Interactive comment on “Impact of surface and near-surface processes on ice crystal concentrations measured at mountain-top research stations” by Alexander Beck et al.

Anonymous Referee #1

We would like to thank the Anonymous Referee #1 for having reviewed this paper and his valuable comments and suggestions. We answer each of them hereafter (bold black) and add when needed the modifications in the revised version of the manuscript (bold blue).

I.) Point-by-point response to specific comments

1) I think the microphysical processes relevant to the work presented should be more clearly described or expanded on in the introduction. Relevant references are included, but I think it would be good to briefly describe in a bit more detail some of the main secondary ice processes in free floating cloud e.g. mechanical break up, rime-splintering, drop shattering. This helps the reader understand some of the mechanisms that are already thought to enhance ice concentrations.

We added a brief description of secondary ice mechanisms in free floating clouds and the production of ice crystals from surface processes to the introduction.

P2 L21: This discrepancy between ice nuclei and ICNC may be explained by so-called secondary ice-multiplication processes. A commonly accepted secondary ice-multiplication process to enhance ICNCs in free floating clouds is the rime-splintering or Hallett-Mossop process. This process describes the production of small splinters after the impact of cloud droplets on ice crystals and a subsequent burst of the cloud droplet during its freezing process. It is active only in a small temperature range between -3 to -8 _C and the presence of small (<~ 13 µm) and large (>~ 25 µm) cloud droplets is required (Hallett and Mossop, 1974; Choularton et al., 1980). Another secondary ice-multiplication process is the fracturing of fragile ice crystals upon collision with other solid cloud particles (Vardiman, 1978; Griggs and Choularton, 1986). Although this process has been studied in the lab and is expected to occur at temperatures of ~ -15 °C , there is little evidence from field measurements for this process to significantly contribute to the ICNC (e.g. Lloyd et al., 2014; Crosier et al., 2011; Crawford et al., 2012). Other processes that produce secondary ice crystals are associated with the freezing of cloud droplets and subsequent break-up or the ejection of small spicules (Lauber et al., 2018).

P3 L3: Riming as a surface process is similar to the previously described rime-splintering process in free floating clouds. For this process to be active, cloud droplets need to be present near the surface, as typically the case with orographic mixed-phase clouds.

P3 L8: Hoar frost describes the formation of vapor grown ice crystals on the crystalline snow surface, which may be detached due to mechanical fracture.

2) I’d like to see if it’s possible to look at only pristine ice crystals or only irregular ice crystals vs wind speed are the dependencies different? I think you say that in general the ratio of irregular to regular

ice crystals stays similar – but I don't think this is the case looking at the habit segregated figures of ICNC concentration vs altitude.

Figure 13 in the submitted manuscript shows the wind speed dependence of only pristine ice crystals and only irregular ice crystals of the measurements on 17 February 2017. As described in section 3.2 both show an increase of the ICNC by approximately a factor of 2 if the vertical wind speed increases from 0-2ms^{-1} to 4-6ms^{-1}. Figure 12 of the submitted manuscript also shows that the ratio of irregular to regular ice crystals stays similar for the different levels of the elevator. While the pristine ice crystals contribute with 20% to the total number the irregular ice crystals contribute with approximately 80%.

3) P6 L30 – This paragraph only really holds true with some pretty big assumptions, no irregular ice crystals are produced in cloud and are therefore only produced from the surface, and that pristine ice crystals are all produced in cloud with no contribution from the surface. Although still very early research I believe there's increasing evidence for pristine ice crystals generated from the surface – though the exact physical mechanisms and the optimum conditions for this to take place is still unclear. The paragraph is also confused by the previous statement that the SBO is out of cloud.

It is true, that these assumptions are questionable. Therefore, we added a paragraph to the discussion section to back up our thoughts on these assumptions. We also added the statement, that a significant contribution of regular ice crystals produced from surface processes can't be excluded and vice versa irregular crystals also originate in cloud. However, the separation in irregular and regular shaped ice crystals is realized as an additional analysis of possible mechanisms to enhance ICNCs near the surface.

P1 L10: **For one case study, the ICNC for regular and irregular ice crystals showed a similar relative decrease with height. This suggests that either surface processes produce both irregular and regular ice crystals or other effects modify the ICNCs near the surface.**

P7 L28: **To disentangle possible sources and mechanisms, which enhance the observed ICNCs at mountain-top research stations, the following discussion will be based on the observed height profile of the ICNC and the observed ice crystal shape.**

In the context of snow redistribution blowing snow has been studied thoroughly. For blowing snow, two main layers are distinguished. In the saltation layer, with a typical thickness of 0.01 – 0.02 m , snow particles are lofted and follow ballistic trajectories. Depending on the crystal size, the crystals in the saltation layer either impact on to the snow surface or are transported by turbulent eddies into the suspension layer (e.g. Comola et al., 2017; Gordon et al., 2009), which can extend up to a height of several 10s of meters above the surface. Nishimura and Nemoto (2005) and Mellor and Fellers (1986) observed the height dependence of blowing sow up to 10m over a flat surface in the Arctic and in Antarctica and found that particles reaching layers higher than 1 m above the surface are usually smaller than 100 µm and the particle concentration gradually decreases with height (Fig. 16 a). Similar to blowing snow we expect such a height dependence for any other surface process. As such, a gradual decrease of ICNCs with height is expected for any surface process and no height dependence is expected for ice crystals produced in free floating clouds.

