Response to comments of reviewer 1

General comment	*Response*
The paper evaluate a method using lidar background signals to retrieve warm cloud optical depth, which provide a new way to provide cloud optical depth in zenith direction, which make it more easy to combine with other zenith pointing measurements, such as, microwave radiometer, to more effectively study cloud microphysical properties. The approach can be used for lidar only measurements world wide to provide a large cloud optical depth dataset with ground-based lidar networks. I'd recommend it for publication after the following comments are properly addressed.	• Thank you.

Response to comments of reviewer 1 (cont.)

Major comment	*Response*
1. How do multi-layer clouds impact the retrievals? The results presented in the paper are based on the ARM SGP site measurements, where radar measurements are available to be used to identify multi-layer clouds. In the summary (page 8990, line 21-28), you indicated that the approach can be applied to lidar network and ceilometer measurements. For these lidar-only measurements, multi-layer clouds identification is a challenging task. Thus, related discussion along the line will be useful for others to implement the approach.	• Since our retrieved optical depth is a column-integrated quantity, multilayer clouds do not affect the retrieval. • We select single-layer clouds in this study because of two reasons: – Microwave radiometers are sensitive to the liquid water in all clouds in the profile. For multilayer clouds, liquid water path is likely to be biased high for a given drizzle rate at lowest cloud base. Therefore, we need to restrict our analysis to single-layer clouds. – Be able to quantify a meaningful cloud geometric thickness. • Applications in other lidar networks: – For the purpose of retrieving cloud optical depth, one does not need to distinguish between single layer and multilayer clouds. – For the purpose of investigating interdependence of cloud microphysical and optical properties, radar measurements will be needed to identify cloud boundaries especially when lidar signal is significantly attenuated. • We have added the following text to stress the points above: – Page 18, Line 20–21: "*With collocated radar and LWP measurements, the new retrieval can also be used to compare and contrast drizzle and drizzle-free cloud properties.*"

Response to comments of reviewer 1 (cont.)

Major comment	***Response***
2. The paper will be enhanced if the discussions consider more underline physical processes. For example, the statement between line 21-23 in page 8975, is hard to make sense in general. For stratiform clouds with the same base temperature and optical depth, continental clouds should be thinner than marine clouds due to higher droplet concentrations in continental clouds. However, marine stratiform clouds typically have warmer base temperature, which could be the main reason behind the statement. Keeping this point in mind, it will be useful to bin data into different temperature ranges for analyses conducted in the paper.	• The reason we binned data by optical depth is to provide a simple way to estimate geometric thicknesses for satellite observations that have a long record of reliable optical depth retrievals. • Indeed, considering the same base temperature, optical depth, *and the same degree of adiabaticity*, clouds with higher droplet concentrations will be geometrically thinner. To properly address this issue, however, one will need to bin data by all three variables, which will require much more data (from one-dimension binning to 3-dimension) and cannot be done by our current dataset. Note that adiabaticity alone can involve many processes and meteorological factors. We prefer to remain cautious here because we need to conduct similar analyses at other continental sites to know if our finding is universally true. If indeed low clouds over land tend to be thicker than over oceans (or the other way around), we then need to collect more data both over lands/oceans and conduct detailed analysis on sounding data in order to discuss the underlying processes and draw conclusions. • Using ARM observations at the Oklahoma site, Del Genio and Wolf (2000) found that geometric thicknesses of low-topped water clouds decreased with increasing surface temperature in warm seasons (June–September), mainly due to a raise in the cloud base height and relatively constant cloud top height in warmer environments. In contrast, geometric thicknesses of low clouds in cold seasons (December–March) did not have a clear trend with surface temperature. Note that their data were quite noisy, though. • We didn't mention Del Genio and Wolf (2000) in our manuscript because this part of discussion is more closely linked to feedback of continental low clouds, which is beyond the scope and should be included somewhere else. In fact, a manuscript entitled "The dependence of cloud optical depth on temperature from ground-based observations at DOE ARM sites" by Zhang et al. is in preparation and planned to submit to JGR. This manuscript will include dependence of LWP and droplet size on temperature as well. *Del Genio, A.D., and A.B. Wolf, 2000: The temperature dependence of the liquid water path of low clouds in the southern Great Plains. J. Climate, 13, 3465-3486.*

