

First Revision of

“Relation between ice and liquid water mass in mixed-phase cloud layers measured with Cloudnet” by Johannes Bühl, Alexander Myagkov, Patric Seifert and Albert Ansmann

We thank the three reviewers for their detailed comments about our work. The comments and the corresponding action taken are listed below.

According to the reviewers' comments and internal discussions we also made some general changes to the paper:

- The title was changed to: “Measuring ice and liquid water properties in mixed-phase cloud layers at the Leipzig Cloudnet station”
- LDR colorscale in plots was changed. Cases for which no LDR could be measured are now shown with empty symbols (“no sig.”).
- An error in the programming code for Figure 11 b was corrected and the Figure was exchanged accordingly, decreasing values of the cloud lifetime index by approximately one order of magnitude.

Anonymous Referee #1

Overall summary: This manuscript used measurements collected by Leipzig Aerosol and Cloud Remote Observations System (LACROS), which includes Raman lidar, ceilometer, cloud radar and microwave radiometer, and then were analyzed with Cloudnet algorithms to take a detailed insight into the microphysics of mixed-phase cloud layers. Authors found that shallow mixed-phase cloud layers mainly produce pristine ice and spaceborne cloud radar might miss a large part of ice formation. This work presents valuable information to understanding of ice formation and to accuracy of satellite measurements. Some minor questions/suggestions need to be solved are listed in the following:

Comment and Question:

1. Line 64, 97 and 115: Authors should define the acronyms (TROPOS, LDR, COSMO-EU) when it firstly appeared in the article.

TROPOS: added to Affiliations

LDR and COSMO explained at first occurrence

2. A suggestion: the paragraph 2 in page 2 (Line 39-line56) is better moved to the ending of the introduction.

We agree and move this section to the end of the introduction.

The following paragraph (Line 59 – line 70 were moved to the front where it makes more sense).

3. As we know, multilayered cloud systems very frequently occur in the atmosphere (Huang, J., P. Minnis, B. Lin, Y. Yi, S. Sun-Mack, T. Fan, and J. Ayers, Determination of ice water path in ice-over-water cloud systems using combined MODIS and AMSR-E

measurements, *Geophysical Research Letters*, 33 (21) (2006), L21801, doi:10.1029/2006GL027038 ; Huang, J., P. Minnis, B. Lin, Y. Yi, M. Khaiyer, R. Arduini, A. Fan, and G. Mace, Advanced retrievals of multilayered cloud properties using multispectral measurements, *Journal of Geophysical Research*, 110 (D15) (2005), D15S18, doi:10.1029/2004JD005101.). For this study, all lidar or Radar profiles were used? How did you considered the attenuation of lidar power when signal penetrate the lower cloud layer in the multilayered cloud system?

There is no correction of lidar attenuation, because the backscatter information from the lidar is not used quantitatively. The lidar is only used for detection of the liquid cloud-top layer. Cloud cases for which the lidar could not (for what reason soever) detect a cloud-top layer for less than 85% of the cloud total occurrence time are omitted due to selection criterion explained in Line 157: "...and at least 85% of the cloud's occurrence time a liquid or mixed-phase cloud top must be detected."

4. For figure1:

'On top the predominantly liquid water top is detected by lidar'. As we know that lidar signal is hard to penetrate mix-phase cloud layer, how could it detects the liquid water top? And the schemes of mixed-phase cloud layer are not well described. If there is mixed-phase cloud, why IWP is only below cloud layer?

In mixed-phase cloud layers ice is usually formed at the very top of the layers. However, the freshly formed ice particles are not yet large enough to be detected by lidar or cloud radar. The lidar signal is strongly dominated by the liquid droplets. We changed the sentence above to "Water droplets within the mixed-phase top layer are detected by lidar." hoping to make that issue more clear.

The ice particles fall through the liquid-water-dominated cloud top layer, grow and can soon be detected by cloud radar, but only when they have left the cloud top they can be analyzed quantitatively by cloud radar. Within the mixed-phase cloud layer, signals of cloud droplets and ice crystals cannot be distinguished easily. This is why we analyze the ice particles in the moment when they leave the cloud top layer. When the falling particles are then "alone" the disambiguation between drizzle and ice particles is easier and – as mentioned above – there the properties of the ice crystals can be analyzed quantitatively.

This is why the phase-classification algorithm only take into account particles detected directly below the mixed-phase cloud top layer.

5. Line 325: 'a minimum cloud layer lifetime of 3 hours around' how could authors get this value herein.

The lifetime of 3 hours relates to the value of the "Lifetime index" at -25°C in Fig. 10. In the original manuscript, unfortunately a wrong version of the figure was presented. The correct version of the figure was added to this revised version of the manuscript.

6. For the retrieval of LWC, the adiabatic model was used in this study. However, the entrainment of cloud top should be considered, thus this process may reduce the LWC. A better method possible is based on the depolarization ratio measurement from lidar (See paper: Hu, Y., S. Rodier, K. Xu, W. Sun, J. Huang, B. Lin, P. Zhai, and D. Josset, Occurrence, liquid water content, and fraction of supercooled water clouds from combined CALIOP/IIR/MODIS measurements, *Journal of Geophysical Research*, 115

(2010), D00H34, doi:10.1029/2009JD012384. Hu, Y., M. Vaughan, C. McClain, M. Behrenfeld, S. Sun-Mack, D. Flittner, J. Huang, B. Wielicki, P. Minnis, C. Trepte, and R. Kuehn, 2007: Global statistics of liquid water content and effective number density of water clouds over ocean derived from combined CALIPSO and MODIS measurements, *Atmos. Chem. Phys.*, 7, 4065-4083.)

Thank You for this interesting hint. For this work, we used LWC values of a purely adiabatic approach. The next step would be to use an advanced method that takes into account measurements of different instruments (e.g., like the paper mentioned). Cloudnet actually delivers LWC measurements of a so-called “scaled adiabatic approach”, which scales the LWP measured by a microwave radiometer to the geometrical extent of the cloud. However, our HATPRO microwave radiometer has a bias of 20g/m² for LWP. Therefore we cannot yet use this method here. Advanced calibration methods are underway (e.g., Maschwitz et. al., AMT, 2013) but unfortunately this is still work in progress.

We added comments about the adiabaticity factor and the alternative methods to the text in Line 280.

Anonymous Referee #2

The authors of the manuscript used the Cloudnet algorithm to analyze mixed phase clouds observed in Leipzig. I find the topic interesting and the article is in general worth to be published. However, I have some major comments which should be addressed. In particular, the authors have to address uncertainties more carefully and summarize their findings better so that they not oversell their results.

1 Major comments

Abstract: In the abstract, the sensitivity of space borne radars is discussed. However, this issue is mentioned only in Figure 7 and the last(!) sentence of the summary. When mentioning this in the abstract, the reader expects a much deeper discussion of that issue. How is this topic related to the key questions of the paper? I think the authors should either discuss that topic in greater detail in the paper or remove it from the abstract.

We agree with this statement, the discussion of space radar is not sufficiently represented in the paper to be emphasized in the abstract. Hence, it is removed from the abstract.

Nevertheless, we consider the finding interesting and leave it in the paper. We added a sentence in Line 247, discussing the issue more balanced, noting additionally that CloudSat and EarthCare are able to detect most of the ice formation in mixed-phase cloud layers below CTT=-10°C. (A fact that has already been demonstrated in Bühl et. al. GRL 2013 and Zhang et. al., JGR, 2010a).

Section 4.1: My major concern is that Cloudnet’s IWC estimations are used uncritically. Even though an uncertainty estimate is presented in L 167, the IWC results are likely biased and the authors should make that clear. How does that impact the authors’

results and conclusions? What happens if other Z-IWC relations are used? From the spread of results when using other Z-IWC relations, is it possible to say something about the robustness of the key results of the study?

We consider the Hogan retrieval as the best that is currently available. A comparison with other IWC retrievals is actually envisioned but at the moment we leave that to another study.

We added comments to the text to Section 4.1, explaining the statistical uncertainties and biases given by Hogan (2006).

Moreover, the authors should discuss in more detail why is there this drop around $-10\text{ }^{\circ}\text{C}$? How can the authors distinguish between impact of particle type and number concentration?

Based on these measurements this is very difficult to decide. DeMott 2010/2015 show that the number of ice nucleating particles is increasing by a factor of 10 each 5 degree, which would be in the order of magnitude of the IWC increase. However, we think we have no basis to raise this issue in the paper and would rather avoid speculation about this topic.

Can the authors exclude the possibility of cloud misclassification (i.e. the clouds are actually liquid)?

Assessing possible misclassifications is difficult, because there is no “truth” dataset or other observations of cloud ice for the clouds observed over Leipzig. We can only compare the results of the algorithm with those of a human observer: The number of mixed-phase clouds found in 5K-temperature intervals between -40 and 0°C are within the errors of the (manual) study of *Bühl et. al, GRL, 2013*. Based on this study the classification accuracy of the algorithm is about 15% in an absolute measure.

Why is there no significant decrease for very cold temperatures when I would expect smaller particles as well?

We cannot fully explain this based on our measurements, but since our paper relies on the Hogan retrieval, which actually becomes more precise when going to lower temperatures, we trust into the IWC measurements.

From Fig. 9d, we see that particles indeed become smaller at very low temperatures. Assuming Hogan et. al. 2006 is right, a strong increase in number concentration of particles would explain the issue.

Section 4.2: I cannot see that Figure 8 shows the ‘necessity to select thin clouds’. I see that IWC is higher for lower temperatures, but how do the authors know that this is due to more non-pristine particles? I would actually recommend to omit Figure 8 (or explain better why its interesting), because the authors motivated the use of a maximum thickness of 350 m already well with references to other studies.

We agree. In the current context of the paper, Figure 8 is misleading.

We leave out the complete Section and move the explanation of thresholds to the introduction.

Section 4.3: What is the influence of vertical air motion? Did the authors correct for that?

Vertical air motion could not be corrected. Correction of vertical velocity has actually been done using a combination of cloud-radar and wind-profiler, (see Bühl et. al., AMT, 2015), but such a system is not available for our study.

