Anonymous Referee #1

The reviewer's comments are presented in italics, followed by our responses. We thank the reviewer for his comments.

The authors describe cloud microphysical measurements made at Storm Peak Laboratory (SPL) during 2 measurement campaigns during 2011 and 2014. They used in-situ microphysics probes to measure cloud particles including ice crystals and liquid droplets and looked at relationships between the different cloud properties but also with ambient meteorological conditions. They find some already established results, for example an inverse relationship between cloud droplet size and concentration due to CCN availability,

While the relationship between drop size and concentration is expected, the original Fig. 3 presents an added dimension to this relationship, which is found to depend on liquid water content. This demonstrates a unique aspect and a potential drawback to studies at mountaintop laboratories, where the cloud base height may vary below the lab.

and some less well understood results such as a correlation between large drops and small ice crystals and enhancement in ice crystal concentrations in general. The paper has the potential to provide useful results but I suggest major corrections are needed before the paper is considered for publication in ACP.

Major Comments

I found the descriptions of the experimental setup to be confusing, particularly the explanation of how the instruments were aspirated, orientated into the wind and the steps taken to quality control the measurements made by instruments subject to the harsh environmental conditions. Any revision should include a new figure detailing the different instruments and the setup at SPL and a more in depth discussion of how the probes were aspirated.

The probe setup was discussed in lines 104-121. A new figure (Fig. 1 (revised), below) was added showing the probe configuration and a view upwind. The last sentence in this section starting on line 119 was moved to the end of line 104: "The cloud probes were mounted on a rotating wind vane (to orient them into the wind) located on the west (upwind) railing of the roof approximately 6 m above the snow surface. The sentence "The cloud probes were calibrated and serviced at DMT prior to each field campaign." was moved to the end of the section (line 121). The revised sentence notes that calibration and servicing was done at DMT. The discussion of how the probes were "aspirated" pertains only to the FSSP-100, which is fitted with a fan that draws air through the probe's sample volume. The CIP is not aspirated. The CIP sample volume is based on the wind speed measured with a sonic anemometer. This was clearly described in the text.

The most novel measurements relate to the enhanced ice crystal concentrations at a mountain top site like this where the cloud is in contact with the surface and interaction processes are poorly understood. The CIP-25 probe is key to this – there should be presentation of some of the imagery from the instrument and a detailed justification of why using a size threshold >62.5um for ice was appropriate.

Figure 8 (revised), below, which is included in the revised manuscript, shows CIP images from the case study on 9 February 2014 (discussed in section 3.3). The following is inserted into the text on line 252: "Figures 8a and 8b present CIP images from the high and low IWC periods, respectively. Note the relatively higher concentration of "dots" in Fig. 8b (low IWC, high LWC). These represent cloud droplets that occluded a single CIP diode."

and a detailed justification of why using a size threshold >62.5um for ice was appropriate.

This is discussed in the paragraph beginning on line 191. The objective was to exclude cloud droplets from the CIP data. There is no evidence for droplets this large in these shallow, orographic clouds when SPL is close to cloud base. Indeed, Lloyd et al. (2015) concluded that there were no droplets larger than 35 µm in orographic clouds at the Jungfraujoch. The original Fig. 2, which compares the CIP size distributions for wet (LWC>0) and dry (LWC=0) cases during StormVEx and IFRACS, demonstrates that only the first CIP size bin was impacted by droplets.

The data is sometimes presented in a confusing way. There are numerous times the data is compared for warm and cold conditions. Cold is defined as below -12 and warm above -8. What happens in between this range?

The logic was that if a process is temperature-dependent, that process will be observed most readily at extremes in temperature. In this case, 93 and 81% of 1-minute average observations occurred at temperatures lower than -10 ºC during StormVEx and IFRACS, respectively. The relationship between large drops and small crystals is similar at cold temperatures defined as either <-12 ºC or <-8 ºC. In response to this question, "cold" is defined as <-8 ºC in the revised manuscript.

