Answers to Anonymous Referee #2

We thank anonymous referee #2 for his/her helpful comments and suggestions. We revised the manuscript according to his/her comments and the comments of anonymous referee #1. 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) *The theory is spread out over several subsections: 3.1, 3.2, 3.3 and 3.4. It applies the adiabatic assumption as the rule and the sub-adiabatic state as the exception. So we get Eq (1) and (2) about the adiabatic state, and then the sub-adiabatic state as an afterthought on line 204 and beyond.*

(A1) We did a comprehensive revision of our theory section. We now introduce the sub-adiabatic state as the rule and the adiabatic state as a special case with $f_{ad} = 1$.

- In Eq (4), (5) and (6) it is unclear whether we are dealing with an adiabatic state or a sub-adiabatic state.

The equations in the theory section now always consider the general sub-adiabatic case.

(C2) *- The following lines do nothing to clarify, as they would be largely incomprehensible to most readers: According to the authors, the factors A1 and A2 are both dependent on the adiabatic factor (line 219), and then in the next line they are not (line 220). In fact, if (6) considers the adiabatic value for the cloud depth, then A2 cannot be dependent on the adiabatic factor.*

(A2) We clarified this issue by avoiding A1 and A2 and give the factors in the equations explicitely.

(C3) *- In the next line (221) it mentions that the uncertainty in A2 is discussed elsewhere, but they do not quantify it. Instead they jump to the factor k in the next line (line 222) and specify its uncertainty.*

(A3) We rephrased the discussion about uncertainties and moved it from the theory section to the discussion of our results. Since we listed all the factors in Eq (4), (5) and (6) explicitely, the discussion about uncertainties of the individual factors should become more clear.

(C4) *- In 3.3.1 they discuss the Remillard retrieval method but its assumptions are unclear: adiabatic? Sub adiabatic?*

(A4) We assume the referee is referring to the Fox and Illingworth (1997) (FI) retrieval method. The Fox and Illingworth (1997) (FI) retrieval method, which is discussed in sect. 2.2.1 in the revised manuscript, is based on the assumption of a gamma-shaped droplet size distribution. It is assumed that N_d is constant with height, but no explicit assumptions about the liquid water content profile are necessary. We added the following sentence to clarify this issue: **Due to the relationship $N \propto \sqrt{Z}$, this retrieval method does not require the assumption of a linearly increasing liquid water content profile.**

(C5) *- In 3.3.2 there are two OE techniques, one which seems to be describing a sub adiabatic model (OE1), the other an adiabatic model (OE2), although it takes a long time to figure that out. - Eq (9) and (10) come out of a Wood (2006) reference, but this reference is not sufficiently specified at the back of the paper in the bibliography.*

(A5.1) According to the suggestions, we only discuss the OE1 method in the revised manuscript to avoid confusion of to many different approaches.

(A5.2) The reference of Wood2006 was corrected in the typeset manuscript.

(C6) - *Furthermore, (9) and (10) have an implicit assumption about the cloud structure (inhomogeneous mixing, or homogeneous mixing, see the Boers 2006 paper) but the authors say nothing about it. This type of unstructured introduction into the theory does not help the reader understand the overall content. It would be much preferable to redo the theory entirely as a separate section (possibly before the data) and start with a set of general equations (such as a general version of (9) and (10), plus the sub adiabatic version of (1)) and derive all the other equations from it.*

(A6) We revised the theory section and moved it before the data section. As suggested we now introduce a general set of equations from which the adiabatic state can be derived by setting $f_{ad} = 1$. We also clarified that we are assuming the homogeneous mixing model for our study.

(C7) *Next, discuss the adiabatic structure as the exception to the general sub adiabatic state. In that way it becomes clear that the power laws (4), (5) and (6) are transparent evolutions from these basic equations.*

(A7) This is done in the revised manuscript.

