

Atmos. Chem. Phys. Discuss., referee comment RC2 <https://doi.org/10.5194/acp-2020-1252-RC2>,  
2021

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## 10 **Comment on acp-2020-1252**

### **Anonymous Referee #2**

Referee comment on "Satellite retrieval of cloud base height and geometric thickness of low-level  
cloud based on CALIPSO" by Xin Lu et al., Atmos. Chem. Phys. Discuss.,  
15 <https://doi.org/10.5194/acp-2020-1252-RC2>, 2021

20 Lu et al. "Satellite retrieval of cloud base height and geometric thickness of low-level cloud based  
on CALIPSO"

This study proposes a method to retrieve the cloud base height from CALIPSO observations, from  
which cloud thickness is further derived. It also shows the statistical results of cloud macrophysical  
properties based on their retrievals. In principle, the study are interesting, while I have some  
25 concerns as listed below. Thus, I would recommend its acceptance for publication after necessary  
modifications.

### ***General comments***

#### **Question 1:**

30 While this study shows the cloud base properties from CALIPSO, the representation of the statistical  
properties should be discussed. Particularly, only partial clouds over the world have been retrieved  
with the proposed method, how could people use the statistical information obtained to represent all  
cloud properties? In addition, the cloud bases along with the statistical values from CALIPSO should  
35 be evaluated with the CloudSat. Particularly, using only two ground station observation (also not  
long-term observations) to evaluate the performance of the method seems to me not sufficient.

**RE:** Thank you for your comment.

We qualify that the cloud base heights only for the conditions satisfying the selection criteria. This  
means mostly broken or thin boundary layer clouds. We have added the description in the paper.

#### **Paragraph 4 in Section 3.3.2:**

40 [After the above processing, we obtained the final CBH of that CALIPSO 1° scene. These cloud base  
height information are mainly extracted from broken or thin boundary layer clouds.](#)

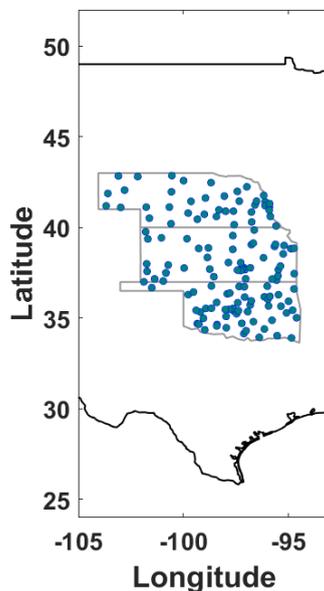
Moreover, CloudSat has difficulties for retrieving CBH of low-level clouds for the following reasons:

1. The ground clutter prevents CloudSat detection of very low cloud base.

2. Rain from precipitating clouds produces radar returns below cloud base.
3. Due to the dependence of radar reflectivity on the 6<sup>th</sup> power of cloud droplet diameter, the reflectivity of clouds with small droplets can be below the CloudSat minimum detectable signal, especially near cloud base where cloud droplets are smallest.

We have also added this description to Paragraph 3 in Introduction in the manuscript.

Furthermore, to validate the applicability over land of the retrieval algorithm in this study and to increase the case number for validation, we conducted additional validation experiments using 4 years of ceilometer data from 138 continental sites in the Great Plains of the USA (Figure R1, this figure is also provided as Figure A2 in the Appendix of the paper). These ceilometer data are derived from Automated Surface Observation System (ASOS). The data source is <https://mesonet.agron.iastate.edu/request/download.phtml> (last access: May 2021), which is maintained by Iowa Environmental Mesonet of Iowa State University. The data period used in this study is taken from 2017 to 2020 because during this period, the ceilometers provide better time resolution of cloud base measurements.



**Figure R1. The ASOS ceilometer distribution over land used for CBH evaluation.**

The ASOS uses a laser beam ceilometer with a time interval of 5-30 minutes, with a vertical resolution of ~30 m, and a vertical detection range of ~3700 m. In order to ensure the data quality of the ASOS ceilometer observations, we only use ceilometer data with CBH less than 3000 m and limit the number of valid cloud observations to no less than 2 during 1 hour.

Then, based on the CBH retrieval algorithm developed from the cloud observations over ocean, we conducted the same experiment on land to test the applicability of our algorithm. Since the cloud base is not as homogeneous over land as over ocean, we consider using the cloud information below the first peak nearest to the surface in the cloud fraction profile of 1° scene as a proxy for all cloud base information in this scene (which we defined as the first local peak above surface). In this way, we avoid missing the newly developed clouds with small size. Therefore instead of using  $H_{\min}$  at 10 % quantile of all clouds as the initial CBH over ocean, we tested the CBH at different quartiles of the first local peak as the initial CBH for the scene. Table R1 shows the corresponding statistical results (this table is also provided as Table B1 in the Appendix of the paper), which can be seen there is a minimum RMSE when the initial CALIPSO CBH is at the 40% quantile of the first local peak which closest to surface. This has also been verified in the results of other years (2007-2016, not shown).