We added a comment to the caption of Fig. 9 and to Line 85: “(cloud-radar Doppler velocity average over a complete cloud case)”.

Section 4.3: One of the key conclusions of the authors is that ‘ice crystals formed in cloud layers with a geometrical thickness of less than 350m are mostly pristine when they fall out of the cloud’ which they support by agreement of observations to literature studies. I think this is not supported by the study (except maybe the 0 to -10 °C range). Even though they show indications for the presence of pristine particles, but they show not evidence that other particles are not present. How would non-pristine particles appear in the data with respect to LDR and fall velocity?

Non-pristine crystals that result, e.g., from ice particle break up, aggregation or graupel formation would be asymmetric and would therefore increase the LDR values. However, the LDR values we find are very close to the literature values of *Reinking and Matrosov (1997)*, which yield -28dB for plate-like crystals and about -20dB for columnar shaped particles. These calculations however depend strongly on the orientation of the ice crystals (i.e. at what angle they “wobble”). Larger angles of orientation would increase the measured LDR values. Finding these very low values of down to -30dB is therefore an indication that pristine particles are dominating and secondary ice formation only plays a minor role within the selected cloud layer type.

More precise estimations of this phenomenon can be found in the study of Myagkov (2015) where a ZDR radar technique was applied and particles were also found pristine (including estimations of the angle of orientation.).

We also changed the statement, now claiming that the “dominating part” of the ice crystals found below these clouds is pristine.

Section 4.4: How do the authors know that the median of LWP was around 20 gm⁻²? From the radiometer or from the adiabatic profiles? Are there differences in the statistic? Even though the general uncertainty of LWP retrievals is around 20 gm⁻², the uncertainty is actually way less if environmental conditions (mainly water vapor) are known. As far as I know, LWP estimation is not standardized in Cloudnet. But if LWP is bias corrected before the cloud (i.e constrain the water vapor), I expect the radiometer to be a better source for LWP than the adiabatic profiles. The adiabatic profiles are more an upper threshold for LWP. Moreover, your analysis of ILCR depends on uncertainties and biases of both LWC and IWC.

It is true that the LWP retrieval is not standardized within Cloudnet. We apply a post processing algorithm with background correction which is in an early development phase and not properly evaluated. This algorithm also requires access to the raw data of the radiometer. In this work, we want to develop a general method applicable to any dataset (as stated in Line 68) and the only standardized algorithms of LWP within Cloudnet is the adiabatic method. We also think that this is not sufficient and are looking with great confidence to methods recently developed by other groups (e.g. U. Löhnert, University of Cologne and B. Pospichal, Institut für Meteorologie, Leipzig). But even for these methods, it currently still unclear if they will be able to provide LWP error below about 5 g/m² which would be needed to detect 20g/m² and accuracy of 25%. Given

these unsolved issues we think that – for the moment – it is best to proceed with the adiabatic method.

We consider ILCR an estimate, which we try to explain in more detail in Section 4.3. The uncertainty is about one order of magnitude given the biases of IWC and LWC together. Nevertheless the standard-deviation within a temperature interval of about 5°C is only a factor of 2. This might be partially due to the reason that both the IWC and the LWC retrieval method rely on the same temperature field, which reduces this part of the bias.

Section 4.5: As the authors note by themselves, this analysis is only for static conditions. I would propose that this can be seen from the nomenclature as well. I would suggest to call the lifetime index e.g. static lifetime index or potential lifetime index etc.

We agree and call the measurement value “static lifetime index”.

Summary:

L 303-305: I guess the authors refer to Figure 10? This interpretation should have been discussed earlier in the manuscript. Moreover, it does not hold given the uncertainties of both LWP and IWC and that the authors show no quantitative evidence that IWC can be really estimated from LWP and CTT.

We agree that the idea of estimating IWC from LWP or vice versa is not developed enough and has no real foundation. It is therefore left out.

L 315: See comment to section 4.3

We changed to “dominating fraction of the ice crystals” (now line 337)

L 340-342: See above, I did not find any relation established and evaluated in this manuscript.

This statement was also left out.

L 346-349: See also comment to abstract: In general, authors should avoid raising totally new issues in the summary as it is done here. Maybe, this part can be moved to the discussion of Figure 7? Is that actually a new, relevant result that pristine ice crystals have low backscattering cross sections and might be missed if the radar sensitivity is not sufficient?

We shifted the discussion about the radar sensitivities to Section 4.2.

2 Minor comments

Title: I find the title of the article misleading. Even though a ratio between LWC and IWC is introduced, it is not discussed in detail.

Perhaps we went to fast with our statement about a “relation”.

We changed the title to “Measuring ice and liquid water properties in mixed-phase cloud layers at the Leipzig Cloudnet station”, in order to make it more precise.

Figure 6 and other: If the authors plot the lines on top of the dots, the figure would be much easier to read.

We changed the layout of the figures to make them easier to read.

Figure 7a and other: What is indicated by the white boxes?

The white boxes indicate “Maximum values in each column are marked with white bars” which is now mentioned in the figure captions of Figs. 7 and 8.

L. 93: Add Hatpro Reference

Added Rose (2005)

L. 98: Because the analysis depends on model temperature, what is the impact of this change on your analysis? Is there a bias between the models?

In *Seifert et. al., JGR, 2010* the bias of the model temperatures compared with local radiosonde launches were found to be about 1°K. This error is insignificant compared to the systematic errors of the Hogan retrieval and/or radar calibration.

L. 118: add 'in Cloudnet below 0

Sentence changed to "on the basis of temperature only, there is no way to unambiguously decide between drizzle and/or falling ice crystals below 0°C."

L. 120: I found this part hard to understand. Please motivate more clearly why you need this algorithm on top of Cloudnet and what it does

Cloudnet only uses single range gates for ice-particle target classification. We go a step further and use distinct cloud layers in order to decide between mixed-phase and liquid-only clouds. This explanation has been added to Line 139.

L. 124-128: What is the motivation for these thresholds?

Explanation added to Line 147: The 300s horizontal separation is derived from experience. Increasing the value increases quality of the cloud cases. The 350m cloud thickness is motivated by Fukuta(1999), as it probably excludes secondary ice formation processes and particle riming.

L. 125: What is meant by 'driving microphysics'?

Exchanged "driving microphysics" by "cloud properties"

L. 139: I found it puzzling that CB refers to the cloud base of the mixed phase cloud and not of the complete cloud. What is actually the author's definition of a cloud? Are pristine ice particles already precipitation and not considered a cloud anymore? The same holds for Figure 2: 'signal below cloud layer' makes little sense if it is not clear that the mixed cloud layer is meant.

In this work, we rely on the definitions in Fig. 1. The mixed-phase cloud layer has a defined base and top. Particles falling from it are defined as falling (precipitating) particles forming the cloud virga. In Figure 2 "Signal below cloud layer" was exchanged to "virga present?" to make this more coherent.

L. 151: At a typical radar range, what Ze value does -10 dB SNR correspond to?

At 5000m distance the detection threshold of the MIRA-35 Radar is about -45 dBZ. At typical ranges the threshold for LDR detection is -30dBZ. We changed the sentence accordingly.

L. 160: Please motivate thresholds already here.

See above at L. 124-128

L. 187: Is this equation valid for all radars? Where is IWC_thr in the plot?

Caption of Fig. 7 has been changed accordingly

L. 192: Replace dramatically by e.g. significantly done

L. 194: The threshold is black instead of red. In general, such descriptions should be indicated in the caption instead of the text.

corrected

Figure 1: My printer did not print the red ice part of the cloud which makes the figure very hard to understand.

Obviously a problem with PDF export  changed to bitmap.

Figure 4: Mention why other clouds are not considered.

Added explanation to figure caption: Clouds are marked due to the selection criteria explained in the text

L 222: Replace 'one has to keep in mind' with 'note'

done

L 224: Are the particles investigated here within this interval?

We left out the comment with the Reynolds number because it is misleading.

L 250: Isn't the fall velocity increased because these particles are more compact?

Yes, this is true. We added "(more compact)" to the text.

L 273: ')' missing

done

L 275: Remove actually

done

L 278: too colloquial: 'actually makes sense'

Changed to "can be applied".

L 302: replace 'seem to be' with 'apparently'. 'seems to be' indicates something that is not true in reality

Thank You for this explanation, we changed the text it accordingly.

Anonymous Referee #3

The authors present an analysis of a long-term dataset of mid-latitude mixed-phase cloud properties observed by a combination of Ka-band cloud radar, lidar and microwave radiometer. The Cloudnet categorization is used in combination with additional algorithms to estimate liquid and ice water content and ice particle motion to derive ice mass flux.

In general, I find the study interesting and certainly worth for publication in ACP. Unfortunately, the manuscript does not adequately discuss previous work in this field. I also had the feeling that many statements and conclusions given miss proper discussion. I therefore recommend publication after the comments and corrections listed below are addressed.

General comments:

Lack of references and discussion of previous work: This manuscript puts a "special focus on mixed-phase cloud layers" and aims at characterizing heterogeneous ice formation within them with a combination of ground-based remote sensors. However, while reading through the manuscript, I found the given references and discussion of the results of this study with former work to be rather insufficient. Mixed-phase clouds either in the arctic or in mid-latitudes have been a focus topic during the last decade of many institutions and observing programs (for example the ARM program). Nevertheless, I hardly could find any citation of the important work which has been done in this field in this manuscript. I especially miss a proper citation in the introduction but also in the discussion of the results. In my opinion, a proper discussion of the work which has done in this field would also help to put your results into perspective and would actually strengthen your study. Just to give one example: I did just a half an hour literature review on this topic and found for example a very similar comparison between LWP

and cloud top temperature as you show it in Fig. 10a in a recent paper by Zhang et al., “Ice Concentration Retrieval in Stratiform Mixed-Phase Clouds Using Cloud Radar Reflectivity Measurements and 1D Ice Growth Model Simulations”, JAS, 2014 (their Fig. 7). Although their paper is about arctic mixed-phase clouds, such work should be discussed in your paper. In fact, I could imagine that the similarities or differences that one finds for arctic and continental mixed-phase clouds would actually be very interesting for both modellers and observationalists. Therefore, I can only recommend publication of this manuscript when the discussion of former literature related to this study is properly included and discussed.

