Response to Referees' Comments

Response to Reviewer #1:

Using long-term observations at the U.S. Department of Energy's Atmospheric Radiation Measurement Program's Southern Great Plains site, this study developed a first-ever lidar-based method (DTDS) to automatically identify coupled and decoupled low clouds over land. The coupled states determined by the DTDS method compared considerably well with that derived from radiosondes. In the meantime, with the ability to provide high-quality retrievals of the PBLH under cloudy conditions, the proposed DTDS method also helps address a long-lasting problem in the PBLH retrieved from lidar. In general, the manuscript is written pretty well with the evidence presented by the authors supports their conclusions. I only have a few minor comments below that I would like to see addressed before the manuscript is accepted for publication.

Response: We appreciate the reviewer's positive and helpful comments on our work. All of the comments and concerns raised by the referee have been carefully considered and incorporated into the revised manuscript. Our detailed responses to the reviewer's questions and comments are listed below.

Minor comments:

1. *Line 107-108: The radiosonde data provides the PBLHs retrieved from four different algorithms. Is there any specific reason why you only select the PBLH*

retrieved by the method of Liu and Liang (2010)? Based on my personal experiences, the PBLH retrieved from different algorithms can vary a lot from each other for some cases.

Response: Thanks for raising this point. In section 2.1, we added a discussion for different algorithms for retrieving PBLH from the radiosonde.

"There are several methods to determine PBLH from RS-measured temperature, pressure, and humidity profiles. These methods include, among others, the parcel method (Holzworth, 1964), the gradient methods (Stull, 1988; Seidel et al., 2010), and the Richardson number method (Vogelezang and Holtslag, 1996). After examining the previous methods, Liu and Liang. (2010) proposed a different approach to determine PBLH that is valid under different thermodynamic conditions. The robust performance was demonstrated over the SGP site and in other major field campaign sites around the world (Liu and Liang, 2010). Thus, we adopted this method to calculate PBLH from RS data in this study."

Reference:

Holzworth, G. C., (1964). Estimates of mean maximum mixing depths in the contiguous United States, Mon. Weather Rev., 92, 235–242, https://doi.org/10.1175/1520-0493(1964)092<0235:eommmd>2.3.co;2.

Seidel, D. J., Ao, C. O., & Li, K. (2010). Estimating climatological planetary boundary layer heights from radiosonde observations: Comparison of methods and uncertainty analysis. Journal of Geophysical Research: Atmospheres, 115(D16).

Vogelezang, D. H. P., & Holtslag, A. A. (1996). Evaluation and model impacts of alternative boundary-layer height formulations. Boundary-Layer Meteorology, 81(3), 245-269.

2. *Figure 2. It would be nice if the information of the data sources for each variable are also included in the figure caption. For example, the PBLH is derived from the RS profiles using the method of Liu and Liang (2010), the cloud layer is obtained from the CLDTYPE/ARSCL data, etc.*

Response: Following your comment, we added the data sources for all the variables used in the figure captions.

3. *Line 354: change "a relatively low biases" to " a relatively low bias"*

Response: Revised as suggested.

4. *Line 432-435: Get confused about this part. Do you mean that the correlation coefficient between the DTDS-derived PBLH and RS-derived PBLH under cloudy conditions is much higher compared with that under clear-sky cases? Why is this kind of comparison important here?*

Response: The comparison in performance between cloudy conditions and clear sky is not highly relevant to the main scope of this study. Thus, we deleted this

sentence.

5. *Please keep your reference formating consistent throughout the manuscript, for instance, Ek and Holtslag (2004) vs. Zheng & Rosenfeld, (2015).*

Response: Per the comment, we thoroughly checked the manuscript and revised the format of reference.

Response to Reviewer #2:

The manuscript described a method to determine the coupling of clouds with the surface using lidar measurement at the ARM SGP site. Determining the coupling status of clouds with the surface is important for cloud process-level analyses and understanding. After reading through the manuscript, I feel the study is more focused on method development and therefore a method-focused journal such as Atmospheric Measurement Techniques (AMT) could probably get the work a better exposure to the atmospheric retrieval/measurement community. In this work, the authors first developed a method to determine coupled and decoupled clouds with boundary layer/surface, then they further developed a method to estimate boundary layer height (PBLH) under cloudy conditions on the basis of their previous work published in 2020. The manuscript is well written but not well structured (details are provided in major comments #1 and #3). There are several concerns about the robustness of the methods and uncertainties of the data used. I suggest resubmitting the paper to a more method-focused journal (e.g., AMT) after these major revisions.