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Thus on land the CALIPSO-retrieved initial CBH is 40% quantile of first local peak, while over the ocean it is  $H_{\min}$  at 10 % quantile.

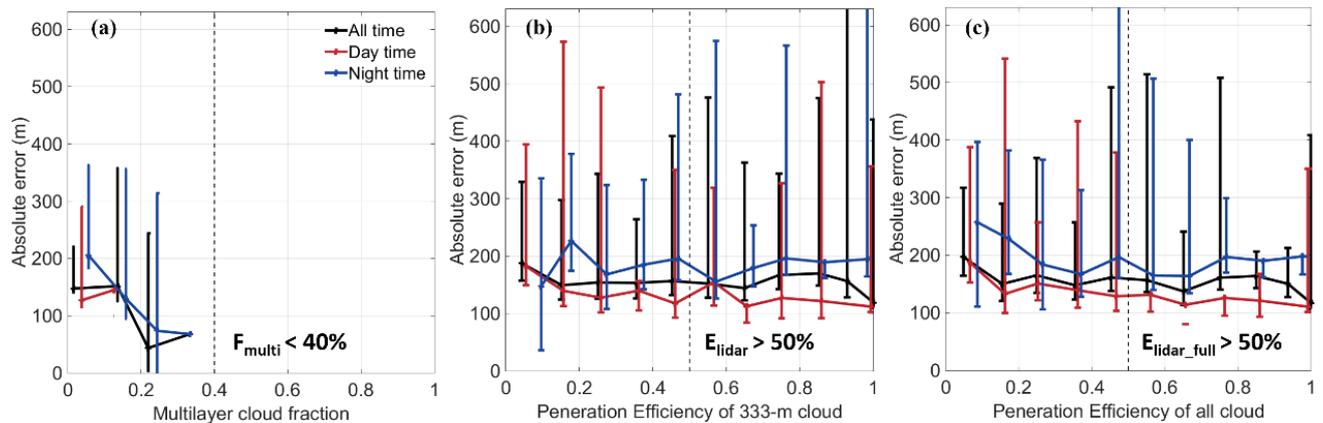
**Table R1.** Validation statistics of CALIPSO-retrieved initial CBH for different conditions of 138 continental ceilometer sites in the southern Great Plains in 2017-2020.

	Case number	RMSE (m)
min CALIPSO CBH	8404	635
$H_{\min}$ at 10 % quantile (same as ocean)	7963	665
10 % quantile of the first local peak	8302	616
20 % quantile of the first local peak	8280	615
30 % quantile of the first local peak	8270	619
<b>40 % quantile of the first local peak</b>	<b>8203</b>	<b>612</b>
50 % quantile of the first local peak	8225	618
60 % quantile of the first local peak	8193	619
70 % quantile of the first local peak	8169	628

80

Then, based on the CBH data obtained from the above processing, we further tested the effects of  $F_{\text{multi}}$ ,  $E_{\text{lidar}}$  and  $F_{\text{lidar\_full}}$  over land following the same process as over ocean, as showed in Figure R2 (this figure is also provided as Figure A3 in the Appendix of the manuscript). From the results it can be seen that the optimal thresholds for  $E_{\text{lidar}} > 50\%$ , and  $F_{\text{lidar\_full}} > 50\%$  over land are consistent with those over ocean, which also shows that the CBH retrieval algorithm we developed based on cloud observations from the ocean is applicable on land. The parameters  $F_{\text{multi}} < 40\%$  has little meaning over land due to the scarcity of the cases that fulfil that condition. It is kept over land for consistency with the ocean criteria.

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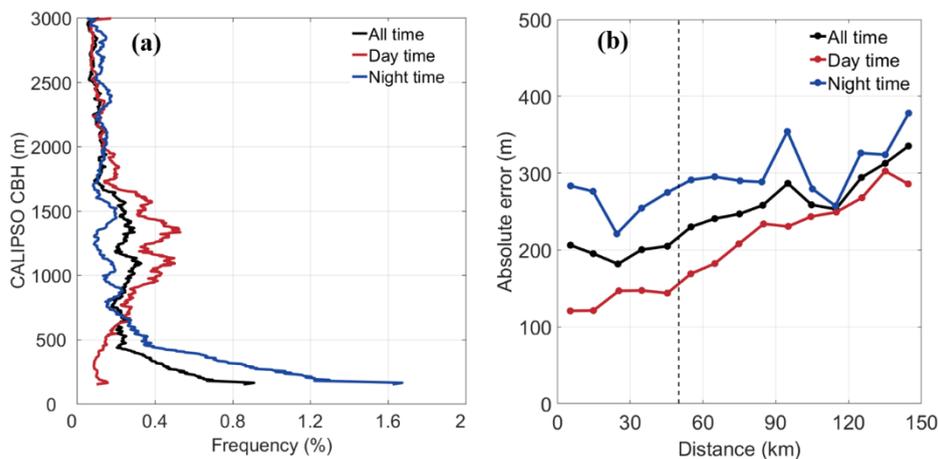
90

