Answers to Anonymous Referee #1

We thank anonymous referee #1 for his/her helpful comments and suggestions. We revised the manuscript according to his/her comments and the comments of anonymous referee #2. In the following answer to the referee we decided to give

- *referee comments in italic*
- our answers in normal format and
- **textual changes in the manuscript in bold format.**

We revised our manuscript according to the comments of anonymous referee #1 and #2, of which the main changes are as follows:

(1) Revision of the theory section: the equations for the sub-adiabatic model do now consider the sub-adiabatic state as the general case and can be transformed to the adiabatic case by setting $f_{ad} = 1$.

(2) The order of the theory and data section was reversed, so that the reader first gets a clear picture of the methods that are used and of the observed data that are available from the satellite and ground perspective. The following results section starts with an overview of parameters observed and used for the retrievals of key parameters which then can be compared to each other.

(3) A comprehensive revision of the introduction to introduce the goals earlier, and give a more focused overview of previous studies that use similar instruments and methods.

(4) We added an overview table of parameters considered in other studies that applied the sub-adiabatic model, to give a better comparison and motivation to what is done in this work.

(5) We omitted the presentation of method OE2, which led to some confusion. Instead we added a comparison of the adiabatic factor as derived from ground based observations using (a) the observed cloud geometrical depth from radar and ceilometer as well as the liquid water path from the microwave radiometer and (b) the observed radar profile and the adiabatic radar profile which can be calculated from the results of the OE1 method.

(6) To avoid confusion by introducing a "virtual adiabatic cloud geometrical depth" calculated from the ground-base microwave radiometer, we splitted the comparison of satellite and ground into Q_L and H. This means the following new structure of the results section: (a) comparison of ground-based parameters: f_{ad} and f_{ad}^{OE} (b) comparison of ground-based parameters: N_d^{FI} and N_d^{OE} (c) comparison of ground- and satellite-based parameters: Q_L (d) comparison of ground- and satellite-based parameters: H (e) comparison of ground- and satellite-based parameters: N_d

(7) We completely redid the figures for this study and hope that these are easier to read now.

We adress more specific remarks in the following:

(C1) *I would encourage the authors to include a more explicit overview of the* f_{ad} *values reported in the literature, of how it is represented in retrievals of* N_d *and* H*, and to provide a more direct comparison to the other studies that have focused on* H *and* N_d *retrievals. I will use the example of the southeast Pacific because I am most familiar with that literature, but I would encourage the authors to be as fully comprehensive as possible.*

(A1.1) To give a better overview of f_{ad} in literature and how it is represented in the retrievals of N_d and H from passive satellite remote sensing, we added a table to our manuscript.

(A1.2) To give a more direct comparison to other studies findings regarding H and N_d retrievals, we added the following sentences to our discussion in the results section:

regarding H: **The correlations for temporally averaged data are within the range of values that were obtained by Roebeling et al. (2008b), Min et al. (2012) and Painemal and Zuidema (2010). Roebeling et al. (2008b) found correlations of 0.71 between SEVIRI and Cloudnet for a homogeneous stratocumulus cloud layer. Min et al. (2012) found correlations of 0.62 between in-situ and MODIS retrieved H, and could show a better agreement of H when the adiabatic factor is explicitely calculated and considered. Painemal and Zuidema (2010) found correlations of 0.54 (0.7 for** $H < 400\,\mathrm{m}$ **with cloud fraction**$> 90\,\%$**) comparing radiosonde-derived cloud geometrical depth to respective MODIS observations. In their study Painemal and Zuidema (2010) reported that satellite values were higher compared to the ground-based ones. The reason for this can potentially be explained by a bias of MODIS-retrieved** r_e **but also in the choice of the adiabatic factor in the retrieval of** H**. Satellite derived** H **increases if we choose** $f_{ad} < 1$ **instead of** $f_{ad} = 1$**.**

(...)

For the cases investigated here, we saw a better agreement in H **for available MODIS retrievals compared to SEVIRI if** $f_{ad} = 1$ **is choosen. Indeed, clouds are actually sub-adiabatic while the retrieval assumes adiabatic clouds. This could counteract a high bias in MODIS** r_e **that is reported in previous studies (Marshak et al., 2006). For the four cases considered in this study, the number of collocated observations with MODIS is not sufficient in order to determine which effect is predominant for the bias. Therefore a larger dataset would be desirable for a more in-depth investigation.**

regarding N_d:

The importance of r_e **for the retrieval of** N_d **from passive satellite imagers has already been pointed out by previuos studies. Those which were mainly based on MODIS (Painemal and Zuidema, 2010, 2011; Ahmad et al., 2013; Zeng et al., 2014). Painemal and Zuidema (2010) report a high bias of MODIS-derived** r_e**, but also state that the choice of the other parameters in the retrieval (namely** k**,** Γ_ad**) is able to compensate for this effect so that still a good agreement between MODIS retrieved and in-situ values could be achieved. A high bias of** r_e **occurs for broken cloud conditions (Marshak et al., 2006). Zeng et al. (2014) also saw a good agreement for MODIS derived** N_d **(using** $f_\mathrm{ad} = 0.8$**) with CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization), although they found a high bias in** r_e **compared to POLDER (Polarization and Directionality of the Earth Reflectance).**

Ahmad et al. (2013) also points out the importance of the effective radius for the N_{d} retrieval. As mentioned before, for our study only few MODIS observation points are available, but we already see that discrepancies in r_{e} in comparison to SEVIRI are a major source of uncertainty for N_{d}.