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Major comment	*Response*
3. The effective radius is derived from LWP and optical depth based on Eq. (1). Thus, they are interlinked by Eq. (1), which makes it hard to understand the results presented in Fig. 6b, d and Fig. 7d. Fig. 6b shows similar LWP and optical depth relationships though the magnitude differences. From Fig. 6b, we could simply expect similar optical depth dependency of effective radius. But Fig. 6d shows quite different trends for low optical depth range. Some discussion to clarify this will be useful.	• Fig. 6 is now Fig. 8; Fig. 7 is now Fig. 9. • In fact, results in the old Fig. 6b and 6d are consistent. For clarifications, we have added the following text on Page 14, Line 1–7: *Since the correlation between τ and reff is positive in non-drizzling clouds but negative in drizzling clouds, the difference in reff between two types of clouds decreases with increasing cloud optical depth, which is as a result of Fig. 8b. Across all optical depth bins, Fig. 8b shows that LWP in drizzling clouds is consistently ~85 g m^{-2} larger than that in non-drizzling clouds. Compared to cases with small τ, this extra LWP in drizzling clouds distributes to more droplets in cases with large τ, leading to a smaller increase in reff (as shown in Eq. (1) having a denominator τ).* • Explanations for the old Fig. 7d are similar to the old Fig. 6d.
4. In the section, it will be useful to highlight the differences of different methods, which make the differences in the case study easier to understand. In the case study, you emphases the approach capturing cumulus on 15 June. For the cumulus clouds, inhomogeneity could be an issue to use plane parallel assumption for the radiative calculation.	• We have provided more details to highlight the difference of various retrieval methods in Sect. 3 (Page 9, Line 18–24, 27–29). • Agreed about the reviewer's concern on inhomogeneity. However, there are two different issues. The first issue is about the homogeneity in FOV. Since the lidar FOV is small, the plane-parallel assumption will be fine as long as we keep temporal resolution as high as possible. The second issue is about the homogeneity of cloud fields, which of course can be far from plane-parallel. This issue can be better handled if information on 3D cloud fields can be obtained from scanning cloud radar measurements (Fielding et al., *A novel ensemble method for retrieving cloud properties in 3D using ground-based scanning radar and zenith radiances*, submitted to JGR). • To address the reviewer's concern and to incorporate the other reviewer's suggestion on including drizzling cases, we have replaced the original Fig. 3 with one non-drizzling broken clouds, and replaced the original Fig. 4 with two relatively overcast clouds having both non-drizzling and drizzling periods (see Page 10, Line 5–20, and the new Fig. 4 and 5).

