Author Response to Reviews of

How frequent is natural cloud seeding over Switzerland?

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Atmospheric Chemistry and Physics, doi:10.5194/acp-2020-1145

RC: ***Reviewer Comment***, AR: *Author Response*, ☐ Manuscript text

We sincerely thank the reviewers for their thoughtful and constructive feedback. We implemented their feedback into a revised version of the manuscript. Please find our answer to the reviewers' points below, followed by a marked-up manuscript verison.

1. Reviewer Comment #1

RC: ***This study develops a method to investigate occurrence frequencies of natural cloud seeding based on DARDAR satellite products. The region of Switzerland is used here as an example, but it is emphasized that the method can be applied to other areas as well. Two seeding cases are separated in the study, the first represent cirrus above other clouds with the $-35\,^{\circ}\mathrm{C}$ isotherm in between, while in the second the cirrus are part of thicker clouds with the $-35\,^{\circ}\mathrm{C}$ isotherm inside. Topographical, day/night and seasonal variations of the frequencies of seeding situations are analyzed. Further, sublimation calculations for the seeder ice crystals are performed showing the part that do not sublimate before reaching the lower feeder cloud. In addition, a method to identify in-situ and liquid origin cirrus clouds based on the DARDAR mean effective ice particle size is presented. The topic of the paper is well suited for ACP and also is of high scientific interest. The methods used are scientifically sound and the results are robust and provide new insights into the field. Thus I recommend the paper for publication in ACP with minor changes. Below you find a number of comments/recommendations to consider for the final version of the paper.***

AR: *Thank you for your clear and detailed feedback. Please find our respective answers directly below your comments below.*

1.1. Figure 1 (and elsewhere in the text)

RC: ***I guess that the indices ‚i‘ and ‚l‘ in Δz_{il} mean ‚ice‘ and ‚liquid‘. To my opinion it would be more consistent to change the ‚l‘ to ‚m‘, because the corresponding clouds are termed mixed-phase clouds and could be ice, liquid or mixed.***

AR: *We agree and changed Δz_{il} to Δz_{im} everywhere for consistency.*

1.2. Page 2, line 50 ff

RC: ***You might take into account to add Wolf et al. (2018), ACP, to the listed references (here and later). They sorted ice particle shapes and size distributions according to liquid and in-situ origin cirrus clouds.***
Wolf, V., Kuhn, T., Milz, M., Voelger, P., Krämer, M., and Rolf, C.: Arctic ice clouds over northern Sweden: microphysical properties studied with the Balloon-borne Ice Cloud particle Imager B-ICI, Atmos. Chem. Phys., 18, 17371–17386, https://doi.org/10.5194/acp-18-17371-2018, 2018.

AR: *We added this reference in line 51, 52, 273, and 389 of the original manuscript version.*

1.3. Page 2, lines 54

RC: ***, ... ice can only be formed via heterogeneous nucleation on ice nucleating particles (Kanji et al., 2017).' I suggest to change this to , ... ice can only be formed via heterogeneous nucleation on ice nucleating particles (e.g. Kanji et al., 2017, and references therein).' because this has been known for a long time and Kanji et al. is a recent overview paper.***

AR: *You are right. We changed this as you suggested:*

> Seeding ice crystals can have a large influence on cloud properties, because in the atmosphere, at temperatures warmer than −38 °C, ice can only be formed via heterogeneous nucleation on ice nucleating particles ~~(Kanji et al., 2017).~~ (e.g. Kanji et al. (2017), and references therein).

1.4. Page 2, line 56 ff

RC: ***, ... the Wegener-Bergeron-Findeisen process, where ice crystals grow at the expense of liquid droplets, when the saturation ratio is between saturation with respect to water and ice ...' The WBF process is where the water vapor saturation ratio is between subsaturation with respect to water and supersaturation with respect to ice (Sw < 1 and Si > 1).***

AR: *We changed the wording as follows to make the required conditions more clear:*

> *Once ice particles are formed within the cloud or enter the cloud from outside, they grow by riming or vapour deposition (rapidly via the Wegener-Bergeron-Findeisen process, where ice crystals grow at the expense of liquid droplets, when the water vapor saturation ratio is ~~between saturation~~ subsaturated with respect to water and supersaturated with respect to ice (Wegener, 1911; Bergeron, 1935; Findeisen, 1938)) . . .*

1.5. Page 3, line 58 ff

RC: ***You might consider to add the recent article of Korolev and Leisner (2020), ACP, to the references of secondary ice production:***
Korolev, A. and Leisner, T.: Review of experimental studies of secondary ice production, Atmos. Chem. Phys., 20, 11767–11797, https://doi.org/10.5194/acp-20-11767-2020, 2020.

AR: *Thank you for pointing us to that work. We added a reference as follows:*

> *. . . and can multiply through secondary ice production (Korolev and Leisner (2020), Hallett-Mossop process (Hallett and Mossop, 1974; Mossop and Hallett, 1974; Mossop and Hallett, 1974), frozen droplet shattering (Lauber et al., 2018), or ice-ice collisional breakup (Sullivan et al., 2018)).*

1.6. Page 5, line 101 ff

RC: ***,The two satellites are designed for their data to be combined: the lidar on CALIPSO is able to identify the thin upper layers of cirrus clouds that the radar on CloudSat misses (Winker et al., 2010), while the***

latter is able to look through thick clouds where the lidar beam is attenuated.‘ You mention the lidar (thin) and radar (thick) clouds, but where/what kind are the clouds from the visible camera and a three-channel infrared radiometer noted before? If all instruments are combined, does the DARDAR product cover the whole range of clouds or are the thinnest/thickest missed ? Can you give an estimate here on the percentage of missed clouds ? This might be important in the especially for thin cirrus, yes ?

AR: *The visible camera and the three-channel infrared radiometer are mentioned here to complete the list of instruments onboard CALIPSO. DARDAR-cloud only uses the radar data from CloudSat and the lidar data from CAlIPSO. Delanoë and Hogan (2010b) also discuss the possibility to combine the radar and lidar data with infrared radiometer data from the A-train satellite MODIS, but this product (DARDAR-rad-cloud) is not available yet.*

> *The ~~DARDAR~~ DARDAR-CLOUD satellite data product used in this study is based on radar ~~, lidar and infrared radiometer~~ and lidar data from the CloudSat and CALIPSO satellites.*

Radar is less sensitive to small particles, while lidar suffers from attenuation Delanoë and Hogan (2010b). DARDAR CLOUD retrieves clouds detected by both or just one of the instruments. Krämer et al. (2020) mention "a decreasing detectability of thin cirrus at $T \leq 190\,\mathrm{K}$" in the DARDAR-N_{ice} climatology. Also, CloudSat and CALIPSO have been found to miss clouds near the surface, within the lowest $1\,\mathrm{km}$ (e.g. Chan and Comiso (2011) and Liu et al. (2015)). However, these clouds are not relevant for this study, because Krämer et al. (2020) discuss tropical clouds and therefore their Δz_{il} is too large. We added this statement to the manuscript:

> *Cirrus clouds in the tropical tropopause layer and clouds close to the surface are known to be missed by the radar and lidar on CloudSat and CALIPSO (Chan and Comiso, 2011; Liu et al., 2015; Krämer et al., 2020), but these are not relevant for this study.*

1.7. Page 5, line 119-120

RC: ***‚... DARDAR categories 1, 2, 3 and 4 (ice, ice + supercooled, liquid>$-35\,°\mathrm{C}$ and supercooled) ...‘ These are only 3 categories, liquid > $-35\,°\mathrm{C}$ and supercooled are the same.***

AR: *You are correct. The DARDAR cloud product specifies the four categories 1, 2, 3 and 4 as ice, ice + supercooled, liquid warm and supercooled (Delanoë and Hogan, 2010a). The disctinction between the two latter categories is not solely based on temperature, but also on pressure and humidity as explained in Delanoë and Hogan (2010b).*

> All variables were derived from a cloud mask, where the DARDAR categories 1, 2, 3 and 4 (ice, ice + supercooled, liquid ~~> −35 °C~~ (warm and supercooled)) were combined to simply signify the presence of cloud layers.

1.8. Page 6, line 124-126

RC: ***‚... liquid cloud droplets have been found to supercool to $-35\,°\mathrm{C}$ before freezing homogeneously (Murray et al., 2010; Herbert et al., 2015). The temperature for homogeneous freezing of water droplets is also***

often given as $-38\,°C$ ***(Kanji et al., 2017).' There are earlier references for the existence of supercooled drops and also for the temperature of homogeneous drop freezing ... e.g. Pruppacher & Klett ?***

AR: *We agree and changed this as you suggested:*

> In this study, cirrus clouds are defined as clouds at temperatures lower than $-35\,°C$, and mixed-phase clouds are defined as all clouds ~~at~~ with temperatures warmer than $-35\,°C$. ~~This is because~~ Depending on their size, liquid cloud droplets ~~have been found to~~ supercool to $-35\,°C$ to $-40\,°C$ before freezing homogeneously ~~(Murray et al., 2010; Herbert et al., 2015).The temperature for homogeneous freezing of water droplets is also often given as (Kanji et al., 2017).~~ (e.g. Pruppacher and Klett (2010), Murray et al. (2010), Herbert et al. (2015), and Kanji et al. (2017)).

1.9. Page 7, line 130

RC: ***,... air density, air temperature and the relative humidity determine the ice crystal sublimation rate and fall velocity.' Aren't the the ice crystal size and the vertical velocity of the air also important for the fall velocity? In line 143 you metion that you use reff...***

AR: *We have changed the wording here to indicate that the environmental parameters are only a part of what determines the sublimation rate and fall velocity:*

> *Environmental parameters such as the air density, air temperature and the relative humidity ~~determine~~ also affect the ice crystal sublimation rate and fall velocity.*

1.10. Page 7, line 141-142

RC: ***,Relative humidity and temperature were therefore taken from ERA5 reanalysis data...' What about the quality of ERA5 RH in the cirrus temperature range? Isn't there a dry bias ?***

AR: *We are not aware of a dry bias in ERA5. Hoffmann et al. (2019) mention a stratospheric dry bias in ERA interim that was reduced for ERA5, which is not relevant for this study. Earlier ECMWF reanalysises have been found to have mid tropospheric dry bias, at least in the tropics (Lohmann et al., 1995), but since we found no other mention of this dry bias for ERA5, we have reason to believe that it is outdated.*

1.11. Page 9, a) line 190-196

RC: ***The percentages stated here, the numbers in the caption of Figure 3 and the graphs shown in Figure 3 b seems not to be consistent. Maybe I misunderstand something, but then it would be good to better explain.***

AR: *Thank you for noticing this mistake! Indeed, the total number of measurements is 853833, with 267354 measuring* Δz_{im} *and 355331 measuring cirrus clouds. The corresponding line in the caption now reads as follows:*

> *The total number of measurements is ~~1440312~~853833, with ~~853833~~ 267354 measuring ~~Δz_{il}~~ Δz_{im} and 355331 measuring cirrus clouds.*

Consequently, the corresponding percentages change to:

> *~~32~~31 % of the measurements contain both a cirrus and a mixed-phase cloud simultaneously. ... Tailoring this result to the sedimentation of ice crystals from a cirrus cloud, ~~77~~75 % of the measurements that detect a cirrus cloud also detect a lower mixed-phase cloud.*

1.12. line 197

RC: ***‚In 56 % of these cases (18 % in total), Δz_{il} is smaller than $100\,\mathrm{m}$.‘ Shouldn‘t these numbers be visible in Figure 3 b (see also previous comment) ? I see the 18 % for cloud free conditions, but the percentage of cirrus clouds with Δz_{il} smaller than $100\,\mathrm{m}$ is $\approx$ 41 %, not 56 % ?***

AR: *This also is a mistake. 44% is the correct fraction of Δz_{il} smaller than $100\,\mathrm{m}$ in cases with cirrus clouds present (instead of 56%). The text was corrected as follows:*

> *In ~~56 % of these cases~~ 44 % of the cases with a detected cirrus cloud (18 % in total), ~~Δz_{il}~~ Δz_{im} is smaller than $100\,\mathrm{m}$.*

1.13. Page 11, line 219

RC: ***‚Our results for multi-layer cloud occurrence frequency are similar to but smaller than the ones given in the literature.‘ ‚Similar to but smaller than‘ is hardly possible ... Also, for convenience for the reader, please repeat the number of ‚our results for multi-layer cloud occurrence frequency‘ so that there is a directly comparison of the numbers in the text.***

AR: *We agree with your propositions and incorporated them as follows:*

> *Our results for multi-layer cloud occurrence frequency~~are similar to but~~, 13 % ($\Delta z_{\mathrm{im}} > 100\,\mathrm{m}$), are smaller than the ones given in the following literature.*

1.14. Table 3

RC: ***The sum of the first two numbers in the first row (18 + 13 = 31 %, all seasons, all day, whole domain) should be the same as stated on page 9, line 194, yes ? ‚32 % of the measurements contain both a cirrus and a mixed-phase cloud simultaneously.‘ This number could be repeated for the convenice of the readers.***

AR: *With the changes applied in comment 1.11 the two statements agree now.*
Also, we added a sentence reminding the reader of the total fraction of Δz_{im} to the table caption.

> ~~Δz_{il}~~ *In total, 31 % of the measurements contain both a cirrus and a mixed-phase cloud. Δz_{im} up to $12\,\mathrm{km}$ in length were evaluated.*

1.15. Page 11, line 248

RC: ***‚Table 3 also contains the results of a climatological analysis of Δz_{il}.‘ I recommend to say ‚seasonal‘ instaed of ‚climatological‘.***

AR: *We agree and changed this accordingly in the text and in the table.*

Table 3 also contains the results of ~~a climatological analysis of Δz_{il}~~the seasonal analysis of Δz_{im}.

1.16. Page 11, line 249

RC: ***‚The relative increase is similar ...‘ More clear is: The relative increase of the fractions of Δz_{il} is similar ...***

AR: *We agree and changed this accordingly.*

The relative increase of the fractions of Δz_{im} is similar for the smaller (~~$\Delta z_{il} < 100$ m~~$\Delta z_{im} \leq 100$ m) and the larger distances (~~$\Delta z_{il} > 100$ m~~$\Delta z_{im} > 100$ m).

1.17. Page 12, line 250-252

RC: ***There is no noticeable difference in frequencies during day and night.‘ There are noticeable differences between day and night (winter), and also differences between the summer and winter days and nights. Please clarify.***

AR: *We changed this statement to be more specific as follows:*

~~There is no noticeable difference in frequencies during~~ Other than the increase in Δz_{im} during night in winter, there are no substantial differences in frequencies between day and night within a seasonal category.

1.18. Page 12, line 266

RC: ***You might cite here also Krämer et al. (2000), ACP. Krämer, M., Rolf, C., Spelten, N., Afchine, A., Fahey, D., Jensen, E., Khaykin, S., Kuhn, T., Lawson, P., Lykov, A., Pan, L. L., Riese, M., Rollins, A., Stroh, F., Thornberry, T., Wolf, V., Woods, S., Spichtinger, P., Quaas, J., and Sourdeval, O.: A microphysics guide to cirrus – Part 2: Climatologies of clouds and humidity from observations, Atmos. Chem. Phys., 20, 12569–12608, https://doi.org/10.5194/acp-20-12569-2020, 2020.***

AR: *Thanks for pointing us to this reference. We added it as suggested.*

1.19. Page 13, line 276-277

RC: ***, ... freeze ... predominantly homogeneously at temperatures below -35 °C.’ More correct: ’... at temperatures around -35 °C.’***

AR: *We agree and changed this accordingly.*

These studies distinguish in situ origin cirrus clouds, which form by homogeneous nucleation of solution droplets or heterogenous nucleation of ice nucleating particles within the cirrus temperature range, and liquid origin clouds, which form from supercooled water droplets which are uplifted to the cirrus temperature range and freeze either heterogeneously at warmer temperatures or predominantly homogeneously at temperatures ~~below~~ around -35 °C.

