0.22	0.21
Mean PBLH (km)	1.72	1.82	1.56	1.51
Standard deviation of PBLH (km)	0.35	0.31	0.30	0.40

Table 2. Detailed descriptions with regard to the classification criteria of scenario of the positions of radiosonde site relative to the closest CALIOP profiles, including the number of CALIPSO ground tracks for each scenario, the shortest distance (SD) to ground tracks, the total number of sites for each scenario in China, as well as the number of sites with overestimated averaged PBLHs (OE) or underestimated averaged PBLHs (UE) from CALIOP compared with radiosonde.

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Scenario	**# of CALIPSO ground tracks**	**SD** (km)	**# of sites**	**# of sites with OE**	**# of sites with UE**
1	2	$37.5<D\leq 75$	22	11	11
2	1	$0\leq D\leq 37.5$	64	18	46

3	1	37.5<D≤75	27	7	20

Figure list

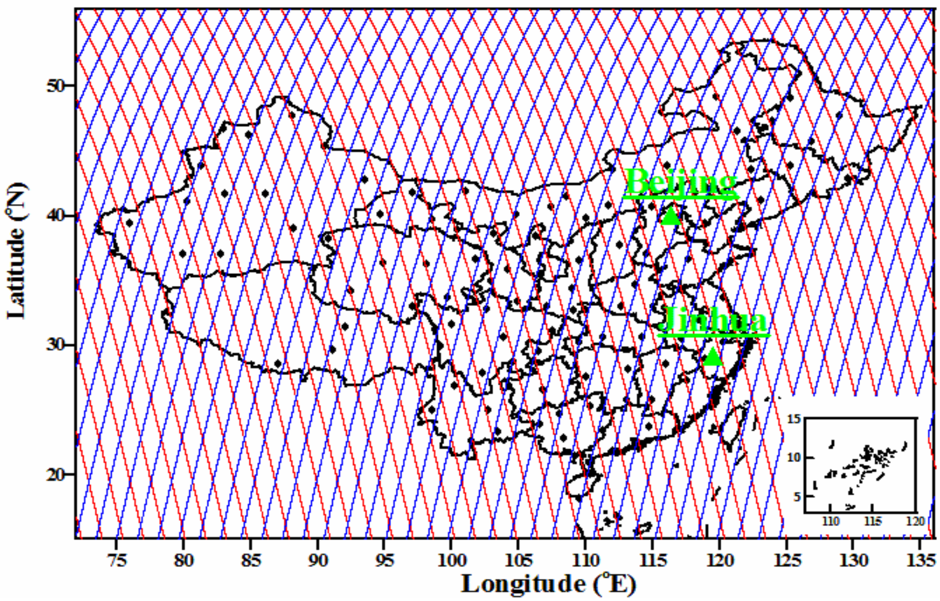
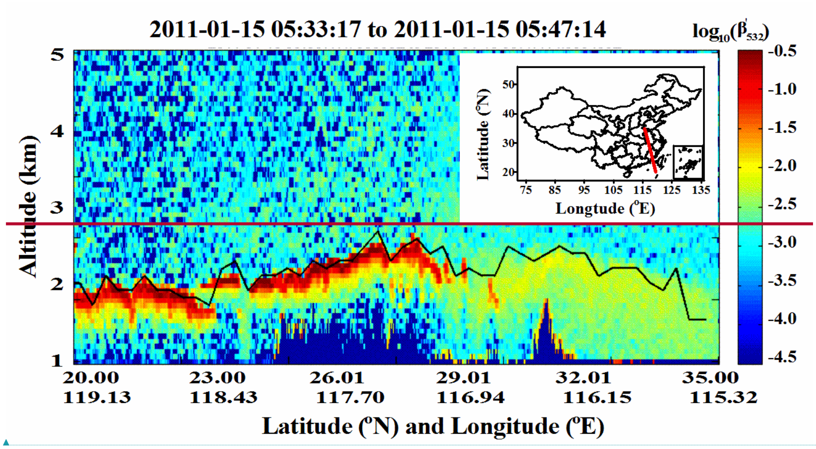


Figure 1. Geographic distribution of radiosonde sites and ground tracks for CALIPSO over China. Red lines represent the ground tracks for the CALIOP daytime orbits (in ascending mode), while blue lines for the CAILOP nighttime orbits (in descending mode). The black dots denote all radiosonde sites operated and maintained by China Meteorological Administration. Beijing and Jinhua (green solid triangles) are two sites deployed with ground-based lidar.