Response: We appreciate the reviewer's detailed comments and suggestions on our work. While we are fully aware of the reviewer's kind consideration to target our paper to the right readers, we do believe our paper is more suitable for the ACP due to the following reasons.

Although this study leads to the development of a method, there is a considerable deal of scientific research that serves the backbone of the method. The determination of the cloud coupling itself requires much physical

understanding of the clouds and boundary layer dynamics/thermodynamics. The scientific investigation involved in developing the methodology falls well within the scope of the ACP. As the first remote sensing method for determining the coupling state of continental clouds, it deals with a lot more scientific issues than solving a technical problem, as it requires an in-depth understanding of boundary-layer processes and clouds. This study provides a novel exploration of this surface-cloud coupling over land which can help us understand the determination, identification, and characteristics of cloud coupling from the perspective of remote sensing. Thus, we believe the study goes beyond presenting a method.

Major comments:

1. *The title is 'to determine the coupling of continental clouds with surface from lidar measurements. However, the manuscript only described the method from lines 277 to 280. More work was presented for estimating PBLH under cloudy conditions. So, I suggest changing the title to include the information of PBLH estimations under cloudy conditions.*

Response: Following your guidance, we revised the tile as "Methodology to determine the coupling of continental clouds with surface and boundary layer height under cloudy conditions from lidar and meteorological data".

2. *Line 218-231: it is confusing here. Usually, the positive/negative sign of a force*

reflects the direction of the force, while the magnitude reflects the strength. Figure 4 shows that small magnitude buoyancy forces correspond to strong buoyancy forces. Following Figure 4, 0 buoyancy force is a pretty strong buoyancy force. That does not make sense! I also feel that Figure 4 does not connect to other parts of the manuscript but distracts the discussion.

Response: We agreed with your comment that this figure may not connect to other parts. Thus, we have deleted this figure.

3. *To determine coupled clouds, there are two categories: lines 278 and 279-280. Each category has two constraints. How often does each category occur and under what conditions does each category occur? Which constraint for each category is more critical? Compared with the method listed in Line 317, why can't the lidar-based cloud coupling determination use a single 'criteria' same as that is used with LCL and RS PBLH showed in Figure 6? Do the complicated algorithms with 5 constants and different constraint strategies perform better than just using a single 'criteria'? At least from Figure 6, the RS PBLH method performs well, even just uses a single 'criteria'.*

Response: Yes, we can use a single criterion to diagnose cloud coupling. The critical parameter is H(i-1), which presents the DTDS-derived PBLH at time i-1. The LCL constraint in the method can reduce the commission error of coupled cloud identifications by 4.2%, and can reduce the absolute biases in PBLH

retrievals under cloudy conditions by 9.3%. In particular, the first condition (line 278) moves 39.5% of low cloud cases to the category of decoupled clouds. Furthermore, the second condition (line 279-280) further moves 17.8% of the remaining cases to the category of decoupled clouds. We required coupled clouds can satisfy these two conditions, which means CBH, LCL, and lidar-derived PBLH are largely consistent with each other. Meanwhile, these two conditions assured that either LCL or PBLH coincides with CBH for identifying coupled cases,

Cloud can considerably interfere with lidar backscatter and generate large signal variations, which cause some difficulties in the identification. Thus, we do not use the single lidar profile, but jointly use lidar backscatters, the previous position of PBL top, and LCL to determine the surface-cloud coupling and PBLH. On the other hand, radiosonde (RS) can provide accurate potential temperature profiles under cloudy conditions. Thus, the RS PBLH is considered the most reliable retrieval and can be used as a relatively good standard to diagnose cloud coupling. However, RS is only available a couple of times a day.

A detailed discussion has been incorporated into the revised Section 3.2.