(C8) *Next the data: the list you have is : cloud base [ceilometer], cloud top[radar], N [OE or Remillard], LWP from microwave data, and (τ, r_e) from satellite. It then would become clear that there is only a single method to derive the adiabatic factor, namely through equation (8) by using the radar and lidar to get cloud dimension and using LWP from the microwave radiometer. This is the key. Next a discussion of parameters you want to compare: a) $N_O E$ with $N_{Remillard}$, b) f_{ad} with f_{OE} [the latter you should be able to derive from OE1 is it not?] c) N and h [ground-based and sat-based] And so on.*

(A8) We revised the results section according to the suggestions. We also added the comparison of f_{ad} with f_{ad}^{OE}. Instead of comparing two differently calculated cloud geometrical depths from ground with cloud geometrical depth from satellite, we decided to compare (a) Q_L^{sat} and Q_L^{ground} and (b) H_{ad}^{sat} and H_{obs}^{ground} in two steps. In this way we were able to clear out H_{ad}^{sat} completely. We hope that this makes the discussion more clear.

The introduction to the results section now reads as follows:

The following investigation is built on the observations from ground (cloud base height from ceilometer, cloud top height and Z from cloud radar, Q_L from the microwave radiometer) and from passive satellites (τ, r_e).

We will first focus on ground-based retrievals and evaluate the adiabatic factor, followed by a comparison of ground-based CDNC retrieval results using the FI and OE method. Aftewards the key quantities H, N_d, Q_L obtained from satellite observations of SEVIRI and MODIS will be evaluated against the respective ground-based observations. We calculate the cloud droplet number concentration and cloud geometrical depth from the passive satellite-derived τ, r_e, assuming in the first step $f_\mathrm{ad} = 1$ and in a second step the f_ad calculated from the ground-based observations.

(C9) *THE USE OF OE2 OE2 is introduced on page 10 in a very unclear fashion. It is in fact almost incomprehensible to me. I gather between the lines that it is an linear adiabatic* *version of OE1. So it begs the question why one wants to use it, if the assumption on which it is based, namely the adiabatic state, is manifest incorrect. In my opinion OE2 should not be used, so that the section that deals with the intercomparison between OE1 and OE2 can be cleared out almost entirely (in section 4.1.2, and figure 5, which is only partly explained anyway).*

(A9) According to the suggestion we dropped OE2 in the revised manuscript.

(C10) *IMPRECISION OF STATEMENTS a) Line 13: The best match between satellite and ground perspectives. . .. .: No idea what this means; possibly: When satellite-based and ground-based retrievals are compared the best agreement was found for one of the homogeneous cloud cases, namely a 15% . . . in cloud geometric depth and a 27% . . . in cloud droplet concentration.*

(A10) Corrected to: **When satellite-based and ground-based retrievals are compared, the best agreement was found for the 21 April 2013 homogeneous case, namely a ...**

(C11) *b) Line 16: The estimation of ...... is especially sensitive to radar reflectivity for ... and to effective radius. . ... for the satellite retrieval. This should be: The estimation of . . .. . . is especially sensitive to variations in radar reflectivity for . . . and to variations in effective radius. . ... for the satellite retrieval.*

(A11) According to referee #1 this sentence is changed 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.**

(C12) *c) Line 360: . . ...points to thicker clouds in general. No idea what this means.*

(A12) This sentence is left out in the revision of the discussion, using Q_L instead of H^{ad}_{ground}.

(C13) *d) Line 366 369: These lines form an unclear introduction to the next set of lines because line 370 starts with the adiabatic factor, not with H or with a vertical velocity.*

(A13) The paragraph is restructured. The discussion about uncertainties of the adiabatic factor went to the discussion of superadiabatic points further above. Afterwards we first investigate the adiabatic factor as a function of cloud geometrical depth and second as a function of Doppler vertical velocity.

(C14) *e) Lines 453 455. . . ..the largest differences in adiabatic cloud depth .. show up as differences in QL. . . as both differences are linearly linked: Cloud depth differences show up as differences in QL, that is apples and oranges for me. In fact, read 453 465 out aloud and you will appreciate that this is an incomprehensible set of statements. Former and latter are used incorrectly too.*

(A14) This sentence is removed in the revision of the discussion, using Q_L instead of H^{ad}_{ground}.

(C15) *f) Line 483: never start an complete new section with the word Also. Also is used when you have already discussed something else.*

(A15) Corrected.