While ice crystals observed in free floating clouds have mainly (> 80%) irregular habits (e.g. Korolev et al., 1999, 2006; Wolf et al., 2018), no studies have investigated the ice crystal shape produced by surface process like hoar frost, blowing snow or riming on trees, rocks or the snow surface. We expect irregular shapes for re-suspended ice crystals, i.e. blowing snow, due to mechanical fracturing upon their impact on the surface or due to successive melting and freezing of the ice crystals on the snow surface.

Ice crystals originating as hoar frost grow in regular shapes on the snow surface. If these vapor grown ice crystals keep their regular shape depends on the exact physical process how they are detached from the surface. While some ice crystals may keep their initial regular habit, for other ice crystals this regular habit may be destroyed when they are detached from the surface due to mechanical fracturing as described by Lloyd et al. (2015). Similar to blowing snow, the ICNC from hoar frost is likely to be increased near the surface, because only smaller ice crystals are lofted higher up. In this layer ice crystals are likely to collide and fracture. On the one hand, this reduces the probability to observe regular ice crystals from surface processes. On the other hand, if small regular and irregular ice crystals (~µm) are produced, they have the potential to grow into larger regular shaped ice crystals being observed at the measurement location.

4) Are there any useful references to convergence zones as described in section 4.1.2? I think convergence zones and sedimenting ice crystal theories need a much more thorough discussion, possibly under their own sub section headings. In its current form I don't find the explanations very well backed up.

The ideas of a convergence zone and sedimenting ice crystals to describe the observed profiles of regular and irregular ice crystals is new to our knowledge. Therefore, we can't provide any references to back them up. We see these explanations only as an alternative to possible influences from the surface and don't want to state that these ideas are the final explanations. We see section 4.1.2 more as a stimulation for further investigation of these idea.

5) ICNCs could be added to the microphysical time series figures.

We included the microphysical time series to the Figures 4 and 5.