I didn't find the interpretation of some of the results very convincing. It is proposed that the relationship between large drops and small ice crystals could be due to immersion or contact freezing. There is a relationship found between larger supercooled drops and ice crystal concentrations but I'm not sure how the jump is made to the impact of these bigger drops being increased appearance of small ice crystals through primary ice nucleation when it would seem more likely to be a secondary process of some kind. One of the key suspects (but not the only one) for enhanced ice crystal concentrations in supercooled orographic clouds in contact with a frozen surface is some process that provides ice from the surface. The mechanism by which this might happen is still very uncertain but I'd like to see a bit of information about the topography and surfaces around SPL. I think the relevant ideas and literature are generally included but the results are framed poorly. My interpretation is that the main findings surround the enhanced ice crystal concentrations vs what you might expect at these temperatures, but I felt that *although the different potential mechanisms for the production of these were stated, the authors didn't present coherent conclusions*.

The hypothesis that ice crystal production is related to large drops was raised in previous studies, as described in lines 70-74 of the original manuscript. Our analysis shows a relatively strong relationship between large droplet and small ice crystal concentration at low temperatures during IFRACS. This is ***new evidence*** for heterogeneous freezing of large droplets, whether by immersion or contact freezing. We see nothing logically or scientifically incoherent about this conclusion. On the other hand, the reviewer states that "it would seem more likely to be a secondary [ice production] process [SIP] of some kind". Upon what evidence is this belief based? There is a lot of speculation about SIP in the literature but in the absence of direct evidence from our studies, we prefer not to engage in it.

Minor Comments:

1. In the abstract I suggest removing acronyms that don't appear in the abstract again and then defining them in the body of the manuscript. 2. StormVEx and IFRACS should be defined in the abstract.

In the revised manuscript, all acronyms are defined at their first use in both the abstract and main text.

3. P2 L35 is second reference in brackets correct?

Corrected to Peng.

4. P3 L86 I may have missed it earlier but if not please define DRI.

Desert Research Institute inserted on L85.

5. P3 L93 variation over a 3 year period? If the campaign periods are correct it isn't over 3 years but you do compare between the two time periods (Nov 2010 – Apr 2011 and Jan – Feb 2014).

Changed "over a 3-year period" to "over two winters".

6. P3 L106 Add FSSP acronym

7. P3 107 the SPP-100 acronym might refer to the electronics revision of the FSSP. I'd prefer this instrument to be referred to as the Forward Scattering Spectrometer Probe (FSSP)

8. P4 L108 who is the manufacturer?

In all cases, "SPP-100" is replaced by FSSP-100, noting that the electronics were modified by DMT. The aspirator was purchased with the original PMS FSSP-100 probe, as noted in the revised manuscript.

9. P4 L109 What is the face velocity?

It's the velocity at the center of the inlet.

10. P4 L142 If the TAS vs the OAP set airspeed is not equal you begin to get distortions of aspect ratio that will lead to changes in size. I think it is inaccurate to state that the misshapen particles will not necessarily be sized incorrectly.

There is no "set" air speed for the CIP. The air speed (TAS) is supplied by the sonic anemometer, as described in lines 116-117. As noted in the manuscript, we used the "area equivalent diameter" to size CIP particles. This is the diameter of a sphere with the same projected area of a particle which may be irregular. We intentionally used this method because distortions may arise from incorrect wind speed. The reviewer is correct that aspect ratios would be sensitive to such distortions but our analysis does not include this parameter.

11. P5 L164 I'd be interested to know with these constraints which contributes to the loss of _ 50 % of data. You say the CIP measures particles for 101.4 and 77.2 hours respectively, so condition 1 is met for this number of hours. You are then left with 49.2 and 43 hours of MPC suggesting you were in glaciated for considerable time periods (condition 2 and 3 not met but condition 1 is true).

The data completeness requirement (75%, line 163) accounts for the reduced number of 1-minute averages. LWC was zero during 10 and 4.3% of seconds when Ni was greater than zero during StormVEx and IFRACS, respectively. This is apparent from the numbers given in the original Fig. 2 and the total number of observations given in the text.

12. Section 3.1 header has SPP-100 I might be getting this wrong but I think this should be the FSSP.

Changed to FSSP, as noted above.