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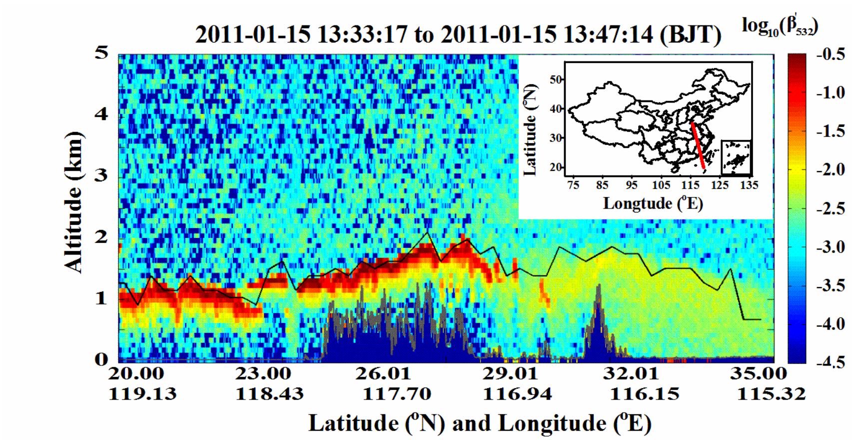


Figure 2. Curtain plot of attenuated backscatter coefficient as observed from CALIOP aboard CALIPSO on 15 January 2011. The black line indicates the derived PBLH (above ~~the~~ ground level) and the grey line immediately on top of ~~with~~ the blue region represents the terrain surface~~. (the terrain height is~~directly extracted from CALIOP data). The red line in the inlet map corresponds to the ground track of CALIOP/CALIPSO over southeastern China.

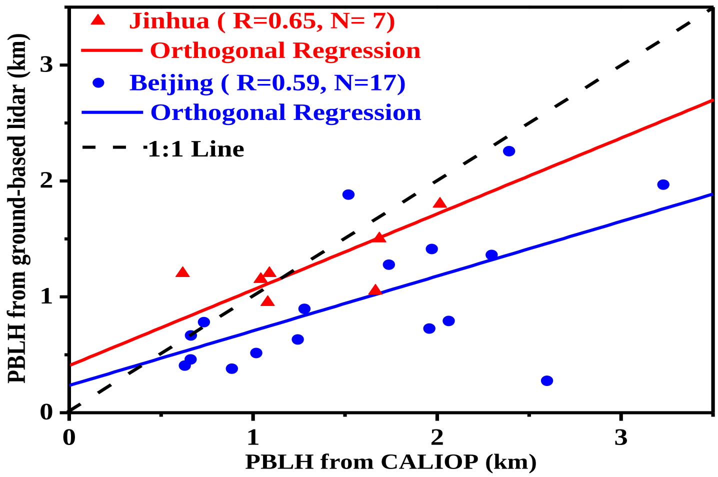


Figure 3. Scatter plot for comparing PBLHs from CALIOP to those from ground-based lidars at Beijing (blue dots) during the period January 1, 2014 to December 31, 2014 and Jinhua (red triangles) during the period of June 1, 2013 to December 31, 2013. Blue and red lines denote the linear fit to the data at Beijing and Jinhua sites, respectivlely, and black dash line the 1:1 correlation. The number of collocated data samples and corresponding correlation coefficient(R) are shown as well.