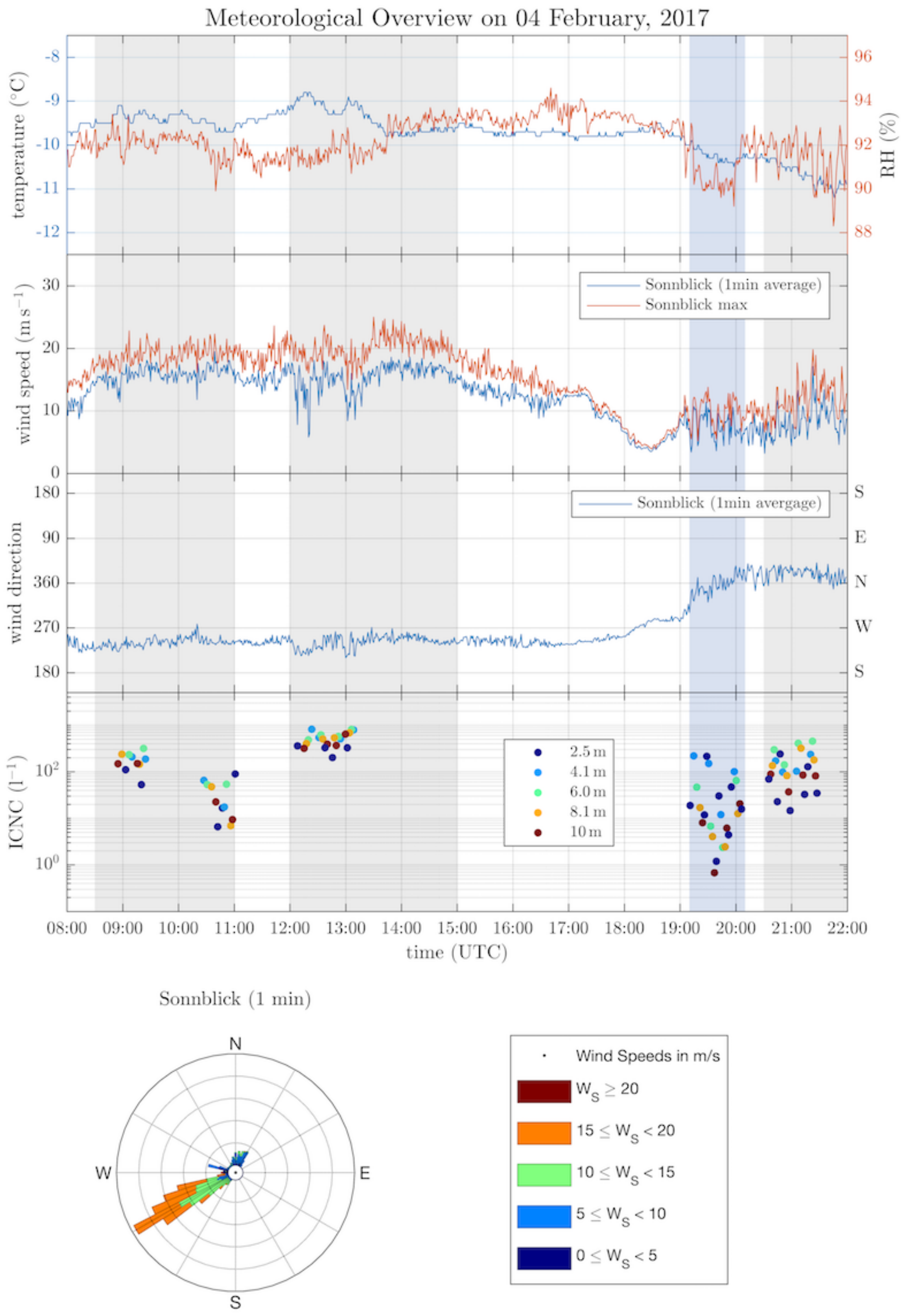

Figure 4: Overview of the meteorological and microphysical parameters on 4 February, 2017. Meteorological measurements are 1-minute averages except for the maximum wind speed, which corresponds to the maximum wind speed observed during a 1-minute average. The shaded areas represent intervals with ice crystal measurements with the SBO in-cloud (gray), respectively not in-cloud (blue). Shown are the temperature and relative humidity (top), wind speed (second from top) and wind direction (third from bottom). A windrose plot is shown in the bottom panel. The ICNC measurements (second from bottom) are averages for each height level during a single profile.