(C2) *For example, Painemal, D., and Zuidema, 2010, ACP, found an overestimate in H_{sat} when compared to ship-board measurements, that they attributed to an overestimate in the satellite re (see their appendix). This is similar to the current studys findings, in that this studys H_{sat} is lower than that measured from the ground - which they attribute to an underestimate in satellite re. So both the Painemal and Zuidema and the current student highlight the importance of the satellite-derived re, with the solar zenith angle differences (I think) resulting in the opposite sense of the bias.*

(A2) See answer A1.2.

(C3) *Regarding N_d, there is some disagreement in the literature on how best to calculate N_d from satellite that is related to f_{ad}. The authors cite Bennartz, 2007 - its N_d calculation assumed an f_{ad} of 0.8. Painemal and Zuidema 2011 (JGR) p. 8 discuss how f_{ad} is represented in their Nd calculation vs. that by George and Wood (2011), and Painemal and Zuidema 2013 (ACP) eqn 9 provide another approach for calculating N_d that allows for a fluctuating f_{ad}. I would encourage the authors to be more explicit on how their study fits in with these and other similar studies, and then use the opportunity to opine on what they think is the best approach for satellite retrievals over Germany.*

(A3.1) According to suggestions of referee #2 we restructured the section about the sub-adiabatic cloud model and introduce the general set of equations considering explicitely the adiabatic factor. We explained more explicitely that in our study for calculating N_d (and H) we use $f_{ad} = 1$ in a first step and try to include the adiabatic factor calculated from ground-based observations in a second step.

(A3.2) For a comparison on the adiabatic factor choosen in other studies we added a table. On the discussion of the importance of the adiabatic factor for the retrieval of H and N_d see also answer A1.2.

Specific comments

(C4) *abstract: the optimal estimation technique only considers variations in f_{ad}. please clarify. also mention location, and the 4 dates (these provide some information on the synoptics). mention that the current SEVIRI retrieval underestimates re relative to ground and MODIS measurements (rather than sensitive to satellite re retrieval).*

(A4.1) For a discussion about the OE method see answer A12.

(A4.2) We added location and dates in the abstract: **We investigate four different cases (27 October 2011, 1 June 2012, 27 September 2012 and 21 April 2013) of temporally homogeneous and inhomogeneous liquid cloud layers observed over Germany.**

(A4.3) We changed the last sentence in the abstract to: **For all evaluated cases, the current SEVIRI retrieval seems to underestimate the effective radius relative to ground-based and MODIS measurements for unfavourable solar zenith angles of**

above approximately 60°. This deviation strongly propagates to the derived cloud droplet number concentration.

(C5) *introduction: many previous studies are cited. at this point the reader is not yet clear on what the authors are doing. please group the studies that have similar goals but use different instruments (eg lidar, solar radiometers) separately, then discuss the papers that have applied similar instrumental datasets to this study. Briefly but more explicitly summarize previous findings relevant to the current study on* f_{ad} *and major uncertainties. Mentioning location of the previous findings and contrasting to the cloudnet site used here can be one way to establish originality. which previous studies are most similar to what the authors pursue here? mention the cloudnet site location explicitly and the 4 dates. mention the OE approach constrains itself to the* f_{ad} *model only, and justify why, including why radiometric noise is not being considered. also, how does this study differentiate itself from the cloudnet products? a table might be a nice way to present the results from previous studies (and this one).*

(A5.1) We restructured the introduction and added a table for easier comparison of values considered by other authors within the sub-adiabatic model. Location of the Cloudnet site and the 4 dates are now explicitely mentioned. We stated the main goal of the paper at an earlier position in the introduction. We decided for the following structure for the revised introduction: The introduction now first motivates the importance for investigating key parameters for the first indirect effect. We afterwards state the overall goal of the study. Then we list a shorter and more focused overview of ground-based retrieval methods for these key parameters. Afterwards we outlined the importance of the adiabatic model for the satellite retrieval. Herein also its major uncertainties are shortly mentioned. Finally, a short outlook on the remaining part of the paper is given.

(A5.2) To also give a stronger motivation for our study we added the following sentence to the introduction: **To our knowledge such evaluations from the SEVIRI instrument for the indirect aerosol effects' key parameters have been rarely carried out (e.g. in Roebeling et al. (2008a))**

(A5.3) The main difference to the standard Cloudnet products lies in the estimation of N_d which is not provided by Cloudnet. We added the following sentence: **Since Cloudnet does not provide N_{d}, we developed and apply an optimal estimation technique to obtain N_{d}, based on the method introduced by Fox and Illingworth (1997), similarly also applied in Rémillard et al. (2013).**

(A5.4) For discussion of the OE method see answer A12.

(C6) *2.1 first paragraph could well go in the introduction. be more specific about the instruments and dates.*

(A7) We listed the ground-based instruments more specifically and moved the first paragraph to the introduction.

(C7) *2.1 bottom of p. 5134. why were no soundings used? the simulated cloud top heights do not match those observed by the radar well according to fig. 1 but I see little discussion of this anywhere.*

(A7) Indeed, there is a disagreement of cloud top height from SEVIRI and the ground-based radar. The reason for the disagreement is multifold. On 21 April 2013 there is a semitransparent cirrus cloud layer present at around 10km. While the radar-based cloud top height refers only to the liquid cloud layer, the effective brightness temperature in the 10.8 channel used for the SEVIRI method is altered due to the semitransparent cirrus cloud.

On 27 October 2011 we hypothize that a inversion layer is present at Leipzig. For the Leipzig site no soundings are available. The closest available sounding is at the DWD site Lindenberg. The 12 UTC sounding shows an inversion layer at around 1000m, consistent with the cloud top height obtained from the radar. But there is also a second less pronounced inversion layer present at around 3000m. This ambuigity is known to result in biases for cloud top height (Derrien et al., 2005).