1.20. Page 13, line 296 ff

RC: ***‚This suggests that the influence of the liquid origin on the microphysical properties of the cirrus clouds is lost once the clouds are lifted, for example because the large ice crystals sediment out, or that lifting of entire clouds above the*** $-35\,^{\circ}\mathrm{C}$ ***isotherm hardly ever occurs. Wernli et al. (2016), who investigated the frequency of the formation pathways in a trajectory-based analysis, already noted that ice crystal sedimentation and cloud turbulence could "potentially alter the local cirrus characteristics and 'confuse' the simple categorization". This seems to be the case with the data presented here, or otherwise the data suggests that liquid origin clouds are hardly ever lifted entirely above the*** $-35\,^{\circ}\mathrm{C}$ ***isotherm.' This is a very good and sound discussion and Figure 4 provides new insights in the characteristics of liquid and in-situ origin cirrus. I like to add here that I think that the latter suggestion ‚liquid origin clouds are hardly ever lifted entirely above the*** $-35\,^{\circ}\mathrm{C}$ ***isotherm.' is more likely. It is truethat especially ice crystal sedimentation alter the characteristics of liquid origin clouds, but not to such an extent that it completely disappears, but the influence decreases with increasing altitude, because the altitude the ice crystals reach depends on their size and the updraft, i.e. the higher the altitude the smaller the largest ice crystals (see also Luebke et al. 2016 and Krämer et al., 2020). But such an effect is nearly not visible in Figure 4c. Another argument that liquid origin clouds are hardly ever lifted entirely above the*** $-35\,^{\circ}\mathrm{C}$ ***isotherm is that they appear mostly in meteorological systems with large vertical extents, namely in warm conveyor belts or convection.***

AR: *Thanks for sharing your ideas! We agree that the distinctively different ice crystal size distributions for the two modes suggest that liquid origin clouds are not altered by sedimentation so much that they are confused for in-situ clouds. We incorporated this point and your thought about the vertical extent as follows:*

> Wernli et al. (2016), who investigated the frequency of the formation pathways in a trajectory-based analysis, ~~already~~ noted that ice crystal sedimentation and cloud turbulence could "potentially alter the local cirrus characteristics and 'confuse' the simple categorization". ~~This seems to be the case with the data presented here, or otherwise the data~~ However, the distinctively different ice crystal size distributions for the two modes in Fig. 4b) and c) suggest that liquid origin clouds are not altered by sedimentation so much that they are confused for in-situ clouds. Instead, the data suggests that liquid origin clouds are hardly ever lifted entirely above the $-35\,^{\circ}\mathrm{C}$ isotherm, which is likely because of their large vertical extent.

1.21. Page 16, line 325

RC: ***‚Figure 5c shows that ice crystals do not survive the fall from cirrus cloud base heights above 11 km.' ... which correpsonds to the temperature limit of*** $-65\,^{\circ}\mathrm{C}$ ***from Figure 5a.***

AR: *We agree and added a clarifying sentence.*

> *We attribute this to smaller ice crystals at these colder temperatures and to the fact that high cirrus cloud bases correspond to large distances to lower lying mixed-phase clouds that ice crystals are less likely to survive. This also explains why ice crystals starting their sedimentation at colder temperatures sublimate more often before reaching a lower cloud than those sedimenting from warmer cloud bases, as the temperature limit of* $-65\,^{\circ}\mathrm{C}$ *corresponds to the height limit of* 11 km *(see Figure 5a).*

1.22. Page 18, line 377-378

RC: ***,... where they act as seeds for the glaciation of clouds.' ... in case they fall in an environment that is subsaturated with respect to water – otherwise (supersaturated) they would grow. By the way: did you consider the updraft in the sublimation calculations? Maybe a point to mention at the appropriate place in the paper.***

AR: *Yes, of course the sedimenting ice crystals themselves may also grow within the cloud, but would still initiate glaciation. We have rephrased the sentence as follows:*

> *The seeder-feeder mechanism here refers to ice crystals that fall from a cirrus cloud into a lower cloud, where they ~~act as seeds for~~ initiate the glaciation of clouds.*

We have not considered updraft in the sublimation calculations and have added a clarifying sentence in the description of the sublimation calculations:

> In between cloud layers, small up- or downdrafts can be expected. For lack of reliable data on such small scales, the updraft velocity was not considered in the sublimation calculations.

The updraft between cloud layers is not available from observations. We expect small scale up- or downdrafts (due to the sublimation of hydrometeors), which are not resolved in ERA5.

1.23. Page 18, line 390

RC: ***,In sublimations calculations ...' Remove the latter ,s' in sublimations.***

AR: *Thank you for noticing. We changed this as suggested.*

> *In ~~sublimations~~ sublimation calculations we found that a significant number of ice crystals reached the lower cloud layers.*

2. Reviewer Comment #2

RC: ***The paper is well written, contains original and interesting results, and is therefore appropriate for ACP.***

AR: *Thank you for your thoughtful feedback. Please find our respective answers directly below your comments below.*

RC: ***Some general remarks in the beginning. The paper (title) deals with a good question! But do we get a proper answer? Seeding of liquid-water clouds by cirrus is one branch, what about another, certainly relevant pathway via stratiform mixed-phase clouds? With other words: The impact of cirrus on cloud seeding ... is in the focus of the article. Ok! However, what about all the mid-tropospheric stratiform clouds (altocumulus, stratus, stratocumulus)? Ice crystals may form via immersion freezing mode. These crystals grow fast in the liquid-water environment, fall out and enter the next liquid-water cloud layer and produce large amounts of ice. This aspect is not covered by the paper, but should be discussed to give the reader a clear chance to judge the value of your paper.***

AR: *Yes, of course other ice containing clouds may act as seeding clouds as well. We had briefly mentioned that in the Conclusion: "This study focuses on natural cloud seeding that originate from cirrus clouds, but seeding ice crystals can also sediment from mixed-phase clouds." For clarity, we have now added a sentence to the Introduction as well:*

> *This study focuses on cirrus clouds as seeding clouds because they can be identified readily in the DARDAR satellite data. Of course, other ice containing clouds such as altocumulus or altostratus clouds may act as seeding clouds as well and may be the subject of a further study.*

In addition, we have changed the title to "How frequent is natural cloud seeding from ice cloud layers ($< -35\,^{\circ}\mathrm{C}$) over Switzerland?" to reflect the focus on seeding from ice cloud layers.

RC: ***Then I struggled with this classification: in situ origin cirrus ... and liquid origin cirrus! In former times, there was a clear separation between outflow cirrus (convectively generated cirrus, as remnants of big cumulus towers ...) and synoptic cirrus (cirrus uncinus, cirrocumulus, cirrostratus). And it was clear that outflow cirrus must have quite different properties than cirrus that formed homogeneously or heterogeneously via deposition nucleation. 'In situ' is some kind of a property and used to describe in situ observations, in situ experiments, in situ instruments, especially to contrast them from remote observation and remote sensing instruments .... But what about 'in situ origin' cirrus? ... I know what you want to say, but is that a proper designation? Is that even correct English? Locally generated cirrus vs convectively generated cirrus would sound better. Liquid origin: 'liquid' is not precise ... could be even sulfate aerosol droplets or oil droplets. One should discuss this kind of designation in a broader way to corroborate that this kind of classification of cirrus is open for discussion.***

AR: *We follow the cirrus characterization into in-situ and liquid origin clouds in Luebke et al. (2013), Krämer et al. (2016), Luebke et al. (2016), Wernli et al. (2016), Gasparini et al. (2018), Wolf et al. (2018), and Wolf et al. (2019) and thus also use their terminology. For a juxtaposition to the cirrus characterization by the synpotic situation in which the cirrus form, please refer to RC 2.4.*

2.1. P2

RC: ***It took me some time after reading all the complex aspects given in the introduction what the goal of the study is: We concentrate on the cirrus impact only! I would suggest to simply state what the seeder-feeder mechanism is (definition), what kind (branches) of seeder-feeder pathways exist, and that you want to concentrate on the one via pure cirrus ..., and why you restrict your study to this specific field (because only for this one can use DARDAR ..., if I understood correctly). That would be more simple and straight forward.***

AR: *We see the need for clarifying this in the introduction and believe that this is achieved with the changed title and the additional sentences added in respondence to your first comment.*

2.2. P3, Figure 3

RC: ***Case (c), the right panel is confusing. The orange line indicates $-35\,^{\circ}\mathrm{C}$ (?) and then you have ice (100%) above the respective height (at temperatures below $-35\,^{\circ}\mathrm{C}$)? . . . and liquid water droplets (100%) below this height? Exactly for all temperatures higher than $-35\,^{\circ}\mathrm{C}$? Is that realistic? Maybe in the case of a thunderstorm with 30m/s upwind. . ... that may be the case, i.e., only water below the orange line. But with slow updrafts and ice sedimentation the picture is certainly more complicated.***

AR: *We believe your comment refers to Figure 1c on page 3. This graphic illustrates the classification applied to the DARDAR data. As you state, we view the cloud as ice at temperatures lower than* $-35\,^{\circ}\mathrm{C}$. *Everything below the isotherm, i.e. at higher temperatures, is viewed as a feeder cloud. In this study, we do not assume anything about the state of the feeder cloud. As stated in the caption, it is termed mixed-phase but could be liquid or ice phase. To make that more clear, we also changed* Δz_{il} *to* Δz_{im} *in response to RC 1.1. Contrary to what you say, we do not suggest that all hydrometeors in the feeder cloud are liquid, as is explicitly shown in the sketches in the top row of Figure 1.*

2.3. P9, l 193

RC: ***Please explain in more detail: You found scences with cirrus and liquid-water cloud in 32 % out of all cases, and then, in 77% out of these 32% cases, a liquid cloud directly below the cirrus? . . .so that the seeder-feeder process can work?***

AR: *We added a clarifying sentence to the first statement:*

> ~~*32 %*~~*31 %of the measurements contain both a cirrus and a mixed-phase cloud simultaneously. This is the percentage of cases in which a seeding of the lower cloud by ice crystals falling from the ice cloud above is possible. Tailoring this result to the sedimentation of ice crystals from a cirrus cloud,* ~~*of*~~ *when only the measurements that detect a cirrus cloud* ~~*also detect a lower*~~ *are taken into account, in* 75 % *of these measurements also a mixed-phase cloud* ~~*.*~~ *below them is detected.*

The 32 % refer to the overall frequency of this seeder-feeder situation. But how frequent do we have a second cloud underneath a cirrus cloud? In 77 % of the times that we see a cirrus cloud, we also see a second mixed-phase cloud underneath.
Please note that the percentages stated changed due to errors noted in RC 1.11.

RC: ***Question: How do you know that the liquid-water cloud is free of ice crystals? Because of the radar observations? Please explain!***

AR: *We do not know that the potential feeder clouds are liquid. We state several times in the paper that these clouds are termed mixed-phase, but could also be liquid or ice phase. To make that more clear, we also changed* Δz_{il} *to* Δz_{im} *as suggested in RC 1.1.*

2.4. P13, l 270

RC: ***I am sure that there are papers from the 1980s-1990s distinguishing the microphysical properties of outflow and synoptic cirrus. Please check! Or did this kind of research started just a few years ago as your references indicate?***

AR: *Cirrus clouds can be characterized either by the synoptic situation in which they form or by their origin. The latter characterization was proposed by Luebke et al. (2013), Krämer et al. (2016), Luebke et al. (2016), Wernli et al. (2016), Gasparini et al. (2018), Wolf et al. (2018), and Wolf et al. (2019). As described by Wolf et al. (2019), "the same weather condition can contain both cloud types" (see also Krämer et al. (2020)), which leads them to conclude that "an origin-based parameterization of cirrus clouds seems to be more adequate and distinct in comparison to a weather-based parameterization". In line with the literature cited above we employ the characterization by origin in our investigation of the cloud microphysical properties. A comparison of the two characterization methods is beyond the scope of this article, especially because the* *synoptic situation that the cirrus formed in is not examined.*

2.5. P13, l 273

RC: ***By listing all available mechanisms, step by step, starting from temperatures above* $-35\,^{\circ}\mathrm{C}$*, and then going to temperatures below* $-35\,^{\circ}\mathrm{C}$ *at which both homogenous and heterogenbous ice nucleation can occur. . .. the separation into different cirrus classes would be process-based and more easy to understand. Why do you not mention the immersion freezing process?***

AR: *We agree, this was a long and compliated sentence. We rephrased it to make the classification more clear:*

> *~~These studies distinguish in situ origin cirrus clouds , which form by homogeneous nucleation of solution droplets or heterogenous nucleation on ice nucleating particles within the cirrus temperature range, and liquid origin clouds, which form~~ Liquid origin clouds form from supercooled water droplets which are uplifted to the cirrus temperature range~~and~~. They freeze either heterogeneously at warmer temperatures or predominantly homogeneously at temperatures ~~below~~ around* $-35\,^{\circ}\mathrm{C}$*. In the cirrus temperature range, cirrus clouds can also form by homogeneous nucleation of solution droplets or heterogeneous nucleation of ice nucleating particles. These cirrus clouds are termed in situ origin cirrus clouds.*

Immersion freezing is not mentioned explicitly, because it is implicitly included as one type of heterogeneous ice nculeation through ice nucleating particles.

2.6. P13, L285

RC: ***What do you want to say? : It also confirms . . . that liquid origin cirrus clouds are composed of ice crystals. . . .I mean: a white horse is white. . . otherwise it is not a white horse.***

AR: *A word is missing here. The sentence should read:*

> *It also confirms the finding from Luebke et al. (2016) that liquid origin cirrus clouds are composed of larger ice crystals.*

2.7. P13

RC: ***I find the full discussion on pager 13 quite a bit too complex and many times confusing.***

AR: *We rephrased these paragraphs and hope that in addition to the changes applied in response to your RC 2.5 this makes the discussion more clear.*

2.8. P18

RC: ***My question remains: Would be nice to have some speculation (some estimation, your opinion) on the relative impact of stratiform clouds (mixed-phase altocumulus etc . . .) on the seeder-feeder processes.***

AR: *As stated in response to your first comment, seeding ice crystals can also sediment from mixed-phase clouds. We state this in the Conclusion, and now also in the Introduction. We agree that it would be intersting to investigate natural cloud seeding from mixed-phase clouds, but this requires a reliable cloud phase satellite* *product.*

3. Reviewer Comment #3

RC: ***In their paper "How frequent is natural cloud seeding over Switzerland", the authors quantify the occurrence of an ice cloud layer above other clouds from CALIOP/CloudSat (DARDAR) data. In addition, the possibility of ice crystals sedimenting into the lower layers is calculated from temperature and relative humidity profiles based on ERA5. The paper is well written, the method is sound, the analysis is careful and the results are very interesting. I recommend the manuscript for publication after minor revisions.***

AR: *Thank you for your clear and thoughtful feedback. Please find our respective answers directly below your comments below.*

3.1. Main comments

RC: ***I don't understand the "filtering" or smoothing of the data. Line 121 mentions a 7x7x7 points cube, but what are these three dimensions? Why is the median used? How sensitive are the results to this filtering?***

AR: *This is a mistake, the cube has only two dimensions since the filtering is applied before the DARDAR data is remapped. These are the horizontal dimension and the altitude, as we have know specified in the text:*

> *This cloud mask was found to be noisy and was therefore filtered (using a median filter over the surrounding ~~$7 \times 7 \times 7$ points cube~~ 7×7 points plane, in altitude and horizontally along the track).*

The cloud mask has values of 1 or 0 (cloud or no cloud). Using the median over the plane or the mean with threshold 0.5 to decide between 1 or 0 in a pixel is therefore the same thing, and using the median is simpler. Figure 1 illustrates the filtering results. We have evaluated other cube sizes as well and 7 seemed to be the most suitable size to exclude small holes in the clouds as well as small cloudy pixels from the analysis. Figure 2 shows the DARDAR results with and without filtering from tests we made in a previous version of the analysis.