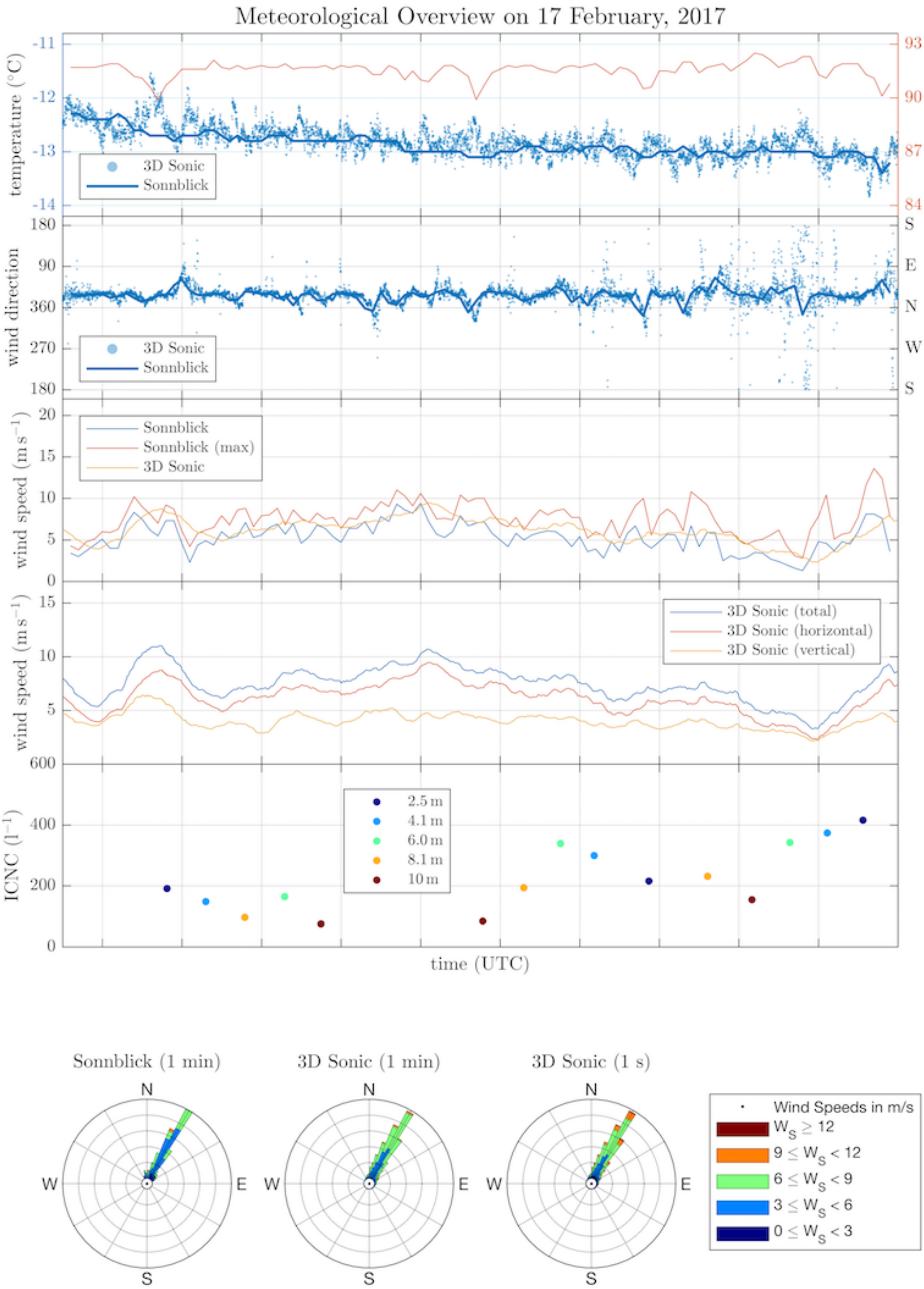

Figure 5: Overview on the meteorological and microphysical parameters on 17 February, 2017. On this day temperature and wind measurements are available from the SBO and the 3D Sonic Anemometer. Shown are the temperature and relative humidity (top), wind direction (second from top), a comparison of the horizontal wind speed (third from top) and detailed wind speed measurements from the 3D Sonic Anemometer (third from bottom). A windrose plot is shown in the bottom panel. The ICNC measurements (second from bottom) are averages for each height level during a single profile.

6) There's 2 different wind measurements – If possible I'd like to see a comparison between the two where available.

As described in the manuscript, temperature and wind measurements from both instruments, a 2D Sonic Anemometer operated by the Sonnblick Observatory and our own 3D Sonic Anemometer are available only for February 17th. Figure 5 of the submitted manuscript shows a comparison of the temperature, horizontal wind speed and wind direction measurements of these instruments. Since the Sonnblick Observatory operates a 2D Sonic, a comparison of the vertical wind speed is not possible.

7) Were the clouds glaciated/mixed phase at the site? Is there any information on the liquid phase from the holography?

Information on the liquid phase is also available. If a cloud was present (all the time except on 4 February 2017 between 1910 and 2030 UTC) the conditions were mixed-phase. However, in contrast to the ICNC, the CDNC shows no height dependence (see Fig. B). In the following, we show similar plots for the liquid phase as shown in the manuscript for the ice phase.

Figure A shows the height dependence of the CDNC on 4 February 2017 for the same profiles as shown for the ICNC in Figure 7 in the submitted manuscript. The CDNC is highly variable within single profiles. This implies that the cloud conditions have a high temporal variability, because a single profile was observed within approximately 15 min. This was confirmed by the inspection of webcam pictures from the Sonnblick Observatory and inspection of the raw holograms showed that this variability is not an artifact of the data analysis. However, the summary of all the profiles obtained in cloud on 4 February 2017 shows that the CDNC is constant with height (see Fig. B).

Figure C shows the height dependence of the CDNC on 17 February 2017. The CDNCs slightly decrease with height on this day.

Figure D shows the relationship between ICNCs and CDNCs. The highest ICNCs (> 1000 l^{-1}) are observed for lower CDNCs (< 40 cm^{-3}), whereas at high CDNCs (> 100 cm^{-3}) ICNCs are much lower (< 300 l^{-1}). This observation suggests, that the high ICNCs can`t be explained by the presence of high CDNCs.

We decided to include the summary plot on the height dependence of CDNCs into the manuscript to show that the high ICNC can't be explained by the presence of cloud droplets. Therefore, we added Figure B to Figure 6 of the revised manuscript.

P6 L1: Figure 6 shows a summary of the height dependence of ICNCs and CDNCs for all 24 profiles. Averaged over the time period of a single measurement on an individual height, the ICNC reached a maximum of 200 l^{-1} at 2.5 m above the surface and decreased by a factor of 2 at a height of 10 m while the median decreased by a factor of 4 in the same height interval. The CDNC in the other hand stayed constant with height. The decrease of ICNCs with height and the height independence of CDNCs suggest that surface processes strongly influence the ICNC close to the surface.