On 01 June 2012 and 27 September 2012 the cloud top height agrees reasonable well when temporally longer overcast periods occur. In the remaining periods broken clouds occur that can not be resolved by the satellites spatial resolution. Therefore the brightness temperature within one satellite pixel stems from clouds and surface within this pixel, leading to warmer brightness temperatures and therefore lower cloud top heights.

We added the following short discussion to the paper: **While for some time periods a good agreement can be seen, also periods with large discrepancies are found. Differences may result from semitransparent cirrus cloud layers (21 April 2013), inversion layers (27 October 2011) or broken cloud conditions (1 June 2012 and 27 September 2012). In the following we sum up the synoptic conditions for each case.**

(C8) *2.2 line 5: the most interesting cloud deck - please make this more specific/objective.*

(A8) We rephrased the sentence: **For this study, we focus on four ideal cases to gain a better understanding of the microphysical processes within the cloud by ruling out side-effects accompanying complicated cloud scenes such as multi-layer clouds as well as possible. We consider single-layer cloud systems which are entirely liquid and non-drizzling as ideal. We chose cases in a way that cloud layers are well-observed by all ground-based instruments and by MODIS and SEVIRI.**

(C9) *2.2 how was the drizzle/no-drizzle threshold specified? how sensitive are your results to this threshold? at the other end, how sensitive is the radar?*

(A9.1) For our study we used the Cloudnet target classification of rain/drizzle which uses the Doppler velocity to identify falling droplets. According to typical thresholds used in other studies we checked the threshold of a maximum column radar reflectivity Z_{max} = -20dBZ.

Rémillard et al. (2013) believed that if Z_{max} stays below -20dBZ drizzle contribution is minimal. Martucci and O'Dowd (2011) found mean radar reflectivity of -8dBZ in drizzle case, and mean radar reflectivity of -44dBZ in non-drizzle case, while Mace and Sassen (2000) demonstrated high frequency of light drizzle with radar reflectivity above -20dBZ (cumulative propability of around 20% at 0dBZ).

None of our profiles not already excluded by the Cloudnet target classification did exceed this value. The daily maximum values for all Z_{max} values are Z_{max} (21 April 2013) = -29.0 dBZ, Z_{max} (27 September 2012) = -24.2 dBZ, Z_{max} (27 October 2011) = -27.3 dBZ, Z_{max} (01

June 2012) = -24.9 dBZ.

(A9.2) The minimum of detectable radar reflectivity (Z sensitivity in Cloudnet) ranges from -88dBZ at the lowermost level ($\sim 150m$) to -40dBZ at the topmost level ($\sim 15.500m$).

(C10) *2.2 p. 5140 lines 6- 19: why not provide your own estimate of the uncertainty in* $\Gamma_{ad}(T,p)$*? you can estimate the cloud base temperature for your 4 cases. given the poor NWP estimate of cloud top temperature, this would provide a stronger argument for a smaller* Γ_{ad} *uncertainty than what you provide here.*

(A10.1) For the calculation of N_d we actually estimated Γ_{ad} for each timestep using T_{cth} and p_{cth} from the satellite, since this can be applied when there is no accomponying ground-based data. We agree that according to the higher uncertainties in satellite derived cloud top temperature and pressure, we could make use of cloud base temperature and pressure instead to calculate Γ_{ad} in this study. We recalculated the results for the 4 cases. This resulted also in a small change of the statistical numbers in our comparison (see revised manuscript [attachment]).

(A10.2) The Γ_{ad} uncertainty of 24% is the value given by Janssen et al. (2011) when they considered the whole seasonal variability of the cloud base temperature. If we compare Γ_{ad} calculated from satellite cloud top temperature and pressure with the one calculated from cloud base values we find an uncertainty of 15% considering all 4 cases. As we see some deviations in the cloud top height, we believe that this can be mainly attributed to uncertain satellite estimates of cloud top properties.

(C11) *p. 5142 line 9: please clarify what the beta index is for the reader rather than referencing other papers.*

(A11) We rephrased the paragraph: **Thereby it is assumed that the droplet size distribution can be described by a gamma distribution with parameter β, where β is the index of the gamma function following the size distribution definition in (Fox and Illingworth, 1997; Martucci and O'Dowd, 2011):**

$$N(r) \propto Ar^{\beta} \exp(-Br) \tag{1}$$

Thereby B is the rate parameter and A a function of the rate parameter.

(C12) *3.3.2: please explain why we should care about* f_{ad} *to the exclusion of other factors. this should go in the introduction. among other factors worth considering Id also suggest the radar vertical resolution and radar sensitivity, and the beta index, which serves as a measure of the droplet spectral width. how confident are you in the ground-based H retrievals?*

(A12) According to comments of referee #2 we decided to limit the investigation to the OE1 method. This method does not require the assumption of an linear increasing liquid water content profile, but N_d is considered vertically constant. The OE method includes error estimates from Cloudnet, also including radiometric noise (in the discussion paper stated ambigiously as observation errors) and forward model error. Only the representativeness error is neglected. The forward model error is estimated as described in the paper by an estimate of the standard deviation when different values for β are assumed. We tried to state this more clearly in the revised manuscript:

The observation error covariance can be split up into individual contributing parts such as forward model error, radiometric noise error, and representativeness error. In this study the representativeness error is neglected, since observations and state variables are on the same grid. Radiometric noise errors are given by the Cloudnet algorithm. The forward model error is estimated by applying values of β in the range of 1 to 6 to the radar forward model and taking the variance of the resulting reflectivity values for a sample cloud profile with a geometrical extent of 700 m and linearly increasing q_L in steps of 0.1 gm^{-2} per 100 m.