13. P5 L178 the nominal size range quotes is below the threshold you stated earlier in the paper.
Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018

Optical array probes have been widely used for decades and a detailed explanation of how they work can found in the literature. 12.5-37.5 µm indicates the lower and upper bounds of the first CIP size channel given the 50% reduction of laser energy needed to trigger a diode. The size bins are typically referred to by their midpoints, i.e., the first channel is 25 µm and the 64th channel is 64x25=1600 µm. In presentations of size distributions, the bin boundaries are taken as the midpoint ±12.5 µm. The following sentence was added at line 115: "An array diode is triggered when a particle obscures >50% of the incident laser energy on the diode.".

References

Lloyd, G., Choularton, T.W., Bower, K.N., Gallagher, M.W., Connolly, P.J., Flynn, M., Farrignton, R., Crosier, J., Schlenczek, O., Fugla, J., and Henneberger, J.: The origins of ice crystals measured in mixed-phase clouds at the high-alpine site Jungfraujoch. Atmos. Chem. Phys., 15, 12953-12969, doi:10.5194/acp-15-12953-2015, 2015.

Figure 1 (revised). Recent picture of SPL probe stand used previously during StormVEx and IFRACS with FSSP-100 and sonic anemometer on top and DMT CIP and PIP (Precipitation Imaging Probe) on left and right sides, respectively. View facing west over the railing (right panel).

(a) (b)

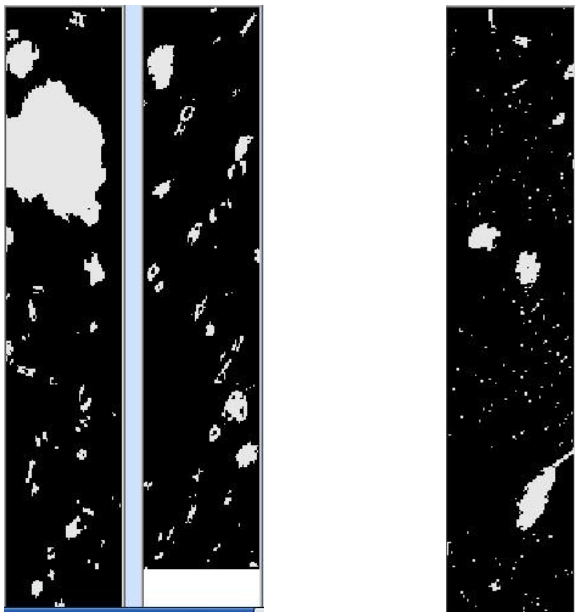

Figure 8 (revised). CIP images from 9 February 2014: (a) 13:12:19 MST, high IWC and low LWC, and (b) 12:29:09 MST, low IWC and high LWC. The vertical bars contain all of the images sampled in 1 second. The width of each bar corresponds to 1600 μm.

Anonymous Referee #2

The reviewer's comments are presented in italics, followed by our responses. The authors thank the reviewer for his insight.

The authors present the analysis of an observation of orographic mixed-phase clouds with ground-based in-situ instruments at the Storm Peak Laboratory. The 92 hours data were analysed in a statistical way to explore relationships between microphysical properties and draw conclusion about the ice crystal formation processes. The impressive dataset of 92 hours of mixed-phase cloud measurement is relevant for a publication and it fits in the scope of ACP, but I suggest major correction are needed before publishing this paper. A large part of the argumentation uses the cloud particle concentration between 25-100 um. This is a delicate size range. On the one hand, the CIP have a larger uncertainty in the smallest sizes bins because of diameter corrections. On the other hand, it cannot be assumed that the transition between liquid droplets and ice crystals is under all condition at the same size range. A more thorough discussion of the uncertainties and assumptions would strengthen the argumentation of the paper.

One of the objectives was to test the hypothesis that ice particles were formed by heterogeneous freezing of large cloud droplets. Correlations between large droplet (25-35 µm, CDNC25-35) and small ice particle (75-200 µm, Conc75-200) concentrations were examined. In response to the reviewer's concerns, a closer look at the 1-second data revealed that the FSSP reported concentrations of 0 for particles larger than 25 µm for 86 and 44% of 1-second measurements during StormVEX and IFRACS, respectively. The paucity of non-zero CDNC25-35 during StormVEx is probably the result of a measurement issue related to the lack of the FSSP-100 scarf tube during that study. StormVEx is thus excluded from this analysis in the revised manuscript.