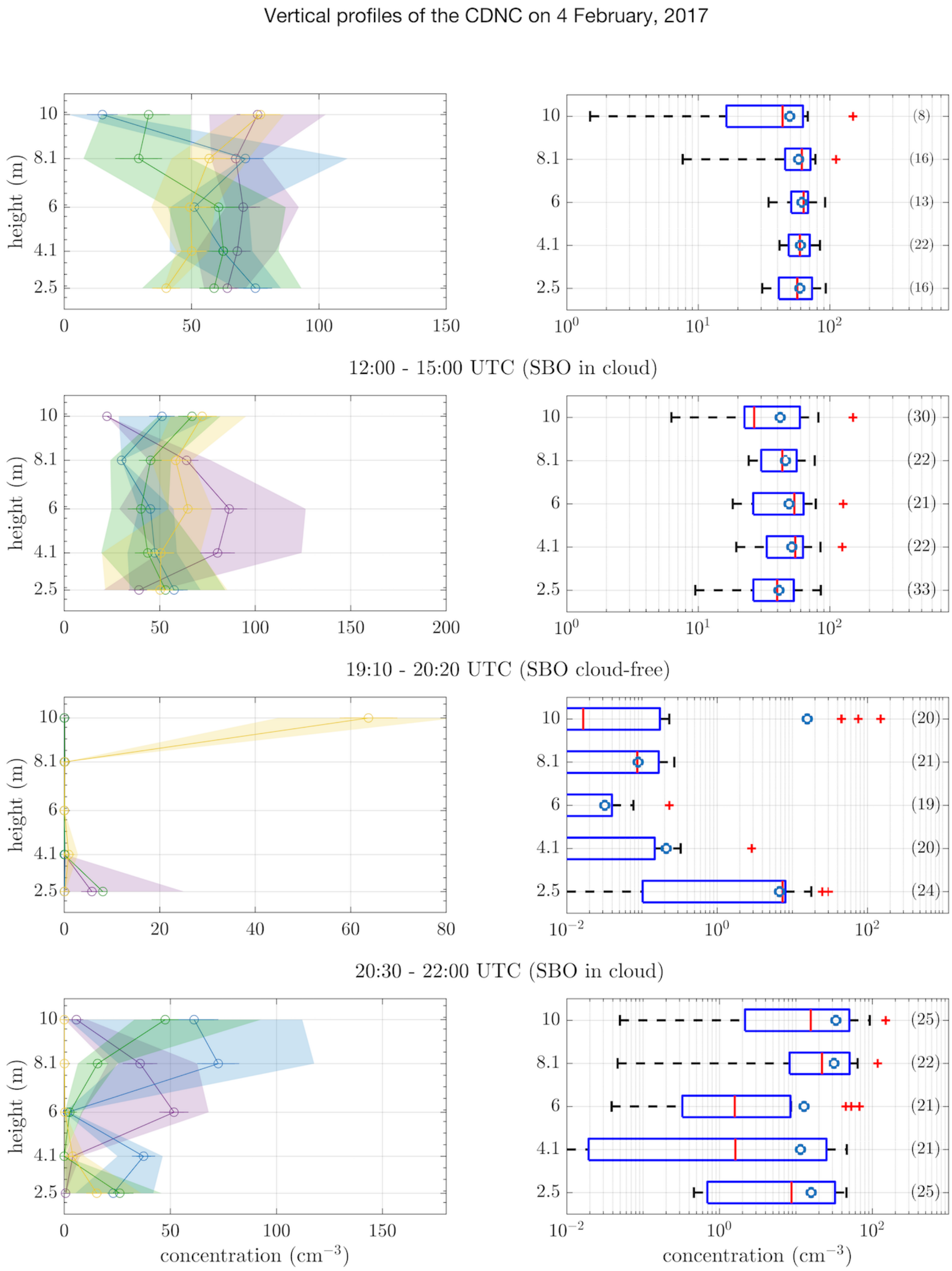

Abbildung A: CDNCs as a function of height of the elevator for four different time intervals on 4 February 2017. From the 24 profiles observed on 4 February 2017 only 16 are shown for a better readability of the figure. In the individual profiles (left), the circles indicate the mean and the error bars the standard error of the mean. The shaded areas extent from the minima to the maxima of the measured CDNCs. Each color represents one profile with the elevator in the corresponding time interval. The box plots (right) show a summary of all profiles in the respective time interval.