We added several citations about recent ARM activities in the Arctic focused on mixed-phase clouds. Also, we included the reference to Zhang et. al. (2014) in line 285. Larson et. al. (2006) and Noh et. al. (2013) were added to Section 4.3.

Pristine Particles: During recent years I realized that people mean different things when they talk about pristine particles. I would like to know more exactly what you mean when you talk about pristine particles. Just single ice particles? Is a single dendrite with some rimed droplets or a broken dendrite still pristine according to your definition? If one reads articles from the in-situ community (e.g. Korolev et al., GRL, 1999) they find even for Arctic clouds in a wide temperature range from 0 to -45 °C that only 3% of the observed particles can be classified as being pristine. Considering that one can expect the conditions for pristine particle growth to be much better in Arctic clouds than in mid-latitude clouds, I wonder how you can be so sure that your remote sensing observations are really related to pristine particles and not to for example polycrystals?

With our definition of “pristine” we follow the laboratory measurements of Fukuta (1999). We consider all particles pristine that have not undergone riming growth, aggregation or splintering.

By restricting the extent of the mixed-phase layers to be less than 350m, particles have growth times less than about 20min.

We added to the introduction that particles are considered pristine if they “do not show signs of riming growth or secondary ice formation”.

Fall velocity: Throughout the paper you use the term “fall velocity” while I suppose you actually show and talk about the measured radar Doppler velocity. I think you should more carefully distinguish between “terminal fall velocity”, “vertical air velocity” and “vertical Doppler velocity”. The latter one needs to be first corrected for vertical air motion which is not trivial in ice clouds and I could not find that you applied such a correction. For example, in L. 235 you use “vertical velocity” and actually mean the vertical Doppler velocity. Please be more accurate with these terms throughout the text and the Figure labeling. I am also not sure whether the vertical air motion in mixed-phase clouds is really equally distributed in such a way that long-time averaging of the Doppler velocity would results in the terminal fall velocity of the particles. Do you have any indication for this, maybe from other studies? Because I think this is the basic implicit assumption you are doing here.

We added a definition in the introduction at the first occurrence of “vertical velocity”, which is defined as cloud-radar Doppler velocity without correction for vertical air motion in Line 85. This makes “fall velocities” the velocity of particles relative to the ground.

The velocity measurements in Figure 8 are averaged over a complete cloud case (minimum 15 minutes), eliminating vertical air motion to a large degree. A general trend is visible showing minimum fall velocities around -17°C with larger fall velocities at -25°C and -5°C . However, a scatter of about $\pm 0.2\text{m/s}$ is still visible, probably introduced by vertical air motions.

Specific comments:

L. 171: I would add to rain attenuation also cloud liquid water in general. Typical attenuation values at Ka-band for cloud liquid water are around (depending on temperature) $1.5\text{ (dB/km) / (g/m)}$ (see for example Hogan et al., JTECH, 2005). In your case where the liquid water is at cloud top this should not be a big issue but one certainly has to account for it when looking for example at multi-layer mixed-phase clouds like your first example in Fig. 3.

For a usual mixed-phase cloud layer a radar attenuation of about 0.15 dB/km is estimated, according to the formula above. Compared to the uncertainties in radar calibration this is negligible. Such small attenuations, (as well as gas attenuation) are automatically corrected in Cloudnet.

Also if the mixed-cloud is at larger heights and the atmosphere is humid, water vapor attenuation cannot be completely neglected at Ka band. In the next sentence you say “strong attenuation is avoided” but what do you consider as “strong”? In fact, any attenuation will introduce a bias in your IWC estimate and hence has to be discussed as a potential source of error.

As stated above, gas attenuation is corrected on the basis of the data from the weather model reanalysis data. This straight forward correction is also usually below 1 dB for conditions in Central Europe.

A comment was added to line 202.

You also state that the 3 dB calibration uncertainty transfers into 30% uncertainty in IWC. However, given the power law in Hogan et al., 2006 for IWC and Z, the IWC error depends on the value of Z. The IWC error for -10 dBZ due to 3 dB uncertainty is certainly larger compared to 0 dBZ .

Indeed there are small differences for different temperatures and radar reflectivities. We checked again and found a 35% value valid for the range from -40 to 0°C and -60 to 0 dBZ .

A comment was added to line 206.

L. 173: “Radar calibration is estimated to be accurate to 3 dB for the LACROS cloud radar”. A 3 dB absolute calibration accuracy for a cloud radar certainly needs comprehensive calibration efforts (e.g. external target calibration, long-term calibration monitoring, etc.) which have to go beyond standard manufacturer calibration. I know that programs like ARM invest a lot of money and man power to reach a 3 dB calibration accuracy for their radars so I and probably many readers would be curious to know more details about the calibration efforts you performed to reach this level of radar calibration accuracy.

Radar calibration is done by measuring transmitted power at the radar feed. Since the LACROS radar is equipped with a scanner this procedure can be relatively easily be

accomplished with a large building nearby. The calibration itself is done regularly by METEK company and we rely on their expertise. Full characterization of the MIRA-35 radar is given in Görsdorf et. al. (2015), which we now cite within the paper.

L. 179-184: From Fig. 6 I find the majority of points being above -23 dB SNR. I can only see that the SNR in general decreases towards higher temperatures. Maybe I missed it, but can you explain this behavior? It is quite unfortunate to use almost the same color (grey) for the data points of LDR between 0 and -14 dB and for the points where a reliable LDR estimate is not possible. Please change.

We changed the colors. Points for which no LDR measurement is available are now marked empty (or white). We think that SNR decreases toward lower temperatures due to smaller particle size and larger distance to the targets.

L. 187: I think I understand what you try to say with your definition of your Z-threshold but for the broader audience I think you should explain a bit more: Why 5000, why -45 dBZ, etc.

The explanation of the threshold was changed and formulated more clearly with a new (corrected) formula for the range-dependent Z-threshold.

L. 215: I can't see why aggregation is the main reason for the low LDRs. Aircraft in-situ data often show that the particles show simply irregular shapes. Also the tendency of the particles to form aggregates in general decreases with lower temperatures.

The respective section was removed due to suggestions of Reviewer #2.

L. 243: I think this statement is a bit oversimplifying since it is only true if all particles within the volume are perfect Rayleigh scatterers. Particularly close to the dendritic growth region you can hardly be sure that no aggregates are present. Also, if the relation between particle mass and reflectivity would be so straight forward as your statement seems to imply then Z-IWC relations for Ka-band wouldn't show such large errors.

The discussion of Rayleigh/Mie effects would go beyond this study. We decided to omit the respective sentence.

L. 261-268: I see the problem of using the MWR LWP for thin clouds. However, I wonder how well mixed-phase clouds can be approximated with your adiabatic approach given that especially at the top of mixed-phase clouds a lot of mixing due to radiative cooling is taking place and therefore entrainment processes might introduce deviations from the adiabatic LWP estimate. Did you prove that the adiabatic approach is superior to the MWR by plotting for example a scatter plot of MWR LWP vs. adiabatic LWP? For the upper part of your LWP distribution with LWP up to 100-200 g/m the MWR estimates should be quite reliable. Are the 20 g/m uncertainty referring to the relative or absolute LWP uncertainty? I would assume the relative uncertainties of LWP should be smaller?

The HATPRO correction algorithm must correct for several different issues (rain, wet radome, multiple scattering, sensor drift) and is currently optimized for other scenarios. This restriction can lead to negative values of LWP (at maximum about -5g/m²) which can occur under mixed-phase cloud conditions, due to an unknown contribution of water vapor radiation. Since the adiabatic approach only take into account the cloud geometry

it is robust. The error due to the unknown adiabaticity is actually lower than using the microwave radiometer data for these clouds. We also need a robust method, that is applicable to any Cloudnet dataset. As explained above, new correction algorithms are underway but implementation is not yet completed.

L. 278: When you say “strongest peak” does this mean you also consider multi-modal spectra? Or do you rather mean “maximum of the radar Doppler spectrum”? I think a statement like “actually makes sense” is not very precise nor scientific, please rephrase. Overall, I do not understand why you are not taking full use of the radar Doppler spectrum itself? You can easily derive IWC for each spectral bin, multiply with the Doppler velocity of the bin and finally integrate the resulting flux. At least you should provide a proof that simply multiplying the moments is a similar good approximation. As we understand the retrieval of Hogan (2006) is not designed in a way that it could be applied to single spectral bins. Also spectra often are broadened due to turbulence and have a positive (upward-moving) component, which results in unphysical results.

L. 291-294: One of your colleagues at IfT just published a study (Kalesse et al., ACP, 2016) that shows the importance to analyze processes and probably also fluxes not along straight vertical profiles but along the fall streaks which can also be seen in your data (e.g. Fig. 3). Have you tried such an attempt?

We actually tried such approaches for case studies but the procedure is automatized in a way that it could be applied automatically to a large dataset. The method of Heike Kalesse is very powerful when multi-layered clouds are analyzed, which we consider the next step. In the current work, we only focus on ice that is falling from the cloud top layer and try to measure it in the moment when it leaves cloud top, so fall-streak tracking is not really applicable. But as noted before, when multi-layered clouds are involved fall-streak tracking is a powerful tool, because it can show the ice evolution and can give information about the influence of different liquid sub layers on the cloud particles. In addition, our approach is based on averages over a full coherent cloud layer which removes the potential need to perform fall streak tracking.

This is certainly an interesting subject for future studies.

L. 297: You leave the reader quite alone with this statement. Is this value realistic? Is it consistent with former studies?

As noted in the beginning, we exchanged the figure and changed the sentence in order to make it more clear.

Style and Typos:

L. 19-21: I would remove the “and” between “aspects” and “involved” and put another comma instead

done

L. 21-22: “Laboratory measurements have already delivered a lot of useful information” sounds quite vague to me. Please be more specific.

Changed the sentence to: “Laboratory measurements have already delivered a lot of useful information, e.g., about the ice nucleation efficiency of aerosol particles with temperature Murray (2012), DeMott (2015).”