**Figure R2.** (a) Joint distribution of CBH absolute error (between CALIPSO CBH and ceilometer CBH) and multilayer cloud fraction of 138 continental ceilometer sites in the southern Great Plains in 2017-2020 with distance less than 50 km. The different coloured line represents at different time (the black line: all time; the red line: day-time; the blue line: night-time). The I-beam line represents the standard error. (b) is the same as (a), but for penetration efficiency of 333-m resolution cloud. (c) is the same as (a), but for penetration efficiency of all cloud.

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As mentioned before due to the complexity of topography and land surface situation, the cloud bases height varies at larger spatial scales. The 150 km distance between the shortest distance from the CALIPSO ground track to the ceilometer site cannot be used for over land validation. We have to shrink the distance to minimize the spatial variability due to the changes over land. We tested the effect of distance (that is the shortest distance from the CALIPSO ground track to the ceilometer site) and observation time on the retrieval results (Figure R3, which is also provided as Figure A4 in the

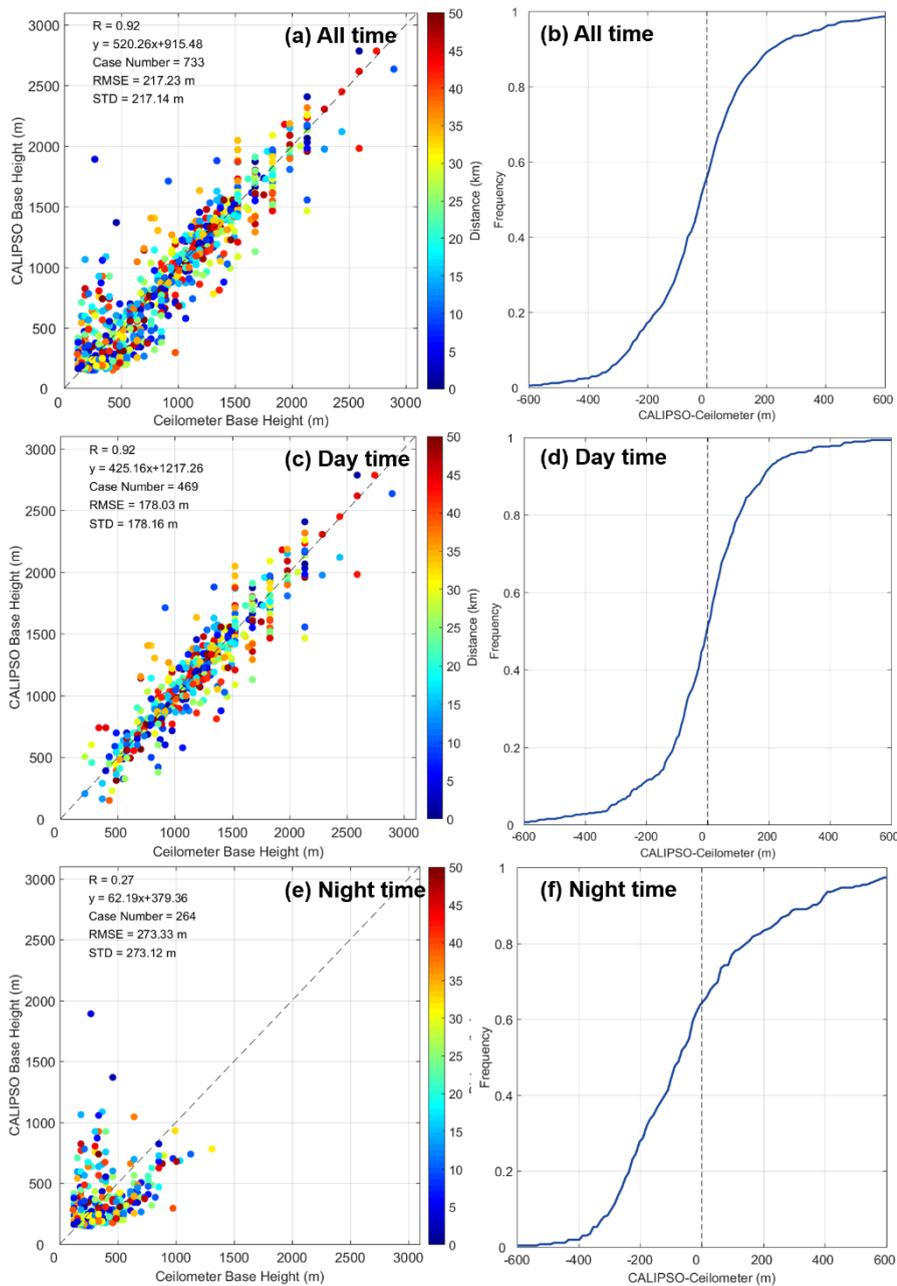
100 Appendix of the manuscript). The results (Figure R3b) show that the absolute error between the  
 CALIPSO CBH and the ceilometer CBH becomes smaller as the distance decreases, stabilizing at  
 distances less than 50 km. It is therefore preferable to limit the distance to 50 km for studies on land  
 to better meet the assumptions of a homogeneous CBH within 1° scenes. It can also be seen that the  
 cloud base heights are more evenly distributed during the day-time (Figure R3a, 300-1800 m) than  
 105 at night, while at night CBHs are mainly concentrated below about 700 m and are most frequent very  
 near the surface, where validation becomes unreliable. In addition to the distance limitation, the  
 cloud base homogeneity further constrained by comparing the lifted condensation level ( $H_{LCL}$ ) to  
 ceilometer cloud base height. To satisfy the cloud base homogeneity assumption (Efraim et al.,  
 2020), cases are selected when the absolute difference between the  $H_{LCL}$ (calculated from ASOS-  
 110 observed air temperature and dew point temperature) and ceilometer CBH is less than 200 m. In  
 summary, the ceilometer measurements need to satisfy the following conditions for validating  
 CALIPSO CBH retrieval: 1) The ceilometer is within 50 km radius to the center of CALIPSO ground  
 track; 2) the ceilometer measured CBH should have an absolute difference less than 200 m against  
 115  $H_{LCL}$  as calculated from surface measured air temperature and dew point.