RC: ***Line 131 says that reff is also filtered "for consistency", but the smoothing applied here is very different. What impact does this have on the results?***

AR: *The reason for why the two smoothing algorithms differ is a physical one: for the cloud mask we want to fill holes. After having done that, the smoothed field may see a cloud where the DARDAR product says that there is none. Now if we take the effective ice crystal radius from that pixel, it will give an unphysical value as it is taken from the product that sees no cloud. That is why we chose to use the median effective radius of clouds detected in the DARDAR data, in vicinity to the pixel in question, instead. We chose to only probe the vertical vicinity of the pixel in order to probe the real cloud base of the ice crystals. Applying no filter or the same filter as used for the cloud mask to the effective radii, their values were reduced compared to those derived using the vertical filter (see Figure 3).*

RC: ***The temperature in the DARDAR dataset is also not a retrieved parameter, but is obtained from interpolated NWP data, if I'm not mistaken. How different is this from the ERA5 temperature? Is the discrepancy in the sublimation calculations only due to a discrepancy in relative humidity or also in temperature? How is this affected by the smoothing?***

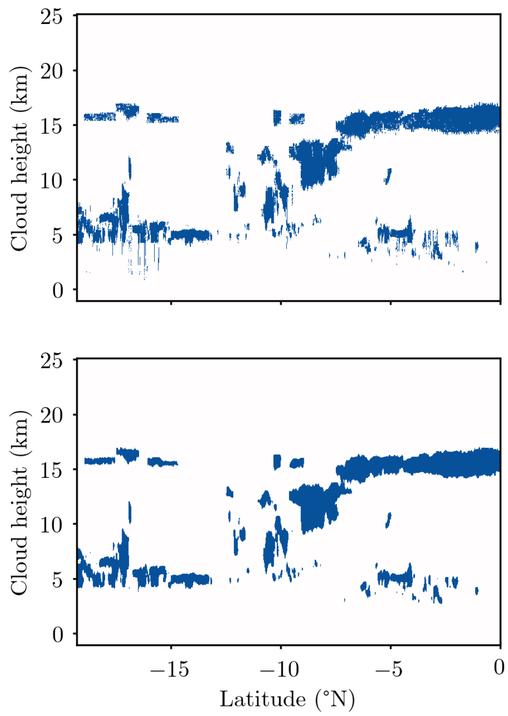


Figure 1: Illustration of the cloud mask applied in the DARDAR analysis: cloud mask without (top) and with a 7 × 7 filter (bottom) for one exemplary satellite track.

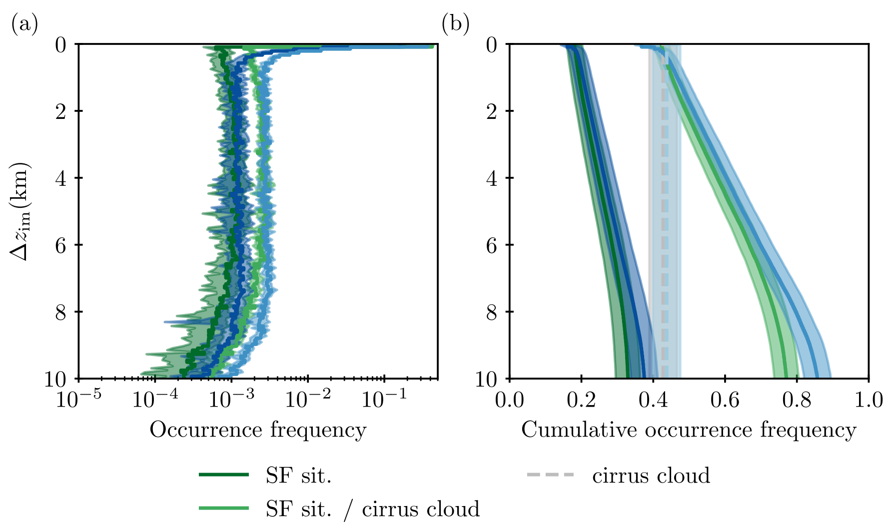
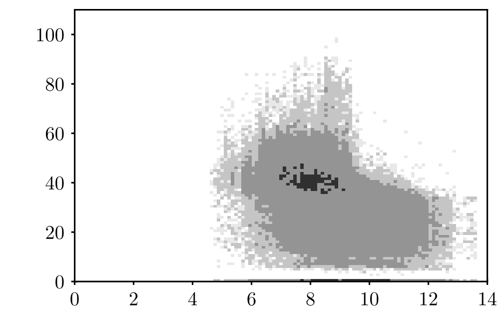
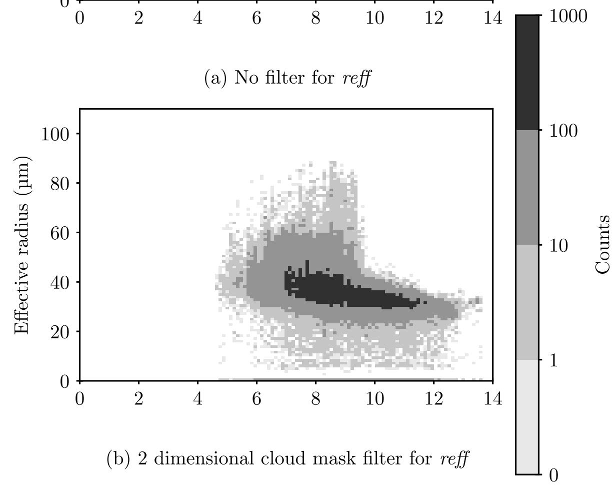


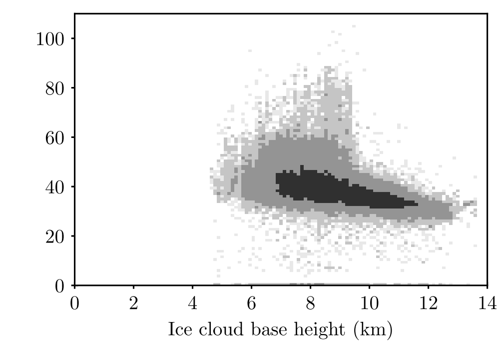
Figure 2: Difference between DARDAR data with (green and gray) and without filtering (blue) from a previous version of the analysis: **(a)** Occurrence frequency of seeder-feeder situations (SF sit.) with respective Δz_{im} as a fraction of measurements (dark green/blue) or cirrus cloud measurements (light green/blue). **(b)** Cumulative occurrence frequency. For Δz_{im} a vertical resolution of $60\,\mathrm{m}$ is used. For comparison, the fraction of measurements with at least one cirrus cloud (light grey/blue) is given. Data from all tracks in the study time (2006 to 2017) and within the study domain were used. The shaded areas visualize the standard deviation of interanual variablility. This Figure corresponds to Fig. 3 in the manuscript.



(a) No filter for *reff*



(b) 2 dimensional cloud mask filter for *reff*



(c) 1 dimensional, vertical filter for *reff*

Figure 3: Distribution of *reff* for three different filter variants: **(a)** no filter, **(b)** 7×7 plane filter as described for cloud mask in the manuscript, **(c)** vertical filter as described for *reff* in the manuscript. The filter used for the cloud mask is the same in all three plots, i.e. the one described in the manuscript. Note that this Figure was produced with lower resolution data from a previous version of the analysis and therefore **(a)** differs from Fig. 4 in the manuscript.

AR: *Indeed, the temperature in the DARDAR dataset is obtained from interpolated NWP data from ECMWF (Delanoë and Hogan, 2010a). As we state in the manuscript, we have compared some temperature profiles in the DARDAR and ERA5 data directly and have found up to* 5 °C *difference in the temperature. We used the relative humidity data from ERA5 in this study, and the DARDAR data does not contain the humidities used to create it, so we were unable to compare them directly. Of course, any difference in clouds and humidity between the reality that the satellites probe and the simulation in ERA5 is a source of error for the sublimation calculations, in the form of temperature as well as in humidity estimates. The smoothing discussed earlier is not applied to the environmental parameters. Therefore we do not expect this to contribute to the difference between the DARDAR and ERA5 datasets.*

RC: ***Sometimes the terminology is a little unconventional. The term "seeder-feeder" is also used for cases in which ice crystals fall into pure ice clouds. I don't think the term is appropriate in this case. Further, the ice cloud layer below*** −35 °C ***is termed "cirrus", even if it is the upper part of a mixed phase cloud e. g. a frontal cloud or a convective cloud. I would reserve "cirrus" for isolated ice clouds.***

AR: *Since we do not determine the phase of the lower lying clouds, we cannot exclude them from our "seeder-feeder" terminology. Similarly, since we do not separate into separate ice clouds and those that are part of a mixed-phase cloud, we chose to use one term for both ice cloud types. To avoid confusion we added a clarifying sentence in the Methods:*

> *Note that clouds termed mixed-phase could in principle be in the liquid or ice phase in reality, depending on their history and the presence of ice nucleating particles (see Fig. 1a). Similarly, in this study we denote all ice clouds at temperatures colder than* −35 °C *as cirrus clouds, which could be isolated ice clouds or the upper parts of mixed-phase clouds.*

3.2. Table 2

RC: ***Table 2 gives coefficients "for cloud droplets", shouldn't this be ice particles?***

AR: *The naming is correct. The parameterization for the velocity-mass-relation for cloud droplets from Seifert and Beheng (2006) is used for spherical ice crystals in this study. We think that this is appropriate because of the similar shape of the two hydrometeors. Due to this assumption we are overestimating the velocity of the spherical ice crystals, because a spherical ice crystal with the same mass as a liquid drop experiences a larger drag force acting on it. However, the relative overestimation for using the cloud droplet formulation for the spherical ice crystal is only about 3%, as detailed in the following for Stokes terminal velocity. With*

$m_i = m_l$, $r_i = \left(\frac{\rho_l}{\rho_i}\right)^{(1/3)} r_l$:

$$v_{T,l} = \frac{2}{9}\frac{r_l^2 g \rho_l}{\mu} \tag{1}$$

$$v_{T,i} = \frac{2}{9}\frac{\left(\frac{\rho_l}{\rho_i}\right)^{(2/3)} g\rho_i r_l^2}{\mu} \tag{2}$$

$$= \left(\frac{\rho_l}{\rho_i}\right)^{(2/3)} \frac{\rho_i}{\rho_l} v_{T,l} \tag{3}$$

$$= \left(\frac{0.92}{1}\right)^{(1/3)} v_{T,l} \tag{4}$$

$$= 0.97 \cdot v_{T,l} \tag{5}$$

We added a clarifying statement to the caption of Table 2.

3.3. Figure 3b

RC: ***Why does the cumulative occurrence frequency for the situation with a cirrus cloud does not reach 1 minus the cirrus cloud frequency (i.e. a little less than 0.6) at 10km?***

AR: *What is shown in light green in Figure 3b is the fraction of cases with a potential feeder cloud within the measurements that contain a cirrus cloud. Thus, theoretically, if every situation with a cirrus cloud had another cloud below, it could go up to 100 %. In total, the fraction of measurements with a cirrus cloud is 42 % of all measurements.*

RC: ***What is the sensitivity to the time step of the sublimation calculations?***

AR: *In tests performed with a more simple set up (constant temperature and relative humidity), the sublimation height of* 50 µm *ice crystals was found to be independent of the time step, at least for those time steps* < 10 s, *where there are no numerical instabilities (see Figure 4).*

3.4. Line 140

RC: ***"mean values" of what?***

AR: *Both Vassel (2018) and Vassel et al. (2019) use "the average conditions of temperature, pressure and moisture of the individual subsaturated layers, measured by the radiosounding" for their sublimation calculations (Vassel, 2018). We corrected and further specified this in the manuscript as follows:*

> *For these parameters, Hall and Pruppacher (1976) used the NACA standard profile, while Vassel (2018) ~~used mean values,~~ and Vassel et al. (2019) used radiosonde profiles that were averaged for each subsaturated layer in their calculations.*

3.5. Line 416

RC: ***I suggest to include the reference to the companion paper only if it is already available (at least as preprint) when the revised version of this manuscript is published. Otherwise, this is more confusing than helpful for the readers.***

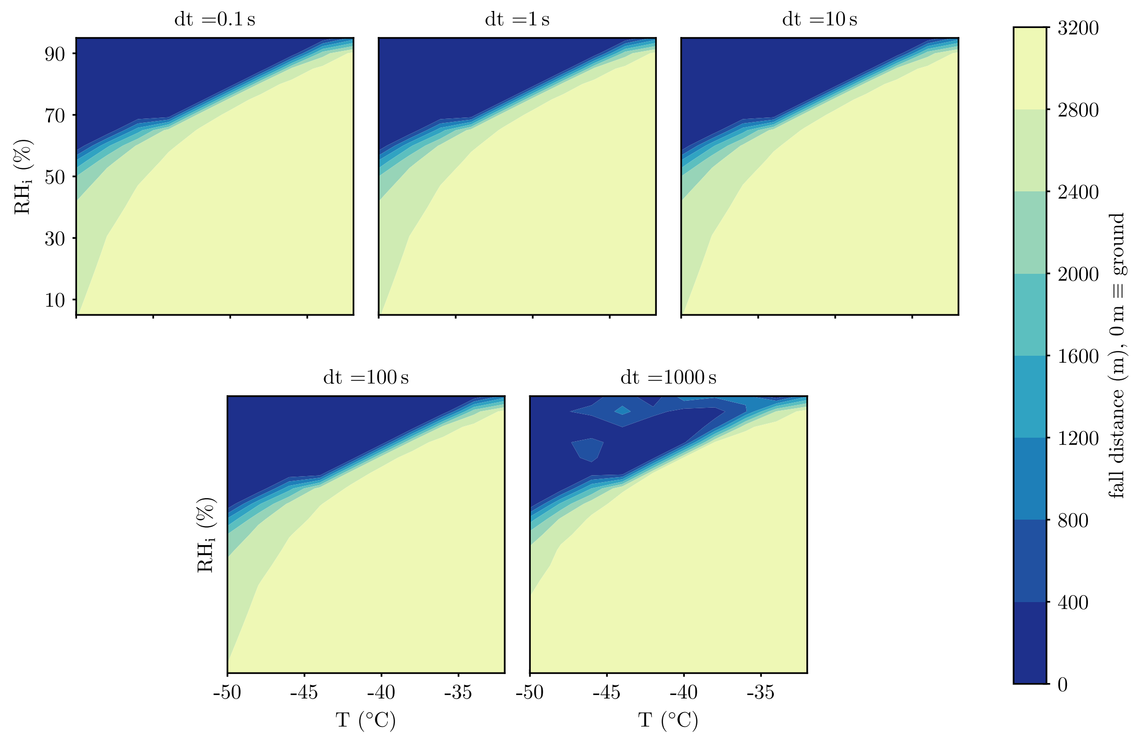


Figure 4: Results of sublimation calculations testing the influence of the time step length (dt). The sublimation calculations were performed for a $50\,\mu m$ spherical ice crystal and deviate from the ones employed in the manuscript only by using a constant temperature and humidity. The ice crystals start sedimenting from an altitude of $3000\,m$ and the fall distance is the altitude at which the ice crystals sublimate. The calculations and this visualisation are based on Vassel (2018).

AR: *We agree and removed the reference.*

3.6. Technical comments

RC: ***Caption of Fig. 3: typo "atmposphere"***
Line 352: "for spheres": blanks missing.
Table A2: typo "Earh".

AR: *Thanks for pointing out these typos. We corrected them in the new version of the manuscript.*

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How frequent is natural cloud seeding from ice cloud layers ($< -35\,°C$) over Switzerland?

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Abstract. Clouds and cloud feedbacks represent one of the largest uncertainties in climate projections. As the ice phase influences many key cloud properties and their lifetime, its formation needs to be better understood in order to improve climate and weather prediction models. Ice crystals sedimenting out of a cloud do not sublimate immediately but can survive certain distances and eventually fall into a cloud below. This natural cloud seeding can trigger glaciation and has been shown to enhance precipitation formation. However, up to date an estimate of its occurrence frequency is lacking. In this study, we estimate the occurrence frequency of natural cloud seeding over Switzerland from satellite data and sublimation calculations.

We use the DARDAR satellite product between April 2006 and October 2017 to estimate the occurrence frequency of multi-layer cloud situations, where a cirrus cloud at $T < -35\,°C$ can provide seeds to a lower lying feeder cloud. These situations are found to occur in $31\,\%$ of the observations. Of these $42\,\%$ have a cirrus cloud above another cloud, separated, while in $58\,\%$ the cirrus is part of a thicker cloud, with a potential for in-cloud seeding. Vertical distances between the cirrus and the lower-lying cloud are distributed uniformly between $100\,m$ and $10\,km$. They are found to not vary with topography. Seasonally, winter nights have the most multilayer cloud occurrences, in $38\,\%$ of the measurements. Additionally, in situ and liquid origin cirrus cloud size modes can be identified according to the ice crystal mean effective radius in the DARDAR data. Using sublimation calculations we show that in a significant number of cases the seeding ice crystals do not sublimate before reaching the lower lying feeder cloud. Depending on whether bullet rosette, plate like or spherical crystals were assumed, $10\,\%$, $11\,\%$ or $20\,\%$ of the crystals, respectively, could provide seeds after sedimenting $2\,km$.

The high occurrence frequency of seeding situations and the survival of the ice crystals indicate that the seeder-feeder process and natural cloud seeding are widespread phenomena over Switzerland. This hints to a large potential for natural cloud seeding to influence cloud properties and thereby the Earth's radiative budget and water cycle, which should be studied globally. Further investigations of the magnitude of the seeding ice crystals' effect on lower lying clouds are necessary to estimate the contribution of natural cloud seeding to precipitation.