The reviewer rightly points out that it is not possible to observe the degree to which large droplets measured with the FSSP were actually small ice crystals. The implication is that if large droplets (25-35 µm) were actually ice crystals, the relationship between CDNC25-35 and Conc75-200 could simply represent autocorrelation between two segments of the ice crystal distribution. In the original Fig. 2, we demonstrated that on average, the CIP distribution was dominated by droplets in its smallest size bin, which corresponds to the large droplet size range. The reviewer suggests that while this may true in general, there may be periods when there is more ice in this size range than on average but it is also true that there may be periods when there is less ice than on average. Since our analysis is statistical in nature, variation in the proportions of liquid and ice in the 25-35 µm size range of the FSSP should manifest as noise in the relationship between CDNC25-35 and Conc75-200. Further, if large droplets were actually crystals, and this accounted for the relationship between CDNC25-35 and Conc75-200 at <-8 ºC, why do we see not see this relationship at >-8 ºC? In the revised manuscript, we acknowledge and discuss the limitations of the instrumentation in this regard and note that higher resolution instruments are needed to directly address these issues.

For some argumentation, the interpretation of the data is inconclusive. Why is a 10-fold increase unrealistic, although the MTAS it doubled? Could the relationships between large cloud droplets (CDNC25-35) and small ice crystals (Conc75-200) also caused because a large percentage of the CDNC25-35 are ice crystals? Can a relative enchainment of small ice crystals be excluded using the relative PSDs in Figure 7?

Correlation of wind speed with crystal concentrations during the day on 9 February 2014 does not necessarily imply blowing snow. The revised analysis of this case (see below) shows an inverse correlation between MTAS and Ni during the High- and Low-Ice periods. This behavior is not consistent with blowing snow. Production of ice is dependent on mesoscale and orographic dynamics (Neiman et al., 2002; Stoelinga et al., 2013). Higher wind speeds across the barrier produce more lifting and produce new ice particles upwind and above the barrier. Clearly, not all of the variation in ice crystal concentration at mountaintop laboratories is due to blowing snow although blowing snow does occur. We provide evidence against the blowing snow hypothesis but acknowledge in the revised Conclusions that it can be a factor: "It is possible that both primary production and blowing snow were active at SPL.".

A key point is that higher-resolution instruments such as holographic imagers used by Beals et al. (2015) (HOLODEC) and Beck et al. (2018) (HOLIMO) are needed to distinguish liquid droplets from ice crystals in mixed-phase clouds. This is noted in the text and at the end of the revised Conclusions.

Specific comments:

Line 119 – 121: A more detailed discussion about the setup, including a picture, would be beneficial to discuss the influence of the local surrounding including building. In particular, if the high Conc75-200 in the NNW sector (discuss in Line 210-214) could be due influence of the railing, terrace, etc.

A new Fig. 1 showing the probes on the wind vane and a view upwind of SPL is included in the revised text. There is no upwind railing, terrace, or building in any direction to the west. The wind data were re-examined to explain high Conc75-200 in the NNW sector. During StormVEx, mostly all of the NNW cases were on 22 January 2011. The 5-minute average wind direction was exactly the same (351.9º) for 3.5 hours. It is not likely that a 5-minute average value could be the same to a tenth of a degree for two consecutive 5-minute periods, much less eighteen. During IFRACS, many of the NNW wind directions exhibited the same value for thirty minutes or more. The reason is that the wind vane becomes iced by riming and doesn't move. The data were screened for repeated 5-minute wind speeds and these were eliminated. This reduced the number of 1-minute observations by 2 and 4.7% during StormVEx and IFRACS, respectively. Table 2 was modified accordingly. The largest difference was in the NNW sector (330-360º) during StormVEx, where Conc75-200 decreased from 460 to 150 L^{-1}.