(C16) *g) Again, lines 503 513: A complete chaos: real cloud do not follow this relationship. What relationship? What are real clouds? What are pure adiabatic clouds? Do you have impure adiabatic clouds?*

(A16) Corrected the sentence, which now reads as follows: **Cloud observations do not always show an increase of effective radius from channel 1.6 μm over 2.1 μm to 3.7 μm as is expected for plane-parallel, adiabatic clouds (Platnick, 2000; King et al., 2013).** We avoided the use of the adjective pure for adiabatic. The terms adiabatic clouds ($f_{ad} = 1$) and sud-adiabatic clouds ($f_{ad} < 1$) are used troughout the whole manuscript.

(C17) *Line 510: The smallest mean absolute difference of effective radius of all channels? What is that?*

(A17) The sentence is rephrased to: **Comparing mean differences of effective radius from SEVIRI and each of the three available MODIS channels, we find the smallest difference in r_e considering the MODIS channel at 1.6 μm. The mean difference in this case is 0.86 μm.**

(C18) *Line 513: Intercomparison . . ..only results in . . .differences with 0.68 m and 0.51.. Differences with what?*

(A18) The sentence is rephrased to: **Intercomparing the effective radii retrieved from the three MODIS channels results in slightly smaller differences. The difference of MODIS channels at 2.1 μm and at 1.6 μm is 0.68 μm, while the difference of the retrieval at MODIS channels at 2.1 μm and at 3.7 μm is 0.51 μm.**

(C19) *h) Line 531: Why would you want to multiply N seviri by an adiabatic factor? No theoretical background is provided. [This should follow out of a complete revamp of the theory, though.]*

(A19) From the revised theory and eq. (5) it should become clear now how the adiabatic factor is applied for the retrieval of N_d. Revised eq. 5:

$$N_d = \frac{\sqrt{10}}{4\pi\rho_w^{0.5}k}(f_{ad}\Gamma_{ad})^{0.5}\tau^{0.5}r_e^{-2.5} \qquad (1)$$

(C20) *i) Line 542: A blending of received signals: no idea what you mean.*

(A20) We revised the sentence: **The underestimation of $N_{\mathrm{d}}^{\mathrm{SEVIRI}}$ comprared to $N_{\mathrm{d}}^{\mathrm{OE}}$ can likely be attributed to broken-cloud effects on the SEVIRI retrieval. For broken clouds within the SEVIRI pixel the satellite receives a combined signal from the clouds but also from the surface.**

(C21) *j) Line 545: Destroys the reliability? What is that?*

(A21) We revised the sentence: **It remains open to which extent the subpixel surface contamination leads to a bias in the retrieved cloud parameters especially for**

inhomogeneous cloud scenes when the brightness temperature actually does not represent the cloud radiative temperature.

(C22) *k) Line 561: both perspectives. What do you mean?*

(A22) We revised the sentence; **Considering the number of uncertainties for both the satellite and ground perspective, and those originating from the issue of representativity of the two perspectives ...**

(C23) *l) Line 571: Virtual adiabatic one? Besides a pure adiabatic one, we now have a virtual adiabatic one? What does that mean?*

(A23) The phrase virtual adiabatic cloud geometrical depth was meant to describe a geometrical depth that was not actually observed, but calculated from the adiabatic theory, meaning that this is only an auxiliary tool. To avoid confusion we stick to the terminology: adiabatic ($f_{ad} = 1$) and sub-adiabatic ($f_{ad} < 1$). For our revised discussion we also avoided this theoretical tool and instead compare directly the liquid water path from ground and satellite.

(C24) *m) Line 588: Ground retrieved one. What?*

(A24) Corrected.

(C25) *And on it goes. In conjunction with the co-authors, the principal author should carefully evaluate each and every sentence they write down and screen on its significance, style and coherence and logical placement in the whole text. This was clearly not done in preparation of this manuscript.*

(A25) We did a major revision of both the structure and discussion style, of our manuscript.

(C26) *OTHER: a) Unless I missed it, it seems that Cahalans work on homogeneity is introduced in the table 1 only, not in the text.*

(A26) We now also introduce the definition of the Cahalan inhomogeneity parameter in the text.

