Interactive comment on “Classification of Arctic multilayer clouds using radiosonde and radar data” by Maiken Vassel et al.

Anonymous Referee #2

Received and published: 23 October 2018

We thank the anonymous reviewer for his/her review and the detailed comments. We have revised the manuscript accordingly, including a revision of all sublimation calculations, updates of all figures, and major changes of the text. Our replies to your comments are given below in blue after the specific comment. Our page references refer to the corrected version of the paper.

Summary of the manuscript

The study titled “Classification of Arctic multilayer clouds using radiosonde and radar data” by Maiken Vassel et al. describes an algorithm for the classification of multi-layer cloud occurrence for a one year dataset in Ny Alesund, Svalbard based on radiosonde and vertically-pointing cloud radar observations. The classification is two-fold: Firstly, only the conditions for cloud occurrence based on radiosonde humidity profiles consisting of two supersaturated layers separated by a subsaturated layer are analyzed. The fall distance of a hexagonal ice crystal of 100 micron size before complete evaporation in the subsaturated layer are estimated. The subsaturated layers are then classified into two categories. The first category is called “seeding”, referring to layers with a vertical extent lower than the fall distance before complete ice crystal sublimation. The second category is called “non-seeding”, referring to layers with a vertical extent higher than the fall distance before complete before complete ice crystal sublimation. These maximum possible occurrence frequencies for multi-layer cloud occurrence based on supersaturated layers as identified by radiosonde ascents are then verified by cloud radar reflectivity profiles obtained within 30min before radiosonde launch and 30min after the radiosonde has reached 10 km altitude. Multilayer mixed-phase cloud occurrence was found in 29% of the cases based on the combined radiosonde-cloud radar estimation. One of the main finding of the paper is that about 50% of the multilayer clouds estimated solely from radiosonde humidity profiles are not classified as such by the radar. - But the conclusion that radiosounding data is not sufficient for multi-layer cloud occurrence classification since not only humidity but also concentrations of ice nucleating particle (INP) and cloud condensation nuclei (CCN) are crucial is not made.

We added an explanation of the missing overlap of radiosonde and radar data on page 11 by referring to Spichtinger et al. (2002):“ In the ice-supersaturated layers above and below missing cloud formation can be explained by the lack of aerosol as INP (Spichtinger et al., 2002)”. Also in the conclusions we refer to this problem. Here we reworded the sentence to: “A high amount of supersaturated layers found in the radiosonde profiles does not coincide with observed cloud occurrence, probably due to lack of INP and thereby missing cloud formation” (page 17).

I would suggest the manuscript to be published after major revisions. The authors should address the following points:

Major comments:

The literature review in the introduction should be extended. For example: p.1 line 20: Some more recent publications on Arctic mixed-phase cloud properties should also be included, for example Shupe 2011 (DOI: 10.1175/2010JAMC2468.1). In this paper. e.g., the occurrence of mixed-phase clouds at Arctic sites was found up to altitudes of 7-8 km.

Thanks for the comment. We have corrected this and added the suggested reference.

p.2 line 18: Please give a broader and more detailed introduction on seeder-feeder mechanism and why it is important to consider it in the Arctic. Also, be more specific in which way the ice crystals falling from the upper cloud "influence" the lower cloud. Since this is a central question of this study, it has to be properly introduced. The points made in various parts of the manuscript (especially Section 2.3) need to be more precise instead of using colloquial expressions like "surviving" ice crystals etc. (e.g., also: p.6 line 24-29; p. 10 line 1-16, p.11, line 29-30, p.16 lines 18-20, etc.: very colloquial language).

