Response to referee #1

General comment:

The authors present a well described technique to separate the contribution of cloud and drizzle from measurements with Sun Photometer, cloud radar and microwave radiometer. This is realized by means of an optimal estimation approach. The approach sounds reasonable, but I see some limitations and sources for uncertainties not well represented. Also some additional questions and comments popped up during reading. I would nevertheless recognize my comments as minor. Basically, the manuscript is suited for publication after the following comments have been considered in a revised version.

- Thank you for your comments. To be clear, our method uses measurements from a sun photometer, cloud radar and lidar. We use observations from a microwave radiometer as independent validation to our retrievals.

Content-related comments:

General: It should be emphasized that the retrieval of the MWR is not valid anymore, when multiple cloud layers are present. This is also the case for the sky radiance measurement which is in addition affected by cirrus clouds. To my feeling the short note on that issue in Line 31-32 on Page 23 does not sufficiently emphasize this limitation.

- It is true that in multi-layer cloud situations the uncertainty in the MWR LWP retrievals are likely to be higher. However, microwave retrievals are valid throughout multiple cloud layers until the brightness temperatures saturate which was certainly not the case in the two case studies. Essentially the radiometer will be able to see all the way to the upper troposphere even in the presence of multiple cloud layers.
- We exclude cases that contain cloud above the boundary layer, see pg 18, l9–10.

P2-L18-20 : Cloudsat has 500-m vertical resolution. How will it help to resolve drizzle processes in Sc clouds?

- CloudSat observations are unlikely to be able to resolve drizzle processes, but can be used to infer average drizzle rates throughout clouds. For clarity we have changed pg2 ln 19 to 'Cloudsat has revealed the vertical structure of clouds and *the presence of* drizzle from space'

P4-L9-11: Please provide references or manufacturer information for the used instruments. I was hoping to find that information in the reference to Lewis & Teixeira 2014, but this reference was not listed in the reference list.

- We have included references for the instrument specifications on pg 4 l8–10, except for the HSRL, where we have included a table with its specifications (new Table 1).

P4-L24: To my knowledge there is no attenuation retrieval presented in the paper of Illingworth.

- Details of the attenuation correction used in CloudNet can be found on page 5 of Illingworth et al., 2007.

Sun Photometer: How does pitch-and-roll of the ship affect the zenith radiance measurement? What happens to the measurement of a vertically pointing Sun Photometer when drizzle reaches the ground as it happened in the MAGIC case study (Fig 13) at around 20.1 and 20.5-20.6 UTC?

- Using information on ship pitch, roll and yaw measurements (stored in navigation data files available in the ARM Archive), we calculated the actual pointing angle of the sunphotometer and defined the departure from the zenith as the beam angle. During the campaign in May–July 2013, 75% of the beam angles are within 1° and 96% are within 2°, which dos not significantly affect radiance measurements and thus retrieval accuracy. Nevertheless, we incorporated the off-zenith effects into our radiative transfer calculations during the retrieval process.
- During the campaign, the wet sensor of the sunphotometers worked fine and thus would force the instrument "park" (i.e., looking down to protect the instrument) at the presence of precipitation. Therefore, zenith radiance measurements won't be available if precipitation reaches the ground. We have checked the time periods that the reviewer mentioned; no surface precipitation was indicated from both sunphotometer wet sensor and microwave radiometer window.

- What information on the transition region between cloud and drizzle will the method reveal? Can there be conclusions drawn on (auto-)conversion rates?

- It would be difficult to infer autoconversion rates using our retrievals, because there are many other processes such as advection or entrainment that affect cloud and drizzle content that would obscure the true autoconversion rate. Having said this, there would be the potential to perform an analysis similar to Stephens and Haynes (2007), who inferred instantaneous collection rates from radar reflectivity, optical depth and effective radius measurements, but the uncertainty is likely to be similarly large (see Fig. 3 in Stephens and Haynes [2007]).

-What does an error of 10-20 g/ (see abstract) in the cloud water path mean, when it is contained in the drizzle instead of the cloud or vice versa. Distribution an additional 10-20 g/mthe drizzle may result in more precipitation. Distributing it into the cloud will produce increased optical depth. Can the effect be estimated based on the used size distributions and size-fall-velocity relationships of Beard (As described in Sec. 5.2.2)?

- Our retrieval is independent of MWR LWP measurements so there is no fixed amount of water path to distribute between cloud and drizzle modes. In drizzling cloud, the cloud water path is almost entirely constrained by the sun photometer radiances.