L. 23-25: Please provide references to the reader by whom this has been measured.

We think that the word “flux” appeared too early in the manuscript. We changed to IWC and added references.

L. 47: In an “only if” construction it should probably be “is there a direct”. Please check.
done

L. 69-71: Again, please provide the references. Especially in the introduction you should help the reader to find the work you are referring to.

References are given. (Now in line 45.)

L. 81: “such clouds and may”

Added the missing text: “Such cloud are difficult to observe and may...”

L. 94: Please also provide a reference for the radiometer.

Added Rose et. al. (2005).

L. 179: “an SNR” -> “a SNR”

done

Caption of Fig. 6: Description is insufficient. Specify what are the single points, the black dots and the error bars.

Description extended.

L. 196: There is no red line in Fig. 7d

“red line removed from the text”

L. 230: What do you mean with “raw values”?

Clarifying statement was added: (30-s integration time and 30 m height resolution)

L. 208: I think you mean “cloud thickness” here?

This part has been removed following comments of Reviewer #2.

L. 255: were investigated

done

Caption Fig. 10: “averaged for”

done

L. 279: Comma after “however” missing; “the order of magnitude” of what? The entire sentence is not very clear to me and should be rephrased.

We changed the sentence to: “The resulting parameter is an estimation within the order of magnitude, but it can savely be compared to the other flux values, presented here.”

L. 348: Comma before “respectively” missing

done

Measuring ice and liquid water properties in mixed-phase cloud layers at the Leipzig Cloudnet station

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Abstract. An analysis of the Cloudnet dataset collected at Leipzig, Germany, with special focus on mixed-phase layered clouds is presented. We derive liquid and ice water content together with vertical motions of ice particles falling through cloud base. The ice mass flux is calculated by combining measurements of ice water content and particle fall velocity. The efficiency of heterogeneous ice formation and its impact on cloud lifetime is estimated for different cloud-top temperatures by relating the ice mass flux and the liquid water content at cloud top. Cloud radar measurements of polarization and fall velocity yield, that ice crystals formed in cloud layers with a geometrical thickness of less than 350m are mostly pristine when they fall out of the cloud.

1 Introduction

Understanding the process of heterogeneous ice formation is currently one of the major topics in weather and climate research (Cantrell and Heymsfield, 2005; Hoose et al., 2008). Heterogeneous ice formation drives the generation of rain (Mülmenstädt et al., 2015), impacts cloud stability (Morrison et al., 2005) and atmospheric radiative transfer (Sun and Shine, 1994). It is therefore a crucial component in the hydrological cycle in the Earth's atmosphere. The interaction between aerosol and clouds in general involves very complex processes. Vertical motions keep mixed-phase clouds alive by activating aerosol particles to cloud droplets, while at the same time ice crystals nucleate and remove water from the cloud. To understand these complex interactions it is necessary to know all influences, process aspects, involved aerosol particles, cloud droplets, ice crystal ensembles as well as the spectrum of vertical air motions in detail. *Laboratory measurements have already delivered a lot of useful information, e.g., about the ice nucleation efficiency of aerosol particles with temperature (Murray et al., 2012; DeMott et al., 2015).* Observations of the process of ice nucleation in nature, however, are limited. *By means of active remote sensing quantities that are directly connected with ice nucleation events, e.g., the ice-water content of ice crystals from cloud layers, can be measured (Zhang et al., 2010a; Bühl et al., 2013).* In the European Union research project BACCHUS (Impact of Biogenic versus Anthropogenic emissions on Clouds and Climate: towards a Holistic

UnderStanding) the ice nucleating properties of aerosols are investigated. It is one major task of this project to study the life cycle of aerosols from its source through the clouds by means of aircraft, in-situ and remote sensing observations. Combined remote sensing observations in the framework of Cloudnet (Illingworth et al., 2007) constitute one main pillar of the BACCHUS project. *Beyond*
30 *other things, Cloudnet provides a target classification scheme for identifying the physical phase of hydrometeors. A similar multi-sensor approach is used by the ARM (Atmospheric Radiation Measurement) program (Shupe et al., 2008), which recently performed several measurement campaigns in the Arctic in order to study the interaction between aerosols and clouds (Zhang et al., 2014).*

Since 2011, the Leipzig Aerosol and Cloud Remote Observations System (LACROS) (Wandinger,
35 2012) belongs to the Cloudnet consortium. In this article, remote measurements of LACROS analyzed with Cloudnet algorithms are used to describe ice formation processes under ambient conditions. Such remote sensing measurements fill a critical gap in the study of mixed-phase processes, because they deliver the information about the entire cloud column from the base to the top, which is not possible with aircraft measurements alone. In this way, the temperature level at which ice nu-
40 cleation takes place can be derived and at the same time the resulting ice water falling from the layer can be analyzed.

Shallow mixed-phase cloud layers like altocumulus (Ac), altostratus (As) or stratocumulus (Sc) have been used before by different groups as atmospheric laboratories in order to study aerosol-cloud-dynamics interaction under ambient conditions (Fleishauer et al., 2002; Zhang et al., 2010b,
45 a; Bühl et al., 2013; Schmidt et al., 2015; Seifert et al., 2015). These cloud types are especially well suited for process studies purposes, because they show narrow constraints on basic environmental variables like temperature, pressure, humidity and the number of potentially involved microphysical processes (Tao and Moncrieff, 2009). The well defined base and top of shallow cloud layers is optimum to study aerosol effects on ice nucleation as well as the impact of up- and downdraft on
50 cloud ice production. As an additional benefit, these shallow cloud layers can easily be penetrated by lidar and cloud radar systems, which is not possible for deep convective clouds due to massive signal attenuation and strong turbulence within their cores. For climate research these shallow cloud layers are important due to their hard-to-predict impact on Earth's radiative budget. From the meteorological point of view, the understanding of ice formation processes in deep convective mixed-phase
55 clouds may be more important. However, such clouds *are difficult to observe* and may not allow to resolve the basic ice processes and aerosol- and dynamics related aspects of ice formation. Both questions can be answered only by studying the process of ice formation itself in the atmosphere.

All of the statistical analysis of ice formation in our former studies (Kanitz et al., 2011; Bühl et al., 2013; Schmidt et al., 2015; Seifert et al., 2015), have been done manually. Such an approach is
60 time consuming and cloud selection criteria can not be applied on a fully objective basis. Until now, some Cloudnet stations have been running continuously for more than 10 years (e.g., Chilbolton and Lindenberg), providing each day a wealth of measurement values. Therefore, the analysis of

clouds within such dataset can only be effective with an automated algorithm. For the present work, a method has been developed to automatically evaluate measurements from the Cloudnet dataset
65 collected between 2011 and 2015 at TROPOS. A modified cloud-classification scheme from Bühl
et al. (2013) is used to automatically discriminate liquid and mixed-phase cloud layers. The method
is generally applicable to any Cloudnet dataset of arbitrary size. Hence, the method can be used
to quickly analyze any dataset with the same objective criteria, and thus harmonizing Cloudnet
measurements from all over the world.

70 The focus of the present work is twofold: Firstly, quantitative statistics about ice and water mass
in shallow mixed-phase cloud layers are derived from the Cloudnet dataset, taking into account
values of each Cloudnet profile individually. This constitutes a step forward compared to Bühl et al.
(2013) where properties of ice and cloud water have been analyzed separately and independently.
Secondly, statistics about fall velocity and radar depolarization of the ice crystals are compiled in
75 order to directly assess ice crystal sedimentation rates and to derive basic information about the
shape of particles at the same time. (Not only quantitative knowledge about the particles themselves
is gathered, but also the usability of cloud layers as atmospheric “laboratories” is characterized.)
Only if ice crystals are pristine (*i.e. do not show signs of riming growth, aggregation or secondary
ice formation*), there is a direct link between the properties of the ice (e.g., size, shape and mass) and
80 their formation process within the mixed-phase cloud top layer. These measurements of ice particle
properties are compared with laboratory studies of Fukuta and Takahashi (1999) in order to assess the
quality of the Cloudnet measurements. Based on our dataset, the ice water content (IWC) produced
by particles falling from cloud layers is derived and compared with the available liquid water within
the cloud top layer. Together with the quality-assured measurements of fall velocity (*cloud-radar
85 Doppler velocity averaged over a complete cloud case*) direct connection between the liquid water
in the cloud top layer and the resulting ice mass flux is established, which can be regarded as a
quantitative measure of heterogeneous ice formation in the atmosphere. With this approach, also
the impact of ice formation on cloud lifetime is estimated for the temperature regime between -35
and 0°C . Fukuta and Takahashi (1999) also provide comprehensive laboratory measurements of the
90 growth of ice crystals. They found different distinct features in the resulting shape of ice crystals for
different growth times and calculated corresponding residence times within a cloud layer, taking into
account increasing fall speed with increasing particle size. For a residence time of 20 minutes within
a mixed-phase cloud layer, particles could still be considered pristine. Also Yano and Phillips (2010)
found that within this time, secondary processes like riming do not influence heterogeneous ice
95 formation significantly. According to Fukuta and Takahashi (1999), a residence time of 20 minutes
corresponds to a geometrical thickness of a mixed-phase cloud top layer of 350 m. Hence, for the
present study only clouds with a geometrical thickness of below 350 m are selected within this work
to avoid altering of the ice crystals by riming, splintering, or aggregation processes.

The paper is structured as follows. Section 2 gives a short overview about the dataset used in
100 the context of this work. In Section 3 the methodology to analyze the dataset is presented. At the
beginning of Section 4 the ice-detection capability of different cloud radar systems is analyzed. After
that, quantitative statistics of ice and liquid water within mixed-phase cloud layers are derived.