(C13) *3.3.2: doesnt the radar Z profile give you some information about f_{ad} ? do all the cases show a Z profile that increases with height, as one would expect for a non- drizzling cloud? I cannot tell from the figures.*

(A13.1) In Fig. 1 of the revised manuscript we added some sample Z profiles to give a better impression than from the Z time-height-plots alone. Here the increase of Z with height can be seen clearly especially for the homogeneous cases.

(A13.2) We can estimate the adiabatic factor by relating the observed Z profile to an adiabatic Z profile. The latter means that we could use the adiabatic liquid water content profile and use the relationship in Fox and Illingworth (1997) to simulate the adiabatic Z profile. This would further require an assumption about cloud droplet number concentration. We use our N_d^{OE} to cross-check the adiabatic factor using this method and the one applying Q_L and H_{cloud}. The results can be seen in the added scatter plots (3) to the revised manuscript. We see that overall both independent methods give results in the same range with good correlation. But also it is observed that the method using H and Q_L gives slightly higher values for the adiabatic factor. Explanations for this difference could be due to the uncertainty in H, but also in retrieved N_d which still has larger uncertainties as our OE method points out.

We added the following paragraph to the ch. 2.2.2 of the revised manuscript:

Given the retrieved N_d^OE and the theoretical adiabatic liquid water content for the observed cloud geometrical depth, we are able to calculate an adiabatic radar profile applying the relationship of q_L, Z and N_d of Fox and Illingworth (1997). If we relate Z_ad to the Z_obs from the cloud radar we obtain a second method to calculate the adiabatic factor ($f_\mathrm{ad}^\mathrm{OE}$):

$$f_\mathrm{ad}^\mathrm{OE} = \frac{\int Z_\mathrm{obs} dz}{\int Z_\mathrm{ad} dz} \tag{2}$$

We also added the following discussion to ch. 4.1.1 of the revised manuscript:

For cross-checking with an independent approach, we also calculate the adiabatic factor using the information of the radar reflectivity profile. We see in Fig. 3 that the mean adiabatic factor calculated from the radar profiles is generally a bit lower, and that the correlation for all four cases is quite good with 62 % to 95 %, and root mean square differences between 0.14 and 0.24. This difference is likely explained by uncertainties in $H_\mathrm{obs}^\mathrm{ground}$ and Q_L, but also in Z obtained from the cloud radar and the retrieved N_d. In the following we will use the adiabatic factor calculated from Q_L and $H_\mathrm{obs}^\mathrm{ground}$.

(C14) *3.3.2 p. 5143 lines 23-26: only now are the readers told the methodological constraints imposed upon this study. these need to go into the introduction and motivated better.*

(A14) We tried to state our methodology and the required assumptions more clear in the revised manuscript.

(C15) *4.1.1. p. 5145 lines 8-9: please be more specific about the contribution to enhanced* Q_L *by drizzle and the underestimation of actual* H_{cloud}. *perhaps subsample your dataset further to exclude such cases? further on on p 5146 you mention it is primarily the* $H < 400\,m$ *clouds that are superadiabatic. is this because the radar doesnt see the upper radar range gates? estimate the resulting uncertainty.*

(A15.1) Indeed, drizzle should not enhance Q_L for the thin clouds considered here, and the cloud radar should be able to see the upper range gates. The cloud radar is known to have issues with the cloud base, but this is covered by the use of a ceilometer. But still, the uncertainties of the MWR of $20\,gm^{-2}$ and of H of $60\,m$ due to the instruments vertical resolution, can easily add up to errors in the adiabatic factors that lead to superadiabatic artefacts. We outlined the uncertainty estimate in the discussion paper on page 5146 for such thin clouds, but move this discussion further up in the revised manuscript.

(A15.2) Since we want to point out the uncertainty in the adiabatic factor due to thin clouds when ground based measurements are taken into account, we will keep the discussion about superadiabatic artefacts but exclude $f_{ad} > 1$ in our further investigation ($f_{ad} > 1.5$ previously).

(C16) *4.1.1. p. 5146, line 12-15: finally, a quantitative assessment of* Q_L *and* H *uncertainty. I would suggest subsetting your sample to reduce the relative size of these contributions.*

(A16) See answer A15.

(C17) *p. 5148 line 7-10: I cannot see this feature in fig. 1b.*

For adiabatic clouds the radar reflectivity profile should increase linearly. For the time-period mentioned here the radar profiles shows two peaks due to a more multi-layer-like cloud structure, which can be seen in Fig. 1b.

(C18) *p. 5150 line 4:I would be surprised if drizzle is strongly contributing to a higher microwave-derived* Q_L. *see Zuidema et al., 2005 (JGR) Appendix A for a quantification, to develop your intuition on this. But if drizzle is apparent in the radar reflectivity profile, that profile doesnt meet the selection criteria and should not be considered, no?*

(A18) We agree with the referee that profiles containing drizzle do not meet the selection criteria. Indeed, none of our considered profiles did exceed the drizzle treshold of -20dBZ. Therefore the explanation for the difference is not found in drizzle as we already tried to point out. The observed difference could as well be attributed to the satellite retrieved value. Since at the same time period also the the CDNC shows larger differences the explanation might be found in problems of the satellite retrieval of τ and r_e.

