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.*

Response to comments of reviewer 1 (cont.)

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).

Response to comments of reviewer 1 (cont.)

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.*

Response to comments of reviewer 1 (cont.)

Minor comment	***Response***
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}.*

Response to comments of reviewer 1 (cont.)

Minor comment	***Response***
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"*

Response to comments of reviewer 2

General comment	*Response*
This paper describes a novel technique to retrieve optical depth from the solar back-ground measured by lidars. The authors show the technique to be valid for stratiform clouds and then go on to explore relationships between retrieved cloud properties. The focus is on comparing drizzling versus non-drizzling stratiform clouds. This paper may be suitable for publication after the authors address the following issues.	• Thank you.

Major comment	*Response*
1. The comparison of cloud properties includes the use of liquid water path (LWP) from a microwave radiometer (MWR). However, LWP is not valid when the MWR window is wet. The authors mention this on page 8970 lines 21-23, stating that these wet window cases are removed. Therefore, the results of drizzling cloud properties in this paper could be biased since they cannot include any observations where drizzle has reached the surface or those observations just after such times when the window will remain wet. Some discussion is needed on how many profiles are excluded because of this and, if this number is significant, the authors need to address the impact on their results.	• For stratiform warm clouds selected in this paper, the fraction of MWR with wet window flags is about 4%. • Additionally, we have also realised that the physically-based approach used in MWRRET products did not use the wet window flag in the retrieval method, because the flag is not necessarily triggered by precipitation. We have therefore removed the statement about excluding observations when the window is wet (i.e., the wet window flag is on). • We found that the time periods with the wet window flag still heavily overlap with the time periods that MWRRET retrieval is unavailable, although occasionally they don't overlap with each other. The fraction of no MWRRET retrieval is ~1% in the time periods used in the paper.
2. page 8968 lines 12-14: Assuming the solar background light has the same uncertainty as an AERONET (5%) is not appropriate. In lidar studies, the background noise is determined by taking the standard deviation in the high altitude region (i.e. 45-55km for the MPL). In addition, there is an uncertainty due to detector noise that depends on signal strength. I suspect the noise is the lidar observations are likely larger then 5% and therefore the authors should revisit their claim of a 10% overall uncertainty.	• Thank you for pointing this out. To give readers an idea of how the uncertainty in cloud optical depth retrievals varies with the uncertainty in calibrated solar background light, we have added the following text on Page 6, Line 18–20: *Note that with an uncertainty of 10% rather than 5% in calibrated solar background light, the overall retrieval uncertainty in cloud optical depth will increase to 17–25%.*

Response to comments of reviewer 2 (cont.)

Major comment	***Response***
3. Throughout the paper the authors write that the cloud optical depth is retrieved using the "solar background light". This is misleading since a radiance is needed for the look- up tables but the "solar background light" is measured by the MPL as photon counts. It be more correct to say "calibrated solar background light" since the photon counts are converted to a radiance via calibration to AERONET.	• Thank you. We have changed most of "solar background light" to "calibrated solar background light", mainly in sections 2–4 after we introduce calibration against AERONET in the beginning of Sect. 2.
4. Page 8969 lines 6-18: Instead of establishing backscatter thresholds, why not just compare the measured backscatter above cloud to the solar background signal? If the two are similar, then the laser beam is completely attenuated and the cloud is optically thicker, otherwise it is optically thin. This would make the author's method more readily adaptable to other lidars beside the ARM MPL and wouldn't require the lidar backscatter profile to be calibrated which is needed if these thresholds are to be used.	• In the ARM Archive, solar background light and signal return are recorded in photon counts. Using these ***uncorrected, uncalibrated*** signals, one will find that the signal return at moderate-to-high tropospheric altitudes in both clear sky conditions and above cloud is often very similar as it is the solar background noise that dominates the signal, especially for locations with a high solar zenith angle. In other words, this won't be able to help distinguish between optically thin and thick clouds. • In principle, applying the same method described in the manuscript (i.e., with help of external data), one can use ***corrected, uncalibrated*** backscatter signals to find suitable thresholds for distinguishing thin/thick clouds. However, we do not prefer uncalibrated signals, because in this case, suitable thresholds vary over time depending on the level of noise, and then we still need to effectively account for all sources of noises in lidar signals, which is equivalent to calibration. Therefore, it is better to calibrate lidar signals first and then find a constant threshold for thin/thick cloud discrimination.
5. Section 3.1: Since the focus later in the paper is on drizzle and non-drizzling cases it seems warranted that an example of retrieval performance for a drizzling case be included here.	• Good point. We have added drizzling cases in Figures 4 and 5 in Sect. 3.1 (Page 10, Line 5–20).
6. Page 8973 line 19: What percentage of the original 1 hour time periods identified by ARSCL does the 5200 min of data points represent? i.e. what fraction of the stratiform periods during these 2 years are included in your analysis of cloud properties?	• 5200-min long data points represent ~35% of daytime ARSCL cases. We have added this information on Page 11, Line 5: *This exclusion process lead to a final sample size of 5,200-min of data points during 2005–2007 that represents ~35% of daytime stratiform cases.*

Response to comments of reviewer 2 (cont.)