2 Dataset

The data analyzed within the frame of this work has been collected with LACROS (Wandinger,
105 2012) at TROPOS Leipzig, Germany (51.3° N, 12.4°E) between 2011 and 2015. The time coverage
of Cloudnet observations at Leipzig is about 85%. Instruments relevant for the present work are the
PollyXT Raman/depolarization lidar (Althausen et al., 2009; Engelmann et al., 2015), the Jenoptik
ceilometer CHM15kx, the MIRA-35 cloud radar (Görsdorf et al., 2015) and the HATPRO (Humid-
ity and Temperature Profiler) microwave radiometer (Rose et al., 2005). The measurements of these
110 instruments are analyzed by the Cloudnet algorithms (Illingworth et al., 2007) to derive microphys-
ical properties of hydrometeors on a continuous basis. Additionally model input of environmental
variables like temperature and humidity is used. For the Cloudnet dataset of Leipzig, forecast data
of COSMO-EU (Consortium for Small-scale Modeling - Europe) was used from 2011 to May 2014.
Since June 2014, forecast data of the integrated forecast system of the ECMWF (European Centre
115 for Medium-Range Weather Forecasts) was used. In the rare cases, when this data is not available,
COSMO-EU is used as a fall-back option. The resulting Cloudnet dataset is the basis for the follow-
ing analysis of cloud layers over Leipzig presented in the following.

3 Automated selection and classification of cloud layers in a Cloudnet dataset

The goal of this study is to obtain a dataset of mixed-phase cloud layers that fulfill certain quality
120 *criteria such as temporal and spatial homogeneity. As stated above, the continuous, homogenized*
Cloudnet-processed dataset is used as a basis for the approach. The automated Cloudnet algorithm
reduces data from a set of remote sensing instruments on a common grid that has a temporal reso-
lution of 30s and a height resolution of 30.2 m (similar to the one of the cloud radar). In a further
step, the physical state of the atmosphere in all height bins is classified into different categories,
125 e.g., containing cloud droplets, ice particles or both. Other definitions concerning aerosol are also
present, but do not play a role in the context of this work. A detailed description of the target catego-
rization scheme of Cloudnet is given in Illingworth et al. (2007). Basically, liquid water droplets are
detected by a threshold in lidar signal followed by a characteristic decrease of the latter above liquid
cloud base. Ice particles are in general defined to be present if the radar-observed vertical velocity
130 of the targets indicates falling particles and the dewpoint temperature within a range gate is below
0°C. If, in addition, the analysis of the lidar signal of the considered pixel meets the criteria for the
presence of liquid droplets, the pixel is categorized as mixed-phase. The height of the melting layer

is derived either from the meteorological data (dewpoint temperature is 0°C) or from measurements of radar linear depolarization ratio (LDR) larger than -15 dB . Thus, the decision between liquid-
135 only, mixed-phase or ice-only cloud layers is made primarily based on the modeled temperature and changes in the vertical-velocity profile. However, *on the basis of temperature only*, there is no way to unambiguously decide between drizzle and/or falling ice crystals below 0°C .

The target-classification of Cloudnet only takes into account single range-gates. *Taking into account measurements of a complete cloud case facilitates the disambiguation between a mixed-phase
140 and a liquid-only case.* Hence, for this work, an automated algorithm has been developed that runs on this basic target-classification product of Cloudnet. Single 30-s profiles are analyzed to search for liquid water at $T < 0^{\circ}\text{C}$. If liquid water is found, the base and top height of the liquid layer is stored and the height-range below this liquid water bin is searched for ice. If ice is found below, also the height of transition between liquid and ice is stored. This procedure is done for all profiles of the
145 dataset. Afterwards neighboring cloud profiles are merged to coherent cloud layers if they lie within 300s of temporal and 350m of vertical distance. *The 300s horizontal separation is derived from experience. Increasing the value increases quality of the cloud cases. The 350m cloud thickness is motivated by Fukuta and Takahashi (1999), as it probably excludes secondary ice formation processes and particle riming. Cloud-top-height (CTH) of the cloud layers is specified to be larger than
150 1500m in order to exclude clouds influenced by the boundary layer. Zhang et al. (2010a) went with a similar approach.* A set of connected profiles constitutes a cloud layer for which we assume that the cloud properties are similar. *In addition, by definition of coherent cloud layers the average vertical velocities can be used as an estimate of the particle fall velocity, because turbulent fluctuations of the vertical air velocity cancel out.* For the statistical analysis, a cloud must pass certain quality
155 criteria: A coherent cloud structure must be found for more than 20 minutes, no seeding of particles from higher-level clouds must be present and at least 85% of the cloud's occurrence time a liquid or mixed-phase cloud top must be detected (*height-range where water vapor saturation over liquid water is close to 1, see Fig. 1*). The properties of the detected clouds, e.g., cloud-top height (CTH), geometrical cloud thickness δ_h , standard-deviation of cloud-top height σ_{CTH} , cloud-top temperature (CTT), radar reflectivity factor (Z), ice-water content (IWC), liquid-water content (LWC), LDR, lidar attenuated backscatter coefficient (β) and lidar volume linear depolarization ratio are stored for further analysis. See Fig. 1 for an overview where the different properties are derived for one cloud case. The picture also shows, that some measurement values are taken only from a height-level 60m
160 below the mixed-phase cloud base. At this point, cloud droplets should be absent and ice particles should still be largely unaltered by evaporation or aggregation processes. Hence their size and shape should only be related to processes having taken place within the mixed-phase cloud top layer. In the context of this work, all measurement values derived in this way are marked with the index "CB" (for "cloud base").

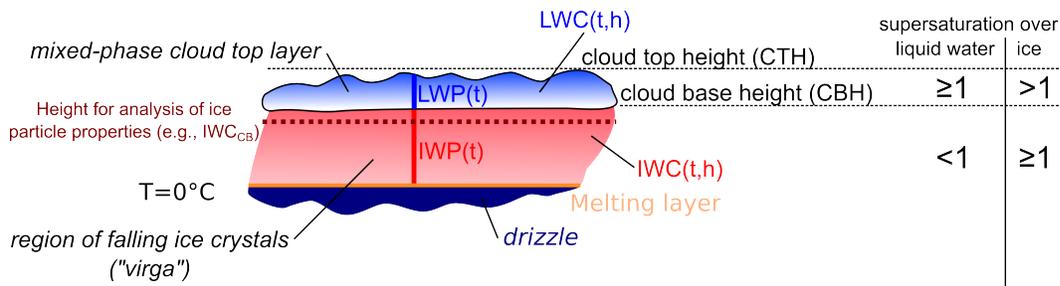


Figure 1. Schematic representation of the different measurement and averaging schemes in a mixed-phase cloud layer. Water droplets within the mixed-phase top layer are detected by lidar. The ice precipitation below is mainly detected by the cloud radar. IWC and LWC are provided by Cloudnet and are a function of height (h) and time (t). IWP and LWP are the column integrated values of LWC and IWC over the liquid cloud top and the ice precipitation, respectively. IWC_{CB} represents the mean of all IWC values measured about 60 m below current cloud base height (CBH). Following Zhang et al. (2014), state of water saturation is indicated for the different parts of the clouds.

After cloud identification, the cloud-classification scheme from Bühl et al. (2013) is used to discriminate between liquid and mixed-phase cloud layers (see Fig. 2). This classification method reduces the dependence on model temperature by taking into account information from all cloud profiles to make a decision between the microphysical states “liquid” or “mixed-phase”. Depolarization measurements from lidar and radar are used to directly identify ice crystals falling from a cloud layer. Mixed-phase clouds close to 0°C also often show a melting layer, which is the most unambiguous sign of the presence of ice particles (Di Girolamo et al., 2012). High LDR values are also produced by the needle-like ice crystals prevailing for clouds with a CTT between -8 and -2°C (Fukuta and Takahashi, 1999). Such clear LDR signal make the decision between ice and liquid water fortunately very easy close to the 0°C level, where model temperature in most cases is not accurate enough and the increase in particle fall speed due to melting is not significant. For low values of Z (typically below -30 dBZ) and no detection of a melting layer, the depolarized signal is usually too weak to be detected by the cross-polarized channel of the MIRA-35 cloud radar. In this case, measurements of volume linear depolarization ratio from a collocated PollyXT lidar is used (Engelmann et al., 2015), if available. In Fig. 3 three example cases with different CTT from different dates are shown together. Cloud radar measurements of Z , LDR and v are shown together with the attenuated backscatter coefficient from the lidar. The CTT of the three cases are chosen in such a way that distinct differences in LDR measurements are visible between the cases. As an example for cloud detection/selection, all clouds with $\delta_h < 350\text{ m}$ and $\sigma_{CTH} < 150\text{ m}$ detected on 2 October 2012 at Leipzig are marked in Fig. 4. The CTT statistics of all selected and classified cloud layers with these selection criteria ($\delta_h < 350\text{ m}$ and $\sigma_{CTH} < 150\text{ m}$) are shown in Figs. 5a and 5b. It is visible that no mixed-phase clouds are detected below -40°C .

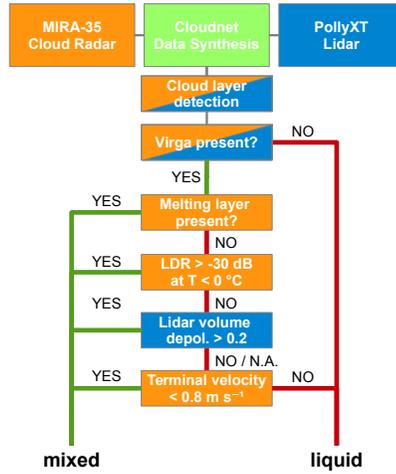


Figure 2. Flowchart of the mixed-phase cloud discrimination method from Bühl et al. (2013) as it is applied in the current work. Most clouds are successfully analyzed with combined lidar/radar.