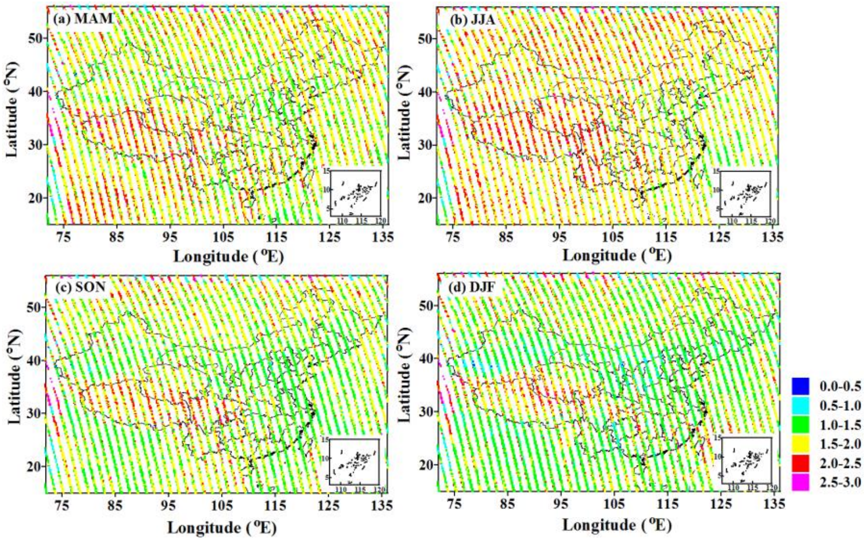


Figure 4. Spatial distributions of mean PBLH climatological PBLHsy derived from CALIOP at 1330 BJT in (a) spring (March-April-May, MAM), (b) summer (June-July-August, JJA), (c) autumn (September-October-November, SON) and (d) winter (December-January-February, DJF) during the period 2011 - 2014. Horizontal resolution is resampled to 20 km along the ground track.

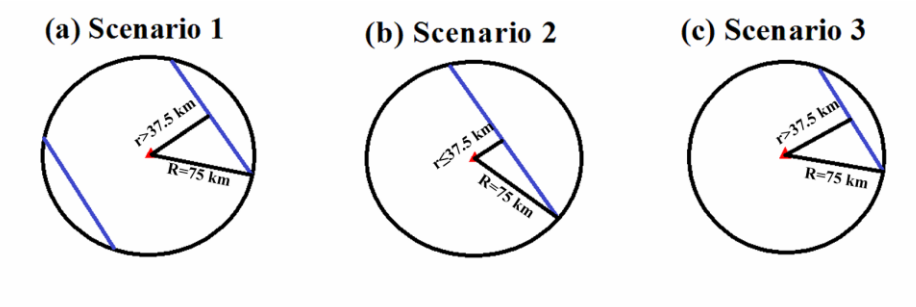


Figure 5. Schematic diagrams s showing the location of CALIOP ground tracks relative to radiosonde sites according to (a) Scenario 1 (with two CALIOP ground tracks, the shortest distance to which each is more than 37.5km from radiosonde site); (b) Scenario 2 (with one CALIOP ground track, the shortest distance to which is less than 37.5km from radiosonde site; (c) Scenario 3 (with one CALIOP ground track, the shortest distance to which is more than 37.5km from radiosonde site) showing the geometric relationship of CALIOP ground tracks relative to radiosonde sites. A circle with a radius of 75 km centered at radiosonde sites was chosen to obtain averaged PBLH from CALIOP, as compared with the measured PBLH from ground-based soundings.

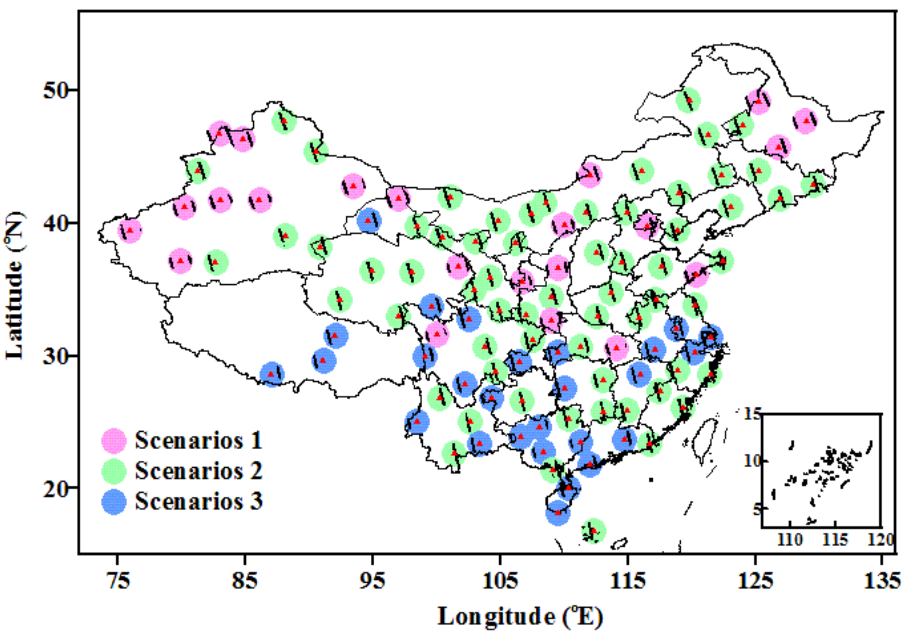
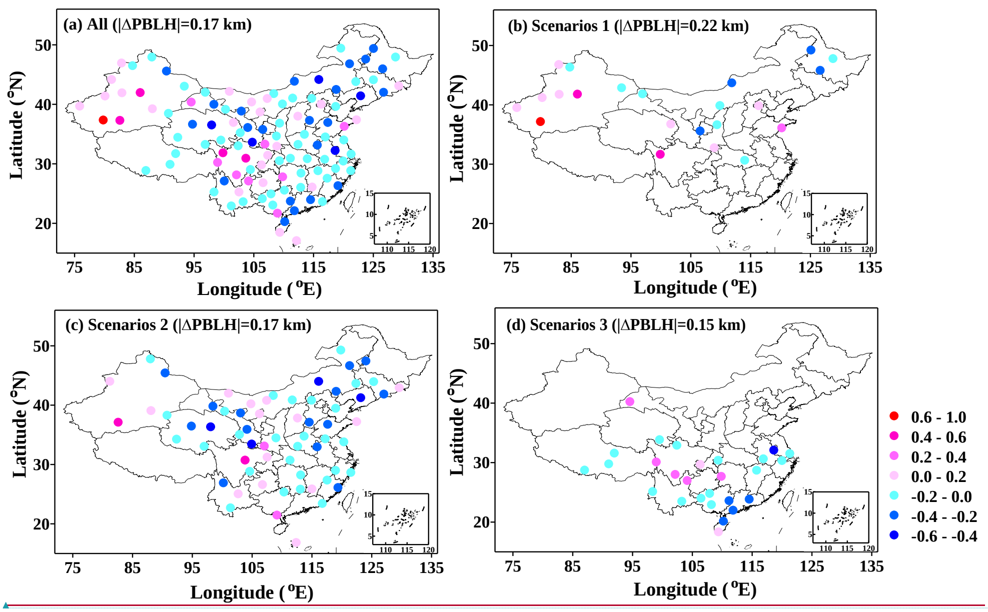