120 **Figure R3. (a)** Frequency profile of CALIPSO-retrieved CBH of 138 continental ceilometer sites in  
 the southern Great Plains in 2017-2020. The different coloured line represents at different time (the  
 black line: all time; the red line: day-time; the blue line: night-time). **(b)** Joint distribution of CBH  
 absolute error (between CALIPSO CBH and ceilometer CBH) and distance (that is the shortest  
 distance from the CALIPSO ground track to the ceilometer site) of 138 continental ceilometer sites  
 in the southern Great Plains in 2017-2020. The different coloured line represents at different time  
 (the black line: all time; the red line: day-time; the blue line: night-time).

125 Figure R4 shows the final verification results over land (this figure is also provided as Figure 8 in  
 Section 4.2 of the paper). Based on 4 years of observations from 138 ceilometer sites in the southern  
 Great Plains, 733 sets of matching cases were obtained in 2017-2020 (day-time: 469 sets; night-time:  
 264 sets). The statistical analysis of these matching cases (Figure R4a) shows that, the CALIPSO-  
 retrieved CBH has a good consistency with the CBH observed by the ceilometers at these continental  
 sites. The R is 0.92, the RMSE is 217.2 m and the standard deviation is 217.1 m. The cumulative  
 130 distribution of the CBH difference between CALIPSO and ceilometer in Figure R4b indicates that  
 ~70% of the matching cases have a deviation of less than 200 m. In addition, the day-time results  
 (R=0.92, RMSE=178.0 m) are better than the night-time results (R=0.27, RMSE=273.3 m). From  
 Figure R4e it can be seen that the CBH at night is mainly concentrated below 800 m. This may be  
 due to the effect of low-level clouds and fog patches, which possibly contaminate the ceilometer  
 135 data. Therefore, it is unreasonable to validate the CALIPSO retrieval against the night-time ceilometer

measurements and day-time data are more suitable for validation.



**Figure R4. Validation of CALIPSO-retrieved CBH against 138 continental ceilometer sites in the southern Great Plains in 2017-2020.** (a) Scatter plot of CALIPSO CBH and ceilometer CBH on day-time. The color represents the shortest distance from the CALIPSO ground track to the ceilometer site. (b) Cumulative distribution of the difference between CALIPSO CBH and Ceilometer CBH on day-time. (c)/(e) and (d)/(f) are the same as (a) and (b), but for day-time and night-time, respectively.