We have added a more detailed description about the possible outcomes of the seeder-feeder mechanism (page 2, line 17 onwards). Regarding the use of the term *survive*, we have now defined it on p.4, l.21 and use it further on. In some passages we have exchanged *surviving* with *not fully sublimated* (e.g. section 2.3).

p.6 line 24-29: We have moved the sentence about the detection limit to the section 2.1.:"The detection limit is -19.47 dBZ at 223 m, -57.31 dBZ at 423 m and -28.61 dBZ at 10 km".

p. 10 line 1-16: We have reworded the passage to: "For the seeding cases the cloud categories are shown in Fig. 8..." (p.10, l.21 - p.11, l.15).

p.11, line 29-30: We have changed it to: "A discontinuous radar signal only existing of small shreds of clouds is not counted as cloud and a continuous radar signal containing some small cloud free holes is counted as cloud."

p.16 lines 18-20: We have changed it to: "Following from our sublimation calculation we find that MLCs, which are clearly (visibly) separated in the radar, do not interact through seeding. However, we have to keep uncertainties like the radar detection limit in mind."

p.4 line 1-14: Please include a conceptual sketch of which kind of cloud layers you are considering indicating minimum depth of the layers, minimum vertical spacing between two supersaturated layers with a subsaturated layer between, temperature restrictions... otherwise it is really hard to follow.

On p.6 we have added a conceptual sketch of how we consider the radiosonde and radar data for potential MLCs.

p.4: It is mentioned that a simplified approach is used to determine the capacitance for a hexagonal plate. (By how much) does the capacitance differ for different ice crystal shape assumptions (columns/dendrites/quasi-spherical spheres)? Also, why do you use a radius-volume relation of a sphere (p.5) if you consider hexagonal plates? As e.g. shown by Mitchell, JAS 1996, ice particle fall speed is a strong function of ice particle shape and density. Only assuming one particular ice crystal shape (hexagonal plates) is not sufficient for the fall distance estimation. Sublimation calculations should at least be repeated for two other ice particle shapes with very different fall speed characteristics such as columns and dendrites which would lead to very different fall distances. Additionally, please mention the influence of up- and downdrafts on ice particle fall velocity and thus fall distance.

The first reviewer also commented on the ice crystal shape. We agree with you that the ice crystal shape should not be treated as a sphere. We changed the calculation and the text accordingly (p.4 and p.6). We have selected the four ice crystal shapes hexagonal plate, rimed particle, stellar and irregular particle which are representative for mixed-phase clouds (Mioche et al., 2016). For these particles we use the fall speed calculation shown in Fig. 1 and given by Mitchell (1996). We selected the particles to be realistic for both mixed-phase clouds and cirrus clouds. Additionally we chose the four shapes where the falls speeds varies the most. The main focus in the paper is on the hexagonal plate. The results for the other shapes is presented in the Appendix. We do not account for the lower limit of ice crystal size given by Mitchell (1996), since in our calculation we have to calculate the speed also for very small ice crystals due to sublimation. Note that this might lead to a small error of too fast falling small ice crystals.

We also corrected the capacitance. We are now using the calculation of Westbrook et al. (2008). The cases selected are listed on p.19 in the paper, as well as the aspect ratios chosen by us. In the last column the calculated capacitances for $r = 400$ μm are shown. For the selected ice particle shapes the values range between $C = 2.00 \times 10^{-4}$ to $C = 3.88 \times 10^{-4}$. Earlier we used a capacitance of $C = 2.55 \times 10^{-4}$ for $r = 400$ μm.

We added a sentence pointing to the uncertainty due to the missing consideration of the up- and downdrafts.

In Fig. 2 we present the impact of the different ice crystal shapes on the result of classification step 2. As mentioned in the paper, for classification step 1 there is a small impact, but for classification step 2 there is almost no impact of the ice crystal shape on the result (p.10, l.4 and p.12, l.14-15).

p.6 line 24-29: Very colloquial language describing the radar reflectivity above the detection limit (p.6) - please rephrase. Please describe you averaging more in detail: I assume you refer to temporal averaging at each altitude? Please include a third Panel in Fig.2 showing the radar reflectivity sensitivity profile and the averaged reflectivity of the example case (for 50% data points within the considered time span).