Figure 3 right side and Figure 5: To decide if the difference is significant, I suggest an estimate of the measurement uncertainty (either by error bars or by a discussion of the measurements uncertainty).

The reviewer is referring to comparisons of FSSP PSDs in the original Figs. 3 and 5. The implication is that the differences in the PSDs at high and low LWC, which occurred in both 2011 and 2014, could have arisen by chance. This seems highly implausible. A statistical comparison of mean PSDs could be used to test the hypothesis that these apparent differences were not significant, i.e., they were fortuitous. In any case, for such a comparison, a simple t-statistic would be the difference divided by the standard error (standard deviation divided by the square root of the number of observations). The standard errors are plotted in the revised Figs. 4 and 7. They are very small because of the large number of measurements used to calculate the mean concentrations as a function of size.

Line 229 and Figure 5: Could the particles larger than 35µm also be ice crystals?

In general, the answer is yes, but as noted in below and in the revised text, measurements of large particles by the FSSP is problematic.

Line 235-237: How can from Fig. 1 and 4 concluded that the liquid cloud was not effected by the ice phase?

We do not conclude here that the FSSP distribution was *not* impacted by the ice phase. We stated that such interactions are not evident in the original Fig. 1. Figure 4 hadn't been introduced at this point and should not have been included in this sentence.

Line 241 – 243: Without the plot, it is hard to follow and visualize the argumentation. Consider to include the plot in the paper?

A new Figure 5 showing these scatter plots is included in the revised text.

Figure 5: Shading of the times used for the low/high IWC analysis would increase comprehensibility.

The high IWC period is between the black lines in the revised plot. The low IWC periods are shaded in grey in the revised plot.

Line 259 – 263: I suggest giving the two cases a clearer name, e.g. Low-Ice and High-Ice. I was confused that in line 259 – 263 concentration where give behind IWC and thought for a while that with IWC is the acronym of ice water concentration.

This section was revised, referring to "High-Ice" and "Low-Ice" periods. Characterization of Ni during the High- and Low-Ice periods has been clarified.

Line 261-262: Could the particles larger than 35 µm also be ice crystals?

Again, yes.

Line 269 – 273: As the amount of blowing snow non-linear increases with the wind speed, I would assume that the MTAS is more relevant for the amount blowing snow particles. I find a 10-fold increase not unrealistic, in particular as in Beck et al., 2018, a case is shown in the upper panel of figure 9, where a 10-fold increase is measured above a sharp threshold wind speed.

As noted in the Methods section, the probes at SPL are mounted in front of a railing 6 m above the snow surface. Winds did not pass over the deck or from the direction of the building during sampling periods. The reviewer suggests that high ice particle concentrations (Ni) should have accompanied or followed the maximum wind gusts (MTAS). Figure 10 (revised), below, plots 1-second MTAS (Fig. 10a) and the corresponding 1-minute average TAS (Fig. 10b) against 1-minute average Ni for High-Ice, Low-Ice, and all other (Intermediate-Ice) periods on 9 February 2014. MTAS was highly correlated with TAS [0.90 (0.90] over the course of the day. The highest Ni correspond to the highest MTAS (and TAS) and *visa versa*. Average MTAS was 16.6±2.4, 8.9±2.0, and 11.3±2.8 m s^{-1} during High-, Low-, and Intermediate-Ice periods, respectively. This could imply that high Ni resulted from blowing snow when the winds were stronger in the early afternoon. Contrary to results reported in Fig. 9a in Beck et al. (2018), there was no clear MTAS threshold that produced a step function in Ni. In Fig. 10 (revised), there appears to be an inverse relationship between 1-minute MTAS and 1-minute Ni, especially for the High- and Low-Ice regimes. Beck et al. (2018) discussed how a relationship between MTAS and blowing snow could be averaged out if the averaging time is too long or obscured because of an [indeterminate] lag between the arrival of the gust and the particles that were lofted by it. Beck et al. (2018) suggested using an averaging time of 10-15 seconds. Figure 11 (revised), below, plots 15-second average (using the 75% data completeness criterion) Ni against MTAS for the High-, Low-, and Intermediate-Ice periods. The figure shows that while both MTAS and Ni varied considerably, there was no obvious wind speed threshold and the correlations between MTAS and Ni were actually negative under High- and Low-Ice conditions. These results are not consistent with the blowing snow hypothesis. This discussion and the new figures are included in the revised manuscript.