The above analysis has been added to the Section 4 (Evaluation of CALIPSO-retrieved CBH) as a new section as follow:

## 4.2 Over land

To validate the applicability over land of the CBH retrieval algorithm, we conducted additional validation experiments using 4 years of continental ceilometer data from 138 sites in the southern

150 Great Plains of the USA (as showed in Figure A2). The data period is taken from 2017 to 2020  
because during this period, the ceilometers provide better time resolution of cloud base  
measurements. Since the cloud base is not as homogeneous over land as over ocean, we consider  
using the cloud information below the first peak nearest to the surface in the cloud fraction profile  
of 1° scenes as a proxy for all cloud base information in this scene (which we defined as the first  
155 local peak above surface). In this way, we avoid missing the newly developed clouds with small size.  
Therefore instead of using  $H_{\min}$  at 10 % quantile of all clouds as the initial CBH over ocean, we  
tested the CBH at different quartiles of the first local peak as the initial CBH for the scene (detailed  
information is provided in Table B1 in the Appendix). The results show that there is a shallow  
minimum RMSE when the initial CALIPSO CBH is at the 40 % quantile of the first local peak which  
160 closest to surface. Thus on land the CALIPSO-retrieved initial CBH is 40 % quantile of the first local  
peak, while over the ocean it is  $H_{\min}$  at 10 % quantile. Then, based on the CBH data obtained from  
the above processing, we further tested the effects of  $F_{multi}$ ,  $E_{lidar}$  and  $F_{lidar\_full}$  over land following the  
same process as over ocean, as showed in Figure A3 in the Appendix. From the results it can be seen  
that the optimal thresholds for these parameters ( $F_{multi}<40\%$ ,  $E_{lidar}>50\%$ , and  $F_{lidar\_full}>50\%$ ) on  
165 land are consistent with those over ocean, which also shows that the CBH retrieval algorithm we  
developed based on cloud observations from the ocean is applicable on land. These final criteria for  
CALIPSO CBH retrieval used over ocean and land is also summarized in Table B2.

As mentioned before due to the complexity of topography and land surface situation, the cloud bases  
height varies at larger spatial scales. The 150 km distance between the shortest distance from the  
CALIPSO ground track to the ceilometer site cannot be used for over land validation. We have to  
170 shrink the distance to minimize the spatial variability due to the changes over land. We tested the  
effect of distance (that is the shortest distance from the CALIPSO ground track to the ceilometer site)  
and observation time on the retrieval results (Figure A4 in the Appendix). The results (Figure A4b)  
show that the absolute error between the CALIPSO CBH and the ceilometer CBH becomes smaller  
as the distance decreases and stabilizes at distances less than 50 km. It is therefore preferable to limit  
175 the distance to 50 km for studies on land to better meet the assumptions of a homogeneous CBH  
within the scene. It can also be seen that the cloud base heights are more evenly distributed during  
the day-time (Figure A4a, 300-1800 m) than at night, while at night CBHs are mainly concentrated  
below about 700 m. In addition to the distance limitation, the cloud base homogeneity is further  
constrained by comparing the lifted condensation level ( $H_{LCL}$ ) to the ceilometer cloud base height.  
180 To satisfy the cloud base homogeneity assumption (Efraim et al., 2020), cases are selected when the  
absolute difference between the  $H_{LCL}$  (calculated from ASOS-observed air temperature and dew  
point temperature) and ceilometer CBH is less than 200. In summary, the ceilometer measurements  
over land need to satisfy the following conditions for validating CALIPSO CBH retrieval: 1) The  
ceilometer is within 50 km radius to the centre of CALIPSO ground track; 2) the ceilometer-  
185 measured CBH should have an absolute difference less than 200 m against  $H_{LCL}$  as calculated from  
the surface measured air temperature and dew point.

Ceilometer data that passed these conditions were used for validating the CALIPSO retrieved cloud  
base height. Figure 8 shows the final verification results over land. Based on 4 years of observations  
from 138 ceilometer sites in the southern Great Plains, 733 sets of matching cases were obtained in  
190 2017-2020 (day-time: 469 sets; night-time: 264 sets). The statistical analysis of these matching cases  
(Figure 8a) shows that, the CALIPSO-retrieved CBH has a good consistency with the CBH observed  
by the ceilometers at these continental sites. The R is 0.92, the RMSE is 217.2 m and the standard  
deviation is 217.1 m. The cumulative distribution of the CBH difference between CALIPSO and  
ceilometer in Figure 8b indicates that ~70 % of the matching cases have a deviation of less than 200  
195 m. In addition, the day-time results (R=0.92, RMSE=178.0 m) are better than the night-time results

( $R=0.27$ ,  $RMSE=273.3$  m). From Figure 8e it can be observed that the CBH at night is mainly concentrated below 800 m. This might be due to the effect of low-level clouds and fog patches, which possibly contaminate the ceilometer data. Therefore, it is unreasonable to validate the CALIPSO retrieval against the night-time ceilometer measurements and day-time data are more suitable for validation.

200

### Question 2:

How do you consider the clouds with multiple layers? Particularly, there are considerable amount of multiple layer clouds on the globe. How do you consider the time representation error and sample representation errors when you do the statistics for only partial clouds that you can retrieve?