We have reworded it in the text to "If more than 50 % of the selected radar data contain radar reflectivity factor data (coloured in Fig. 3b), then it is defined as cloud by the algorithm" (p.8,l.6 onwards). We consider a box with 100 m height (see dashed boxes

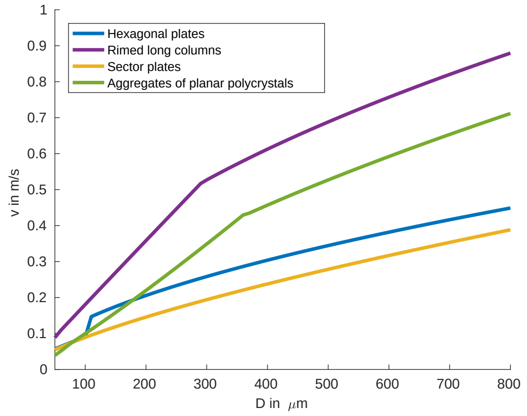

Figure 1: Ice crystal fall speed in dependence of particle size (Mitchell, 1996)

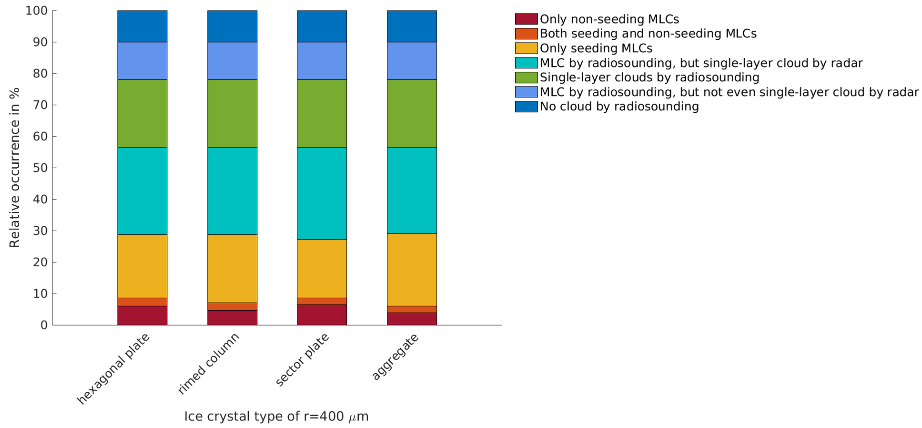

Figure 2: Classification step 2 using different ice crystal shapes with $r = 400$ μm.

in Fig. 2 in the paper) and within this box we do not average but evaluate if more than 50% of the pixels contain radar reflectivity data. In Fig. 3 we show the radar sensitivity and the averaged reflectivity for each layer for the 3 November 2016. The measured reflectivity is above the radar sensitivity limit. On p.3 we added the sentence: "The detection limit is -19.47 dBZ at 223 m, -57.31 dBZ at 423 m and -28.61 dBZ at 10 km, and the evaluated values are about these limits.“

p.8: I haven't seen a definition for a cloud case – how long of a gap in time is needed to refer to a scene having two separate clouds at one altitude– one radar profile (30s?) or a few minutes? Or is this not considered at all and averaging over time around RS launch is done in a way that separate cloud occurrences at one height are averaged into "one"?

Two clouds at one altitude are not considered separately. The evaluation over time is

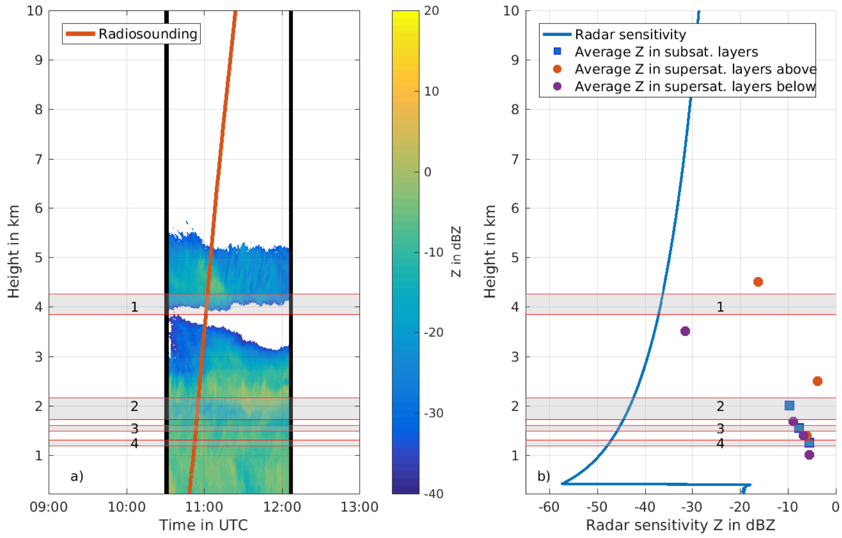

Figure 3: a) Radar reflectivity factor, b) Radar sensitivity: Minimum detectable radar reflectivity as a function of height. It includes the effect of ground clutter and gas attenuation but not liquid attenuation. The averaged reflectivity is shown for each layer.