(C27) *Furthermore, you have homogeneous / inhomogeneous clouds, and the homogeneous mixing and the inhomogeneous mixing assumption. These terms are mixed throughout the paper and it is not always clear what is meant by what.*

(A27) In the paper the term homogeneous / inhomogeneous clouds is used in terms of temporally homogeneous / inhomogeneous clouds. If the mixing process is meant, we explicitely mention homogeneous mixing or inhomogeneous mixing. To clarify that we also added the following sentence to the revised manuscript: **In the following the terms homogeneous and inhomogeneous clouds always refer to the temporal homogeneity if not stated otherwise.**

(C28) *b) In the print-out that I made, Table 1 and table 2 appear in the text, rather than at the end of it.*

(A28) This should not be the case in the typeset discussion paper. This issue occured only in the first version of the uploaded manuscript.

(C29) *c) Acronyms are not always introduced: SEVIRI, MODIS, MIRA, HATPRO. They are mixed with acronyms that are introduced: LACROS, DFOV etc etc.*

(A29) We went trough the paper again and checked for acronyms not correctly introduced.

(C30) *d) Equation (13) this is not an equation when you use the sign :*

(A30) Corrected in the revised manuscript.

(C31) *e) The colors in the figures are insufficiently separated. Green en blue hues, then something yellow or reddish. The result is that one needs a microscope to see the differences*

(A31) We revised the colors and size of the figures. See revised figures below:

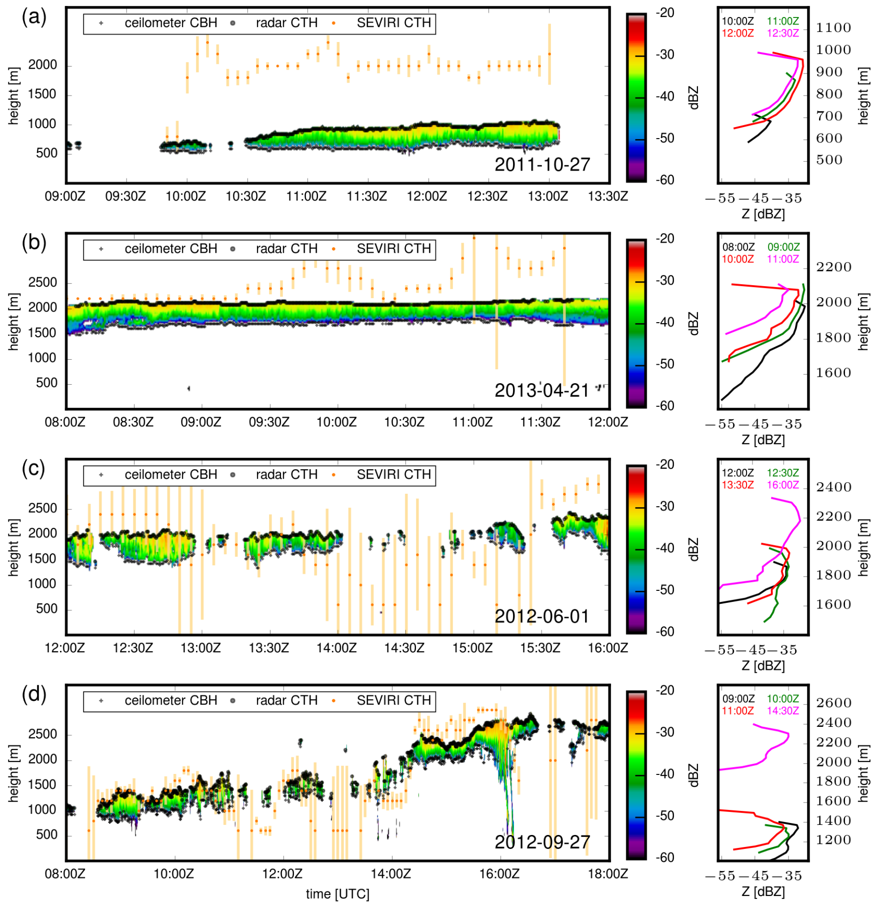

Figure 1: Time series of radar reflectivity (in dBZ) and cloud borders for the 4 cases; (a) 27 October 2011, (b) 21 April 2013, (c) 1 June 2012, (d) 27 September 2012. Cloud borders are shown as detected by Cloudnet with black dots and by SEVIRI using NWCSAF in orange dots. Sample profiles of radar reflectivity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