205

**RE:** We exclude the situations where elevated obscure cloud bases. For each CALIPSO 1° scene, approximately 345 CALIPSO lidar profiles exist and we extracted the cloud base height using only the profiles containing single-layer clouds. In addition, we also considered the effect of the fraction of multi-layered clouds in each scene; when the fraction of multi-layered clouds was greater than 40%, the CALIPSO-retrieved CBH for that scene was considered invalid. That is, we qualify that the cloud base heights only for the conditions satisfying the multiple-layer cloud selection criteria.

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Moreover, given there are considerable amount of multi-layered clouds on the globe, we have actually been more lenient in our restrictions on multilayered clouds, rejecting only a small number of data with unusually large multilayered cloud fractions (greater than 40%) on a global scale. Figure R5 shows the ratio of scenes were rejected based on which criterion (this figure is also provided as Figure A6 in the Appendix of the manuscript). It can be seen that only a small number of data (~0.5%) were rejected by the multilayer cloud criteria (Figure R5b). The results also show a global average rejection ratio of ~29.5%, which is mainly influenced from penetration efficiency (penetration efficiency of 333-m resolution cloud: 28.4%; penetration efficiency of all resolution cloud: 29.5%).

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Since the CBH is homogeneous over a certain range (over ocean: 100 km; over land: 50 km), as pointed out in Figure R3, it is reasonable to use a permeable cloud base as a proxy for the entire cloud base of the scene.

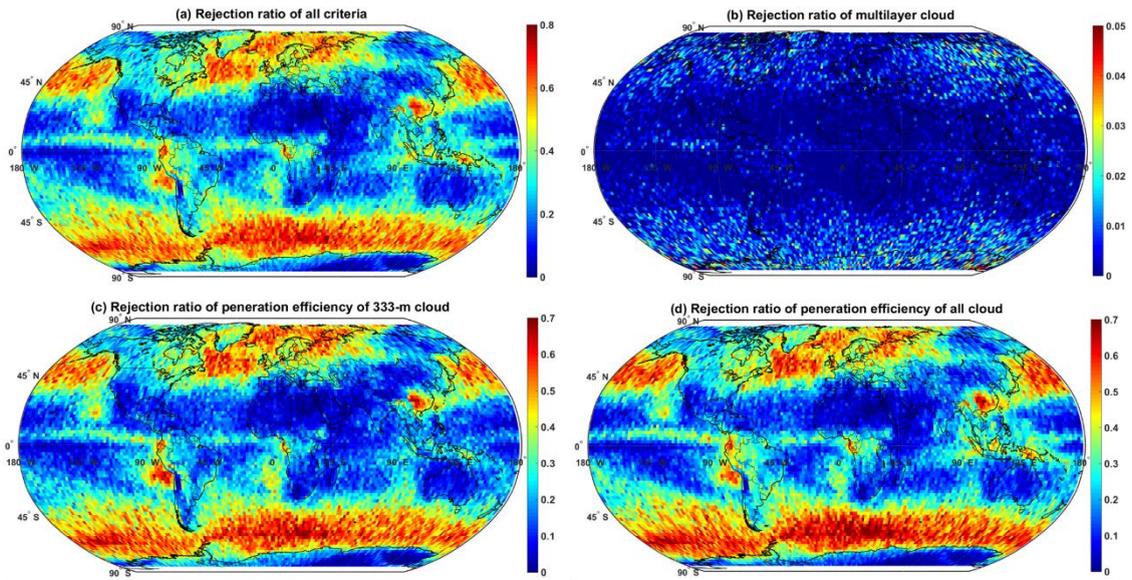
220

We have also added these information to the manuscript:

### Paragraph 4 in Section 5.1:

We also counted the ratio of scenes were rejected based on each criterion (as shown in Figure A6 in the Appendix). The results show a global average rejection ratio of ~29.5 %, which is mainly influenced from penetration efficiency (penetration efficiency of 333-m resolution cloud: 28.4 %; penetration efficiency of all resolution cloud: 29.5 %), with less influence from multilayer clouds. In addition, the results in Figure A6a show that a higher rejection ratio is at high latitudes than at middle and low latitudes, particularly in the Southern Ocean region.

230



235 **Figure R5.** (a) Geographic distribution of rejection ratio of all criteria (multilayer cloud, penetration efficiency of 333-m resolution cloud, and penetration efficiency of all resolution cloud) on a  $2^\circ \times 2^\circ$  latitude–longitude grid in 2014 and 2017. (b), (c) and (d) are the same as (a), but for multilayer cloud, penetration efficiency of 333-m resolution cloud, and penetration efficiency of all resolution cloud, respectively.