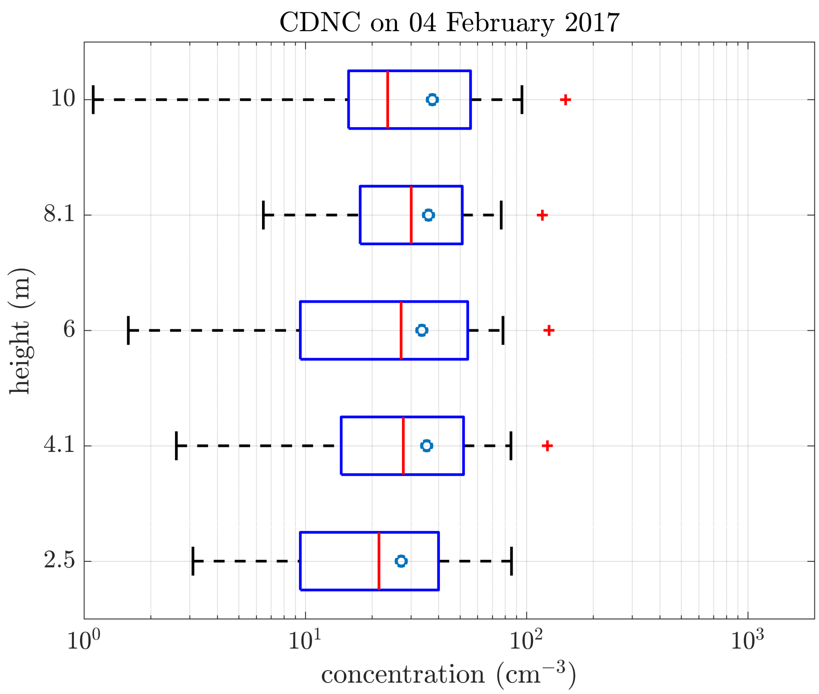

Abbildung B: CDNC as a function of the height of the elevator at the meteorological tower of the SBO. This plot is a summary of the 24 profiles obtained on 4 February 2017. The data was averaged for each height over the entire time period. For each box, the central line marks the median value of the measurement and the left and right edges of the box represent 25th and the 75th percentiles, respectively. The whiskers extend to the minima and maxima of the data; outliers are marked as red pluses. The mean values of the measurements are indicated as blue circles.

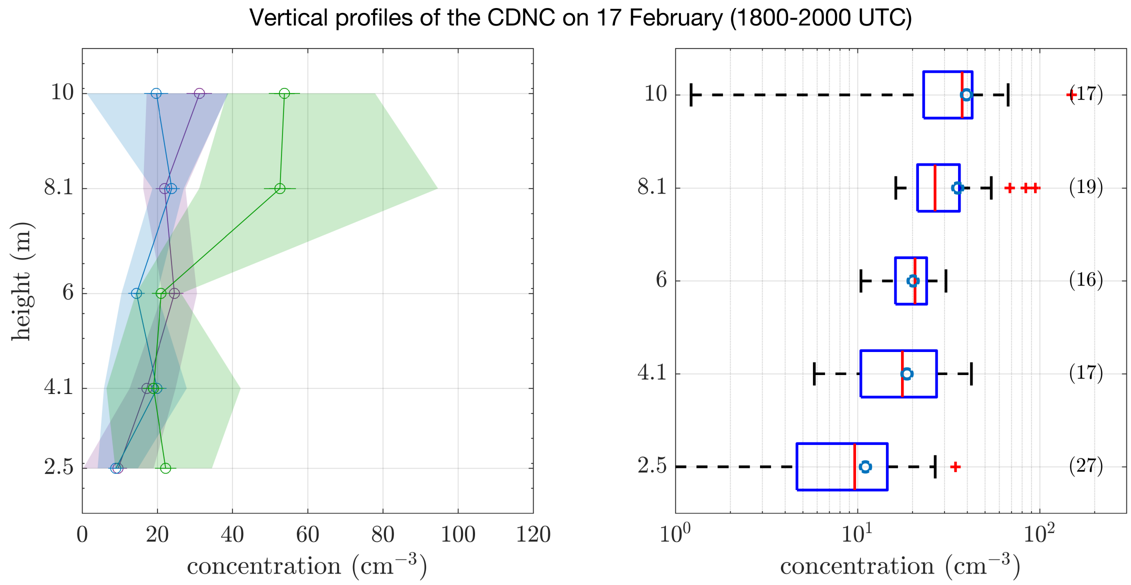

Abbildung C : CDNCs as a function of height of the elevator on 17 February, 2017. In the individual profiles (left), the circles indicate the mean and the error bars the standard error of the mean. The shaded areas extent from the minima to the maxima of the measured ICNC. Each color represents one profile with the elevator in the corresponding time interval. The box plots (right) show a summary of all profiles.