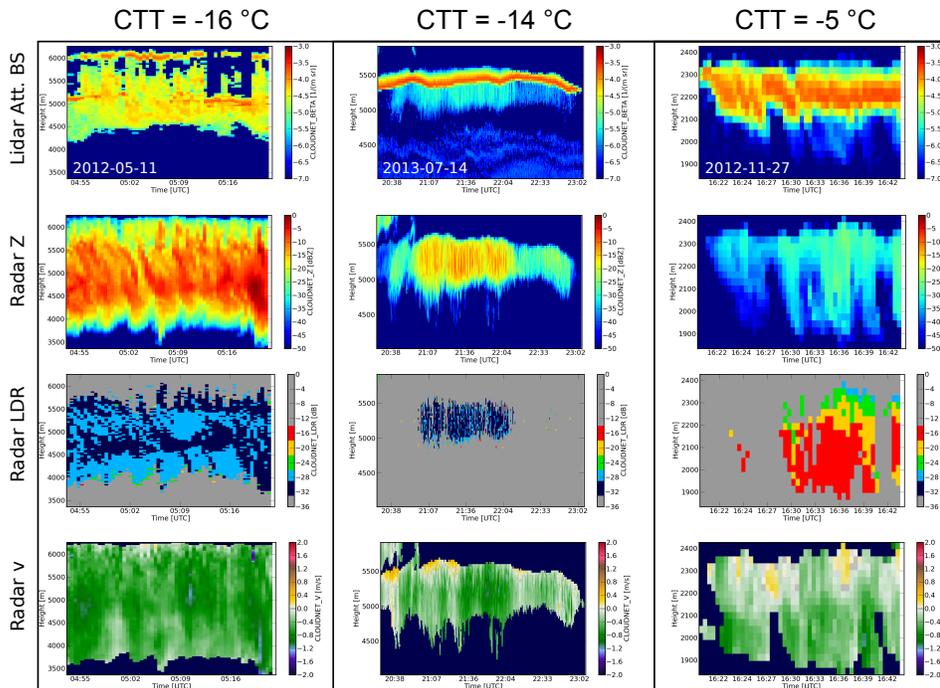


Figure 3. Three example case-studies of mixed-phase clouds identified with the automated algorithm described in Section 3.

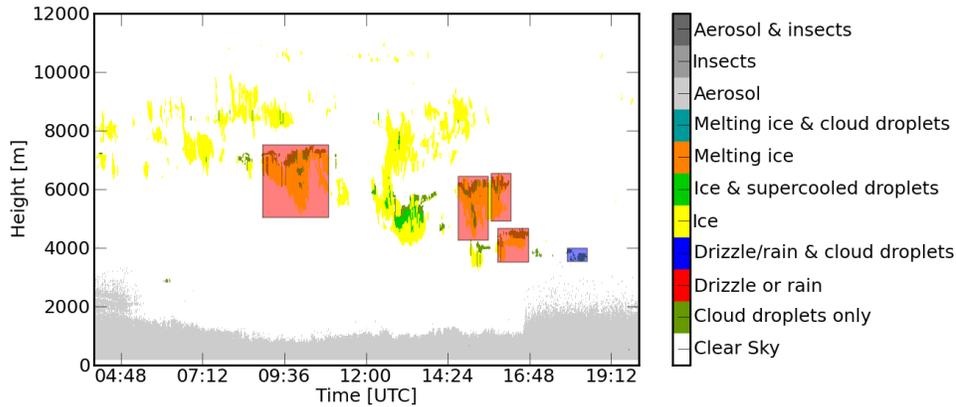


Figure 4. Example of automated detection of mixed-phase cloud layers on the basis of the Cloudnet target classification scheme for 2 October 2012. Clouds are marked due to the selection criteria explained in the text. Blue squares mark liquid-only layers and red squares mark mixed-phase layers. The colors are only for a very basic visualization of the layer detection. The decision between mixed-phase and liquid clouds in the following analysis is more complex and described in the text.

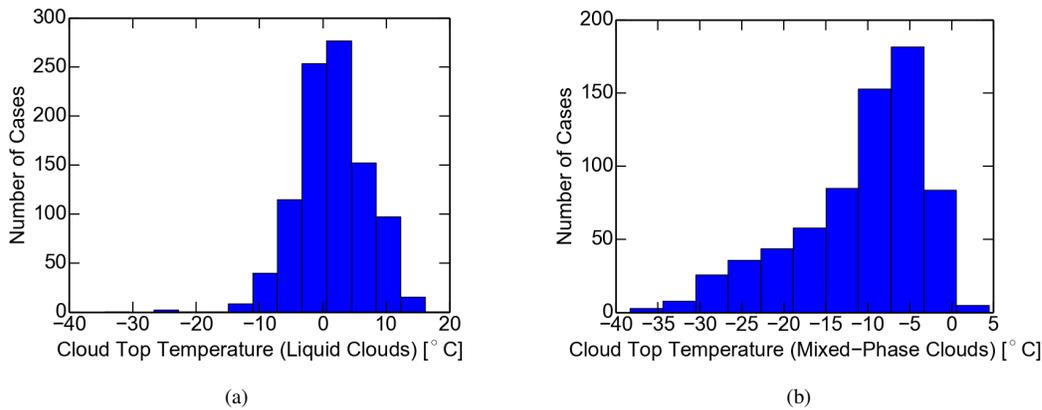


Figure 5. Distribution of cloud-top temperature for all pure liquid (a) and mixed phase (b) cloud layers detected between 2011 and 2015 over Leipzig.

4 Quantitative description of heterogeneous ice formation in cloud layers over Leipzig

4.1 Ice-mass retrieval and detection thresholds

A quantitative retrieval of ice mass is done by Cloudnet via the method of Hogan et al. (2006). IWC values are obtained for each range bin with a simple empirical function depending on Z and the ambient temperature. The uncertainty of the method is estimated by Hogan et al. (2006) to be $(+50/-30)\%$ below a temperature of -10°C and $(+100/-50)\%$ above. A possible bias of $(+15/-10)\%$ is estimated by Hogan et al. (2006). Uncertainties in the measurements of Z add to

these errors. Hence, for the quantitative understanding of ice formation in the atmosphere, knowledge about the accuracy and – especially – about the signal detection threshold of the cloud radar is critical. In the case of ground-based radar, different factors can affect the measured values of Z , e.g., unknown attenuation in rain and uncertainties in radar calibration. *Attenuation induced by water vapor and liquid cloud layers is corrected in Cloudnet. Additionally,* attenuation is avoided by excluding clouds from the analysis that are measured above other clouds or rain. Radar calibration is estimated to be accurate to 3 dB for the LACROS cloud radar (Görsdorf et al., 2015), resulting in an additional bias in the IWC retrieval of about 35% (*for the range between -60 and 0 dBZ and -40 to 0 °C*), making them an estimation within the order of magnitude.

The starting point for the characterization of the IWC dataset is Fig. 6. In this figure, the signal-to-noise ratio (SNR) detected within cloud virgae (streams of ice particles falling from cloud top *in which water is close to saturation over ice, see Fig. 1*) is depicted together with the detected average LDR (color scale). The LACROS cloud radar can detect a signal down to a SNR of -23 dB. From Fig. 6 it becomes obvious that particle detection at higher temperatures above -10 °C are often close to the detection limit. In this temperature regime, the detection of some ice below cloud bases might be missed and clouds could be erroneously be classified as liquid-clouds. In contrast, ice detection seems to be quite reliable below -10 °C, where all cases have a mean SNR well above the detection threshold. It is also visible from the figure, that LDR values can only be detected if a certain SNR threshold is reached.

Figure 7a depicts all measurements of Z_{CB} sorted by CTT. In Fig. 7b the values of Z_{CB} are shown averaged for individual cloud cases. The equivalent values of IWC_{CB} are shown in Fig. 7c. *The LACROS MIRA-35 cloud radar has a detection threshold of $Z_{thr} = -45$ dBZ at a range of 5000.0 m* (Görsdorf et al., 2015). *For other ranges r we hence find a threshold of*

$$Z_{thr} = -10 \times (2 \log(5000^2 / r^2)) - 45 \text{ dBZ}, \quad (1)$$

due to the quadratic decrease of received radiation with range. The corresponding thresholds of IWC (IWC_{thr}) for different radar systems are drawn within the plots. Please note that the ice detection threshold is not only depending on the radar signal threshold, but also on temperature, according to the retrieval of Hogan et al. (2006). For spaceborne systems Z_{thr} is nearly constant for the complete troposphere. The measurement distance of about $400 - 800$ km leads to a range-induced signal variation of maximum 5% between 0 and 12 km height. For ground-based systems, however, the detection threshold varies significantly for different heights. This phenomenon is depicted in Fig. 7d, where mean Z_{CB} is plotted against CTH instead of CTT. The height-dependent detection threshold of the LACROS cloud radar is shown.

The LACROS cloud radar has a depolarization decoupling of -33 dB, which stands out from all radars currently operated within the framework of Cloudnet. Only this technical prerequisite makes high-quality measurements of LDR possible. Also the detection threshold of -47 dBZ at a range of 5000 m is outstanding. Satellite missions equipped with cloud radars like Cloudsat (Stephens et al.,

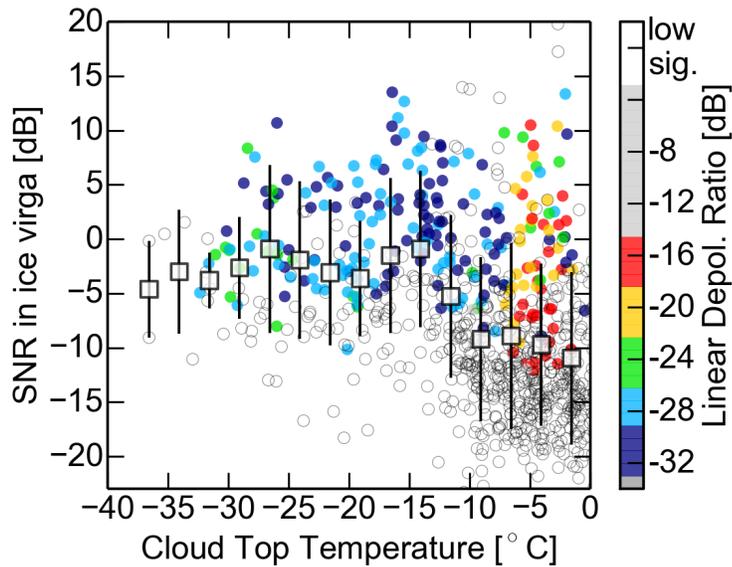


Figure 6. The 90% percentile of cloud-radar SNR is shown for each cloud case together with mean detected LDR. For $\pm 2.5^\circ\text{C}$ intervals mean values (white squares) and standard deviation (black bars) are given.