(C19) *4.2.2: do you find modis-seviri differences in re and tau as a function of sza? if not previously reported, it would be useful to do so.*

(A19) Since only 4 cases with very few MODIS data points were considered in this study we are not able to draw statistically robust conclusion in this direction. But since a large solar zenith angle is known to lead to biases in the CPP retrieval for SEVIRI, we believe that it plays a role especially for the late autumn case of 2011-10-27. It definitely would be useful to investigate the MODIS-SEVIRI differences of r_e and τ as a function of the solar zenith angle for a larger dataset. This is currently investigated, but we feel that this is beyond the scope of the current study.

(C20) *4.2.2. page 5153, end: please, somewhere you need to discuss your drizzle reflectivity threshold and your sensitivity to that threshold.*

(A20) See answer A9.

(C21) *conclusions: it seems to me that the main contribution of the study could be to suggest a subadiabaticity factor for the satellite retrievals, or a way of incorporating subadiaticity into the satellite retrievals based on the initial retrieval of H and Nd. do the authors have any thoughts on how to do this? it is mentioned at the end but rather vaguely. or is a good take-away point that the SEVIRI re retrievals appear to be too low - is this an original finding? you mention solar radiation observations - are those available at the cloudnet sites?*

(A21.1) Adressing the suggestion of the adiabatic factor that can be used for satellite retrievals of H and N_d, we added the following paragraphs to the conclusion:

For 3 out of 4 cases we obtained similar median values around 0.65 ± 0.2 at different seasons. Although larger datasets are required to draw robust conclusions about a typical adiabtic factor, this value could be a first guess for homogeneous stratocumulus clouds as they occur over Central Europe.

So far only four cases were analyzed, but given the network of Cloudnet/ACTRIS in Central Europe this offers the opportunity to investigate the climatology of the adiabatic factor and investigate its regional, seasonal or synoptical dependency. Using more data from a greater network would give statistically more robust insights.

(A21.2) Regarding solar radiation measurements: Cloudnet sites generally require only a instrument set including cloud radar, microwave radiometer and ceilometer. At the LACROS site and also many other Cloudnet sites also solar radiation measurements (e.g. from a shadowband radiometer) are available.

(C22) *figures: the figures 1-2 are very difficult to read. perhaps in final form they will be a larger format? I would at least suggest using the plot size better, e.g., selecting y-ranges in fig 1 that show more of the data. could they perhaps be shown as 2x2 panels rather than one row of 4?*

(A22) We revised the figures. See revised figures below.

(C23) *fig. 1 a: I dont believe I saw the Seviri CTH overestimate discussed anywhere... fig. 6: modis and seviri are difficult to distinguish. fig. 7: extremely difficult to read. please find a way of enlarging.*

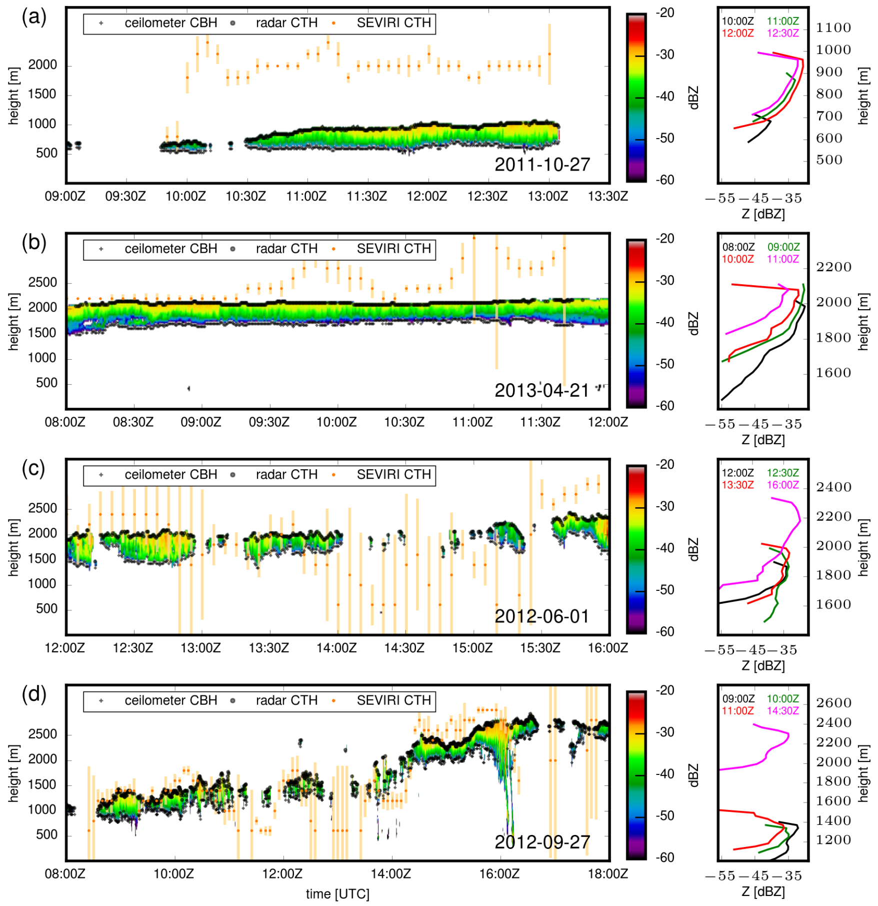

Figure 1: Time series of radar reflectivity (in dBZ) and cloud borders for the 4 cases; (a) 27 October 2011, (b) 21 April 2013, (c) 1 June 2012, (d) 27 September 2012. Cloud borders are shown as detected by Cloudnet with black dots and by SEVIRI using NWCSAF in orange dots. Sample profiles of radar reflectivity are shown for each case at different times.

(A23.1) We added the discussion of CTH differences (see answer A7). (A23.2) We also revised these figures. See revised figures below.