Figure 6. The geographic distribution map showing the location of radiosonde sites relative to CALIOP ground tracks over China. The red triangles denote the radiosonde sites, and the black lines show CALIOP tracks chosen for comparison analysis. The solid circles in cayon, green and blue correspond to Scenarios 1, 2, and 3 as defined in Figure 5.


(a) All (|ΔPBLH|=0.17 km)
(b) Scenarios 1 (|ΔPBLH|=0.22 km)
(c) Scenarios 2 (|ΔPBLH|=0.17 km)
(d) Scenarios 3 (|ΔPBLH|=0.15 km)
Latitude (°N)
Longitude (°E)
50
40
30
20
75
85
95
105
115
125
135
0.6 - 1.0
0.4 - 0.6
0.2 - 0.4
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-0.2 - 0.0
-0.4 - -0.2
-0.6 - -0.4

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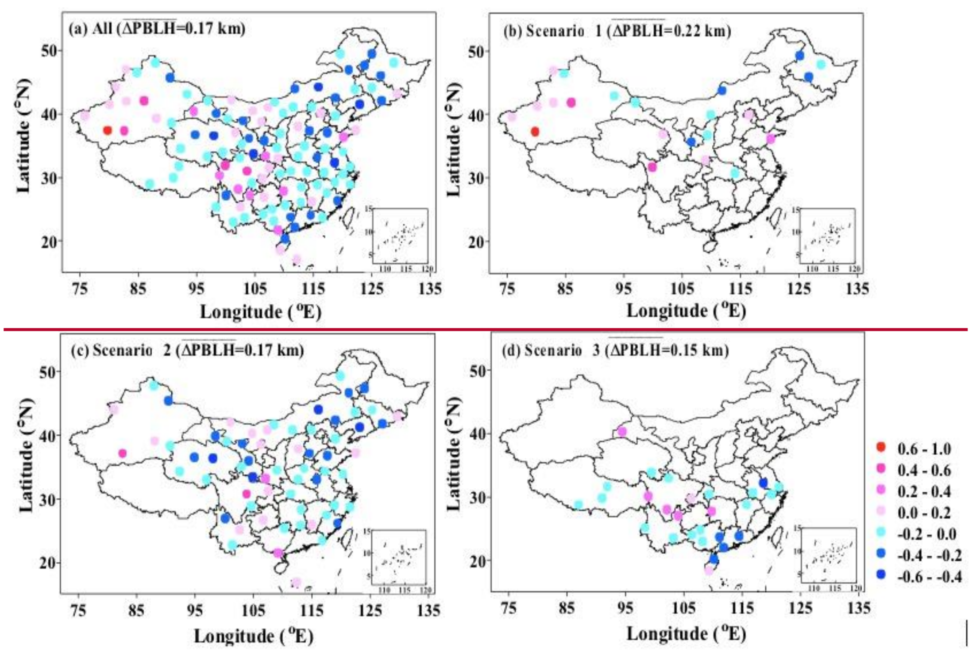