Line 275 – 279: Could also a higher percentage of the CDNC25-35 be ice crystals than indicated by the wet/dry ratio?

This is discussed in detail in response to the reviewer's introductory remarks. There could be more but also less ice particles in CDNC25-35 than indicated by the average wet/dry ratio, which suggests that CDNC25-35 represents droplets. The fact that we see a relationship between CDNC25-35 and Conc75-200 at cold but not warm temperatures also suggests that CDNC25-35 represents droplets and not ice crystals.

During wet condition, processes like hoar/surface frost (Lloyd et al., 2015) could have produced more small ice crystals or a stronger overestimation of the concentration in smallest bin of the SSP due to wrongly correction of the size of ice particles. A look at the overlap of in the size distribution (similar to Fig. 1) stratified by wet and dry condition could help to understand it.

The suggestion that splintering of hoar frost on the snow surface leads to high Ni is speculation. There is no direct evidence in our data to support this. It is difficult to see how hoar frost on the surface would have been a source of ice particles since snow was always accumulating on the surface during the measurements at SPL. The most plausible surface-based mechanism for ice production is blowing snow, which is discussed at length.

Line 333 – 340: In my view, there is a misunderstanding in some of the conclusion from the Beck et al., 2017 paper. In the Beck et al., 2017, paper the authors conclude that ICNCs decrease with height. ICNCs near the ground are at least a factor of 2 larger also when the SBO was in liquid clouds.

This paragraph was replaced by the following sentence at line 331: "Beck et al. (2018) reported a large increase in Ni when the maximum wind speed increased from 14-16 to ≥16 m s^{-1} at the Sonnblick Observatory in Rauris, Austria when winds were from the south.".

Line 347 – 354: If the CDNC25-35 were dominated by ice crystal produced by a ground-based process depending on the TAS, the high importance of CDNC25-35 could be also a consequence of the TAS.

See above. The reviewer keeps coming back to a hypothetical while the evidences suggests that in general, CDNC25-35 was not dominated by ice crystals.

Line 356 – 363: The authors want to find a relative enchainment of small ice crystals due to blowing snow by using the relative PSDs of low and high wind cases (Figure 7). What effect would a relative a relative enchainment of small ice crystals have on Figure 7? In my understanding, the relative PSD would slightly increase for small diameter (because an increase of small ice crystal concentration, but also an increase in the total concentration) and would lead to a stronger decrease for large diameter (because the big ice does not increase much, but the total concentration increase).

We assume that by "enchainment" the reviewer means "enrichment". First, Fig. 7 (revised Fig. 12) was modified to represent the same low wind speed range as presented in Table 3, i.e., 1-3 m s^{-1} rather than 1-4 m s^{-1}. The result is that there was an enrichment in small crystals (Conc75-200) at high wind speed of 10% during StormVEx and 8%

during IFRACS. However, this difference is small compared to the factor of 4.5-6.5 increase in the absolute concentration of Conc75-200 at the higher wind speed. Ice crystal concentration is not simply a function of blowing snow but varies with synoptic and orographic dynamics, i.e., stronger uplift nucleates more crystals upwind and above the mountain barrier (e.g., Neiman et al., 2002; Stoelinga et al., 2013). In fact, there were moderately strong correlations between 1-minute horizontal and vertical wind speeds during StormVEx [0.75(0.72)] and IFRACS [0.66(0.67)].

This changes, where observed in Figure 7. Maybe the author could show how different PSD would translate to differences in the relative PSD of Figure 7?

It is unclear what the reviewer is asking for. The contrast in the original Fig. 7 was used to test a specific hypothesis, i.e., that blowing snow would be relatively enriched in small particles. Is the reviewer suggesting that we address a different hypothesis using relative PSDs?

Technical Corrections/Minor Comments

Line 17: to be consistent: "cloud condensation nuclei"

Done.