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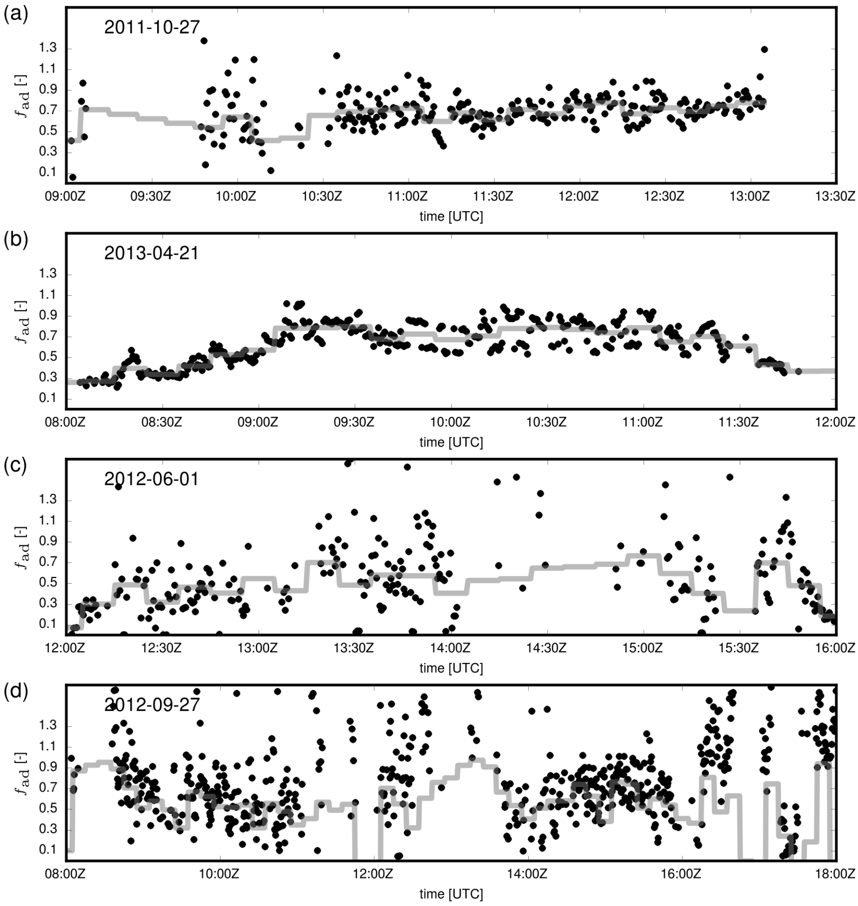

Figure 2: Adiabatic factor for all four cases. Black dots represent the adiabatic factor derived using ground-based geometrical depth and liquid water path from the microwave radiometer. The gray line represents the 10-min averaged and interpolated adiabatic factor neglecting superadiabatic values.

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Marshak, A., Platnick, S., Várnai, T., Wen, G., and Cahalan, R. F.: Impact of three-dimensional radiative effects on satellite retrievals of cloud droplet sizes, Journal of Geophysical Research: Atmospheres, 111, n/a–n/a, doi:10.1029/2005JD006686, URL `http://dx.doi.org/10.1029/2005JD006686`, d09207, 2006.

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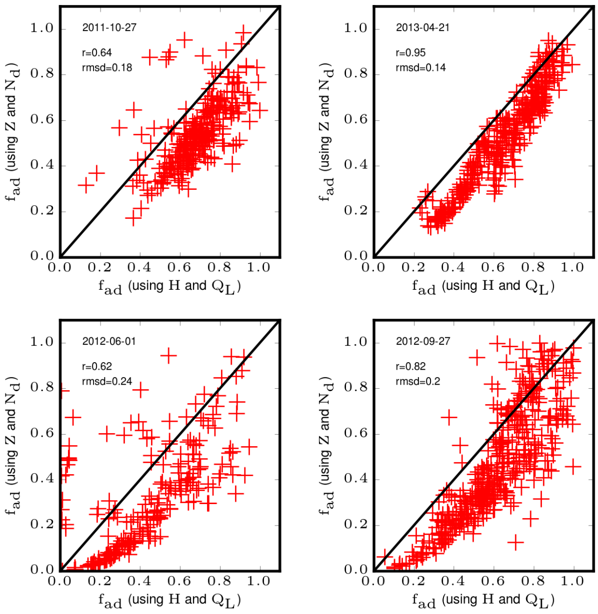

Figure 3: Adiabatic factor calculated from ground-based observations using H and Q_L (x-axis) and from Z and N_d (y-axis). Superadiabatic values are omitted. The graphs correspond to our four investigated cases.

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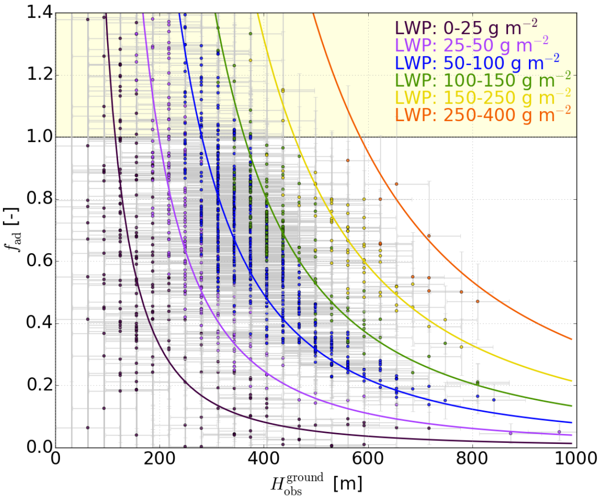

Figure 4: Adiabatic factor as a function of observed cloud geometrical depth ($H_{\mathrm{obs}}^{\mathrm{ground}}$) including data of all four cases. Colors indicate different liquid water path bins. The range with $f_{ad} > 1$ is shaded with light yellow. This superadiabatic range is neglected for the further study. The solid lines represent the theoretical relationship for bin mean liquid water path and $\Gamma_{\mathrm{ad}} = 1.9 \cdot 10^{-3}\mathrm{gm}^{-4}$.