done so that separate clouds at the same altitude are considered as one cloud within this timespan (±30 min).

p.10 lines 1-4: I do not fully agree with your conclusion that no cloud return in the radar data always means cloud-free conditions. There could be situations in which the sensitivity of the radar is not high enough (LWC and IWC too low). – I thus strongly suggest to also use available profiling lidar data (ceilometer) instead of only radar data to check for cloud occurrence in supersaturated conditions. Although the ceilometer suffers from full attenuation at sufficiently optically thick clouds, it will likely increase the number of detected cloud occurrences from ground-based remote sensing observations.

On p.11 we added the sentence: "Indeed, a very low liquid and ice water content could also result in a value below the radar sensitivity limit explaining these cases."

From 10.6.2016 onwards radar data was recorded in Ny-Ålesund and therefore we started our time period on this date. We would have liked to include micro-pulse lidar data as provided by `https://mplnet.gsfc.nasa.gov/data?v=V2&s=Ny_Alesund&t=20160616`, but this record ended at 16.06.2016. In Fig. 4b) we show the ceilometer attenuated backscatter coefficient for the 3 November 2016. It gives us the lowest cloud base height, but not any information on the additional cloud base heights above.

Moreover, in the Arctic frequently clouds occur at very low altitudes which might sometimes be below the lowest radar/lidar range gate. On page 16 (line 15-16) you mention

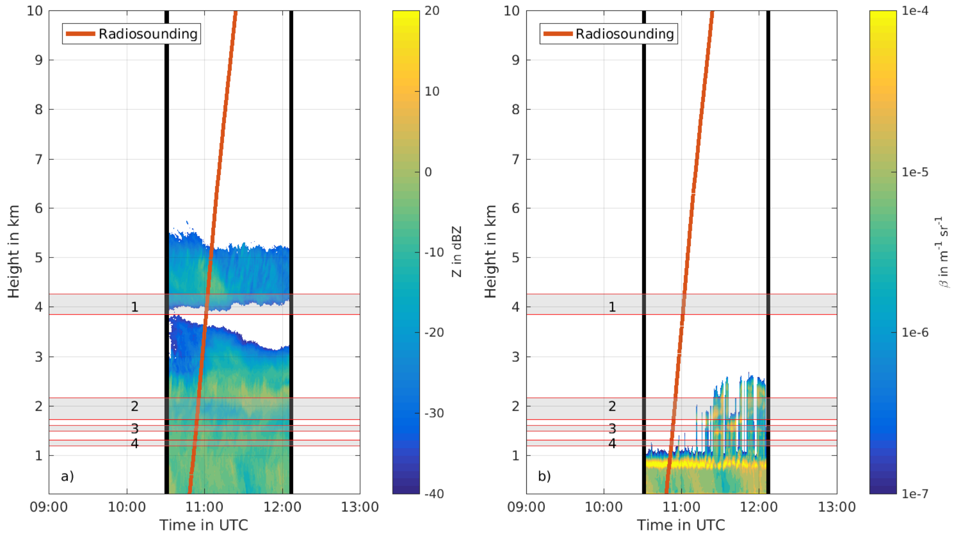

Figure 4: a) Radar reflectivity factor, b) Attenuated backscatter coefficient measured by Vaisala 910-nm CL51 lidar ceilometer in Ny-Ålesund

that a lidar would be useful. I strongly suggest making use of the existing ceilometer data (https://www.awipev.eu/awipev-observatories/cloud-cover/) in your study.