Line 40: write out acronym "mixed-phase clouds (MPC)"

Done.

Table 1: Unclear where the parameters measured by the CIP stops and where the SPP-100 parameter starts. For consistency write out TAS.

In the revised table, a vertical line separates CIP and FSSP parameters. TAS is defined as horizontal wind speed in the footnotes.

Line 182: To be consistent with units it should be "sampling flow speed"

Done, however, since the scarf tube accelerated the flow during IFRACS, the wording was changed to "sampling flow speed at the inlet".

Line 183: In my understanding with higher flow speeds in the inlet than outside you have superisokinetic sampling, which leads to an undersampling of the large particles and not an oversampling of smaller droplets.

The reviewer is correct. This could explain a loss of large droplets in the aspirated FSSP during StormVEx. Note that the flow accelerator (scarf tube) was used during IFRACS but not StormVEx. Gerber et al. (1999) discussed inertial concentration of large droplets in an aspirated FSSP fitted with a scarf tube (flow accelerator). Because the FSSP and CIP PSDs overlap more closely during IFRACS than StormVEx, the loss of large droplets due to super-isokinetic sampling may be somewhat offset by the inertial concentration of large droplets caused by the scarf tube. This is discussed in the revised text.

Line 198 – 207: This part was hard to follow and a rephrasing might help. If the first two CIP channels cannot be trusted, which I agree to, than the argumentation might be obsolete.

We agree and have removed this section.

Figure 3: Mention that the colors on the left side are the liquid water contents

Done in the revised figure heading.

Line 240: The sentence "Henceforth, the Spearman Rank correlation is displayed in parenthesis after the Pearson correlation." is confusing, in particular as the Spearman Rank is not in parenthesis two sentence before.

Line 240 begins with "Henceforth", meaning after line 240.

Line 286: In the text is written "29 data points" are used, but in Figure 6 N=79.
Line 296: I think it should be "IFRACS (Figure 6b)."

This section has been extensively revised, as discussed above.

References

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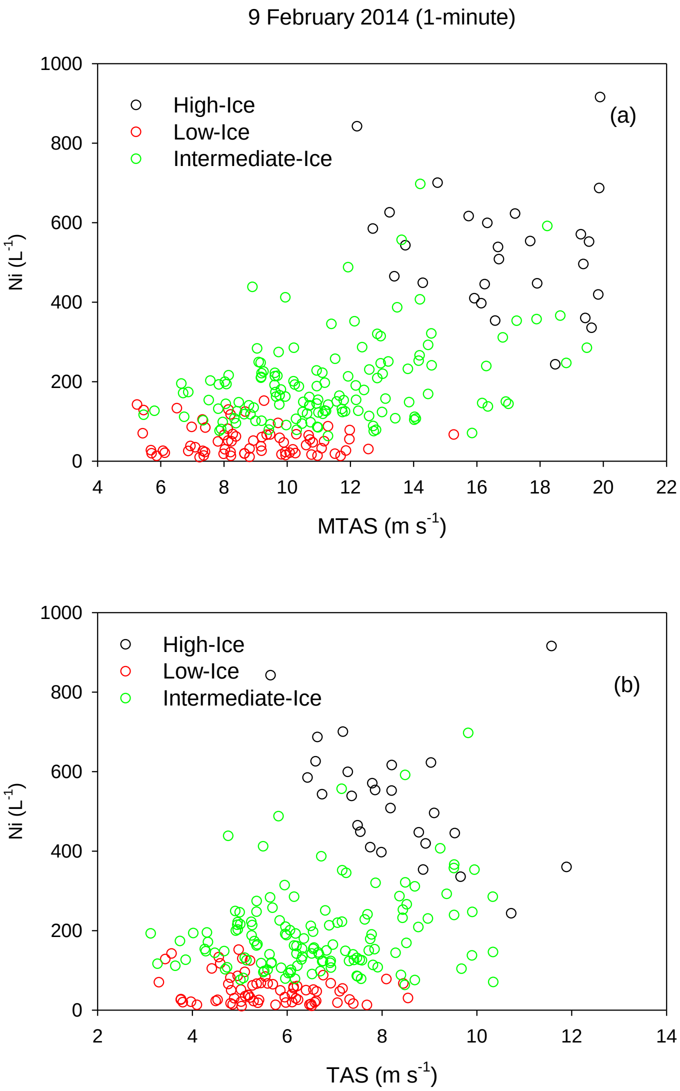

Figure 10 (revised). Relationships between 1-minute average TAS (a) and maximum 1-second TAS (MTAS) (b) and Ni for High-Ice, Low-Ice, and Intermediate-Ice (all other 1-minute periods) periods on 9 February 2014.