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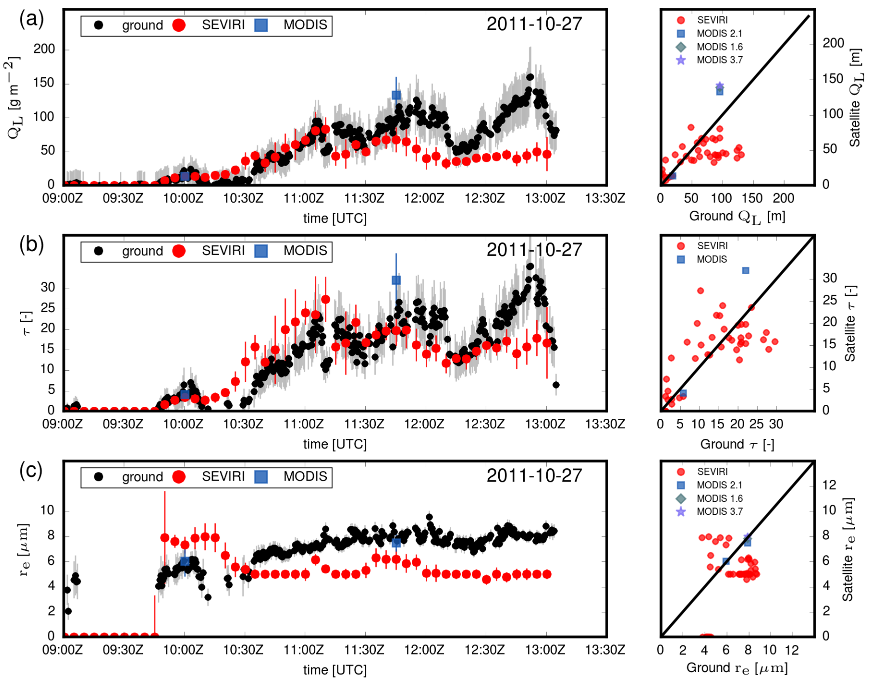

Figure 5: (a) Liquid water path for 27 October 2011 as obtained from the microwave radiometer (black dots), adiabatically from SEVIRI (red dots), and MODIS (green dots), respectively. For MODIS the effective radius obtained with three different channels is shown in the scatter plot with different symbols (square: 2.1 μm, diamond: 1.6 μm, star: 3.7 μm). (b) Time series of optical depth as obtained from SEVIRI (red), MODIS (green), and calculated from ground retrievals, respectively (black). (c) Time series of effective radius with the same colors. The variability of SEVIRI- and MODIS-derived values is given in terms of standard deviation of the surrounding area of ± 1 and ± 9 pixels, respectively.

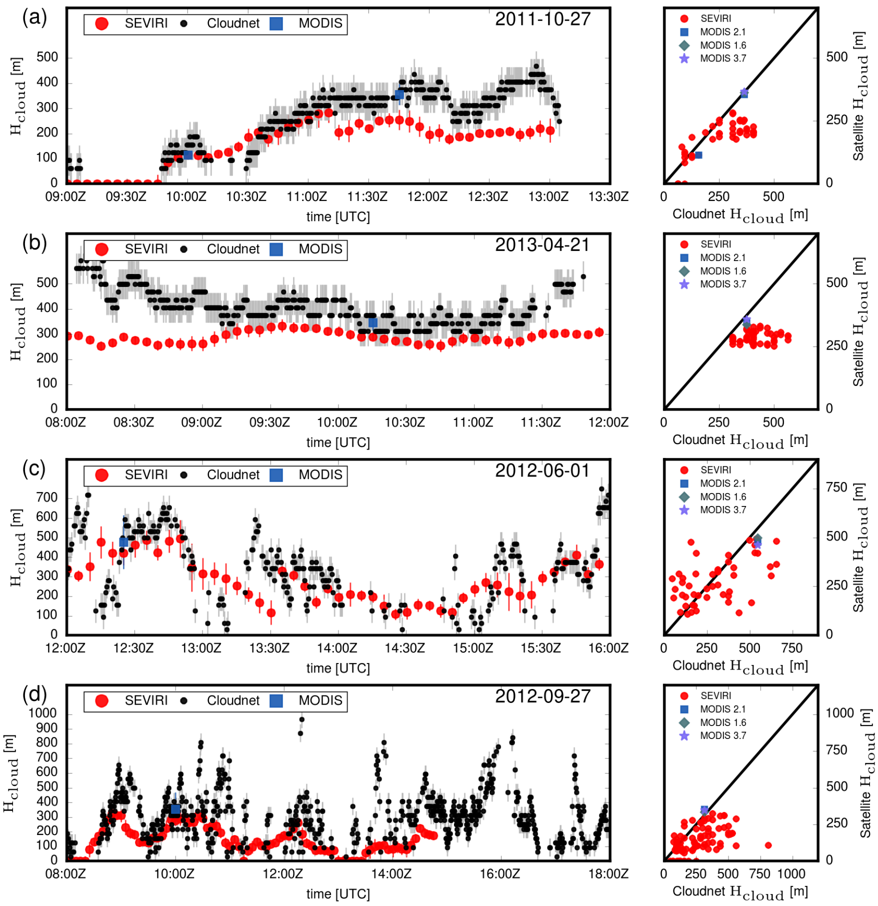

Figure 6: H_{cloud} for the four cases. Black dots represent the geometrical cloud depth observed from ground, red dots the SEVIRI adiabatically derived values, and green dots the MODIS adiabatically derived values. The uncertainties for the ground-based values are shown as shaded areas. The uncertainty estimates of MODIS and SEVIRI are represented in the same way as described in Fig. 5. In the scatter plots diamonds and stars represent the MODIS adiabatically derived values using available channels 1.6 μm and 3.7 μm, respectively.