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Minor comment	***Response***
1. Page 8965, line 4: compared with low cloud over ocean, the amount over land is much lower (see Sassen and Wang 2008, Geophys. Res. Lett., 35, L04805, doi:10.1029/2007GL032591).	• Thank you. Since this reference shows that the occurrence of frequency of stratus and stratocumulus is the highest compared to other cloud types over land, we have made the following revision on Page 3, Line 11–12: *However, similar efforts have not been made for mid-latitude continental stratus and stratocumulus clouds, despite their strong links to local weather and climate (Del Genio and Wolf, 2000; Kollias et al., 2007)**,** and their high occurrences compared to other cloud types over land (Sassen and Wang, 2008).*
2. Page 8966, bottom paragraph: MPL has a small FOV and the other system has large FOV. How does your Fig. 1 depend on FOV if the approach is applied to other system.	• Radiance in Figure 1 is calculated based on homogeneous clouds. As one can imagine, this won't work well for a radiometer with a FOV of 6°, and cloud scenes in a large FOV will need to be accounted for in the retrieval process. That's why it is appealing to use high-temporal measurements from a small FOV like lidar.
3. Page 8967, line 14-15: Providing more details related to calibration will be helpful. If there are not AERONET measurements, how the calibration should be done?	• We have added the following text on Page 5, Line 16–21: *Note that for sites where collocated AERONET measurements are unavailable, one can calibrate solar background light by capitalising on the optical depth of thin clouds retrieved from active lidar signals. Specifically, radiance can be calculated through radiative transfer using thin cloud properties as input, and then be further used to calibrate the corresponding measured solar background light. Details of this alternative calibration approach can be found in Yang et al. (2008).* ***Reference:*** *Yang, Y., et a., 2008: Retrievals of thick cloud optical depth from the Geoscience Laser Altimeter System (GLAS) by calibration of solar background signal. J. Atmos. Sci., 65, 3513–3526.*

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4. Page 8968, line 28-29: -7.5 is the typical value for optical depth large than 3, which is still at the right site of the peak in the Fig. 1. Page 8969, line 11: Fig. 1a shows the peak larger than 5.	• We don't quite understand this comment, because we don't see any inconsistency here. As explained on Page 7, Line 9–13, we found the optimal threshold of lidar backscatter using cases with cloud optical depths less than 5. The reason we chose 5 optical depths is because the zenith radiance typically peaks at this optical depth (as shown in Fig. 1a and pointed out by the reviewer). • The mean logarithm (with base 10) lidar attenuated backscatter signal of –7.5 (Figure 1b, red) is typical for very thick clouds. The corresponding optical depth can be found in the old Fig. 4, which is larger than 20 and consistent with Fig. 1a.
5. Page 8969, line 17: To use these thresholds, MPL signals need to be calibrated. Achieved MPL data are not calibrated. More details along the line will be useful for readers.	• We have briefly described calibrations of backscatter signals on Page 6, Line 25–29 (see below): *We calibrated lidar backscatter signals in clear-air periods using the known molecular scattering at the lidar wavelength. Since the lidar energy was monitored and the lidar optics were assumed to not vary significantly, calibration coefficients from a suitable clear-air period were then extrapolated into cloudy periods.*
6. Page 8973, line 17: Provide details for "unphysical".	• We meant any negative 1-min average LWP values unphysical. Since a negative LWP leads to a negative cloud effective radius and will be excluded in our analysis anyway, this bit "*exclude time periods with unphysical 1 min averaged LWP*" is redundant and we have deleted it.
7. Page 8974, line 6: What does "later" refer to?	• Sorry about this – we meant a few minutes later. To make it clearer and more concise, we have revised it (Page 11, Line 19–20) as the following: *…we have found that these points are associated with intermittent cloudy conditions having LWP between –10 and 80 g m^{-2}.*

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8. Page 8978, line 19: For difference indicated here could be linked with different targeted clouds. Thus, providing a few details of clouds studied by Nauss and Kokhanovsky (2006) will be useful.	• We have added the following information on Page 16, Line 18–19: *…the optimal coefficient A is 380 µm, rather than 920 µm found in satellite observations (Nauss and Kokhanovsky, 2006) for convective systems over Central Europe taken during the extreme summer floods in 2002.*
9. Page 8980, line 13: Is the 15um is for continental clouds or marine clouds or all clouds in general.	• Thank you for pointing this out. The critical radius of 15 µm is for marine clouds so we have made the following revisions: – *Page 13, Line 13: "smaller than the so-called critical radius (~15 µm) reported in literature for marine low clouds (Nakajima and Nakajima, 1995; Kobayashi and Masuda, 2008; Painemal and Zuidema, 2011)"* – *Page 18, Line 9: "on the order of 15 µm may be a good indicator to distinguish between non-drizzling and drizzling marine clouds"*