In the comment before we explained the problems when including the ceilometer. You are right, it is possible that we miss cloud layers existing only below 223 m. On p.3 we have added: "The detection height extend from 223 m until 10 km." and on p.11 we have added: "Additionally, the minimum detection height of 223 m might lead to some cases not considered." in order to point out that we might miss some cases. However, we have looked through this lowest layer in the relative humidity measurements and we do not think that there are many cases we miss.

Minor comments:

We have added all the following minor corrections.

Title: I suggest adding "in Svalbard" to narrow down the geographical range of the study. Also, since you are only considering $T < 0°C$, you can add "cold" clouds in the title.

The new title is now: "Classification of Arctic multilayer clouds using radiosonde and radar data in Svalbard". We have added "in Svalbard" but we did not add "cold". We do not find this specification necessary. There is almost no case of MLC that we miss due to the temperature restriction < 0°C.

p.4: For all variables in the equations the units should be included.

p.1 Line 10-13: It is unclear which kind of "deviations" you refer to – please specify more in detail.

We have changed the sentence to the following: "Since there are various deviations between the relative humidity profiles and the radar images, e.g. due to horizontal wind drift and time restriction, an evaluation by manual visual inspection is additionally done for the non-seeding cases."

p.1 line 16: it should be "improve" instead of "improved"

p.1 line 16: hydrometeor shape and density (and thus terminal fall velocity) are of great importance, too.

p.1 line 21: You could add that the typical structure of stratiform mixed-phase cloud with supercooled liquid top layer and precipitating ice points to heteorogeneous ice formation processes (add citation).

p.1 line 21: rather from the "remote sensing point of view"

p.1 line 22ff: "variable lidar signals inside a more or less continuous radar signal" sounds very imprecise – please rephrase and refer to "cloud profiles obtained with vertically-pointing instruments" or sth. similar

We have changed the sentence to:"From the remote sensing point of view, Verlinde et al. (2007, 2013) obtained cloud profiles with vertically-pointing instruments and described multilayered clouds as multiple distinct liquid layers within one vertical extensive cloud."

p.1 line 24: make it easier for the reader and put multilayered vs. multilayer in Italics or bold font

p.1 line 24: In which measurement is the interstice of multilayer clouds visible – in profiles of radar or lidar or both?

In both lidar and radar measurements the interstice of multilayer clouds could be visible. However, since the lidar is usually not able to penetrate the lower cloud layer, we focus here on radar measurements.

p.2 line 2: I suppose, you mean "at least" two clouds in different heights since there can be very low boundary layer clouds, midlevel clouds, and high-level clouds occurring simultaneously

p.2 line 20: Please modify the sentence since you look at one specific Arctic site (... occur at Ny Alesund not "the Arctic")

p.2 line 20: Why "thereby"?

We exchanged "Thereby we include..." with "We include..."

p.2 line 22: it should be "ground-based remote sensing" measurements

p.2 line 23: What do you mean by "easily accessible"?

Ground-based measurements are rare in the Arctic. Field campaigns are only limited to a short time period. Radiosondings have the great advantage, that they are conducted all year around, each day and at multiple places all over the Arctic. In order to construct a classification, data availability over a full year is a great advantage. To compare various Arctic sites, the same type of measurement (radiosonde) is favourable.

p.2 line 25: be more precise in your wording: Instead of “radar” it should be profiling/zenith-pointing Doppler cloud radar

p.3 line 20: Please give a rough estimate of horizontal drift of the sondes based on their GPS tracking.

The first reviewer commented this as well. We present the same correction to both of you: In order to account for the horizontal drift, we calculate the wind speed in each layer. Using this information together with the distance between the radiosonde and the radar, we calculate the time at which the air parcel measured by the radiosonde was at the position of the radar. For this we do not consider the wind direction, but assume that the air parcel drifts the same direction as the radiosonde. As an example we show the results of the calculation for 3 November 2016 (Fig. 5). For the 3 November 2016 the average time over all heights is 12.94 min. For our statistics we add the average time for each day to the time chosen for the evaluation of the radar data. For the 3 November 2016 the resulting radar time period is shown in Fig. 6.