1 Introduction

Clouds and cloud feedbacks contribute the largest uncertainty to projections of climate sensitivity in global climate models (Cess et al., 1990; Soden and Held, 2006; Williams and Tselioudis, 2007; Boucher et al., 2013). Cloud microphysics, and especially cloud ice / water content, determine key cloud properties, such as their albedo and lifetime, and control precipitation formation (Mülmenstädt et al., 2015). The representation of the ice phase in clouds is therefore necessary to estimate the Earth's radiation budget and its response to climate change (Sun and Shine, 1995; Tan et al., 2016; Matus and L'Ecuyer, 2017; Lohmann and Neubauer, 2018) as well as to improve forecasts of precipitation in numerical weather prediction models. Natural cloud seeding can be a source of ice crystals in clouds, lead to the glaciation of clouds and enhance precipitation. Moreover, the seeder-feeder mechanism has been associated with the enhancement of extreme precipitation and flooding (Rössler et al., 2014). An understanding of the seeder-feeder mechanism is therefore necessary to improve the representation of the cloud ice phase in weather and climate models, to improve weather forecasts of precipitation, and ultimately to reduce uncertainty in climate simulations.

The seeder-feeder mechanism was originally proposed to explain an observed enhancement of precipitation over mountains. In this classical setting, precipitation from an overlying "seeder" cloud falls into an orographic "feeder" cloud. In the lower cloud, the precipitation particles grow by accretion, coalescence, or riming, which leads to an enhancement of precipitation over the orography (Roe, 2005). This classical seeder-feeder mechanism has been observed in field studies in various locations (Dore et al., 1999; Purdy et al., 2005; Hill et al., 2007) and has been reproduced in a number of idealized modelling studies (e.g. Carruthers and Choularton (1983); Robichaud and Austin (1988)).

Braham (1967) noted the possibility of ice crystals from cirrus clouds acting as seeds for ice formation in lower-lying warmer clouds. In this special case of the seeder-feeder mechanism, the seeding precipitation is specified as ice, but the presence of orography is not a prerequisite for the mechanism's occurrence. This natural cloud seeding is the focus of the current study, where hereafter the seeder-feeder mechanism and natural cloud seeding refer to ice particles falling from a cirrus cloud into a lower-lying cloud or a lower-lying part of the same cloud, which is either liquid, ice or mixed-phase (Fig. 1). In a widened sense, the process of falling precipitation particles that feed on the hydrometeors in a lower part within the same cloud can also be understood as a seeder-feeder process (in-cloud seeder-feeder mechanism, Hobbs et al. (1980), see Fig. 1b). This study focuses on cirrus clouds as seeding clouds because they can be identified readily in the DARDAR satellite data. Of course, other ice containing clouds such as altocumulus or altostratus clouds may act as seeding clouds as well and may be the subject of a further study.

Cirrus clouds, which act as seeder clouds in this study, can form either from freezing of liquid droplets or in-situ from homogeneous freezing of solution droplets or heterogeneous nucleation. Recent studies have suggested to classify cirrus clouds accordingly, as liquid or in situ origin ice clouds (Luebke et al., 2013; Krämer et al., 2016; Luebke et al., 2016; Wernli et al., 2016; Gasparini et al., 2018; Wolf et al., 2018, 2019). The formation mechanism has been shown to influence clouds' microphysical properties (Luebke et al., 2016; Wolf et al., 2018, 2019).

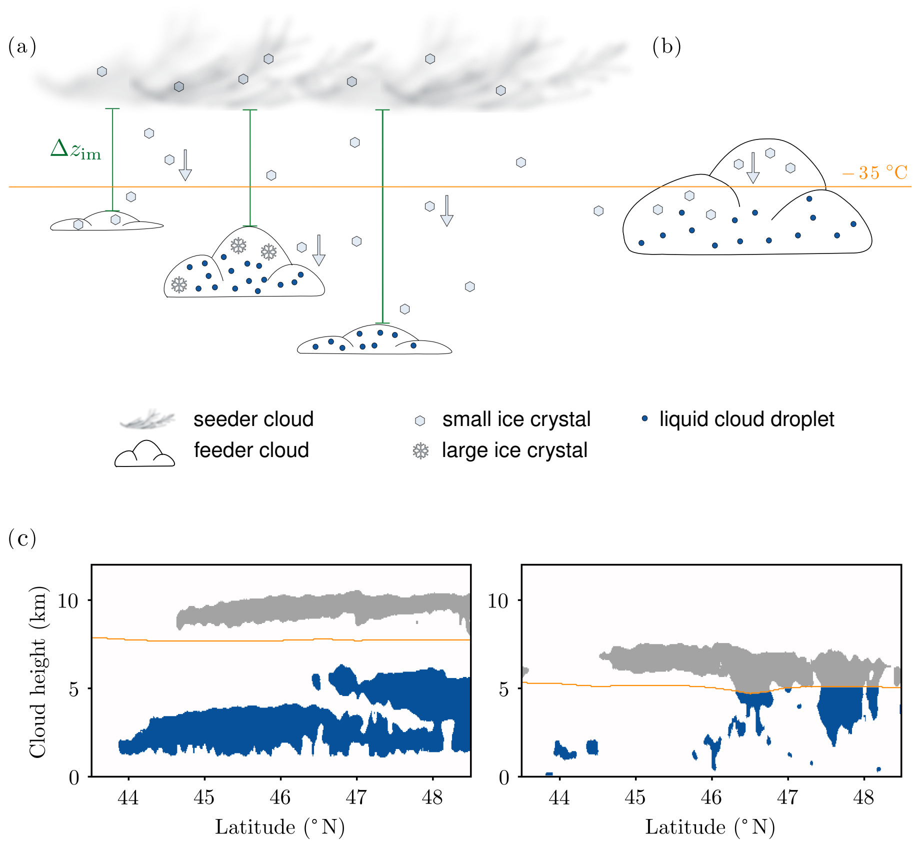

Figure 1. Sketch of the two seeder-feeder situations observed in this study. The orange lines depict the $-35\,^{\circ}\mathrm{C}$ isotherm, ~~Δz_{ll}~~ Δz_{im} is the distance between the lowest base of the cirrus cloud and the highest top of the cloud below. **(a)** Classical external seeder-feeder situation: a cirrus cloud ($T < -35\,^{\circ}\mathrm{C}$) is detected at least 100 m above a cloud at $T > -35\,^{\circ}\mathrm{C}$ (~~$\Delta z_{\mathrm{ll}} > 100\,\mathrm{m}$~~$\Delta z_{\mathrm{im}} > 100\,\mathrm{m}$). The latter cloud is termed *mixed-phase* cloud for simplicity, but could also be liquid or ice phase. **(b)** In-cloud seeder-feeder situation: the algorithm detects the cloud part above the $-35\,^{\circ}\mathrm{C}$ isotherm as a cirrus cloud, and the cloud part below as a mixed-phase cloud (~~$\Delta z_{\mathrm{ll}} < 100\,\mathrm{m}$~~$\Delta z_{\mathrm{im}} < 100\,\mathrm{m}$). Ice crystal shapes are depicted according to Libbrecht (2005, Fig. 2). **(c)** Seeder-feeder situations as seen in the DARDAR data. Cirrus clouds above the $-35\,^{\circ}\mathrm{C}$ isotherm are depicted in grey, clouds below in blue. Left: exemplary plot of the classical external seeder-feeder situation (data from 29.05.2007), right: exemplary plot of only a mixed-phase or a cirrus cloud present (latitudes equatorwards of $46\,^{\circ}\mathrm{N}$) and the in-cloud seeder-feeder situation (polewards of $46\,^{\circ}\mathrm{N}$, data from 03.12.2010).

Seeding ice crystals can have a large influence on cloud properties, because in the atmosphere, at temperatures warmer than $-38\,^{\circ}\mathrm{C}$, ice can only be formed via heterogeneous nucleation on ice nucleating particles (Kanji et al., 2017).(e.g. Kanji et al. (2017), and references therein). Once ice particles are formed within the cloud or enter the cloud from outside, they grow by riming or vapour deposition (rapidly via the Wegener-Bergeron-Findeisen process, where ice crystals grow at the expense of liquid droplets, when the water vapor saturation ratio is between saturation subsaturated with respect to water and supersaturated with respect to ice (Wegener, 1911; Bergeron, 1935; Findeisen, 1938)), and can multiply through secondary ice production (Korolev and Leisner (2020), Hallett-Mossop process (Hallett and Mossop, 1974; Mossop and Hallett, 1974, ?)(Hallett and Mossop, 1974; frozen droplet shattering (Lauber et al., 2018), or ice-ice collisional breakup (Sullivan et al., 2018)). Thereby, seeding ice crystals destabilize a cloud, which subsequently could glaciate and/or form precipitation. Because of the aforementioned enhancement processes in the ice phase, the seeder-feeder mechanism with seeding ice crystals is more efficient than the classical liquid seeder-feeder mechanism, and has been found to lead to a larger precipitation enhancement (Choularton and Perry, 1986).

For natural cloud seeding to take place, the ice crystals' survival during the sedimentation through a subsaturated layer of air and into the lower cloud layer is crucial. Braham (1967) observed a spectacular case of ice crystals that survived a distance of $5\,\mathrm{km}$ in cloud-free air. This demonstrated the feasibility of natural cloud seeding (Hitschfeld, 1968; Locatelli et al., 1983). In a first theoretical study, Hall and Pruppacher (1976) found that "ice particles could survive distances of up to $2\,\mathrm{km}$ when the relative humidity with respect to ice was below $70\,\%$". Natural cloud seeding through sedimenting ice crystals has been observed in a multitude of remote sensing and aircraft campaigns (Dennis, 1954; Hobbs et al., 1980, 1981; Locatelli et al., 1983; Hobbs et al., 2001; Pinto et al., 2001; Fleishauer et al., 2002; Ansmann et al., 2008; Creamean et al., 2013) and has been studied in mostly idealized model simulations (Rutledge and Hobbs, 1983; Fernández-González et al., 2015; Chen et al., 2020), where it has been found to mainly enhance ice and precipitation formation.

Seifert et al. (2009) and Ansmann et al. (2009) estimated such an occurrence frequency of natural cloud seeding for their lidar field study datasets indirectly when aiming to exclude all seeded clouds. They simply defined all mixed-phase clouds that had an ice cloud within $2\,\mathrm{km}$ above cloud top as a seeded ice cloud. For example, in Leipzig, about $10\,\%$ of ice-containing clouds at $-20\,^{\circ}\mathrm{C}$ were marked as seeded (ice containing clouds made up $90\,\%$ of the observations at that temperature). A more thorough, regional estimate of seeder-feeder occurrence frequency in the Arctic was derived by Vassel et al. (2019). Using radiosonde and radar data from Svalbard, they deduced the frequency of multilayer clouds as $29\,\%$. Calculating the sublimation height of hexagonal plate ice crystals with a radius of $400\,\mu\mathrm{m}$ (radius meaning here: half of the maximum span across the hexagonal face), $26\,\%$ of observations contained a seeding case.

Such field studies have begun to elucidate the frequency and thereby the importance of natural cloud seeding regionally, but a thorough estimate is still lacking. With global coverage and sensors increasingly capable of resolving clouds and their vertical distribution, satellite data offers an opportunity to fill the gap from single observations to whole-earth long-time observations to derive such a frequency estimate. Multilayer clouds can be investigated using CloudSat and CALIPSO data (e.g. Wang et al. (2000); Mace et al. (2009); Das et al. (2017); Matus and L'Ecuyer (2017)). To provide an estimate of the natural cloud seeding frequency, sublimation calculations need to be combined with the seeder-feeder situation/multilayer cloud occurrence frequencies as done by Vassel et al. (2019).

In this study, we employ the DARDAR (ra*dar* li*dar*) satellite product that is based on CloudSat and CALIPSO data (Delanoë and Hogan, 2008, 2010b; Ceccaldi et al., 2013) and combine it with sublimation calculations to derive a frequency estimate of seeder-feeder situations over Switzerland. Note that we consider as seeder clouds only cirrus clouds to ensure that the they contain ice. In the following Sect. 2, the DARDAR satellite product, our analysis and the sublimation calculations are described. In Sect. 3.1, findings from the analysis of the DARDAR data are presented and discussed, followed by the results from the sublimation calculations in Sect. 3.2. Conclusions and an outlook are given in Sect. 4.

2 Methods and Data

2.1 Satellite data

The ~~DARDAR~~ DARDAR-CLOUD satellite data product used in this study is based on radar ~~, lidar and infrared radiometer~~ and lidar data from the CloudSat and CALIPSO satellites. The satellites were launched jointly on 28 April 2006 into the A-Train or Afternoon Constellation, a coordinated group of satellites in a sun-synchronos polar orbit (Stephens et al., 2002). CloudSat has a cloud profiling radar on-board that senses cloud particles and detects precipitation (Stephens et al., 2008). CALIPSO carries the CALIOP lidar (Cloud-Aerosol Lidar with Orthogonal Polarization) and two passive sensors, a visible camera and a three-channel infrared radiometer (Winker et al., 2010). The two satellites are designed for their data to be combined: the lidar on CALIPSO is able to identify the thin upper layers of cirrus clouds that the radar on CloudSat misses (Winker et al., 2010), while the latter is able to look through thick clouds where the lidar beam is attenuated. Because of their joint operations and almost simultaneous time measurements, the two satellites provide novel ways to look at precipitation, aerosols and the vertical distribution of clouds (Gao et al., 2014; Hong and Liu, 2015; Naud et al., 2015; Stephens et al., 2018; Witkowski et al., 2018).

From the CloudSat and CALIPSO data, Delanoë and Hogan (2010b) developed the DARDAR (radar lidar) satellite product that provides cloud classification and ice cloud properties. It was developed further into a DARDAR v2 by Ceccaldi et al. (2013). DARDAR data is retrieved at $60\,\mathrm{m}$ vertical resolution up to an altitude of $25\,\mathrm{km}$ and a horizontal resolution of $1.4\,\mathrm{km}$ (Delanoë and Hogan, 2010a). Next to other cloud properties it contains a classification of the layer at each grid point with categories like clear sky, ice, liquid or supercooled clouds, aerosols, etc. as well as the retrieved effective ice crystal radius.

In this study, DARDAR-CLOUD v2.1.1 data (as described in Ceccaldi et al. (2013)) from April 2006 through October 2017 was used. Due to CloudSat's battery problems there is no data between April 2011 and April 2012 and merely Daylight-Only Operations mode data thereafter (Stephens et al., 2008; Witkowski et al., 2018; CloudSat radar status).

2.1.1 Analysis method

The study domain surrounds Switzerland ($4°$E to $12°$E and $43.5°$N to $48.5°$N) and contains most of the Alps. Figure 2 shows the geographic distribution of all satellite tracks that go through the chosen domain. In order to evaluate the frequency of seeder-feeder situations four variables were created:

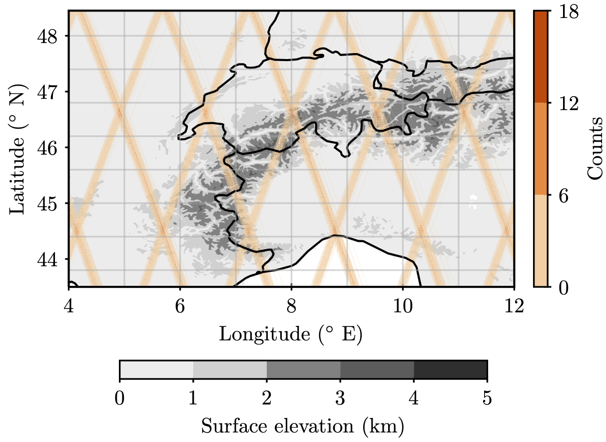

Figure 2. Geographical distribution of the satellite observations: number of tracks through each point within the study domain (4°E to 12°E and 43.5°N to 48.5°N) over the whole time period analysed in this study (2006-2017).

frac_cov (-)	The fraction of sky covered with a specific combination of cloud top and cloud base temperatures.
icebase (m)	The height (altitude above sea level) of the lowest cloud grid point with $T < -35\,^{\circ}\mathrm{C}$ (lowest base of a cirrus cloud).
$\boldsymbol{\Delta z_{\mathrm{il}}}$ $\boldsymbol{\Delta z_{\mathrm{im}}}$ (m)	The distance between the lowest cirrus cloud base and the highest top of the cloud below (in the following called mixed-phase cloud).
reff (µm)	The effective radius of ice crystals at the lowest cirrus cloud base.