References

Fox, N. I. and Illingworth, A. J.: The Retrieval of Stratocumulus Cloud Properties by Ground-Based Cloud Radar, Journal of Applied Meteorology, 36, 485–492, doi:10.1175/1520-0450(1997)036¡0485:TROSCP¿2.0.CO;2, URL `http://dx.doi.org/10.1175/1520-0450(1997)036<0485:TROSCP>2.0.CO;2`, 1997.

King, N. J., Bower, K. N., Crosier, J., and Crawford, I.: Evaluating MODIS cloud retrievals with in situ observations from VOCALS-REx, Atmospheric Chemistry and Physics, 13, 191–209, doi:10.5194/acp-13-191-2013, URL http://www.atmos-chem-phys.net/13/191/2013/, 2013.

Platnick, S.: Vertical photon transport in cloud remote sensing problems, Journal of Geophysical Research: Atmospheres, 105, 22 919–22 935, doi:10.1029/2000JD900333, URL http://dx.doi.org/10.1029/2000JD900333, 2000.

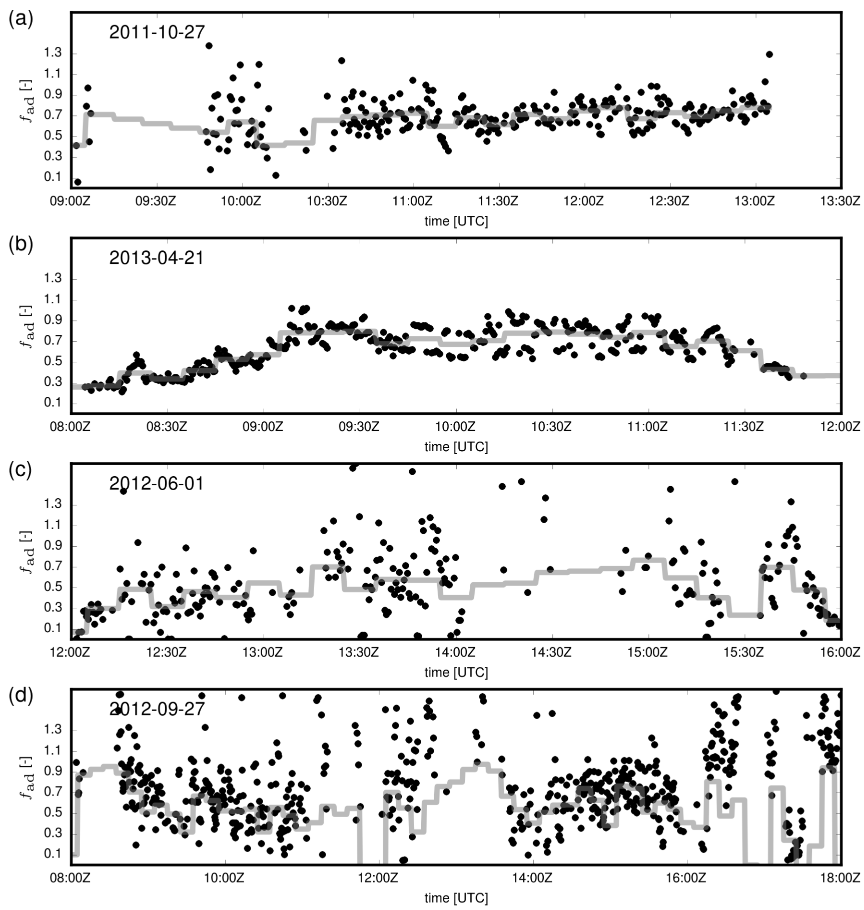

Figure 2: Adiabatic factor for all four cases. Black dots represent the adiabatic factor derived using ground-based geometrical depth and liquid water path from the microwave radiometer. The gray line represents the 10-min averaged and interpolated adiabatic factor neglecting superadiabatic values.