Major comment	*Response*
7. Repeating the validation in Fig 5 with the AERONET observations would be nice to see. Although the sample size would be smaller than the ARM Min observations, if other researchers wanted to extend this lidar optical depth method to other sites a sun photometer may be their only means of validation (since one is required for calibration).	• As suggested, we repeat the same comparison using AERONET observations. An additional figure (new Fig. 7) and the following text has been included on Page 11, Line 24–28: *Similarly, Fig. 7 shows a scatterplot for evaluating retrievals against the AERONET official cloud-mode product. The mean cloud optical depth from lidar measurements is 30, smaller than cloud-mode retrievals by 3 optical depths. The correlation coefficient is 0.95, while the root-mean-squared difference between the two is 8 (24% relative to the mean of cloud-mode retrievals).*
8. Does using the Min observations result in the same relationships between cloud properties (i.e. Fig 6-7 and the power law relationships)? Many readers, including myself, may wonder if the differences between the more established ARM Min product and the authors' new lidar retrieval in Fig 5 has any effect on the resulting relationships between cloud properties.	• We have repeated the same analysis using the ARM Min product. For a better flow of discussions, we focus on results binned by cloud optical depth (i.e., similar to the old Fig. 6) and include them in Section 4.3 (Page 14–15). Results are shown in Fig. 10 in the revised version.
9. Fig 6: There is an extra bin in panel (b) at optical depth = 75 that is not present in panel (c) or (d).	• Thanks for spotting this error. We have removed the point in (b) at optical depth of 75 for drizzling clouds, since the corresponding sample size is smaller than 25. Fig. 6 becomes the new Fig. 8.
10. Fig 5b: increase the limits of x and y axis to 100 so it matches the optical depth histogram in 5a	• Thanks. We have changed the X-range from 100 to 80 in 5a (now Fig. 6a) to be consistent with Fig. 6 (new Fig. 8) and to focus on the optical depth range of 0–80.

Minor comment	*Response*
1. page 8964 line 5: change "signal" to "signals"	• Thank you. It is done. • We have also corrected some other "signal" to "signals" throughout the manuscript.
2. page 8965 lines 2-3: remove "and many others"	• Done.

Response to comments of reviewer 2 (cont.)

Minor comment	*Response*
3. page 8965 line 18: why is the relationship "of particular interest"?	• We have made the following changes on Page 3, Line 25–28: *The relationship between cloud optical depth and droplet size is of particular interest, because their correlation patterns are highly related to the stages of warm cloud developments (Suzuki et al., 2010) and have been used for drizzle delineation (Nauss and Kokhanovsky, 2006; Suzuki et al., 2011).*
4. page 8966 line 14: suggest changing "Campbell et al. 2002" to "e.g. Campbell et al. 2002"	• Done (Page 4, Line 16).
5. page 8967 line 14: suggest changing "between 45 and 55 km" to "between 45 and 55 km where the molecular backscatter is negligible"	• Done (Page 5, Line 13).
6. page 8970 line 15: explain what is meant by "worked better"	• Sorry about this. We have added the following text on Page 8, Line 11–14: *Using simultaneous retrievals of cloud optical depth and effective radius at the ARM Oklahoma site, Chiu et al. (2012) found that the second assumption led to a better agreement with LWP measured by microwave radiometers (MWR) in all sky conditions.*
7. page 8973 line 17: Define what an "unphysical 1 min averaged LWP" is.	• 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.
8. page 8974 lines 8-10: Aren't both flux and lidar retrievals averaged to 1 min for this comparison? Why then does only the flux-based retrievals smear out these variations?	• Because fluxes are collected from a hemispheric FOV and lidar has a very small FOV, even when both retrievals are averaged to 1 min, the temporal variations of the flux-based retrievals will be still much smaller than those of lidar retrievals. To make it clearer, we have revised this sentence on Page 11, Line 20–23: *Therefore, the discrepancy in cloud optical depth for these data points is likely because lidar has a narrow FOV to capture larger variations that tend to be smeared out in irradiance-based retrievals due to a hemispheric FOV of shadowband radiometers.*
9. page 8980 lines 24-26: It would be more accurate to say that: "This new method can be easily adapted to existing lidar networks where sun photometer measurements are available"	• Done (Page 18, Line 22).