All variables were derived from a cloud mask, where the DARDAR categories 1, 2, 3 and 4 (ice, ice + supercooled, liquid $> -35\,^{\circ}\mathrm{C}$ (warm and supercooled)) were combined to simply signify the presence of cloud layers. This cloud mask was found to be noisy and was therefore filtered (using a median filter over the surrounding $7\times7\times7$ points cube 7×7 points plane, in altitude and horizontally along the track). For *icebase*, Δz_{il} Δz_{im}, and *reff* the cloud mask was combined with a temperature mask to differentiate between mixed-phase and cirrus clouds. In this study, cirrus clouds are defined as clouds at temperatures lower than $-35\,^{\circ}\mathrm{C}$, and mixed-phase clouds are defined as all clouds at with temperatures warmer than $-35\,^{\circ}\mathrm{C}$. This is because Depending on their size, liquid cloud droplets have been found to supercool to $-35\,^{\circ}\mathrm{C}$ to $-40\,^{\circ}\mathrm{C}$ before freezing homogeneously (Murray et al., 2010; Herbert et al., 2015).The temperature for homogeneous freezing of water droplets is also often given as (Kanji et al., 2017). (e.g. Pruppacher and Klett (2010); Murray et al. (2010); Herbert et al. (2015); Kanji et al. (2017)). However, in tests preceding this study, a threshold of $-38\,^{\circ}\mathrm{C}$ instead of $-35\,^{\circ}\mathrm{C}$ proved to have no evident impact on the results. Note that clouds termed mixed-phase could in principle be in the liquid or ice phase in reality, depending on their history and the presence of ice nucleating particles (see Fig. 1a). Similarly, in this study we denote all ice clouds at temperatures colder than $-35\,^{\circ}\mathrm{C}$ as cirrus clouds, which could be isolated ice clouds or the upper parts of mixed-phase clouds.

Table 1. Variables used in the sublimation calculations as described in the text. For a comprehensive list, also see Table A1.

Symbol	Long Name	Units
C	capacitance of the ice particle	m
D_{v}	diffusivity of water vapour in air	$\mathrm{m^2\,s^{-1}}$
G	growth factor	$\mathrm{kg\,m^{-1}\,s^{-1}}$
m	mass of the ice particle	kg
r	effective radius of the ice particle	m
ρ_{air}	air density	$\mathrm{kg\,m^{-3}}$
s	supersaturation with respect to ice	-
v	fall speed of the ice particle	$\mathrm{m\,s^{-1}}$
z	height of the ice particle	m

The combined cloud and temperature masks were applied to the altitude and effective ice crystal variable in the DARDAR data to find the values at the lowest cirrus cloud base (for *icebase*, *reff* and ~~Δz_{ll}~~Δz_{im}) and at the highest mixed-phase cloud top (for ~~Δz_{ll}~~Δz_{im}). Prior to this, the effective ice crystal radius was also filtered, for consistency. As a filter for the effective radius, the vertical median with an extent of four pixels up and four pixels down from the one in question was applied, using only those pixels where the unfiltered cloud mask detected a cloud. For ~~Δz_{ll}~~Δz_{im}, the altitude of the highest mixed-phase cloud top was substracted from the altitude of the lowest cirrus cloud base. Finally, the dataset was saved on a grid with a resolution of $0.005° \times 0.005°$ with no quality loss compared to the original DARDAR data. During regridding, areas containing no satellite tracks were set to missing data, to be able to derive the total number of observations later on.

2.2 Ice crystal sublimation calculations

Environmental parameters such as the air density, air temperature and the relative humidity ~~determine~~ also affect the ice crystal sublimation rate and fall velocity. For these parameters, Hall and Pruppacher (1976) used the NACA standard profile, while Vassel (2018) ~~used mean values,~~ and Vassel et al. (2019) used radiosonde profiles that were averaged for each subsaturated layer in their calculations. Since the environmental conditions are primary determinants of the sublimation height, we chose the most detailed information available. Relative humidity and temperature were therefore taken from ERA5 reanalysis data from the European Centre for Medium Range Weather Forecast (ECMWF, Hersbach et al. (2020)). From the DARDAR data *icebase*, ~~Δz_{ll}~~Δz_{im}, and *reff* were used. Prior to calculations, the ERA5 data was regridded: vertically to match the DARDAR 60 m resolution; horizontally points closest to the DARDAR points were chosen. As only hourly ERA5 data was available, data from the hour closest to the entry time of the satellites into the study domain was used. The sublimation height was calculated individually for every point in every available track file where there was at least one cirrus cloud above a mixed-phase cloud present. The algorithm is based on work in Vassel (2018). It was applied to three different shapes of ice crystals, namely spheres, hexagonal plates and bullett rosettes. These three were chosen to sample ice crystal properties, e.g. to span the possible range of terminal velocities. In particular, bullet rosettes have been found to be one of the most abundant shapes in cirrus clouds

Table 2. Constants used in the sublimation calculations for a sphere as described in the text. For a comprehensive list, also see Table A2. ~~Where~~ Note that the ~~constants are different~~ parameterization for the velocity-mass-relation for cloud droplets from Seifert and Beheng (2006) is used for spherical ice crystals in this study. Constants that differ for a hexagonal plate or rosette crystal ~~,~~ ~~they~~ are given in Table A4 and A6.

Symbol	Long Name	Value
α	coefficient for the velocity-mass-relation for cloud droplets (Seifert and Beheng, 2006, Table 1)	$3.75 \times 10^5\ \mathrm{m\,s^{-1}\,kg^{-\beta}}$
β	coefficient for the velocity-mass-relation for cloud droplets (Seifert and Beheng, 2006, Table 1)	$2/3$
γ	coefficient for the velocity-mass-relation for cloud droplets (Seifert and Beheng, 2006, Table 1)	1
$\rho_{\mathrm{air},0}$	reference density of air	$1.225\ \mathrm{kg\,m^{-3}}$
ρ_{i}	density of ice	$0.92 \times 10^3\ \mathrm{kg\,m^{-3}}$

(Lawson et al., 2019; Heymsfield and Iaquinta, 2000). And ice crystals have been found to evolve into spherical shape while sublimating (Nelson, 1998), which makes these ideal shapes to use. Additionally, the computations were run for plate like ice crystals, which experience intermediate drag and can also occur in cirrus clouds (Libbrecht, 2005), to include an ice crystal type used in Vassel et al. (2019). The equations shown refer to the spherical particle. Information for the computations using hexagonal plates and bullett rosettes is given in Tables A3 and A4 in the Appendix.

The sublimation algorithm was applied in $0.01\,\mathrm{s}$ timesteps ($\mathrm{d}t$) as follows, where the initial height of the ice particle was *icebase*. The variables and constants used are given in Tables 1 and 2. The mass of the ice crystal was calculated from the radius:

$$m[0] = \frac{4}{3} r[0]^3 \rho_i \pi \tag{1}$$

For a sphere, the capacitance of the ice particle is simply equal to the radius at timestep i (Lohmann et al., 2016, pg. 240):

$$C = r[i] \tag{2}$$

Following Lamb and Verlinde (2011), the change in mass is

$$\mathrm{d}m = 4\pi C[i]\rho_{\mathrm{i}} G[i] s[i] f[i] \mathrm{d}t \tag{3}$$

which was used to time step mass and radius of the ice crystal:

$$m[i+1] = m[i] + \mathrm{d}m \tag{4}$$

$$r[i+1] = \sqrt[3]{\frac{3m[i+1]}{4\rho_{\mathrm{i}}\pi}} \tag{5}$$

using the ventilation factor f determined from Eq. (A5). The fall speed is calculated following Seifert and Beheng (2006), with coefficients given in Table 2, and used to timestep the height of the particle:

$$v[i+1] = \alpha m[i+1]^{\beta} \left(\frac{\rho_{\mathrm{air},0}}{\rho_{\mathrm{air}}}\right)^{\gamma} \tag{6}$$

$$z[i+1] = z[i] - v[i+1] \cdot \mathrm{d}t \tag{7}$$

Equations used to generate the values needed in the above equations are given in Appendix A, with additional variables and constants in Tables A1 and A2.

In ~~the calculations~~between cloud layers, small up- or downdrafts can be expected. For lack of reliable data on such small scales, the updraft velocity was not considered in the sublimation calculations. Also, radiative heat transfer to and from the ice particles was ignored since Hall and Pruppacher (1976) found that it “is only of secondary importance in determining [an ice particle’s] survival distance in subsaturated air”. While the calculations are based on a scheme developed in Vassel (2018), here additional factors such as the ventilation factor and the temperature dependency in the dynamic viscosity were added. Furthermore, Vassel et al. (2019) used mass-diameter relations and fall speed derived in Mitchell (1996), which in this study are taken from Pruppacher and Klett (2010), Heymsfield and Iaquinta (2000) and Seifert and Beheng (2006) due to the differing ice crystal types used here.

The timestepping script was set to run for a day, but was stopped when the particle had reached Earth’s surface or sublimated (zero mass or a radius less than 10^{-8} m). The sublimation height was returned and compared to the height of the mixed-phase cloud top, which was derived from *icebase* and ~~Δz_{il}~~Δz_{im} in the DARDAR data. When the sublimation height was lower than the height of the mixed-phase cloud top, the ice crystals at that grid point were marked as seeding.

These calculations present a conservative estimate. In reality, ice crystals have a size distribution. The large ice crystals within a distribution survive longer sedimentation distances than the ones with the effective radius, for which the survival is calculated. Also, the effective radius of ice crystals is underestimated in DARDAR v2 compared to the newer version v3 (which is not available yet), by 5 % to as much as 40 % (Cazenave et al., 2019).

3 Results and Discussion

3.1 DARDAR data

3.1.1 Distribution of distances between ice and mixed-phase cloud layer

Figure 3 shows the average frequency of ~~Δz_{il}~~Δz_{im}, the distance between the cirrus and mixed-phase cloud, within the DARDAR data set (as described in Sect. 2.1.1, any cloud at temperatures $> -35\,°\mathrm{C}$ is termed mixed-phase in this study). It can be understood as the average distribution of ~~Δz_{il}~~Δz_{im} within a unit area. 69 % of all measurements do not show a cirrus-mixed-phase cloud distance at all. In those cases, either only clouds of one category were present, or none at all (30 % of the measurements are cloud free). ~~32~~31 % of the measurements contain both a cirrus and a mixed-phase cloud simultaneously. This is the percentage of cases in which a seeding of the lower cloud by ice crystals falling from the ice cloud above is possible.

Tailoring this result to the sedimentation of ice crystals from a cirrus cloud, of when only the measurements that detect a cirrus cloud also detect a lower are taken into account, in 75 % of these measurements also a mixed-phase cloud . below them is detected.

In of these cases 44 % of the cases with a detected cirrus cloud (18 % in total), Δz_{il} Δz_{im} is smaller than 100 m. This may either be the case when the cirrus and the mixed-phase cloud are truly separated by a small distance, or when the two differently classified layers are actually part of the same cloud. From the construction of the classification algorithm, the latter would be the case when the $-35\,°\mathrm{C}$ isotherm intersects the cloud. This case is illustrated in Fig. 1b. In contrast to Mace et al. (2009) and Vassel et al. (2019), our algorithm does not require a cloud-free layer in between the mixed-phase and the cirrus cloud, so we also observe a potential for in-cloud seeding. However, clouds connected by sedimenting ice would also be seen as a cirrus cloud with a very small or no distance to the next mixed-phase cloud in our analysis. Ansmann et al. (2009) observed ice virga between the seeder and the feeder cloud and Mace et al. (2009) also mentioned this as a cause of misclassification in their study. Of course, in cases where the $-35\,°\mathrm{C}$ isotherm lies within the cirrus cloud, there could be another mixed-phase cloud underneath. The distance to this second cloud does not appear in our analysis.

The other half of the cases ($\Delta z_{\mathrm{il}} >$ $\Delta z_{\mathrm{im}} \geq$ 100 m) represents the classical external seeder-feeder situation, with a cirrus cloud clearly separated from a mixed-phase cloud below (see Fig. 1a). The Δz_{il} Δz_{im} are distributed equally between 2000 m and 6000 m, increase for smaller and decrease for larger $\Delta z_{\mathrm{il}}$$\Delta z_{\mathrm{im}}$. The smaller frequencies at $\Delta z_{\mathrm{il}} <$ $\Delta z_{\mathrm{im}} \leq$ 2000 m are due to the few possibilities for both cirrus and mixed-phase cloud to be located close to the $-35\,°\mathrm{C}$ isotherm. Because the cirrus cloud frequency decreases for large heights, the Δz_{il} Δz_{im} occurrence frequency decreases as well for $\Delta z_{\mathrm{il}} > 6000$ m$\Delta z_{\mathrm{im}} \geq 6000$ m. Generally speaking, Δz_{il} Δz_{im} increases with increasing upper cloud height (see Fig. B2).

In this distribution and in the following analysis, the effect of vertical wind shear of the horizontal wind cannot be taken into account, because the satellite retrieval only obtains instantaneous profiles, without any information on their temporal development. In the time that ice crystals need to sediment distances of a few kilometers, undoubtedly the clouds in question move relative to each other when wind shear is present. However, this movement can go in both ways, either removing or creating a multilayer cloud situation. On average, these two effects are expected to cancel out, so that the results with and without considering wind shear should be similar.

Our results for multi-layer cloud occurrence frequencyare similar to but , 13 % ($\Delta z_{\mathrm{im}} \geq 100$ m), are smaller than the ones given in the following literature. In their analysis of CALIPSO and CloudSat data, Mace et al. (2009) estimated the global occurrence of multiple layers to be 24 %. Wang et al. (2000) derived an estimate of 42 % from a radiosonde dataset. Of course the domain around Switzerland in this study is not expected to reproduce the global average, but Fig. 17a in Mace et al. (2009) and Fig. 5 in Wang et al. (2000) show average frequencies for Switzerland that are similar to the global average frequency. Using CloudSat and CALIPSO data as well, Matus and L'Ecuyer (2017) found an average multilayer cloud fraction of about 25 % for the mid latitudes of Switzerland. The layers derived from radiosonde data by Wang et al. (2000) are much thinner than the ones found with remote sensing, possibly because large sedimenting particles cause multiple thin layers to be identified as one large layer by the radar (Mace et al., 2009). One might therefore expect that the results from this current satellite study are closer to the ones from Mace et al. (2009) and Matus and L'Ecuyer (2017). Most importantly, the present study only

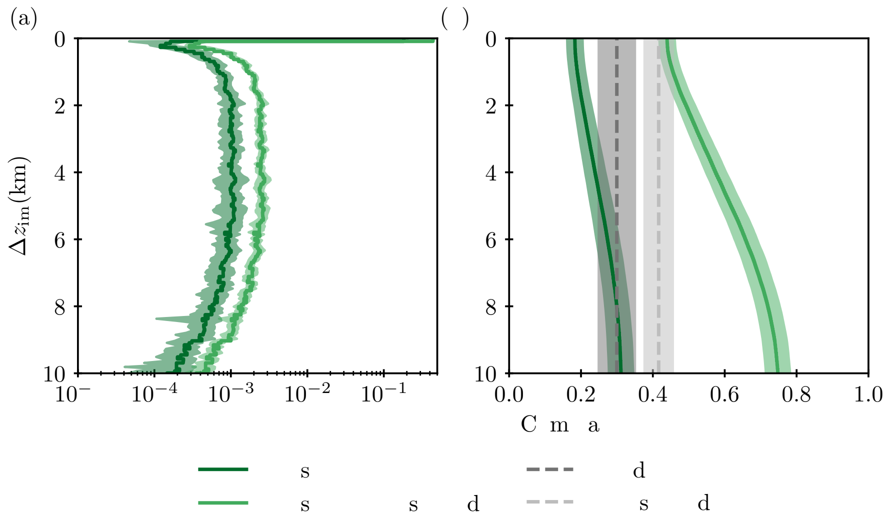

Figure 3. (a) Occurrence frequency of seeder-feeder situations (SF sit.) with respective ~~Δz_{il}~~ Δz_{im} as a fraction of measurements (dark green) or cirrus cloud measurements (light green). **(b)** Cumulative occurrence frequency. For ~~Δz_{il}~~ Δz_{im} a vertical resolution of 60 m is used. For comparison, the fraction of measurements with at least one cirrus cloud (light grey) and with a cloud free ~~atmposphere~~ atmosphere (dark grey) are given. Here and in the following data from all tracks in the study time (2006 to 2017) and within the study domain were used (2210 satellite tracks). The total number of measurements is ~~1440312~~853833, with ~~853833~~ 267354 measuring ~~Δz_{il}~~ Δz_{im} and 355331 measuring cirrus clouds. The shaded areas visualize the standard deviation of interanual variablility. Note that ~~$\Delta z_{\mathrm{il}} = 0$ m~~ $\Delta z_{\mathrm{im}} = 0$ m is at the base of the lowest cirrus cloud layer with $T < -35\,^{\circ}$C.

looks at multiple layer occurrence between cirrus and mixed-phase clouds, which is lower than the total multilayer occurrence frequency. As a proxy for this, one might use the relative occurrence frequency of low with high and mid with high clouds from Mace et al. (2009) (about 70 % and 10 %), relative to their overall multilayer occurrence frequency of 24 %. Their resulting absolute high with low or mid cloud layer occurrence frequency is then approximately 20 %. The result for two cloud cases in this study of ~~15~~13 % is smaller than the value derived by Mace et al. (2009), although they used even more restrictive conditions for their classification of multiple layers, requiring almost 1 km of cloud free space in between them. As mentioned before, the in-cloud seeder-feeder situations provide no information on the occurrence of mixed-phase layers below, hiding possible two cloud cases. Cirrus clouds in the tropical tropopause layer and clouds close to the surface are known to be missed by the radar and lidar on CloudSat and CALIPSO (Chan and Comiso, 2011; Liu et al., 2015; Krämer et al., 2020), but these are not relevant for this study.