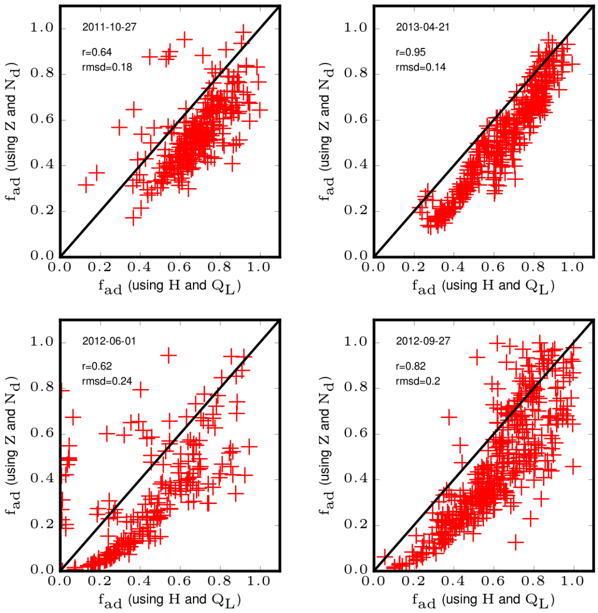

Figure 3: Adiabatic factor calculated from ground-based observations using H and Q_{L} (x-axis) and from Z and N_{d} (y-axis). Superadiabatic values are omitted. The graphs correspond to our four investigated cases.

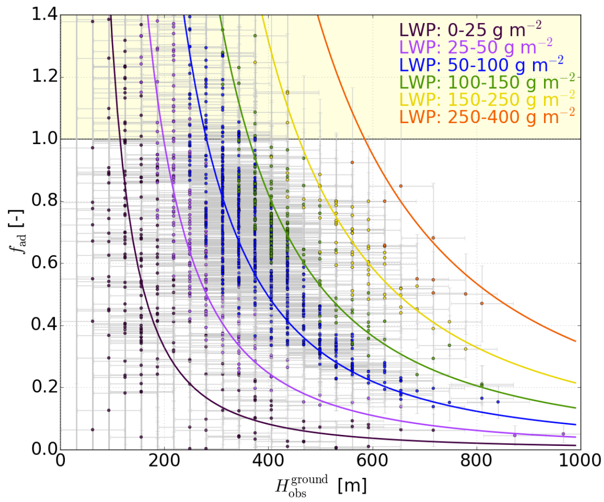

Figure 4: Adiabatic factor as a function of observed cloud geometrical depth ($H_{\mathrm{obs}}^{\mathrm{ground}}$) including data of all four cases. Colors indicate different liquid water path bins. The range with $f_{ad} > 1$ is shaded with light yellow. This superadiabatic range is neglected for the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