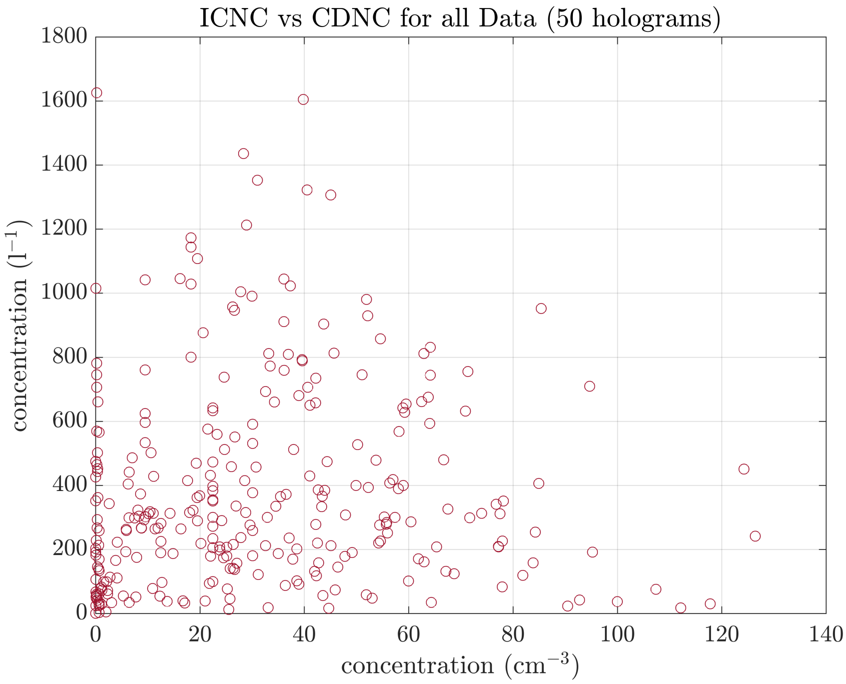

Abbildung D: ICNC vs CDNC for all in cloud measurements on 04 February and 17 February.

8) What were the reasons for the dataset being limited to 2 events?

Due to the technical limitations, unfortunately, the data set is limit to those two events.

9) English is generally good, but the manuscript should be carefully checked as there were several grammatical/spelling mistakes.

We prove read the manuscript once more and corrected several grammar and spelling mistakes.

II.) Technical Corrections/Further Comments

1) P1 L3-4 These all refer to secondary ice processes? It's worth stating this.

We don't think, that these processes are exactly secondary ice processes. In our opinion, secondary ice processes occur in free-floating clouds. The processes on P1 L3-4 refer to surface processes, which have similar mechanisms than secondary ice processes, but do not occur in free-floating clouds.

2) P1 L5 relevance with respect to which processes? Primary ice nucleation? Secondary ice processes? I think that you are correct - the measurements at these sites are definitely complicated by the potential for surface generated ice particles.

If ground-based measurements are influenced by surface processes, such measurements do not represent any microphysical properties and/or processes in free floating clouds. We changed the last sentence of the first paragraph of the abstract for clarification:

P1 L4: This limits the relevance of such measurements for the study of microphysical properties and processes in free floating clouds.

3) P1 L15 Agreed - they are not representative when compared with free floating clouds away from ice surfaces, but it is important to consider potential impacts of surface ice processes on clouds above these surface, whether in contact or close enough to be influenced.

Agree. That's what we state in the manuscript and also conclude. As stated before we changed the last sentence of the first paragraph of the abstract for clarification.

4) P2 L2 distribution(s)

Corrected.

5) P2 L6 Precipitation?

Corrected.

6) P2 L7 The bergeron findiesen process should be stated here.

Included a reference to the WBF process.

P2 L5: In the mid-latitudes, mixed-phase clouds (MPCs) consisting of a mixture of ice crystals and supercooled liquid droplets, produce 30 to 50% of liquid precipitation (Mülmenstädt et al., 2015), due to the rapid grow of ice crystals to precipitation size in the presence of supercooled liquid droplets. This is due to a higher saturation vapor pressure over liquid water than over ice and thus, ice crystals grow at the expense of evaporating cloud droplets. This process was first described in the works of Bergeron (1935), Findeisen (1938) and Wegener (1911) and is referred to as Wegener-Bergeron-Findeisen (WBF) process. As such, a good representation of orographic MPCs is crucial for

accurate weather predictions in alpine terrain.

7) P2 L15 primary ice concentrations

We do not think that the observed ICNC of 1-10 l^{-1} are necessary only primary ice. Therefore, we would like to keep the more general form and speak of ICNC in general without a statement of the exact origin of the observed ice crystals.

8) P2 L20 'lack of large'

Changed to 'absence of large'.

9) P3 L14 I think the other important conclusions from Farrington et al (2015) could be described here including the finding that secondary ice could not account for the concentrations in the model

We agree that this conclusion is also of importance for our paper and included it in our revised manuscript.

P3 L31: **To our knowledge, only one modeling study exists, which assesses the impact of hoar frost on the development of a cloud. Farrington et al. (2015) increased the IN concentration and simulated secondary ice processes in the WRF (Weather Research and Forecasting) model to produce such high ICNCs measured at the Jungfraujoch by Lloyd et al. (2015). In addition, they implemented a flux of surface hoar crystals based on a frost flower aerosol flux. They concluded that an increased IN concentration can better represent the high ICNCs observed at the Jungfraujoch, but also removed the liquid water from the model and prevented the existence of mixed phase clouds. They also found that secondary ice processes are not sufficient to explain such high ICNCs at cold temperatures. However, they found that a flux of surface-based ice crystals, i.e. hoar frost, provided a good agreement with the ICNCs measured by Lloyd et al. (2015).On the other hand, surface-based ice crystals are not advected high into the atmosphere and as such have a limited impact on 5 orographic clouds. To verify their findings regarding the impact of a surface flux on orographic clouds more measurements of ice crystal fluxes from the snow covered surface are necessary (Farrington et al., 2015).**

10) P3 L23 subvisible

Corrected.