3.1.2 Effect of topography

A geographical difference in cloud cover could be expected from the differing impacts that weather regimes have on different European regions in general (Pasquier et al., 2019; Grams et al., 2017). The study domain contains locations with a large range

Table 3. ~~Δz_{ll} climatology~~ Δz_{im} seasonality: Fraction (%) of ~~Δz_{ll}~~ Δz_{im} smaller than 100 m and larger than 100 m in all measurements with the specified surface height, for summer vs. winter and day vs. night (Julian days ≥ 106 and < 289 are summer, hours ≥ 6 and < 18 are day). ~~Δz_{ll}~~ In total, 31 % of the measurements contain both a cirrus and a mixed-phase cloud. Δz_{im} up to 12 km in length were evaluated.

		Whole domain		Surface < 1 km	
Season	Time of day	~~$\Delta z_{ll} < 100$ m~~ $\Delta z_{im} < 100$ m	~~$\Delta z_{ll} > 100$ m~~ $\Delta z_{im} > 100$ m	~~$\Delta z_{ll} < 100$ m~~ $\Delta z_{im} < 100$ m	~~$\Delta z_{ll} > 100$ m~~ Δz_{im}
All	All	18	13	18	13
	Day	18	13	18	13
	Night	18	14	18	14
Summer	All	17	11	16	12
	Day	17	11	16	12
	Night	16	12	16	12
Winter	All	21	15	21	14
	Day	21	13	20	14
	Night	21	17	21	17

of surface altitudes (see Fig. 2). One could imagine the ~~Δz_{ll}~~ Δz_{im} to be smaller in the Alps than over the Swiss Plateau, simply because of a thinner troposphere over orography. Also the orographic forcing would be expected to increase cloud cover. For an analysis of topographical influence, we split the dataset by surface altitudes above or below 1 km and analyse the distribution of ~~Δz_{ll}~~ Δz_{im}, shown in Table 3. The difference in the fraction of distances larger than 100 m between locations with a topography higher or lower than 1 km is less than 1 %. The distribution of total ~~Δz_{ll}~~ Δz_{im} between mountaineous terrain and flat land reproduces the distribution of measurements (about 30 % are taken over orography higher than 1000 m and about 70 % over terrain lower than 1000 m, not shown). Contrary to what we expected, we find no topographical effect in the distribution of ~~Δz_{ll}~~ Δz_{im} (see also Fig. B1).

3.1.3 Effect of season and time of day

Table 3 also contains the results of ~~a climatological analysis of Δz_{ll}~~ the seasonal analysis of Δz_{im}. Winter measurements have more multi-layer clouds according to our definition than summer measurements. The relative increase of the fractions of Δz_{im} is similar for the smaller (~~$\Delta z_{ll} < 100$ m~~ $\Delta z_{im} < 100$ m) and the larger distances (~~$\Delta z_{ll} > 100$ m~~ $\Delta z_{im} > 100$ m). In particular, winter nights have the highest fraction of multiple layer cloud measurements. Multiple cloud layers are about 23 % more frequent in winter nights than in summer nights, mostly due to an increase in ~~Δz_{ll}~~ Δz_{im} larger than 100 m. ~~There is no noticeable difference in frequencies during~~ Other than the increase in Δz_{im} during night in winter, there are no substantial differences in frequencies between day and night within a seasonal category.

The simplest explanation for the increased frequency of multi-layer clouds in winter measurements is simply an increased cloud cover in winter. To see whether this is a robust finding, it was tested with the CALIPSO-GOCCP dataset (Chepfer et al., 2010, 2013). With a comparison of *frac_cov* from DARDAR vs. CALIPSO cloud cover data (Fig. C1), the two datasets were found to mostly agree. Therefore, the CALIPSO dataset can be used to validate the hypothesis of an increased cloud cover in winter. Indeed in CALIPSO, total winter cloud cover is higher over almost the whole domain (Fig. C1c). The increase of cloud cover in winter is strongest for low and high clouds (low clouds: pressure $> 680\,\mathrm{hPa}$, height $< 3.2\,\mathrm{km}$, high clouds: pressure $< 400\,\mathrm{hPa}$, height $> 6.5\,\mathrm{km}$ in the CALIPSO data; not shown). This confirms the finding that in winter we see an increase in both small and large Δz_{il} Δz_{im}. In addition, *icebase* is lower in winter (not shown), in particular for $\Delta z_{\mathrm{il}} < 100\,\mathrm{m}$ $\Delta z_{\mathrm{im}} < 100\,\mathrm{m}$, which also increases the number of Δz_{il} Δz_{im}.

3.1.4 Ice crystal effective radius and cirrus cloud origin

The DARDAR dataset provides the mean effective ice crystal radius, which we use in our sublimation calculations. In Fig. 4, the size distribution is displayed by the ice crystals' occurrence height, namely the lowest cirrus cloud base heights (*icebase*). The ice crystal size range, between $25\,\mu\mathrm{m}$ and $60\,\mu\mathrm{m}$ in radius, agrees with the one found in another DARDAR study by Hong and Liu (2015). It is also within the range from $1\,\mu\mathrm{m}$ to $100\,\mu\mathrm{m}$ that Krämer et al. (2009) Krämer et al. (2009, 2020) find for cirrus clouds in aircraft campaigns.

There is a visible trend for smaller ice crystals at higher altitudes. This again agrees with Hong and Liu (2015) and Heymsfield et al. (2013), who find that ice crystal size decreases with decreasing temperature. An interesting feature in Fig. 4a is that while the shape of the distribution is rather symmetrical around this trend, large ice crystals abruptly stop appearing at heights larger than about $9.5\,\mathrm{km}$. This hints to two modes within the size distribution. These have been found in earlier studies, and have lately been linked to the different origins of cirrus clouds by Luebke et al. (2013), Luebke et al. (2016), Krämer et al. (2016), Wernli et al. (2016), Gasparini et al. (2018), Wolf et al. (2018) and Wolf et al. (2019). These studies distinguish in situ origin cirrus clouds , which form by homogeneous nucleation of solution droplets or heterogenous nucleation of ice nucleating particles within the cirrus temperature range, and liquid origin clouds, which form Liquid origin clouds form from supercooled water droplets which are uplifted to the cirrus temperature rangeand . They freeze either heterogeneously at warmer temperatures or predominantly homogeneously at temperatures below around $-35\,^{\circ}\mathrm{C}$. In the cirrus temperature range, cirrus clouds can also form by homogeneous nucleation of solution droplets or heterogeneous nucleation on ice nucleating particles. These cirrus clouds are termed in situ origin cirrus clouds. The two types mostly differ in their ice water content and the ice crystal size, with both being larger for liquid origin cirrus clouds (Luebke et al., 2016).

We split the dataset into one part with $\Delta z_{\mathrm{il}} > 100\,\mathrm{m}$ $\Delta z_{\mathrm{im}} > 100\,\mathrm{m}$ and one with $\Delta z_{\mathrm{il}} < 100\,\mathrm{m}$ $\Delta z_{\mathrm{im}} < 100\,\mathrm{m}$ as a proxy for the two cloud origins: in situ origin cirrus have large distances to the next underlying mixed-phase cloud, while liquid origin cirrus appear close to the $-35\,^{\circ}\mathrm{C}$ isotherm. This separation indeed produces two different modes, as can be seen in Fig. 4b and 4c. Figure 4b corresponds to liquid origin cirrus clouds. It displays larger ice crystals, from $\approx 35\,\mu\mathrm{m}$ to $\approx 90\,\mu\mathrm{m}$ at cirrus cloud base heights from $4500\,\mathrm{m}$ to $9500\,\mathrm{m}$, with an abrupt decrease in occurrence frequency at cirrus cloud base heights higher than $9500\,\mathrm{m}$. The decrease at the maximum cirrus cloud base height is associated with $\Delta z_{\mathrm{il}} < 100\,\mathrm{m}$ $\Delta z_{\mathrm{im}} < 100\,\mathrm{m}$ (see Fig. B2). On the other hand, The in situ cirrus clouds in Fig. 4c displays display smaller crystals, from $\approx 30\,\mu\mathrm{m}$ to $\approx 60\,\mu\mathrm{m}$, over a larger cirrus cloud height range, from roughly $6\,\mathrm{km}$ to $13\,\mathrm{km}$. Here the trend of smaller ice crystals at larger cirrus cloud heights is obvious. Figure 4 confirms the distinction between in situ and liquid origin liquid origin and in situ cirrus clouds as

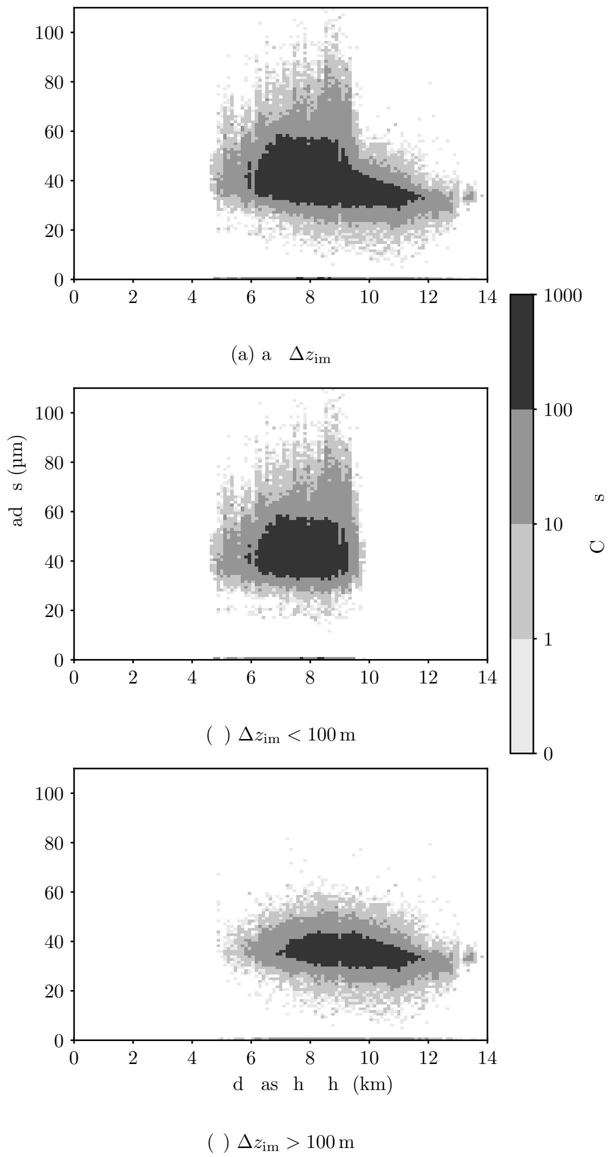

Figure 4. Distribution of *reff*. **(a)** For all multilayer clouds. **(b)** Only those data points with a distance $< 100\,\mathrm{m}$ to the next mixed-phase cloud top. **(c)** Only those data points with a distance $> 100\,\mathrm{m}$ to the next mixed-phase cloud top.

proposed e.g. by Krämer et al. (2016). It also confirms the finding from Luebke et al. (2016) that liquid origin cirrus clouds are composed of larger ice crystals.

There are a few caveats to this result. First, by the construction of the classification algorithm, in situ cirrus clouds are sampled for the ice crystal radius at their base, while liquid origin clouds are sampled in the interior. However, this difference is expected to have the opposite effect of what we observed (larger ice crystals for liquid origin clouds). At the cloud bases, the ice crystals are expected to be larger than in their middle (Miloshevich and Heymsfield, 1997; Heymsfield and Iaquinta, 2000), simply because of larger particles sedimenting further down within a cloud. Secondly, the classification scheme only has liquid origin clouds in the $\Delta z_{\mathrm{il}} < 100\,\mathrm{m}$ $\Delta z_{\mathrm{im}} < 100\,\mathrm{m}$ part, while liquid origin clouds that have been uplifted entirely to heights above the $-35\,°\mathrm{C}$ isotherm are present in the second, in situ origin cirrus part of the dataset ($\Delta z_{\mathrm{il}} > 100\,\mathrm{m}$$\Delta z_{\mathrm{im}} > 100\,\mathrm{m}$), if such a lifting occurs. This erroneous classification has already been noted by Gasparini et al. (2018). However, Fig. 4c displays only one mode, missing any signal of the mode present in the $\Delta z_{\mathrm{il}} < 100\,\mathrm{m}$ $\Delta z_{\mathrm{im}} < 100\,\mathrm{m}$ part of the dataset (see Fig. 4b). This suggests that the influence of the liquid origin on the microphysical properties of the cirrus clouds is lost once the clouds are lifted, for example because the large ice crystals sediment out, or that lifting of entire clouds above the $-35\,°\mathrm{C}$ isotherm hardly ever occurs. Wernli et al. (2016), who investigated the frequency of the formation pathways in a trajectory-based analysis, already noted that ice crystal sedimentation and cloud turbulence could “potentially alter the local cirrus characteristics and ‘confuse’ the simple categorization”. This seems to be the case with the data presented here, or otherwise the data However, the distinctively different ice crystal size distributions for the two modes in Fig. 4b) and c) suggest that liquid origin clouds are not altered by sedimentation so much that they are confused for in-situ clouds. The data suggests that liquid origin clouds are hardly ever lifted entirely above the $-35\,°\mathrm{C}$ isotherm, which is likely because of their large vertical extent.

In a broader context, the results in Fig. 4 show that satellite data, in particular the DARDAR dataset, are valid means to explore the classification of cirrus clouds into liquid and in situ origin further, as it has been called for by Wolf et al. (2019).

Note that the ice crystals radii, the cirrus cloud base heights and the $\Delta z_{\mathrm{il}}$$\Delta z_{\mathrm{im}}$'s span a wide range of values (see Fig. 3 and 4). Therefore, sublimation calculations needed to be applied to each instance individually, as detailed in the next section.

3.2 Sublimation between cloud layers

As described in Sect. 2.2, the sublimation calculation was applied to each grid point within the DARDAR data that had a cirrus cloud present above a mixed-phase cloud layer, using DARDAR and ERA5 data as input. The sublimation height of the ice crystals was calculated three times, assuming spherical ice crystals, plates and bullet rosettes. If the sublimation height was lower than the mixed-phase cloud top, the case was marked as a seeder-feeder situation.