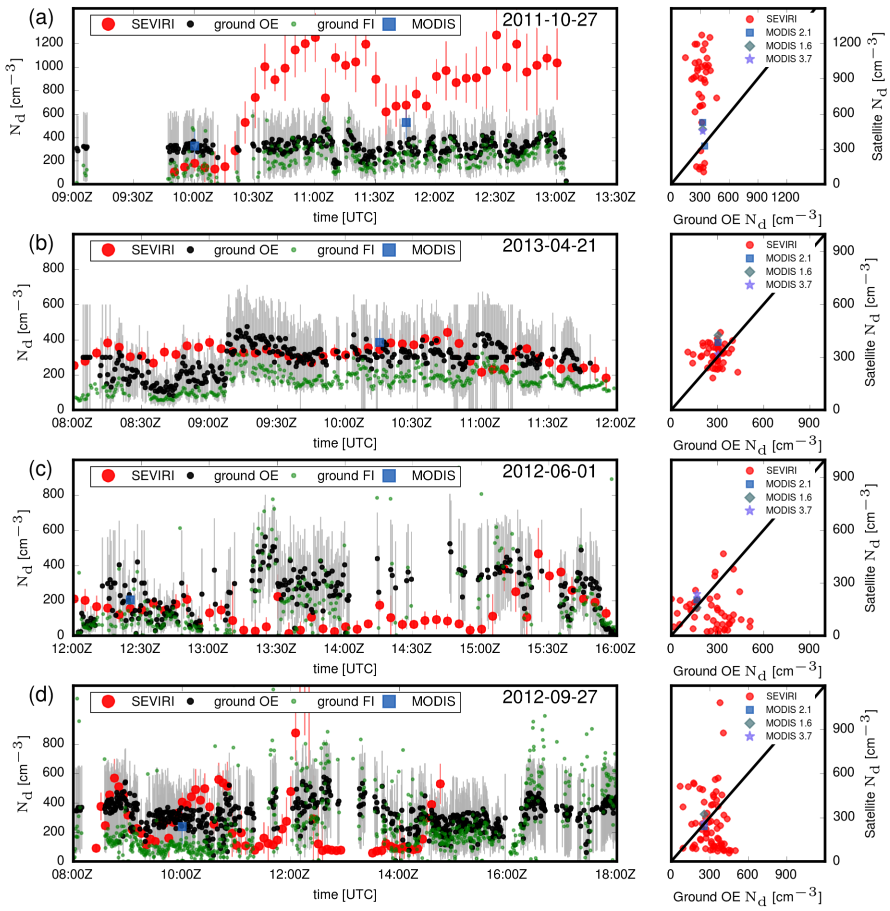

Figure 7: Time series of retrievals of the estimated cloud droplet number concentration. Black dots represent the OE method, using ground-based data (N_d^{OE}). The gray shaded area illustrates the uncertainty, calculated from the error covariance matrix of OE. Blue dots represent the retrieval with the FI method applied to ground site data (N_d^{FI}). Red dots represent the adiabatically derived values from SEVIRI (N_d^{SEVIRI}), while green dots those from MODIS (N_d^{MODIS}). Different MODIS channels used in the retrieval are denoted with the same symbols as in the figures before. Variability for SEVIRI and MODIS is given in terms of standard deviation of the surrounding area of ± 1 and ± 9 pixels, respectively.

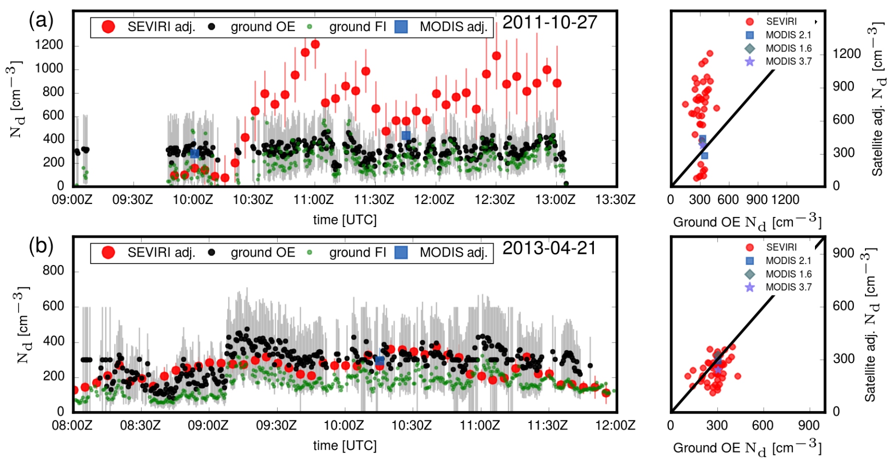

Figure 8: Adjusted cloud droplet number concentration from SEVIRI and MODIS applying f_{ad} from ground-based observations for the two homogeneous cases. Colors and symbols are the same as in Fig. 7.