-Sec 3.3.2 – attenuated backscatter. First, the shown formulation (eq 15 and 16) is different compared to the common one. In the present case it does not include the molecular extinction and backscatter coefficient (as, e.g., CALIPSO). Better refer to it as the 'liquid water attenuated backscatter coefficient'.

- Changed pg10 l22-23 'The lidar attenuated backscatter coefficient due to drizzle drops is then given as'

-Second: Aerosols can produce quite significant backscatter coefficients which can easily be in the same order of magnitude as the values produced by drizzle. Can the error of an aerosol-increased attenuated backscatter on the drizzle retrieval be estimated for different aerosol loads? E.g., taking the aerosol loads of the two LES studies as reference? (see next question).

- If the lidar backscatter is increased by aerosols, this will reduce the retrieved drizzle drop size. This error will only be significant when the aerosol backscatter is of the order of the drizzle drop backscatter. However, in more polluted conditions, to reduce error from aerosol contamination an estimation of the extinction due to aerosols could be included in the forward model for lidar attenuated backscatter. This could be estimated from the nearest drizzle-free period.

-P 13 – 2nd Paragraph: Into what kind of size distribution are the aerosol particles distributed? What is the resulting aerosol backscatter of these aerosol concentrations? What is the ratio between the aerosol backscatter and the drizzle backscatter in the model (A question that is related to the previous comment)?

- The model aerosol is prescribed and distributed using a lognormal size distribution with geometric radius 0.1 μm and geometric standard deviation of 1.5. Assuming a lidar ratio of 20 and geometric optics (extinction efficiency of 2) gives a backscatter of approximately 1.1×10^{-7} m^{-1} sr^{-1} in polluted conditions (total number concentration 100 cm^{-3}) and 2.8×10^{-8} m^{-1} sr^{-1} in clean conditions (total number concentration 25 cm^{-3}). This is an order of magnitude less than the liquid water backscatter in the LES (see Figure 7).

- Another comment on attenuated backscatter within clouds: Signal attenuation and detector responses (afterpulsing) are huge problems, when an aerosol-optimised lidar system is used for low-cloud observations. Was this problem considered in the data analysis?

- Signal attenuation is included in the lidar forward model for drizzle below cloud base. Lidar signal within cloud is not used in the retrieval.
- The HSRL data processing includes a correction for afterpulsing generated by the detector response to the outgoing laser pulse. The HSRL uses a single for the transmitter and receiver. Internal scattering in the telescope produces a bright flash on the detectors. We provide a afterpulse correction for this flash and this correction preforms quite well.
- After pulsing in the molecular channel is not very serious--this channel does not see as large a dynamic range as the combined channel. We have attempted an afterpulse correction for the signal inducesd afterpulsing in the combined channel, but have not been able to devise a successful correction. The correction is very non-linear in our Geiger-Mode APD's at the signal levels seen by this channel. Combined channel afterpulsing is a serious issue in the water clouds. We expect that it is rather small in the drizzle because the signal strength does not decrease at a very high rate like it does in cloud.

P15, L7-8: Is there a reference to the vertical structure of Nc?

- This was a reference to the vertical structure of Nc seen in the LES; we have therefore added a reference to figure 8d, which shows the structure of droplet number concentration seen in the LES. Height invariant Nc is shown to be a reasonable assumption in in-situ observations (see e.g., Miles et al., 2000), particularly for marine clouds.

Sec. 4 – LES Simulation: How do the modelled droplet size distributions fit to the assumed logarithmic (cloud droplets) and gamma distributions (drizzle)?

- Before running the simulation experiments we checked that the modelled droplet size distributions were a reasonable fit to the LES. Figure 1 shows an example of the fits for both within and below cloud for the clean case LES. The drizzle drop size distribution tends to have more variability in shape than the cloud droplet size distributions.

Would it be possible to separate droplets that formed according to Koehler theory (vapour diffusion) from droplets that form by autoconversion?

- Within the LES, yes it would be possible to separate the cloud droplets and drizzle drops formed through different processes, however as discussed earlier this is unlikely to be possible from current remote sensing techniques.

P24-L19: What are these 'additional difficulties of ship-borne observations'?

- This sentence is subjective, so we have decided to remove it.

How does the drizzle retrieval method of O'Connor 2005 perform in comparison to the presented one?

- The underlying principle of both retrievals for retrieving drizzle below cloud base is very similar and so we would expect a good agreement. Figure 2 shows a comparison between the two retrievals for the drizzling case study (1st June 2013, 2000–2100 UTC). The spread in points is predominantly due to measurement noise; here the O'Connor method uses attenuated backscatter from the ceilometer and radar reflectivity from MWACR, while ENCORE used HSRL backscatter and KAZR reflectivity.