3.2.1 Variation of survival with environmental parameters

For the evaluation of the survival chance, only cases with $\Delta z_{\mathrm{il}} > 100\,\mathrm{m}$ $\Delta z_{\mathrm{im}} > 100\,\mathrm{m}$ were taken into account. Distances smaller than $100\,\mathrm{m}$ represent the in-cloud seeder-feeder mechanism, where ice crystals fall through saturated or supersaturated cloudy air only before interacting with other hydrometeors. Comparing Fig. 5a and 5b, one can see the effect of temperature and relative humidity: ice crystals only reach the lower cloud if $\mathrm{RH_i} > 90\,\%$. Only those starting at temperatures warmer than $-65\,°\mathrm{C}$ seed. At lower temperatures, the ice crystals sublimate, even if the air was supersaturated at the start of the sedimentation. Note that due to data storage constraints, we can only show the impact of the temperature and relative humidity at the starting cirrus cloud base height on the falling ice crystals. But height resolved ERA5 data of temperature and relative humidity was used for the calculations. These starting values can be seen as proxies for the values during sedimentation, but for large sedimentation distances of up to about $5\,\mathrm{km}$, the starting values are not representative. Vassel et al. (2019) conducted

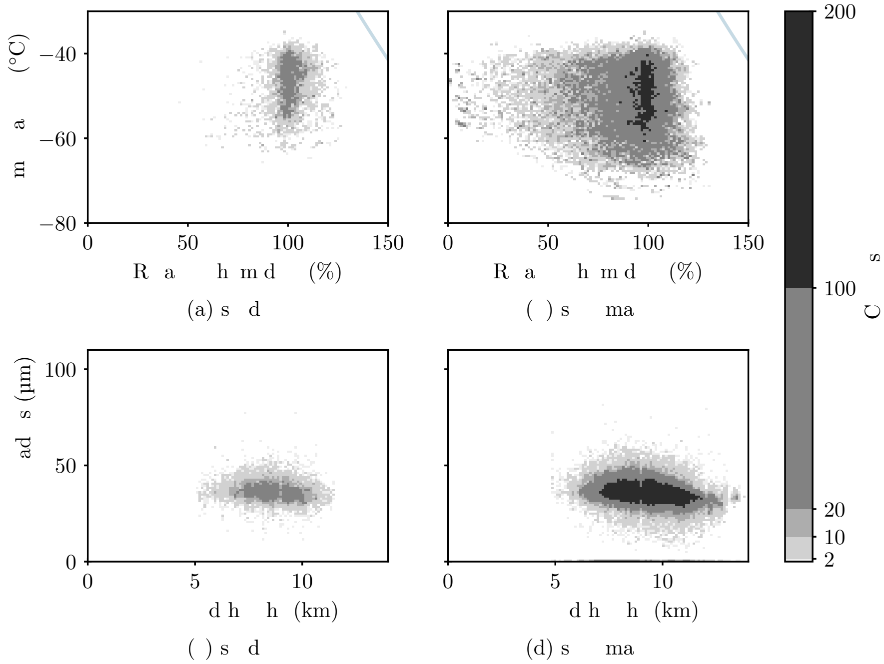

Figure 5. Environmental conditions at cirrus cloud base. Absolute frequency of temperature as a function of relative humidity with respect to ice at cirrus cloud bases with $\Delta z_{\mathrm{il}} > 100\,\mathrm{m}$ $\Delta z_{\mathrm{im}} > 100\,\mathrm{m}$ and **(a)** where spherical ice crystals survive the sedimentation and seed the lower cloud, **(b)** where spherical ice crystals sublimate before reaching the mixed-phase cloud. The light blue line depicts saturation with respect to water. Absolute frequency of effective ice crystal radius at cirrus cloud base as a function of cirrus cloud height with $\Delta z_{\mathrm{il}} > 100\,\mathrm{m}$ $\Delta z_{\mathrm{im}} > 100\,\mathrm{m}$ and **(c)** where spherical ice crystals survive the sedimentation and seed the lower cloud, **(d)** where spherical ice crystals sublimate before reaching the mixed-phase cloud. The sum of **(c)** and **(d)** is displayed in Fig. 4c. For improved readability the colorbar label for bin 1 is not shown.

a sensitivity study with relative humidities varying by $\pm 5\,\%$, but this variation is rather small. In this, their resulting seeding fraction does not change substantially. However, the relative humidity variations over the distances traveled by ice crystals in our calculations can exceed $5\,\%$ substantially.

Figure 5c shows that ice crystals do not survive the fall from cirrus cloud base heights above $11\,\mathrm{km}$. We attribute this to smaller ice crystals at these colder temperatures and to the fact that high cirrus cloud bases correspond to large distances to lower lying mixed-phase clouds that ice crystals are less likely to survive. This also explains why ice crystals starting their sedimentation at colder temperatures sublimate more often before reaching a lower cloud than those sedimenting from warmer cloud bases, as the temperature limit of $-65\,^{\circ}\mathrm{C}$ corresponds to the height limit of $11\,\mathrm{km}$ (see Figure 5). Both Hall and Pruppacher (1976) and Vassel et al. (2019) identified the ice crystal size as important determinant for ice crystal survival. Here, we find that ice crystals with radii smaller than $30\,\mu\mathrm{m}$ usually do not survive the sedimentation. On the other hand also larger

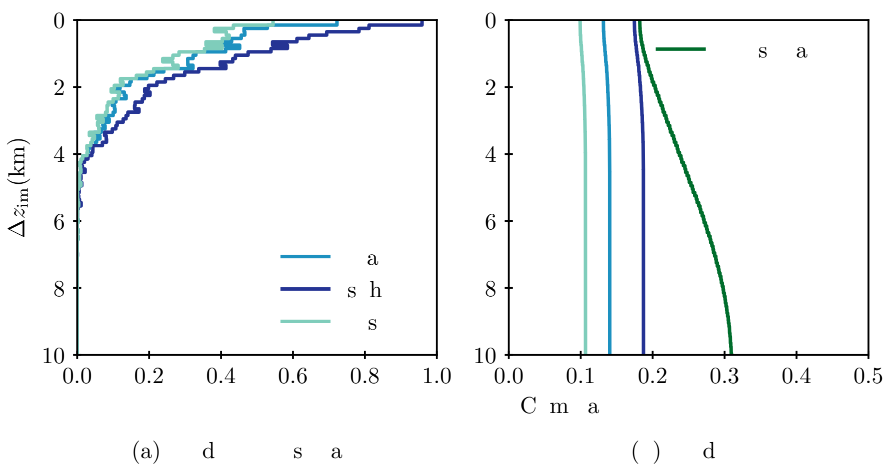

Figure 6. (a) Seeding cases per seeder-feeder situation. **(b)** Cumulative occurrence frequency of possible seeder-feeder situations (SF situation, green), and successful seeding assuming plate like, spherical and bullet rosette ice crystals. Note that ~~$\Delta z_{\rm il} = 0$ m~~ $\Delta z_{\rm im} = 0$ m is at the base of the lowest cirrus cloud layer with $T < -35\,^\circ$C.

ice crystal sizes, above $50\,\mu$m, do not guarantee a successful seeding. Note that we only evaluate the mean ice crystal size is used in this study so that the large spread which occurs in ice crystal size distributions is not represented.

For both the analysis of environmental parameters and DARDAR variables on ice crystal survival, the results assuming ice crystals to be plates and bullet rosettes are similar to those presented in here. One marked difference is that crystals starting in a subsaturated environment with respect to ice sublimate and do not seed when assuming them to be plates or bullet rosettes (see Fig. B3).

A comparison to literature data is difficult because the assumptions vary greatly between studies. Hall and Pruppacher (1976) compute sublimation heights for ice particles with an initial radius of $160\,\mu$m, at fixed relative humidities with respect to ice between $30\,\%$ and $90\,\%$. Their spherical ice particles sublimated at distances of 1 km to 4 km from the starting altitude of about 9 km. The relative humidities that we find at the starting altitudes are similar to their range, as are our survival distances. Vassel et al. (2019) did not provide information on the distances between the cloud layers they studied. Preliminary work in Vassel (2018) contained the result of two exemplary sublimation calculations assuming constant temperature and relative humidity in the subsaturated layer. Her result is in line with the results presented in Fig. 6, where about $42\,\%$, $47\,\%$ or $64\,\%$ of cases with ~~$\Delta z_{\rm il} = 500$ m~~ $\Delta z_{\rm im} = 500$ m lead to successful seeding (for rosettes, plates and spheres respectively).

3.2.2 Influence of the ice crystal shape

The fraction of ~~$\Delta z_{\rm il}$~~ $\Delta z_{\rm im}$ with successful seeding is shown in Fig. 6 for plates, spherical ice crystals and bullet rosettes. For ~~$\Delta z_{\rm il} > 5$ km~~ $\Delta z_{\rm im} > 5$ km, there is a only a slight chance for ice crystals to survive the fall between the cirrus and the underlying mixed-phase cloud. For ~~$\Delta z_{\rm il} = 2$ km~~ $\Delta z_{\rm im} = 2$ km the survival rate of spherical ice crystals increases to $20\,\%$.

Survival chances increase linearly, until $81\,\%$ of the spherical ice crystals cause seeding at a falling distance of $200\,\mathrm{m}$. Plate like ice crystals experience a larger drag force and therefore fall slower than spheres. As they have more time to sublimate during their slower fall, they are less likely to survive at any of the distances. This was also found by Hall and Pruppacher (1976), and is even more pronounced for bullet rosettes. Combining this with the respective ~~Δz_{il}~~ Δz_{im} frequencies, Fig. 6 also displays the fraction of successful seedings in our measurements. In $14\,\%$ of the measurements, we see a seeder-feeder situation where plate-like ice crystals do not sublimate but can seed the lower lying cloud after sedimentation ($11\,\%$ for rosettes, and $19\,\%$ for spheres).

A surprising result for all ice crystal shapes is that the survival fraction for ~~$\Delta z_{\mathrm{il}} < 100\,\mathrm{m}$~~ $\Delta z_{\mathrm{im}} < 100\,\mathrm{m}$ is smaller than 1. As explained before, there is no subsaturated layer in this continuous cloud, so the sedimenting ice crystals should not sublimate at all. The reason for the discrepancy most likely lies in the usage of two independent datasets in the classification of cloud layers and the calculation of ice crystal survival: the distance between the two layers and the cloud heights are taken from the DARDAR dataset, while the relative humidity was taken from ERA5. For example, the temperature profile in ERA5 over Switzerland is about $5\,^{\circ}\mathrm{C}$ colder than the one in the DARDAR data, which also originates from ECMWF. A reason for this discrepancy could not be found and it is not thought to change our findings significantly, but the discrepancy between the data sets should be investigated further. One might correct for this by simply setting the survival fraction to 1 within the ~~$\Delta z_{\mathrm{il}} < 100\,\mathrm{m}$~~ $\Delta z_{\mathrm{im}} < 100\,\mathrm{m}$ bin, i.e. within cloud. However, we chose to leave the inconsistency as an estimate of the uncertainty associated with the seeding fractions given for larger distances.

In general, as stated before, the ice crystal radius and hence the survival fraction shown in Fig. 6 are conservative estimates. In particular, with the new DARDAR dataset (v3) (Cazenave et al., 2019), survival fractions are expected to be higher than shown here for DARDAR v2, since the effective ice crystal radii are larger in the former (see Sect. 2). In their sublimation calculations, Vassel et al. (2019) use larger ice crystal radii of $100\,\mu\mathrm{m}$ for cirrus clouds as well. Additionally, there is the possibility of seeding by pre-activated particles even after the macroscopic ice crystal has sublimated, as described in Marcolli (2017). Some ice in pores or shielded pockets of these particles could survive the subsaturated air in between cloud layers and initiate new ice crystal formation once the particle reaches the supersaturated air in the lower cloud layer.

With the results presented here, one can comment on the method used in Seifert et al. (2009) to filter out ice clouds that were seeded. They simply reclassified any cloud with an ice cloud less than $2\,\mathrm{km}$ above as a liquid cloud. Given that Fig. 6 shows that only 10 to $20\,\%$ of ice crystals survive ~~$\Delta z_{\mathrm{il}} = 2\,\mathrm{km}$~~ $\Delta z_{\mathrm{im}} = 2\,\mathrm{km}$, it is likely that Seifert et al. (2009) find too many seeded clouds. Finally, comparing to observations, the case of a survival of ~~$\Delta z_{\mathrm{il}} = 5\,\mathrm{km}$~~ $\Delta z_{\mathrm{im}} = 5\,\mathrm{km}$, as the one case evaluated in Braham (1967), is rather unlikely according to our data.

4 Summary and conclusions

This study uses satellite data and sublimation calculations to establish the occurrence frequency of seeder-feeder cases over Switzerland. The seeder-feeder mechanism here refers to ice crystals that fall from a cirrus cloud into a lower cloud, where they ~~act as seeds for~~ initiate the glaciation of clouds.

In the DARDAR data, we distinguish two situations: in 13 % of all (including clear-sky) measurement cases, distances between the two cloud types are distributed uniformly between 100 m and 10 km. This is the classical external seeder-feeder situation, where the seeding ice crystals fall through clear air between two clouds. In-cloud seeder-feeder situations are found to occur in 18 % of all measurements. In total, seeder-feeder cloud situations were found to occur in 31 % of all measurements. As the estimate only includes cases with a cirrus cloud as the seeder cloud, it underestimates the total seeder-feeder cloud situation occurrence frequency. The frequency was found to not vary with the differing topography in Switzerland. Seasonally, winter nights exhibit the highest frequency of possible seeder-feeder situations due to an increased high cloud cover in winter and at night.

We find two modes for the ice crystals size at the base of cirrus clouds. These correspond to in situ and liquid origin cirrus clouds, which confirms the new classification scheme for cirrus clouds (Luebke et al., 2013, 2016; Krämer et al., 2016; Wernli et al., 2016;

In sublimations sublimation calculations we found that a significant number of ice crystals reached the lower cloud layers. 20 % of ice crystals survived distances of 2 km when assuming that they were spherically shaped. Assuming plate-like crystals or bullet rosettes in the calculations, only about 10 % of them survived 2 km distances. On the one hand, this clearly shows that natural cloud seeding occurs regularly over Switzerland. On the other hand, it demonstrates that in these calculations, the distinction between ice crystal shapes is critical, in contrast to the small ice crystal shape impact found in Vassel et al. (2019).

We found that ice crystals only survive the fall between cloud layers when the relative humidity with respect to ice at cirrus cloud base is larger than 90 %, while temperature seems to be of secondary importance. In terms of the ice crystal radius, ice crystals with effective radii smaller than 30 µm mostly sublimate before reaching the lower cloud layer. On the other hand, larger ice crystal sizes, above 50 µm, do not guarantee a survival.

Taking a broader perspective, this study demonstrates that satellite data is a viable mean to explore cloud distributions also in regional settings. It can be combined with timestepping calculations to study processes on which the satellite data, which is merely a snapshot in time, provides no information by itself.

Of course the scope of this work could be broadened in the future. This study focuses on natural cloud seeding that originates from cirrus clouds, but seeding ice crystals can also sediment from mixed-phase clouds. Additionally, multilayer clouds interact in other ways, for example via radiation (Christensen et al., 2013; Vassel, 2018). Moreover, seeing that natural cloud seeding occurs over Switzerland, the global distribution of seeder-feeder cloud situations and the seeding frequency are an interesting next goal of study. Differences in the global distribution of multilayer clouds have already been demonstrated (Mace et al., 2009), and Ansmann et al. (2009) observed an increase in in-cloud seeding frequency in their data from the tropics compared to data from the mid latitudes (Seifert et al., 2009), so a thorough study of global natural cloud seeding frequency promises to be interesting. The satellite data analysis within this study can easily be extended to a global dataset. Solely the sublimation calculations could not be applied to each measurement point in such a large dataset, but instead the seeding situations could be classified and sublimation calculations could be applied to the classes in a representative fashion. Future work could sample the whole range in ice crystal size distributions instead of only using the mean size to represent the distribution as done in this study.

We show that natural cloud seeding is a widespread phenomena over Switzerland. This hints to a large potential for natural cloud seeding to alter cloud properties and thereby influence Earth's radiative budget and water cycle, which should be investigated in future studies. We do so in a companion paper, using sensitivity simulations with the regional climate model COSMO.

Code and data availability. Analysis and plotting scripts are archived at https://doi.org/10.5281/zenodo.3987754. Generated data is archived at https://doi.org/10.5281/zenodo.3987757. DARDAR-CLOUD data can be obtained from the AERIS/ICARE Data and Services Center, ftp://ftp.icare.univ-lille1.fr/SPACEBORNE/MULTI_SENSOR/DARDAR_CLOUD/ (last access: 5 October 2020). Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), 7 November 2019.

Table A1. Variables used in the sublimation height calculation (addition to Table 1).

Symbol	Long Name	Units
e	saturation of vapour pressure in air	Pa
$e_{\mathrm{sat,i}}$	saturation vapour pressure with respect to ice	Pa
$e_{\mathrm{sat,w}}$	saturation vapour pressure with respect to water	Pa
L_{s}	latent heat of sublimation	$\mathrm{J\,mol^{-1}}$
μ	dynamic viscosity	$\mathrm{kg\,m^{-1}\,s^{-1}}$
N_{Re}	Reynolds number	-
p	pressure	Pa
RH	relative humidity	$\%$
ρ_{air}	air density	$\mathrm{kg\,m^{-3}}$
T	temperature in K	K
$T_{^\circ\mathrm{C}}$	temperature in $^\circ\mathrm{C}$	$^\circ\mathrm{C}$

Appendix A: Sublimation calculations

Here we detail the equations used in the sublimation calculations. Additional variables and constants used are given in Tables A1 and A2. Where they differ, equations and constants used for the computations for hexagonal plates are given in Tables A3 and A4.