## Detailed comments

- 240 1. Line 39-40, As I know, these two references are about the aerosol-cloud interactions. The importance of cloud boundaries to the cloud microphysical properties are mainly for the remote sensing of retrievals, such as the various retrieval methods indicated in Zhao et al. (2012, doi:10.1029/2011JD016792) along a lot of recent retrieval algorithms.  
**RE:** The description and citations in Lines 39-40 have been revised as “Satellite retrievals of cloud base height (CBH), cloud top height (CTH) and cloud geometrical thickness (CGT) are essential for quantifying cloud dynamic and microphysical properties (Rosenfeld et al., 2016;Zhao et al., 2012).”.
- 245 2. Line 41-42, this sentence has two verbs and should be rephrased. In addition, the finding that aerosols which can serve as CCN change the radiation balance by modifying the cloud properties was provided long time ago. In addition to the recent reference by Rosenfeld et al. (2019), other studies particularly those important are recommended, such as Twomey et al. (1977, doi:10.1175/1520-0469(1977)034<1149:TIOPO>2.0.CO;2), Albrecht (1989, doi:10.1126/science.245.4923.1227), and Garrett and Zhao (2006, doi:10.1038/nature04636).  
**RE:** The description and citations in Lines 41-42 have been revised as “Atmospheric aerosols, which serve as cloud condensation nuclei (CCN), control size and number concentration of cloud droplets and regulate the radiation balance of the Earth-atmosphere system (Rosenfeld et al., 2019;Twomey, 1977;Albrecht, 1989;Garrett and Zhao, 2006)”.
- 250 3. Line 46-49, a transition sentence from adiabatic fraction to cloud base is necessary.  
**RE:** We have added a transition sentence as “Accurate information on cloud base and cloud thickness is a necessary condition for retrieval of adiabatic fraction.” at Paragraph 1 in Introduction.
- 255 4. Line 50, why? For radar-based cloud retrieval, I do not think CTH is crucial unless the retrieval method is based on MWR LWP (to adjust).  
**RE:** Thank you for your comment. This sentence about CTH at Paragraph 2 in Introduction has been removed.
- 260 5. Line 59-60, how about the satellite radar observations, such as CloudSat?  
**RE:** For CloudSat radar observations, we have added the following to the paper.  
**Paragraph 3 in Introduction:**  
CloudSat is an essential active cloud radar observation satellite. However, CloudSat has difficulties to retrieve CBH of low-level clouds for the following reasons: a) The ground clutter prevents detection of very low base. b) Rain from precipitating clouds produces radar returns below cloud base. c) Due to the dependence of radar reflectivity on the 6<sup>th</sup> power of cloud droplet diameter, the reflectivity of clouds with small droplets can be below the CloudSat minimum detectable signal, especially near cloud base where cloud droplets are smallest.
- 265 6. Line 82-84, it is not always this case, depending on the amount of aerosols. This case is particularly significant over East Asia, South Asia and desert regions.  
**RE:** The sentence has been revised as “In addition, in aerosol-prone regions, such as East Asia, South Asia and desert regions, due to the influence of aerosols in the boundary layer, the low-level cloud may be masked by dense aerosol layers, thereby affecting the determination of the cloud layer (Vaughan et al., 2005)” at Paragraph 4 in Introduction.
- 270 7. Data part, what are the potential uncertainties for the data used in this study?  
**RE:** The detailed description of the data have been added in Section 2 as following:  
**Section 2.1:**  
CALIPSO, jointly developed by NASA and CNES, is a sun-synchronous orbiting satellite with an orbital inclination of 98.2°, an orbital altitude of 705 km, a revisit period of 16 days, and an
- 275  
280

285 equatorial crossing time of approximately 13:30 local time.  
The official CALIPSO classification algorithm suffers from misclassification of clouds and aerosols at low resolution (Mace and Zhang, 2014; Vaughan et al., 2005).

**Section 2.2:**

290 The temporal resolution of the ceilometer at Barbados site is 10 seconds, and the vertical resolution is 15 m.

At the ENA site, the ceilometer has a temporal resolution of 16 seconds, a vertical resolution of 30 m and a maximum detection range of 7700 m.

295 The ASOS uses a laser beam ceilometer with a time interval of 5-30 minutes, with a vertical resolution of ~30 m, and a vertical detection range of ~3700 m. In order to ensure the data quality of the ASOS ceilometer observations, we only use ceilometer data with cloud base heights less than 3000 m.

8. Line 109-110. This sentence is too redundant. You can simply use “The retrieval algorithm is validated using the ground-based ceilometer observations.”

300 **RE:** Thank you for your suggestion. The sentence has been revised as “The retrieval algorithm is developed and validated using the ground-based ceilometer observations.” at Paragraph 1 in Section 2.2.

9. Line 110-111, do you have any reference or support that much of the low-level cloud occurs over the ocean, while it might be true?

**RE:** The description here have been revised as following:

305 **Section 2.2:**

The retrieval algorithm is developed and validated using the ground-based ceilometer observations. To represent the different types of low-level clouds around the world, we used ceilometer sites located at different latitudes over ocean and land (two marine sites and 138 continental sites) respectively to validate the CALIPSO-retrieved CBH.