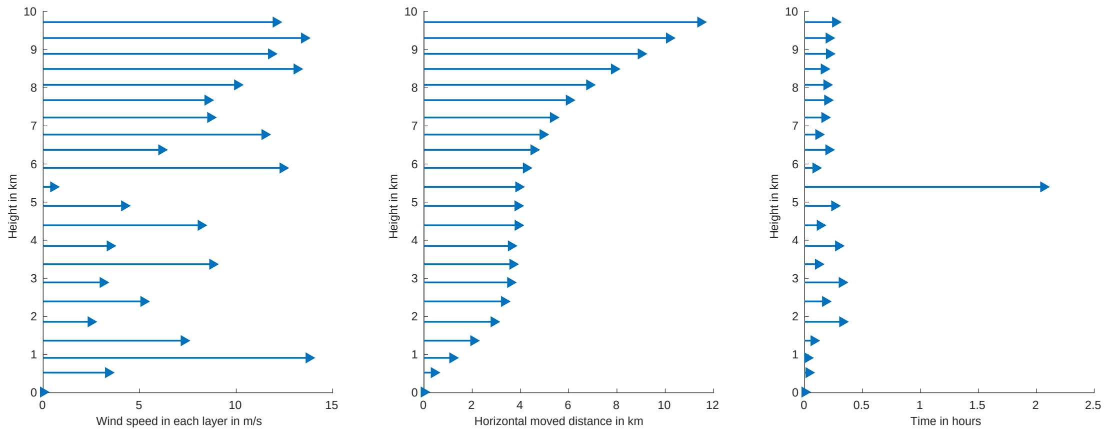

Figure 5: Advection on 3 November 2016: a) windspeed in each height layer, b)distance between radar and radiosonde, c) time the air parcel needs to drift from the radar to the position of the radiosonde.

p.3 line 23: Please also indicate the lowest radar range gate and mention that the cloud Doppler radar is zenith-pointing. You mention a vertical radar range gate resolution of 20m, is it really the same at all altitudes (i.e., all chirps) and was the RPG radar really operated in the same mode (with the same vertical and temporal resolution) over the entire year? 30s temporal resolution seems very low – please verify this temporal resolution... or are you using data already averaged to Cloudnet temporal resolution?

You are right, we use data already averaged to Cloudnet resolution. That is why our

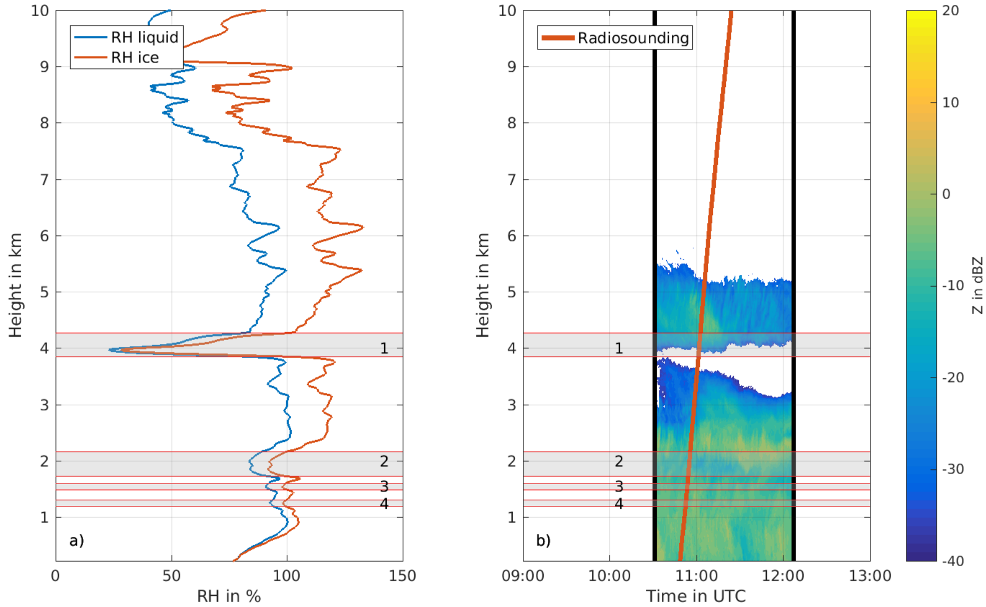

Figure 6: a) Radiosonde data, b) radar time period corrected due to advection. At the time when the radiosonde reached the supersaturated layer 1 at 3.85 km the radiosonde is 3.70 km away from the radar due to horizontal wind drift.