At each timestep $i+1$ the barometric formula was applied to find the pressure corresponding to the height of the ice particle:

$$p = p_0 \left(\frac{T_{\mathrm{b}}}{T_{\mathrm{b}} + L_{\mathrm{b}} \cdot z[i]} \right)^{\frac{gM_{\mathrm{air}}}{RL_{\mathrm{b}}}} \tag{A1}$$

The density of the air surrounding the particle was calculated using the ideal gas law. The saturation vapour pressure of water with respect to ice and water was derived with the Magnus formula. And together with the relative humidity from the ERA5 data (given with respect to water), the supersaturation with respect to ice was calculated. The diffusivity of water vapour in air was calculated following Hall and Pruppacher (1976, Eq. 13):

$$D_{\mathrm{v}} = 0.211 \times 10^{-4} \left(\frac{T}{T_0} \right)^{1.94} \frac{p_0}{p} \tag{A2}$$

From this, the growth factor was determined following Lamb and Verlinde (2011, pg. 328):

$$G = \frac{1}{\frac{\rho_{\mathrm{i}} RT}{M_{\mathrm{w}} D_{\mathrm{v}} e_{\mathrm{sat,i}}} + \frac{\rho_{\mathrm{i}} L_{\mathrm{s}}}{M_{\mathrm{w}} k_{\mathrm{T}} T} \cdot \left(\frac{L_{\mathrm{s}}}{RT} - 1 \right)} \tag{A3}$$

which uses the latent heat of sublimation (valid between $236\,\mathrm{K}$ and $273.16\,\mathrm{K}$, Lohmann et al. (2016)):

$$L_{\mathrm{s}} = 46782.5 + 35.8925 \cdot T - 0.07414 \cdot T^2 + 541.5 \cdot e^{-\left(\frac{T}{123.75}\right)^2} \tag{A4}$$

Table A2. Constants used in the sublimation calculations for a sphere (addition to Table 2). Note that the parameterization for the velocity-mass-relation for cloud droplets from Seifert and Beheng (2006) is used for spherical ice crystals here. Where ~~they~~ the constants are different for a hexagonal plate, they are given in Table A4.

Symbol	Long Name	Value
g	gravitational constant	$9.81\,\mathrm{m\,s^{-2}}$
k_T	thermal conductivity of air	$0.024\,\mathrm{J\,m^{-1}\,s^{-1}\,K^{-1}}$
L_b	lapse rate	$-0.0065\,\mathrm{K\,m^{-1}}$
M_w	molecular mass of water	$18.02\times10^{-3}\,\mathrm{kg\,mol^{-1}}$
M_air	molecular mass of ~~Earh~~Earth's air	$28.9644\times10^{-3}\,\mathrm{kg\,mol^{-1}}$
μ_0	viscosity of air at $T=273\,\mathrm{K}$ and $p=101325\,\mathrm{Pa}$ (Seinfeld and Pandis, 2006, Table A.7, pg. 1178)	$1.72\times10^{-5}\,\mathrm{kg\,m^{-1}\,s^{-1}}$
p_0	reference pressure	$101325\,\mathrm{Pa}$
R	universal gas constant	$8.314\,\mathrm{J\,K^{-1}\,mol^{-1}}$
R_s	specific gas constant for air	$287.06\,\mathrm{J\,kg^{-1}\,K^{-1}}$
ρ_i	density of ice	$0.92\times10^{3}\,\mathrm{kg\,m^{-3}}$
S	Sutherland's constant for air (Chapman and Cowling, 1960, Table 15), in a temperature range from $0\,^\circ\mathrm{C}$ to $300\,^\circ\mathrm{C}$	114 ± 24
T_0	reference temperature	$273.15\,\mathrm{K}$
T_b	reference temperature in the barometric formula	$288.15\,\mathrm{K}$

and the ventilation factor is given by (Pruppacher and Klett, 2010, eq. 13-61):

$$f = 1.0 + 0.108\cdot\left(\frac{X}{10}\right)^2 \tag{A5}$$

where

$$X = 0.71^{\frac{1}{3}}\cdot N_\mathrm{Re} \tag{A6}$$

$$N_\mathrm{Re} = \frac{2U_\infty r \rho_\mathrm{air}}{\mu} \tag{A7}$$

(Lohmann et al., 2016, eq. 7.36). Where the Reynolds number exceeded the scope of the parameterization, the value for the ventilation factor from the last time step was used. For the terminal velocity, U_∞, v was used. The dynamic viscosity μ can be derived from Sutherland's formula (Chapman and Cowling, 1960, eq. 12.32-2), which can be rewritten and expanded to:

$$\mu = \frac{BT_0^{\frac{3}{2}}}{S+T_0} + \frac{B\sqrt{T_0}(3S+T_0)(T-T_0)}{2(S+T_0)^2} \tag{A8}$$

with $B = \frac{\mu_0\cdot(T_0+S)}{T_0^{\frac{3}{2}}}$.

Table A3. Equations used in the sublimation calculations for a hexagonal plate. The other equations used are the same as for a sphere and are given in the text.

Equation for hexagonal plates	Replaces Eq.
$C = 2r/\pi$ (Pruppacher and Klett, 2010, eq. 13-77)	(2)
$f = 1.0 - 0.6042 \cdot \left(\frac{X}{10}\right) + 2.79820 \cdot \left(\frac{X}{10}\right)^2 - 0.31933 \cdot \left(\frac{X}{10}\right)^3 - 0.06247 \cdot \left(\frac{X}{10}\right)^4$ where $X = 0.632^{\frac{1}{3}} \cdot N_{\mathrm{Re}}$ (Pruppacher and Klett, 2010, eq. 13-90b) and (Ji and Wang, 1999)	(A5)
$m = \rho_i \cdot 9.17 \times 10^{-3} \cdot (2r)^{2.475}$ (Pruppacher and Klett, 2010, Table 2.2a)	(1) and (5)

Table A4. Same as Table 2 but for hexagonal plates. Only those constants that differ from Table 2 are shown.

Symbol	Long name	Value
α	coefficient for the velocity-mass-relation for cloud ice (Seifert and Beheng, 2006, Table 1)	$317\,\mathrm{m\,s^{-1}\,kg^{-\beta}}$
β	coefficient for the velocity-mass-relation for cloud ice (Seifert and Beheng, 2006, Table 1)	0.363
γ	coefficient for the velocity-mass-relation for cloud ice (Seifert and Beheng, 2006, Table 1)	0.5
ρ_i	density of ice (Pruppacher and Klett, 2010, Table 2.3)	$0.9 \times 10^3\ \mathrm{kg\,m^{-3}}$

Table A5. Equations used in the sublimation calculations for bullet rosettes. The other equations used are the same as for a sphere and are given in the text.

Equation for bullet rosettes	Replaces eq.
$C = 0.434 \cdot n_{\mathrm{lobes}}^{0.257} \cdot r$ (Chiruta and Wang, 2003)	(2)
$f = 1.0 + 0.35463 \cdot \left(\frac{X}{10}\right) + 3.55333 \cdot \left(\frac{X}{10}\right)^2$ where $X = 0.632^{\frac{1}{3}} \cdot N_{\mathrm{Re}}$ (Pruppacher and Klett, 2010, eq. 13-90c) and (Ji and Wang, 1999)	(A5)
$m = \alpha_{\mathrm{br}} \cdot (2r \times 10^2)^{\beta_{\mathrm{br}}} \times 10^{-3}$ (Heymsfield and Iaquinta, 2000)	(1) and (5)
$\rho_i = 0.78 \cdot (r \cdot 10^3)^{-0.0038} \cdot 10^3 \mathrm{kg\,m^{-3}}$ (Pruppacher and Klett, 2010, Table 2.3)	ρ_i in Table A2
$v = x \cdot (2r \times 10^2)^y \times 10^{-2}$ (Heymsfield and Iaquinta, 2000)	6

Table A6. Same as Table 2 but for bullet rosettes. Only those constants that differ from Table 2 are shown.

Symbol	Long name	Value
α_{br}	coefficient for the mass-radius-relation (Heymsfield and Iaquinta, 2000)	1.25×10^{-5}
β_{br}	coefficient for the mass-radius-relation (Heymsfield and Iaquinta, 2000)	1.52
n_{lobes}	number of lobes in a bullet rosette (typical value, Heymsfield and Iaquinta (2000))	3
x	coefficient for the velocity-radius-relation (Heymsfield and Iaquinta, 2000)	2150
y	coefficient for the velocity-radius-relation (Heymsfield and Iaquinta, 2000)	1.225

Appendix B: Additional DARDAR analysis

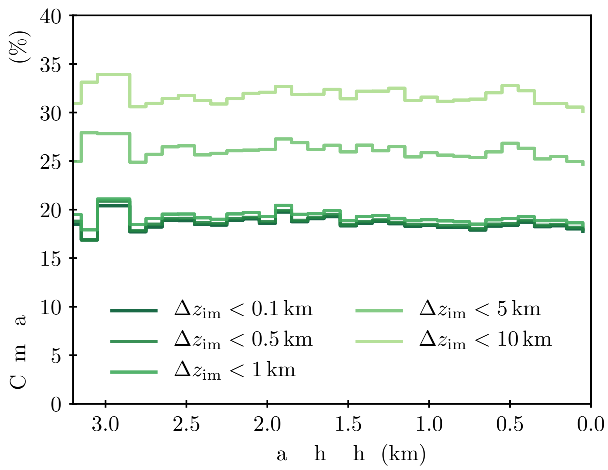

Figure B1. Distribution of ~~Δz_{ll}~~ Δz_{im} with underlying surface topography.

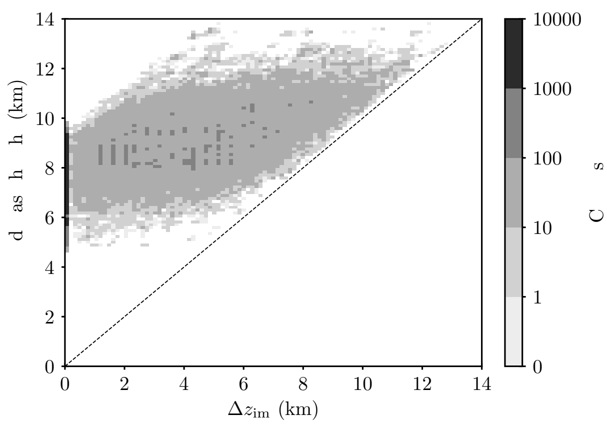

Figure B2. Distribution of *icebase* with ~~Δz_{ll}~~ Δz_{im}.

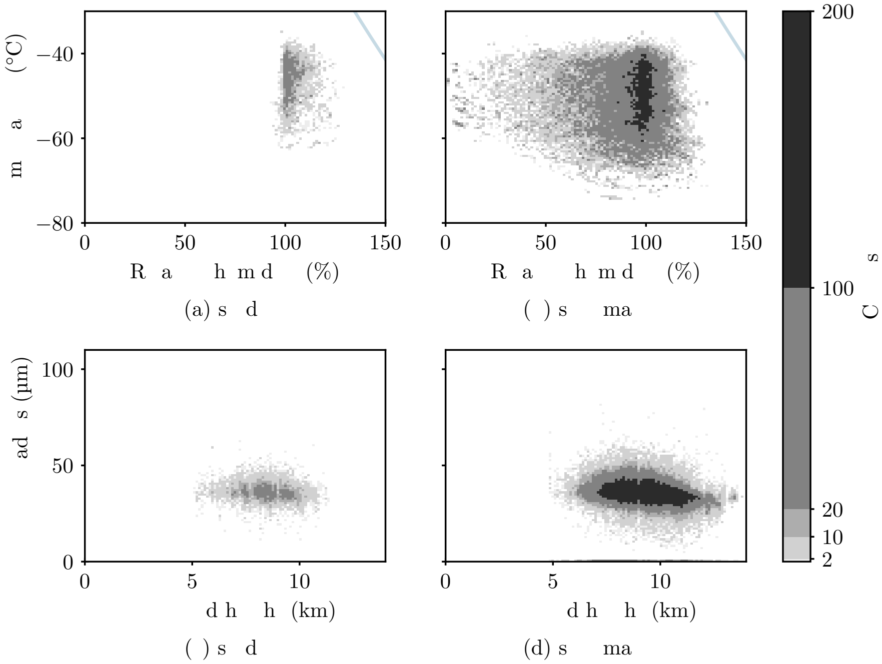

Figure B3. Same as Fig. 5, but assuming bullet rosettes as seeding ice crystals.

Appendix C: Cloud cover data comparison to CALIPSO

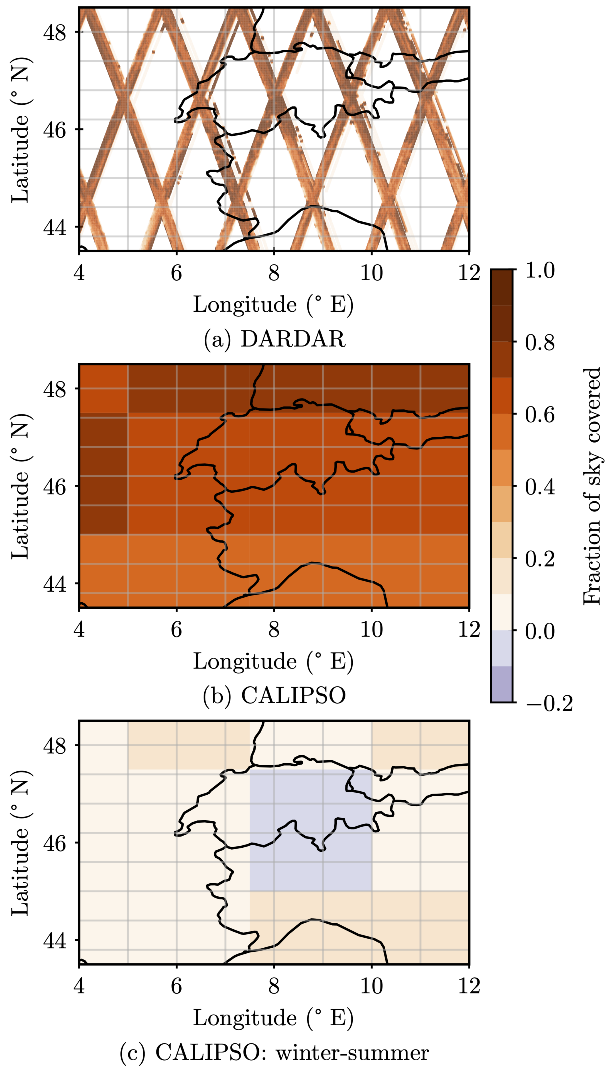

Figure C1. Comparison between **(a)** cloud cover derived from the DARDAR satellite product in this study and **(b)** CALIPSO-GOCCP total fraction of sky covered (2006-2017) (Chepfer et al., 2010, 2013). For the DARDAR data, the cloud cover was calculated as the mean (over all tracks within 2006-2017) of the sum of all fractions of sky covered (sum of frac_cov at all temperatures) at each grid point. Sums that were larger than 1 were set to be 1. This method corresponds to the assumption of minimal overlap. **c)** CALIPSO-GOCCP seasonal difference in total cloud cover. To allow for a visual comparison, DARDAR cloud cover data was filtered with a mean over 10×10 squares.

Author contributions. UP conducted the data analysis and sublimation calculations, analysed the results, and was the main author of the paper. VB developed the initial version of the data analysis and sublimation code. DN conceived the idea of the study. ZD, UL and DN contributed to the design of the study and the analysis of the results. All authors contributed to the writing of the study.

Competing interests. The authors declare no conflict of interest.

Acknowledgements. We are grateful for insightful comments from three anonymous reviewers, which helped clarifying the manuscript. We thank Maiken Vassel for her advice during the development of the sublimation calculations. We thank the AERIS/ICARE Data and Services Center for providing access to the data used in this study. Sublimation calculations were generated using Copernicus Climate Change Service Information. Throughout this study, the programming languages CDO (Schulzweida, 2018) and Python (Python Software Foundation, www.python.org) were used to handle data and analyse it. The satellite data analysis and the sublimation calculations were conducted with Python as well. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821205 (FORCeS).

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