235 2002) and EarthCare (Illingworth et al., 2014) have detection thresholds within the troposphere of -27 dBZ and -33 dBZ, respectively. Hence, the CloudSat and EarthCare satellites are both able to detect most of the ice formation in clouds with CTT $< -10^\circ\text{C}$. At temperatures warmer than this, probably 90% of the ice-signals below the cloud layers will be missed (see Fig. 7a).

4.2 Fall velocity and radar depolarization of pristine ice crystals

240 In contrast to the extensive properties Z_{CB} and IWC_{CB} , the measurements of the cloud radar can also be used to derive the intensive properties of the ice crystals (e.g., v and LDR). The latter are connected to size, shape and orientation of the ice particles. Values of LDR and v_{CB} averaged for each cloud case are shown in Figs. 8c and 8d. Note that LDR is dependent both on particle shape and particle orientation, so this information is not unambiguous (Reinking et al., 1997). However, 245 if particles are oriented, high LDR values indicate prolate (column-shaped) particles and low values point towards more oblate particles like dendrites. For randomly oriented aspherical particles, LDR is always elevated. In this way, LDR gives only basic information about particle shape, but LDR has the advantage that it can be derived easily together with v_{CB} values with a vertical pointing radar.

The single values (30-s integration time and 30 m height resolution) of LDR and v_{CB} from all cases 250 are shown in Figs. 8a and 8b. The values are taken from the virgae where the target classification of Cloudnet states “ice only” (red-zone in Fig. 1). These representations already show interesting features. In Fig. 7a, e.g., it has already been shown that at temperatures above -10°C the average value of Z_{CB} is often below -30 dBZ. The depolarization measurements show a clear feature of elevated

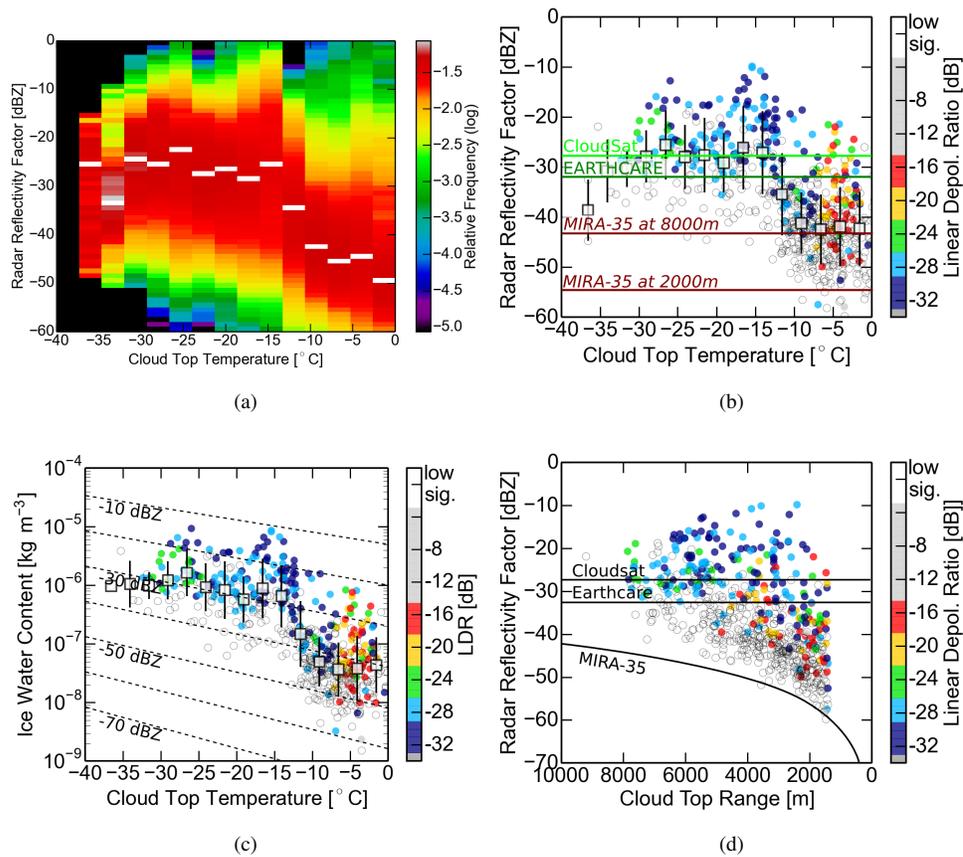


Figure 7. (a) All values of Z_{CB} column-normalized. Maximum values in each column are marked with white bars. (b) Z_{CB} averaged for each cloud case together with averaged LDR values. (c) IWC_{CB} averaged for each cloud case. (d) values of Z_{CB} depicted depending on CTH instead of CTT; the cut-off at lower heights appears due to the selection criterion $CTH > 1500$ m. Thresholds for Z and IWC are *illustrated within the graphs as solid lines with labels*.

LDR values in this temperature range, pointing towards the presence of highly prolate and oriented
 255 ice particles. The vertical velocity measurements in 8b also show features of enhanced fall velocities
 indicating the different prevailing particle habits over the temperature range of heterogeneous ice
 formation.

Fukuta and Takahashi (1999) also found several distinct features in the distribution of ice particle
 size, shape and mass with temperature. Some of these features can be seen within the measurements
 260 of LDR and v_{CB} :

- An enhanced growth of ice crystal mass around -14°C was found by Fukuta and Takahashi (1999). The effect can also be seen in Figs. 7a and Fig. 7b as a strong increase of Z_{CB} at this temperature.

- 265 – The high values of LDR measured at a CTT of -5°C correspond to a needle- or column-like particle shape (see Figs. 8a and 8c). In the temperature range around -14°C LDR values can be found to be around -28dB , corresponding to plate-like crystal shapes. Please note that these features are also displayed in Fig. 3. In Reinking et al. (1997) the LDR values values of -15 to -20dB are computed for these ice crystals shapes.
- 270 – Hints on the presence of these isometric ice crystals are found in the increase of fall velocity in Fig. 8d. Measured fall velocities peak at around -10 and -22°C , while minima of LDR can be found at -12 and -22°C . This connection also points towards more isometric, *more compact* ice crystals around these temperatures.

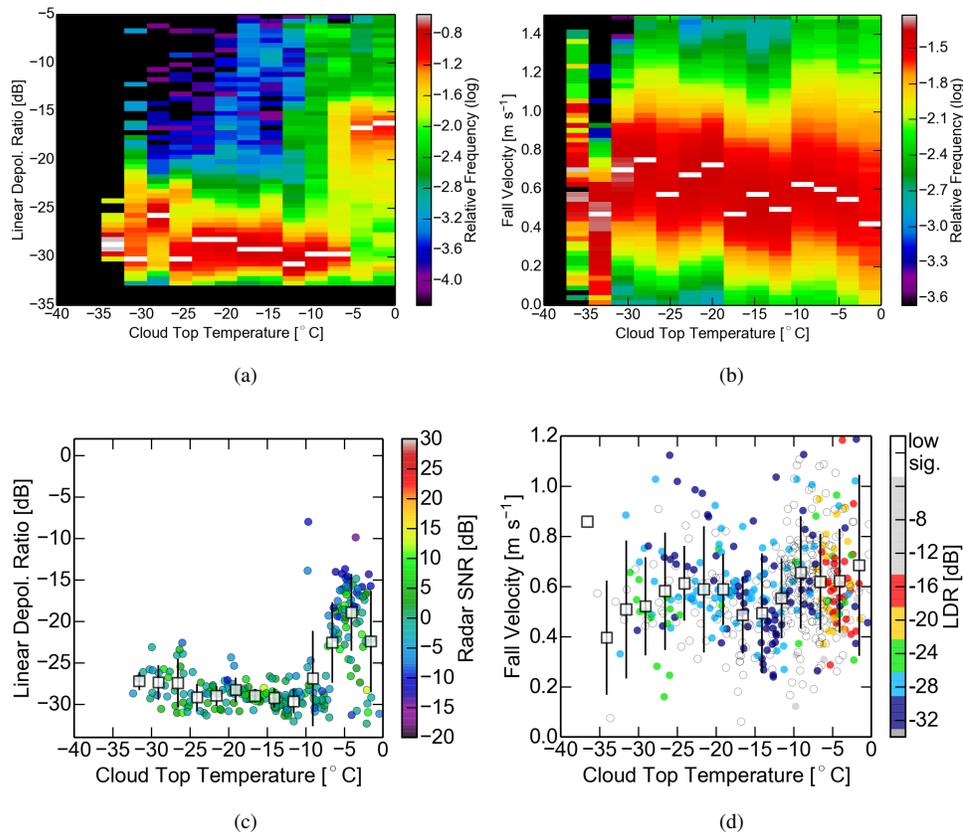


Figure 8. All values of (a) LDR and (b) v_{CB} measured with cloud radar MIRA-35 in the virgae below cloud layers over Leipzig. *The visible spread in v is due to vertical air motion (see velocity plots in Fig. 3).* Averaged values for the individual cloud cases are depicted in (c) and (d), respectively. Maximum values in each column are marked with white bars.

4.3 IWC_{CB} and LWC at cloud top

In the previous sections the properties of the ice particles produced within mixed-phase clouds were investigated. For the estimation of cloud stability by static approaches like the one presented by Korolev and Field (2008), however, the ratio of IWC/LWC=ILCR (ice- to liquid mass ratio) at cloud top is important. *For that estimation, the LWC has to be retrieved in addition to the IWC.*

In this work, the liquid-water content (LWC) of a cloud layer is calculated for each cloud profile adiabatically between cloud bases and cloud tops, assuming an adiabaticity of 1. Cloudnet also provides operationally adiabatic profiles scaled with the LWP measured with the microwave radiometer (Merk et al., 2016). However, the LWP measurements of the microwave radiometer have an uncertainty of about $\pm 20 \text{ gm}^{-2}$. Since the average liquid water path of the cloud under study is actually around 20 gm^{-2} , the adiabatically calculated profiles are used in the context of this work. An overview about the LWP of all cloud layers under study is given in Fig. 9a. Zhang et al. (2014) found a similar relationship between LWP and T for Arctic supercooled mid-level clouds. For the current work, the retrieved adiabatic LWP can be considered as a maximum guess. The actual LWP may be lower, which is described by the adiabaticity factor f . Merk et al. (2016) report f to be within 0.6 to 1.0. Airborne studies of mixed-phase clouds found rather good agreement between observed and adiabatic LWC profiles for shallow cloud layers (Larson et al., 2006; Noh et al., 2013). Hence, the adiabatic LWC profiles serves as an estimation until better calibration methods for the microwave radiometers are available. Such methods are currently under investigation by different groups, e.g. Maschwitz et al. (2013). A completely different future approach may be lwp measurements with depolarization lidar (Hu et al., 2010; Donovan et al., 2015).