data has a vertical resolution of 20 m at all heights and a temporal resolution of 30 s. The lowest range gate provided in our data set is 223 m. We have highlighted in the text that we use the averaged data. The original resolutions are different: The radar was operated in the high resolution mode. Here the vertical resolution varies from 4 m at 100 m height to 17 m at 10 km. The lowest range gate measured by the radar is 100 m. The temporal resolution is continuously 2.5 s.

p.3 line 25: Please indicate typical values of attenuation correction for the 94GHz radar at Ny Alesund.

Typical values of two-way radar attenuation due to atmospheric gases are between 0.09 dB at 223 m height and 1.20 dB at 10 km height (Fig. 7).

p.3 line 25: What do you mean by “at all frequencies”?

We have deleted “by all frequencies”. It was formulated in this way as calibration convention in the data description, but for this specific radar there is only one frequency.

p.6 line 4: ice crystal size r refers to maximum dimension? Motivate the choices of ice crystal size of 50/100/150 microns by citing typical values found in Arctic clouds.

Already the first reviewer commented this. We present the same correction and answer to both of you: This is a valid comment, and we have revised the calculations taking into account larger crystal sizes. The upper cloud of a MLC, from where the falling ice crystals origin, can either be a mixed-phase cloud or a cirrus cloud. In mixed-phase

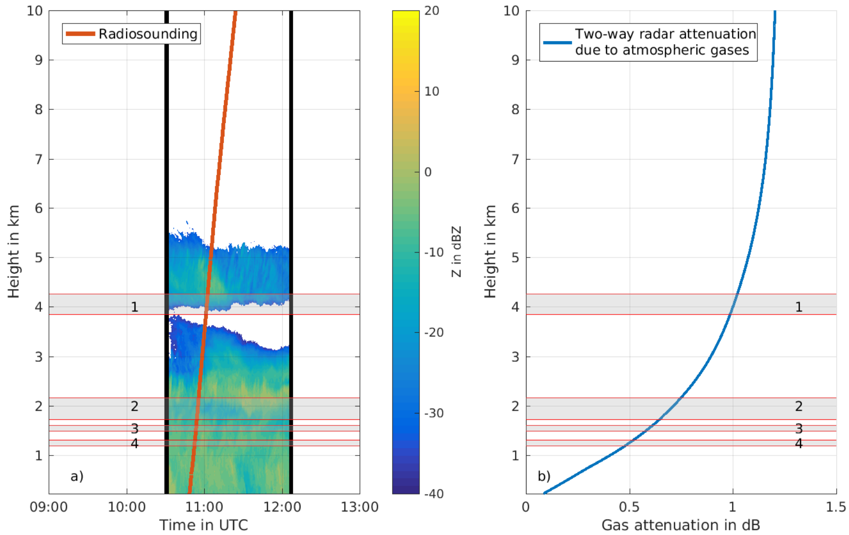

Figure 7: a) Radar reflectivity factor, b) Two-way radar attenuation due to atmospheric gases used for correcting Z.

clouds Korolev et al. (1999) measured ice crystals with radii of about r =400 μm. We also refer to Fig. 5e in Mioche et al. (2016), where a radius of r =400 - 500 μm can occur in mixed-phase clouds. For cirrus clouds Krämer et al. (2009) showed that the radii of ice crystals range between r =1 - 100 μm. In order to account for both cloud types, we have redone our calculations for the ice crystal sizes r =100, 200 and 400 μm. Our main focus is now on r =400 μm, assuming in most cases the upper cloud to be mixed-phase. With r we refer to the maximum dimension, $r = D_{\mathrm{max}}/2$.

p.6 line 4: It is unclear what you mean by "mean conditions": Mean over one hour after radiosonde launch?

By mean conditions we mean the average of the variable (pressure, temperature, humidity) over the height levels of the specific subsaturated layer.

p.6 line 5: "survive" is very colloquial, please replace or describe what you mean. Please change accordingly throughout the text.