4. *From line 278-281: cloud coupling status is determined profile by profile. Therefore, in theory, it is possible that a part of the cloud system is coupled while the rest is decoupled. Is such a situation observed in this work? If yes, how often?*

Response: It is an interesting problem whether the entire cloud layer is coupled. It

depends on whether the liquid water potential temperature is conserved within the cloud layer, which represents a moisture adiabatic process. In the cloud parameterizations, the entire stratocumulus layer is considered to be well-mixed, while the cumulus-capped layer is usually partially mixed (Lock, 2000). For stratocumulus clouds, the entire cloud layer and PBL are typically fully coupled with surface, when the cloud base is coupled with surface. For the cumulus-capped PBL, the entire cloud layer may not be completely coupled, despite the coupling between cloud base and surface. The well-established parameterizations also are supported by many observational studies (e.g., Betts, 1986; Storer et al., 2015; Berkes et al., 2016; Ott et al., 2009). Meanwhile, Roode and Wang. (2006) use aircraft data to present the top part of stratocumulus also can be partially mixed due to the turbulent mixing between the free atmosphere and cloud across the cloud-top interface.

As presented by previous works, the coupling of entire cloud layer is closely related to the cloud types. Nonetheless, as the liquid potential temperature profiles within clouds cannot be retrieved by lidar, we are not able to determine whether the entire cloud layer is coupled. Same to the previous studies (Jones et al., 2010; Dong et al., 2015; Zheng and Rosenfeld, 2015), our study identified the coupled clouds as the thermodynamics coupling between surface and cloud base.

A detailed discussion has been incorporated into the revised Section 3.1.

References:

Lock, A. P., Brown, A. R., Bush, M. R., Martin, G. M., & Smith, R. N. B. (2000). A new boundary layer mixing scheme. Part I: Scheme description and single-column model tests. *Monthly weather review*, 128(9), 3187-3199.

Storer, R.L., Griffin, B.M., Höft, J., Weber, J.K., Raut, E., Larson, V.E., Wang, M. and Rasch, P.J. (2015). Parameterizing deep convection using the assumed probability density function method. *Geoscientific Model Development*, 8(1), pp.1-19.

Ott, L. E., Bacmeister, J., Pawson, S., Pickering, K., Stenchikov, G., Suarez, M., ... and Xueref-Remy, I. (2009). Analysis of convective transport and parameter sensitivity in a single column version of the Goddard earth observation system, version 5, general circulation model. *Journal of the Atmospheric Sciences*, 66(3), 627-646.

Berkes, F., Hoor, P., Bozem, H., Kunkel, D., Sprenger, M. and Henne, S. (2016). Airborne observation of mixing across the entrainment zone during PARADE 2011. *Atmospheric Chemistry and Physics*, 16(10), pp.6011-6025.

Roode, S.R. and Wang, Q. (2007). Do stratocumulus clouds detrain? FIRE I data revisited. *Boundary-layer meteorology*, 122(2), pp.479-491.

5. *The manuscript did not talk about the uncertainties of LCL estimation and CBH estimation. Ceilometer generally overestimates CBH by 100 m or more (Silber et*

al., 2018), while the ARM MPL CMASK generally exaggerates cloud boundary estimations (e.g. underestimates CBH, but overestimates the apparent CTH) (Cromwell et a., 2019). What are the impacts of uncertainties in LCL and CBH on cloud coupling determination? In addition, what are the impacts of precipitation (drizzle, rain) on cloud coupling determination?

Response: To address your question, we discussed the uncertainties of LCL estimation and CBH estimation and their potential impacts on the cloud coupling determination as follows in the revised Section 4 and Section 3.2:

"Despite the laser-based detection of CBH is considered as the standard method (Platt et al., 1994; Clothiaux et al., 2000; Lim et al., 2019), the CBH retrievals from ceilometer or lidar still bear some uncertainties, which can potentially lead to a mean bias of 0.1km (Silber et al., 2018; Cromwell et a., 2019). In our method, a systematic increase of 0.1 km in the CBH can lead to an increase of 2.1% in omission errors and a decrease of 1% in commission errors.

"Romps. (2017) proposed an exact, explicit, analytic expression for LCL as a function of surface pressure, temperature, and relative humidity. Compared to the previous approximate expressions, some of which may have an uncertainty in the order of hundreds of meters, the Romps expression can be considered as the precise value. The uncertainty of empirical vapor pressure data may lead to a bias of ~5-m (Romps, 2017), which may be neglected in the analyses."