11) P5 L12 'northerly'

Corrected. We also changed south-west to south-westerly in the same sentence.

12) P8 L17 'Maintained their habits, because they don't reach the surface'

We corrected this sentence to: However, in this case the sedimenting particles may maintain their habits, because they don't reach the surface.

13) P8 L25 Has this been studied over ice/snow free surfaces?

To our knowledge such a near-surface process as described in Section 4.1.2 has not been proposed before and we don't know of any study that shows such an effect.

14) P9 L12 – is curtain supposed to be curtail?

We changed the first paragraphs in Section for a better readability. With this also the word curtain was dropped. The paragraphs are now:

P10 L2: Turbulent eddies near the surface are responsible for the lofting of snow particles into the suspension layer (see sec. 4.1.1). Observations in the Arctic or Antarctica usually use wind measurements close to the surface (< 3 m) to estimate these turbulent eddies using friction velocity. In this study, only wind measurements on top of the meteorological tower at a height of 15 m are available. For 4 February, 2017 only the horizontal wind speed averaged over 1-minute is available from the 2D Sonic Anemometer operated by the SBO. On 17 February 1-second averages are also available for horizontal and vertical wind speed from our own 3D Sonic Anemometer.

Similar to Lloyd et al. (2015), who observed a dependence of the observed ICNCs on horizontal wind speed only for a small fraction of cloud events (27% in 2013 and 13% in 2014), we observed a dependence of ICNCs on horizontal wind speeds on 4 February only when horizontal wind speeds were less than 14 ms^{-1}. At higher horizontal wind speeds or on 17 February such a dependence was not observed. While Lloyd et al. (2015) proposed blowing snow to explain observations when a correlation was observed between ICNCs and horizontal wind speed, they proposed hoar frost to explain observation when no such correlation was present. However, in our opinion also the orography in the proximity of the measurement site and the positioning of the different measurement instruments (i.e. cloud probes and Sonic Anemometers) have an impact on the observable correlation between ICNC and wind speed. As such, it is much more difficult to distinguish between blowing snow and hoar frost as the relevant processes responsible for enhanced ICNCs.

For example, the lack of dependence on horizontal wind speed on 17 February may be explained by a process that lofts ice crystals from a steep mountain slope to form a mountain-induced ice crystal convergence zone near the surface on the leeward site of the mountain ridge (Fig. 13). In such a case, horizontal wind speed may not be a good predictor for the presence of turbulent eddies near the surface capable to of lofting ice crystals from the surface, but vertical wind speed may be a better indicator as we observed on 17 February. Additionally, a dependence on horizontal wind speed may be lost due to the exact set-up of the measurement instruments at the measurement site (Fig. 17). In the following we discuss possible reasons that possibly masks the wind dependence of the observed ICNCs:

15) P10 L20 of should be 'off' the surface.

Corrected.

16) P11 L16-17 Sentence needs rephrasing

Changed.

P13 L1: The contribution of surface and near-surface processes to the observed ICNC at mountain-

top research stations is estimated to account for several hundreds of ice crystals per liter. ICNCs in clouds without any contribution from surface and near-surface processes are estimated with several 10 s per liter, based on the observations between 2030 and 2200 UTC on 4 February 2017. This is still orders of magnitude higher than the measured INP concentration (Fig. 18). As such, additional processes must be active, e.g. ice multiplication processes, and contribute significantly to the ICNC in orographic clouds.

17) P11 L24 poor sentence with grammatical/spelling mistakes

Changed.

P13 L13: Ideally, one 3D sonic anemometer should be placed upwind of the ICNC measurement to observe the turbulent eddies that are responsible for the re-suspension of ice crystals, one 3D sonic anemometer should be placed on the elevator and one on the top of the tower.

18) P11 L28 particle should be 'particles'

Corrected.

19) Figure 7 – what are the different colours for shading? I assume it's regular, irregular and aggregates, but what is purple?

Figure 7 shows the total ICNC versus height, but no profiles for different ice crystal habits. The colors indicate different profiles with the elevator. This means that four profiles with the elevator are displayed for each time interval. We added this explanation to the caption of the figure.

P22 L1: Figure 7. ICNCs as a function of height of the elevator for four different time intervals during 4 February, representing different conditions (Fig. 4). From the 24 profiles observed on 4 February, 2017 only 16 are shown for a better readability of the figure. In the individual profiles (left), the circles indicate the mean and the error bars the standard error of the mean. The shaded areas extent from the minima to the maxima of the measured ICNC. Each color represents one profile with the elevator in the corresponding time interval. The box plots (right) show a summary of all 24 profiles in the respective time interval as in Figure 6.