We have now defined seeding on p.4, l.20 and use it therefore in the following text. In some passages we have exchanged *surviving* with *not fully sublimated* (e.g. p.6 l.11).

p.6 line 17: The way it is presented it sounds like as if the radar is used to test for cloud occurrence (above/between/below) in general and not only for cloud occurrence in general (Also see Table 1). (?)

We have corrected the sentence to: "The aim of adding radar data to the classification is to cross-check the super- and subsaturated layers in the radiosonde profiles with actual cloud occurrence."

p.6 line 19-20: Clarify why you use 30min after the radiosonde reached 10km as end time and not e.g. simply a one hour time around RS launch (start 30min before and end 30min after launch)?

If we simply use a one hour time slot around the radiosonde launch start, we have cases (30.6.16) where in the height levels above 8 km the averaging of the radar data ends before the launched radiosonde reaches this height level. In order to avoid this we use + 30min after the radiosonde reached 10km as end time.

p.6 line 29-30: "Evaluated" in which way?

We have changed it to: "For the *subsaturated layer in between* only the lowermost 100 m are analysed in order to address the question if the ice crystal survives so far."

p.6 line 31: 50% of what? Of all pixel within a 100m x time from RS launch to 30min after RS end? Or 50% of pixel at a certain altitude?

We mean the 50% data points in the area of 100 m x time from RS launch (- 30min + advection time) to RS end (+ 30min + advection time).

p.6 line 34: Specify that the ice crystal is actually growing in the supersaturated layer and which microphysical growth processes could occur and specify in which way the ice crystal can "influence" the cloud.

We have changed it to: "The ice crystal begins to grow and can influence a cloud no matter at which height it is within the supersaturated layer." Further details on the influence of additional ice crystals on the cloud is mentioned when explaining the seeder-feeder effect (p.2,l.16-26).

p.7 line 12 -13: Why do you refer to seeding situations here when you describe non-seeding situations in line 10-11?

We have resorted and reformulated the sentences. We want to point out which two cloud categories we have chosen to be MLC cases (one non-seeding and one seeding case).

p.9 line 8-10: Describe the influence of varying ice crystal size more in detail: 57% of possible seeding for 150micron ice particle size and only 37% for 50micron...

We reworded it at p.10, l.6-l.12.

p.9 line 11: Please expand your discussion of Figure 5. In number indicate the number of cases considered for each month (February maybe has a much lower number of cases?).

We have added the number of cases (days) to Fig 5. You are right, during February there are less analysed days. This is due to the lack of radar data during this month. We reworded and expanded section 3.1.

p.10 line 2: Define acronym IN(P)

We already defined INP on page 2.

p.16 line 2: vertically-pointing cloud Doppler radar (instead of only “radar”)

References

Korolev, A., Isaac, G., and Hallett, J.: Ice particle habits in Arctic clouds, Geophysical research letters, 26, 1299–1302, 1999.

Krämer, M., Schiller, C., Afchine, A., Bauer, R., Gensch, I., Mangold, A., Schlicht, S., Spelten, N., Sitnikov, N., Borrmann, S., et al.: Ice supersaturations and cirrus cloud crystal numbers, Atmospheric Chemistry and Physics, 9, 3505–3522, 2009.

Mioche, G., Jourdan, O., Delanoë, J., Gourbeyre, C., Febvre, G., Dupuy, R., Monier, M., Szczap, F., Schwarzenboeck, A., and Gayet, J.-F.: Vertical distribution of microphysical properties of Arctic springtime low-level mixed-phase clouds over the Greenland and Norwegian seas, Atmospheric Chemistry and Physics, 17, 12 845–12 869, 2016.

Mitchell, D. L.: Use of mass-and area-dimensional power laws for determining precipitation particle terminal velocities, Journal of the atmospheric sciences, 53, 1710–1723, 1996.

Spichtinger, P., Gierens, K., and Read, W.: The statistical distribution law of relative humidity in the global tropopause region, Meteorologische Zeitschrift, 11, 83–88, 2002.

Westbrook, C. D., Hogan, R. J., and Illingworth, A. J.: The capacitance of pristine ice crystals and aggregate snowflakes, Journal of the Atmospheric Sciences, 65, 206–219, 2008.