- 310 10. Section 2, in addition to the ground-site observation based evaluation, why do not the authors evaluate the retrieval results using CloudSat observations, which can give the performance globally?

**RE:** Please see the reply to Question 5 of Detailed comments.

- 315 11. Line 114-119 and Figure 1, by selecting so large domain, it would assume the cloud base heights vary little within this region. It might be not the truth sometimes. Have you checked the horizontal variation of cloud base heights using other observations such as CloudSat, and thin clouds with CALIPSO?

320 **RE:** We have perform a sensitivity study to the size of the domain as shown in above Figure R3. Over land, when the distance is less than 50 km, the deviation between CALIPSO-retrieved CBH and ceilometer CBH has little to do with the distance. (Please see the reply to Question 1 of General comments for detailed responses.) Over ocean this distance can be extended to 150 km (Section 4.1 in the manuscript).

12. Line 125-126. Sine this assumption is a key basis of this study, the authors need approve its reliability based on further in-detail analysis using observations, such as what I mentioned above.

325 **RE:** Please see the reply to Question 11 of Detailed comments.

13. Line 135-139. The question is that clouds can form via various mechanisms, the mixing of cold and warm air masses, the surface heating, the fronts, the radiative cooling, and so on. Based on the point mentioned here, could all cloud bases be determined? If yes, may you please explain more? If not, how many clouds (in fraction) globally could be determined with this method?

330 **RE:** Please see the reply to Question 2 of General comments for detailed responses.

14. Section 3.2, I am not sure if this section is necessary or not. To me, most of the information here are redundant information, which have been introduced earlier.

335 **RE:** Thank you for your comment. This section has been removed and the relevant content has been consolidated in Paragraph 1 of Section 3.

15. Figure 4 and corresponding analysis. As I know, there are long-term observations of clouds over the Azores site, why do not the authors use long-term observations to evaluate the performance of the retrieval algorithm? Anyway, the sample number seems too small to me in current Figure 4.

340 **RE:** The results in Figure 4 are all available valid data for the year 2017 at the two marine sites. These data were used to develop our CBH retrieval method. To validate the applicability of the retrieval algorithm in this study and to increase the number of coincident satellite- and ground-based observations for validation, we conducted additional validation experiments using 4 years of ceilometer data from 138 terrestrial sites in the southern Great Plains of the USA. Please see the reply to Question 1 of General comments for detailed responses.

345

16. Section 3.4.1 Are you sure with the method, all multi-layer clouds can be excluded.

**RE:** The CBH information for this algorithm is extracted from the CALIPSO single layer cloud profile only. For the treatment of multi-layer clouds, please refer to the response to Question 2 of General comments.

350

17. Lines 260-270, with these limitations, I wonder how many cloud samples have been removed and how many cloud samples are kept. In addition, the CALIPSO not continuously observe the clouds at a fixed location (coarse time resolution). How could these sample limitation, time limitation affect the statistical results obtained in later analysis (Section 5).

355

**RE:** The remaining cases are those which boundary layer clouds are not obscured by higher layers and do not form a solid thick cloud deck. These are the conditions that allow us to sample the cloud base heights. Moreover, we also have provided the geographic distribution of rejection ratio by each selection criterion in Figure R5. Please see the reply to Question 2 of General comments for detailed responses.

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In addition we address the sample and time limitations of CALIPSO by assuming that the cloud base height is homogeneous over a certain range (over ocean: ~100 km; over land: ~50 km), which is consistent with the study of Mülmenstädt et al. (2018). We also provide a detailed analysis of the effect of distance. Please see the reply to Question 1 of General comments for detailed responses.

18. Line 291, “indicates” -> “indicate”

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**RE:** This “indicates” has been revised as “[indicate](#)” at Paragraph 1 in Section 5.1.

19. Line 294, do you have a reference to support this claim that there are more scenes with lots of optical thicker clouds and multilayer clouds over land.

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**RE:** According to the geographic distribution of rejection ratio by each selection criterion in Figure R5 (the reply to Question 2 of General comments), the description here has been revised as “...[because there are more scenes with cloud bases above 3 km or more cloud free scenes \(e.g. Sahara, Australia\)](#)” at Paragraph 1 in Section 5.1.

20. Line 297-300, personally, I think the CTHs are particularly large over the Tibetan Plateau region, which is worthy to mention. Also, you may compare your statistical findings (actually only partial of clouds existing) with those from MODIS (polar-orbiting satellite) and Himawari (such as Yang et al. 2020, doi: 10.1016/j.atmosres.2020.104927).

375

**RE:** Thank you for your suggestion. We have added the following at Paragraph 2 in Section 5.1. [In particular, there is a peak area of CTH in the Tibetan Plateau region, essentially greater than 2800 m, which is consistent with the conclusions obtained by Yang et al. \(2020\) based on high spatial resolution Himawari imager data.](#)

380 **References**

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