"Following the original method (Su et al. 2020), the rainy cases are eliminated

in the quality control process.”

References:

Silber, I., J. Verlinde, E. W. Eloranta, C. J. Flynn, and D. M. Flynn (2018), Polar liquid cloud base detection algorithms for high spectral resolution or micropulse lidar data, *J. Geophys. Res.: Atmos.*, doi: 10.1029/2017JD027840.

Cromwell, E., and Flynn, D. (2019). Lidar cloud detection with fully convolutional networks. In 2019 *IEEE Winter Conference on Applications of Computer Vision* (WACV) (pp. 619-627). IEEE.

Lim, K.S.S., Riihimaki, L.D., Shi, Y., Flynn, D., Kleiss, J.M., Berg, L.K., Gustafson, W.I., Zhang, Y. and Johnson, K.L. (2019). Long-term retrievals of cloud type and fair-weather shallow cumulus events at the ARM SGP site. *Journal of Atmospheric and Oceanic Technology*, 36(10), pp.2031-2043.

Romps, D. M. (2017). Exact expression for the lifting condensation level. *Journal of the Atmospheric Sciences*, *74*(12), 3891–3900. https://doi.org/10.1175/JAS-D-17-0102.1

6. *Figure 5, similar to comment #3, under coupled cloudy conditions, how often is the PBLH determined using minimum ([CTH and A4*CBH]) or using A5*CBH? Are they correspondent to different PBLH structures? Since PBLH is determined a constant (A4 or A5) * CBH, why can't we just use a single constant * CBH. Do the category-dependent algorithms perform better than just using a single constant?*

Response: In general, the parameter, CTH, is used for thin cloud layers. In particular, A5 * CBH can be notably larger than the CTH for a thin cloud. Under this situation, if we use A5*CBH to denote the PBL top, CTHs of coupled clouds would be smaller than the retrieved PBLH. We believe it is unphysical.

As presented in current Figure 6 and Figure 7, A5 is a critical parameter for the PBLH detection under cloudy conditions, while the selection of A4 would not notably influence the retrievals of surface-cloud coupling and PBLH. Therefore, we can set A4 to the same value as A5, and meanwhile, achieve similar performance. Since it is not directly involved in the coupling determination, the parameter, minimum ([CTH and A4*CBH]), has little impact on the detection of surface-cloud coupling. The purpose of using CTH is to assure that the CTH of the coupled cloud is always higher than the retrieved PBLH to fit the real situation. These discussions have been incorporated into the revised Section 3.2.

Minor comments:

1) *Line 194: what does 'identical cases' mean?*

Response: For clarity, we revised this statement as follows.

"As the basic framework of PBL, the slab model assumes that θ_v is constant within the PBL (Wallace and Hobbs, 2006)."

2) *Line 197: How was the inversion strength calculated? What is the difference*

between inversion strength and âθ (line 202)?

Response: Specifically, inversions represent the layers with continuously increased structures of θ_v. For an inversion layer, the inversion strength is calculated as the differences in θ_v between the layer top and bottom. Meanwhile, we define $\Delta\theta_v$ as the difference in θ_v between the CBH and the PBLH.

We incorporated these statements into Section 3.1.

3) *Line 315 and Figure 6: it is better to state that RS virtual potential temperature method was used as the ground truth for determining the cloud coupling status. In Figure 6, how many RS samples are there? Do the commission and omission errors change with the time of a day and with seasons?*

Response: Per your comment, we added the following statement to both the main text and the figure caption. "By using ~7500 RS profiles, the cloud coupling state derived from the virtual potential temperature method (Section 3.1) is considered as the ground truth for evaluation."

The seasonal differences in commission and omission errors depend on different criteria. We will address the climatology of surface-cloud coupling and seasonal variations for different datasets in a future study.

4) *Line 317: 'some criteria' -> maybe 'âˆ†h' is better?*

Response: Yes, revised.

5) *Figure 9 b) and c) mpl backscatters show large signals down to near-surface, why do cloud bases are detected at much higher levels?*

Response: The cloud base detection is not based on the signal strength, but largely depends on the signal gradient. We check the profiles of normalized lidar signals, and believe that the CBH detection is appropriate.