In Fig. 9b, IWC_{CB} is divided by the mean LWC in the mixed-phase cloud top in order to derive an estimate of ILCR. *Assuming that particles directly below the mixed-phase layer have the same properties as within the layer, this estimate of ILCR is representative for the average ratio between ice and liquid water content within the mixed-phase cloud layer. The uncertainty of ILCR is about one order of magnitude, given both biases of IWC and LWC. Nevertheless the standard-deviation within a temperature interval of about -5°C is only a factor of 2. That comparably low value might be partially due to the reason that both the IWC and the LWC retrieval method rely on the same temperature field, reducing this part of the error. Systematic uncertainties of both the IWC and LWC remain.*

4.4 Estimating the ice mass flux from a cloud layer

The ILCR connects measurements of ice and liquid water mass. However, ice formation is a dynamic process: Ice crystals formed inside the mixed-phase cloud top layer are falling with $v_{\text{CB}} > 0.2 \text{ m s}^{-1}$ (see Fig. 8d), while the majority of cloud droplets have negligible fall velocity. The same number of particles creates a different IWC when falling at different terminal velocities, because the stream of

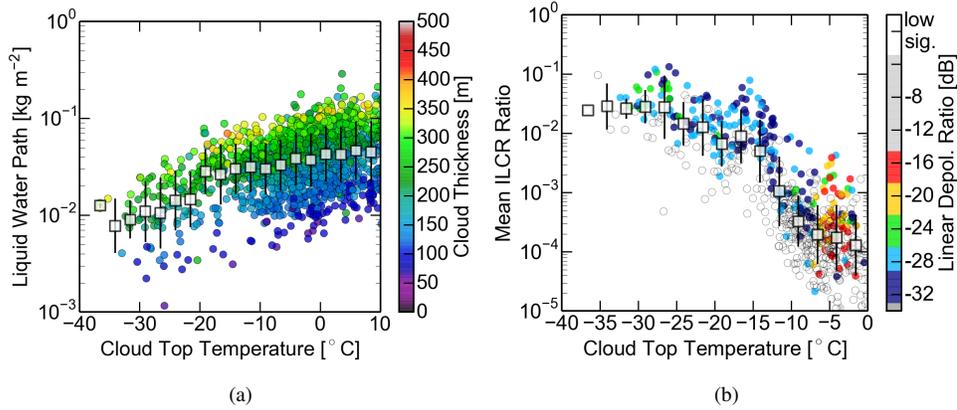


Figure 9. (a) LWP of all clouds under study is shown in dependence of temperature and mean cloud top thickness. (b) The ratio between IWC_{CB} and mean LWC is calculated for each cloud-profile and averaged for each cloud case.

particles is “stretched” differently. Hence, the ice flux $F = IWC_{CB} \times v$ at cloud base gives the most accurate description of ice formation per time interval inside the cloud top layer. In this very simple picture, F describes the flux quite coarsely. However, since both v and IWC are calculated from the same radar signal, a direct multiplication can be applied. The resulting parameter is an estimation within the order of magnitude, but it can safely be compared to the other flux values, presented here. Figure 10a displays averaged F for all cloud cases under study. Especially at temperatures below -20°C it can be seen that the flux of ice mass is only weakly depending on temperature. In this temperature range IWC_{CB} (Fig. 7c) is decreasing with temperature while v (Fig. 8d) is increasing. Also the peak at -15°C is less pronounced compared to Figs. 7b and 7c as it coincides with a minimum in particle fall velocity.

The concept of ice mass flux also opens the possibility to derive basic information about the impact of ice formation on cloud lifetime. Water particles most probably glaciates at cloud top and fall through the mixed-phase layer. Having connected v with IWC_{CB} to the ice flux, it is also possible to relate this quantity to the available LWP within the ice-generating liquid cloud layer. Since ice particles grow through the Wegener-Bergeron-Findeisen process (Korolev and Field, 2008), there is an indirect connection between the amount of available water vapor and ice crystal growth. Hence, a dynamic view of ice formation in the cloud layers can be established by dividing F and LWP profile-wise.

$$\frac{LWP}{F} = \frac{LWP}{IWC_{CB} \times v} \stackrel{!}{=} T_l, \quad (2)$$

Defined in this way, T_l is a time measured in seconds. Assuming steady conditions T_l is the time the liquid cloud top layer would have depleted all its liquid water by ice sedimentation alone. It is

a theoretical quantity, but it gives an impression of the relative impact of ice *formation* on different
 330 cloud layers. An overview of T_l for all cloud cases under study is shown in Figure 10b, indicating
 that T_l varies over 4 orders over the temperature range of heterogeneous ice formation (-40 to
 0°C).

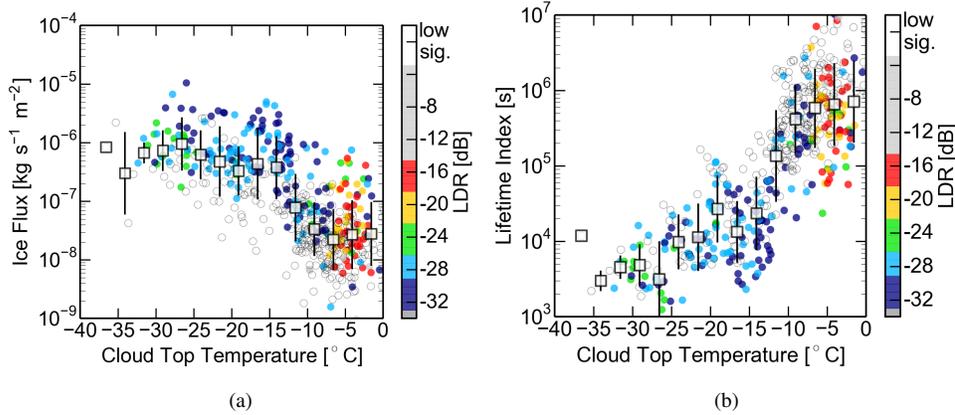


Figure 10. (a) The ice mass flux at cloud base. (b) The estimated static lifetime index $T_l = \text{LWP}/F$ of each cloud.

5 Summary and Conclusions

Quantitative retrievals of ice crystal properties like basic information about particle shape and fall
 335 velocity have been found to be quantitatively in line with theoretical computations of Reinking
 et al. (1997) and laboratory studies of Fukuta and Takahashi (1999). *The dominating part of the
 ice particles falling from mixed-phase cloud layers with a geometrical thickness of the mixed-phase
 top layer < 350m are apparently mostly pristine. Hence, these particles are probably the result
 of primary ice formation and secondary ice formation is a minor process in these cloud layers.*

340 Additionally, a profile-based connection between the measured liquid water path (LWP) and the
 retrieved IWC has been established. The flux of ice mass at cloud base height is found to increase
 within two orders of magnitude within the CTT range from -40 to 0°C . The relative influence of
 the loss of ice on *static lifetime index* is found to increase even by 4 orders of magnitude within
 the same range of CTT.

345 It is demonstrated in this work that a detailed insight into the microphysics of mixed-phase cloud
 layers is possible with a combination of the LACROS instrumentation and Cloudnet. Vertical ve-
 locity measurements show the dynamical state of the turbulent layer and cloud radar measurements
 show the ice flux from that layer. Together with the retrieval of ice nuclei properties with Raman
 lidar (Mamouri and Ansmann, 2015) the life cycle of an ice nucleus in mixed-phase clouds from
 350 entrainment over activation to ice nucleation and sedimentation can be closed.

It is an important finding that the dominating part of ice crystals produced mixed-phase cloud layers with $\delta_h < 350\text{m}$ are pristine. This means that the flux of ice crystals measured at cloud base is directly connected to the rate of ice nucleation within the mixed-phase layer. The direct measurement of the complete process of ice nucleation seems therefore feasible with remote sensing. However, 355 in future, more advanced particle typing methods such as presented in Myagkov et al. (2015a, b) should be applied to further characterize shape and size of the particles on an operational basis.

The relative impact of the loss of ice water on a mixed-phase cloud layer can be measured. However, it has to be noted again, that the cloud static lifetime parameter index presented here might not directly be connected to the absolute lifetime of a cloud. Even the definition of a cloud lifetime is 360 difficult, because particles are mixed between cloud parcels and the apparent motion of clouds can be independent from horizontal wind speed. However, the static lifetime value presented here can be used to study the impact of ice on predominantly liquid cloud layers occurring at different temperature levels. Measurements of ice mass flux and the static lifetime index T_l indicate a minimum cloud layer lifetime of 3 hours at -25°C (see Fig. 10b). At temperatures above -15°C the relative 365 impact of ice formation has already shrunk by 2 orders of magnitude. Given the fact that Korolev and Field (2008) showed that the cloud layers under study here actually are able to recreate liquid water via recurring upward air motion, these clouds seem to be extremely stable with respect to water depletion due to ice formation. The static lifetime index is a step forward compared to Bühl et al. (2013), where the mass ratio of ice and liquid water in mixed-phase layered clouds was estimated 370 with a ratio of IWP and LWP on manually selected clouds. The ratio of IWC_{CB} and LWP, combined with the particle fall velocity gives a much more direct measure of the actual impact of the ice on the liquid water within a mixed-phase layer.

The presented algorithm to classify mixed-phase clouds in Cloudnet datasets is universal. It is not only applicable on Cloudnet datasets, but in general on all datasets that separate an atmospheric 375 column into liquid, ice and mixed-phase. The evaluation of mixed-phase clouds predicted by weather models seems therefore possible if suitable data output is given.

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