Figure 7. The geographicphysical distribution map concerning the absolute difference of PBLH derived from CALIOP 1330 LT minus that derived from radiosonde observations at 1400 BJT in the summertime (June-July-August) during the period of 2011-2014. The differences of PBLHs are shown for all radiosonde sites in China (a), the radiosonde sites belonging to Scenario 1 (b), Scenario 2 (c), and Scenario 3 (d), respectively.

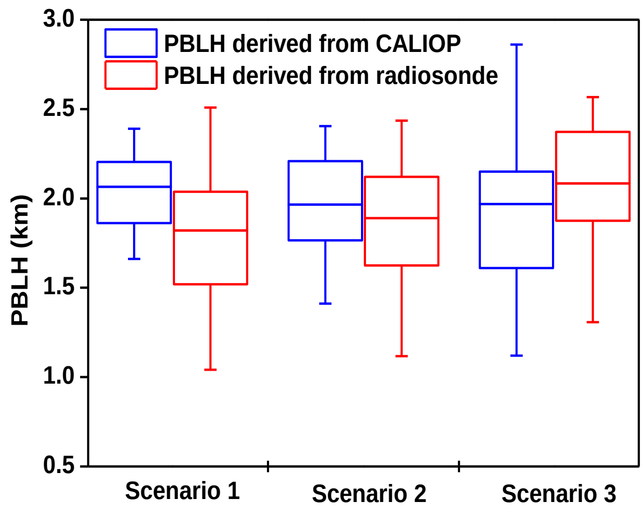

Figure 8. Box-and-whisker plot showing the 5^{th}, 25^{th}, 50^{th}, 75^{th} and 95^{th} percentile values of PBLH derived from CALIOP (in blue) and radiosonde (in red) for each scenario. Note that only 1400 BJT radiosonde are used to make comparison with afternoon CALIOP-derived PBLHs.

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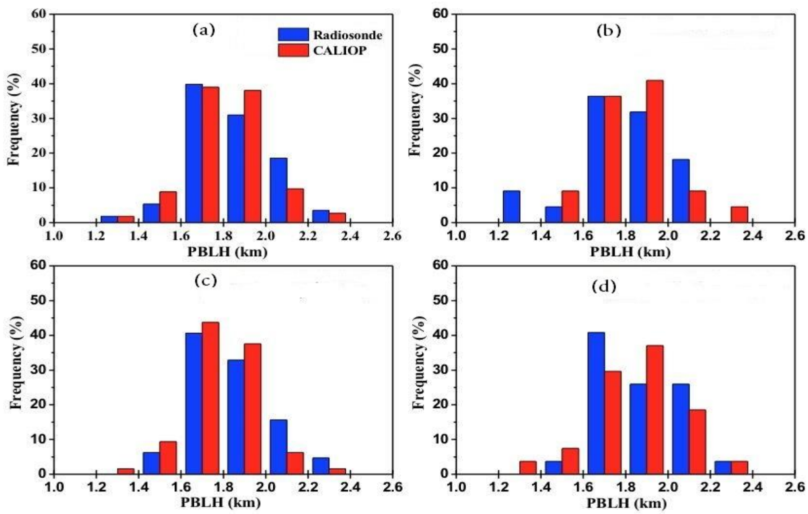

Figure 9~~8~~. Histogram of the number of radiosonde sites, stratified by binned radiosonde-derived mean PBLHs (blue bars, 1400 BJ~~L~~T) and CALIOP-derived mean PBLHs (red bar, around 1330 LT) over China in the summertime (June-July-August) during the period of 2011-2014 for all radiosonde sites (a), the radiosonde sites belonging to Scenario 1 (b), Scenario 2 (c), and Scenario 3 (d), respectively. The frequency is calculated as the ratio of the number of radiosonde site in each PBLH bin to the total number of radiosonde sites. Note that t~~. Due to the lack of the radiosonde measurements and revisit cycle of CALIPSO (16 days), we just selected~~he statistic results are only limited to the samples with collocated ~~, part of the~~ CALIOP- and radiosonde-derived PBLHs~~, which~~ ~~, could match up to the radiosonde measurements to do comparison.~~

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