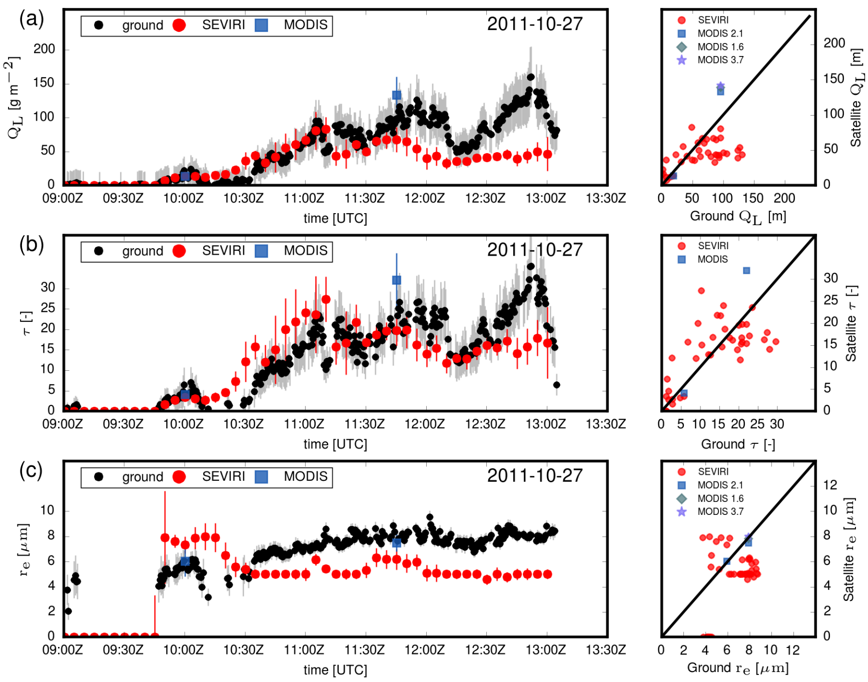

Figure 5: (a) Liquid water path for 27 October 2011 as obtained from the microwave radiometer (black dots), adiabatically from SEVIRI (red dots), and MODIS (green dots), respectively. For MODIS the effective radius obtained with three different channels is shown in the scatter plot with different symbols (square: $2.1\,\mu$m, diamond: $1.6\,\mu$m, star: $3.7\,\mu$m). (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.

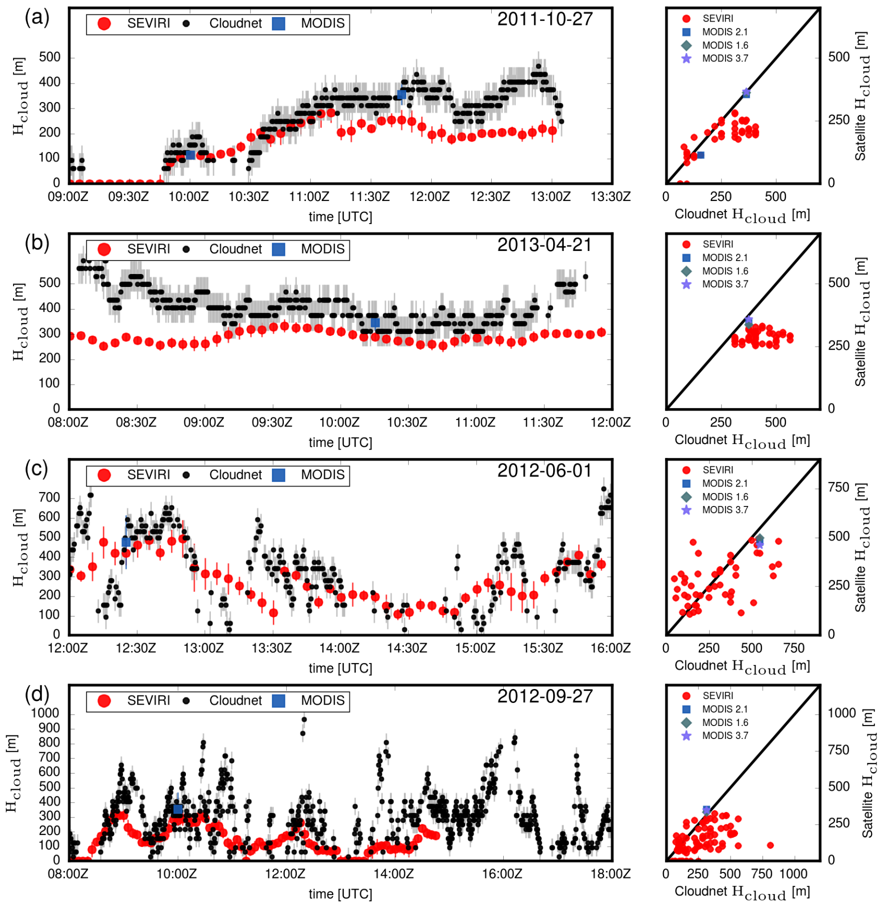

Figure 6: H_{cloud} for the four cases. Black dots represent the geometrical cloud depth observed from ground, red dots the SEVIRI adiabatically derived values, and green dots the MODIS adiabatically derived values. The uncertainties for the ground-based values are shown as shaded areas. The uncertainty 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.