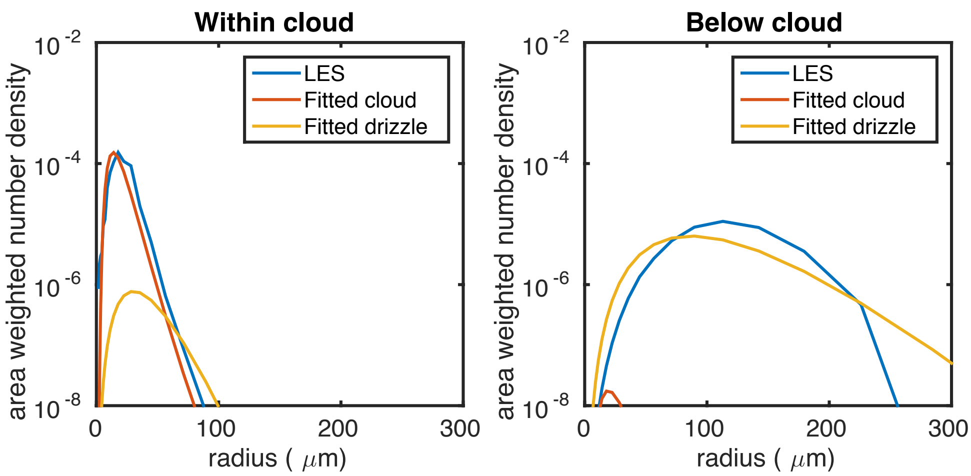

Figure 1. Sample drop size distributions for the ATEX LES clean case. Left plot for Y = 0 km, height = 1.5 km, and right plot for Y = 0 km, height = 1.2 km.

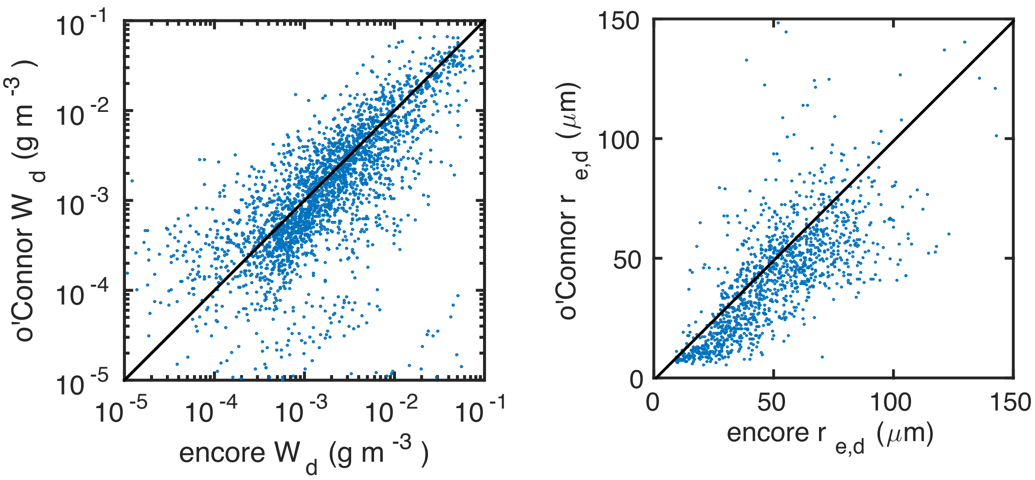

Figure 2. Comparison of ENCORE and O'Connor et al., 2005 retrieved drizzle properties below cloud base for the MAGIC drizzling case. Left plot shows drizzle water content and right plot shows drizzle effective radius.

Writing style:

P1-L 17: 'clouds'

- OK as it is.

P2-L16: 'clouds'

- changed.

P7-L15: 'assumptions'

- changed.

P7-Eq 1: Is it the same equation as previously used by Frisch? Maybe it's worth to mentioning this.

- Yes it is, have inserted reference to Frisch et al., 1995.

P9-L12: '. . .within the cloud . . .' P14-L8: '. . .define the cloud . . .' P23-L10: '. . .lead to a retrieved. . .' P24-L1: '. . .non-drizzling clouds . . .' P25-L6: . . .retrieval of . . .

- Changed.

Figure 1: Can constrained and relaxed mode be marked in the scheme?

- Yes, this is now included.

References

Natasha L. Miles, Johannes Verlinde, and Eugene E. Clothiaux, 2000: Cloud Droplet Size

Distributions in Low-Level Stratiform Clouds. *J. Atmos. Sci.*, **57**, 295–311.

Stephens, G. L., and J. M. Haynes, 2007: Near global observations of the warm rain coalescence process, *Geophys. Res. Lett.*, 34, L20805