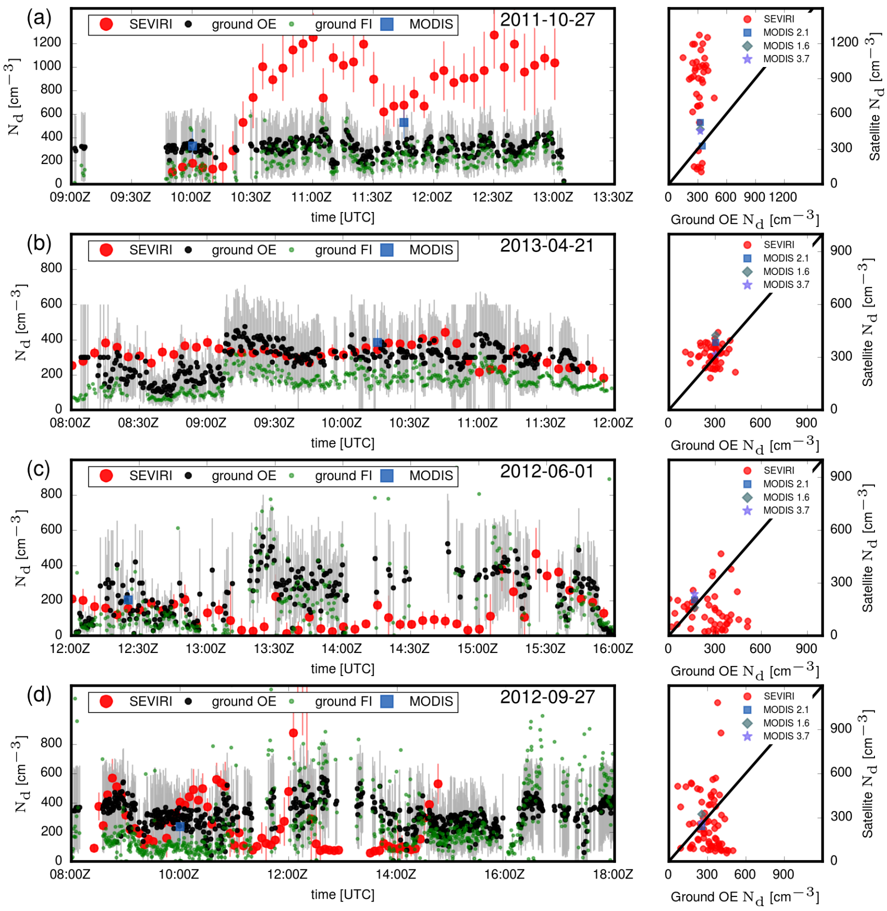

Figure 7: Time series of retrievals of the estimated cloud droplet number concentration. Black dots represent the OE method, using ground-based data (N_d^{OE}). The gray shaded area illustrates the uncertainty, calculated from the error covariance matrix of OE. Blue dots represent the retrieval with 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.

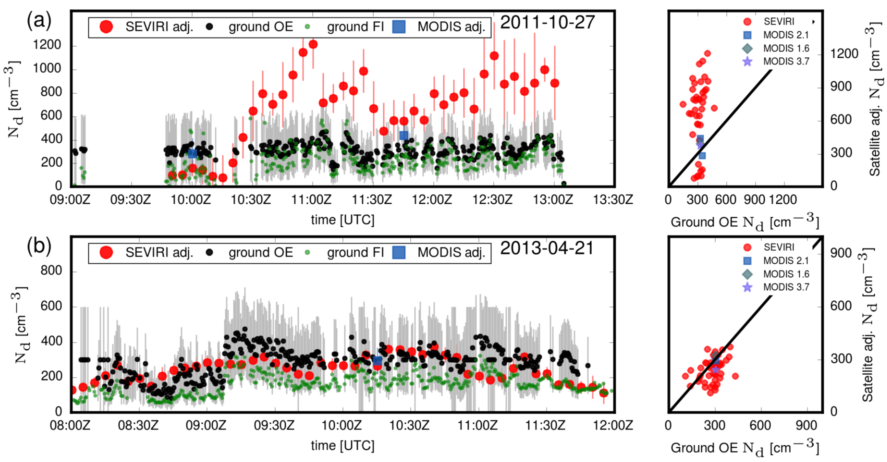

Figure 8: Adjusted cloud droplet number concentration from SEVIRI and MODIS applying f_{ad} from ground-based observations for the two homogeneous cases. Colors and symbols are the same as in Fig. 7.