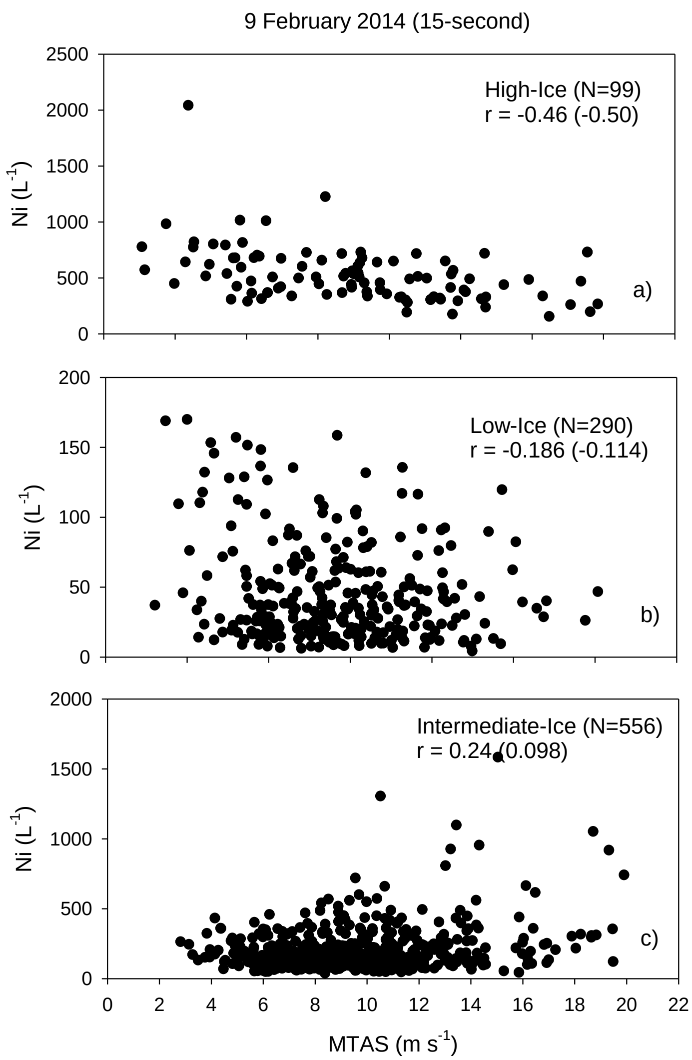

Figure 11 (revised). Relationships between 15-second average Ni and MTAS for High-Ice (a), Low-Ice (b), and Intermediate-Ice (c) periods on 9 February 2014.

Mixed~~ Phase~~-phase Orographic Cloud Microphysics during StormVEx and IFRACS

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Abstract. Wintertime mixed~~-~~-phase orographic cloud (MPC) measurements were conducted at the Storm Peak Laboratory (SPL) during the Storm Peak Lab Cloud Property Validation Experiment (StormVEx) and Isoptopic Fractionation in Snow (IFRACS) programs in 2011 and 2014, respectively. The data include 92 hours of simultaneous measurements of ~~supercooled~~super-cooled liquid cloud droplet and ice particle size distributions (PSD). Average cloud droplet number concentration (CDNC), droplet size (NMD) and liquid water content (LWC) were similar in both years while ice particle concentration (Ni) and ice water content (IWC) were higher during IFRACS. The consistency of the liquid cloud suggests that SPL is essentially a cloud chamber that produces a consistent cloud under moist, westerly flow during the winter. A variable ~~Cloud Condensation Nuclei~~cloud condensation nuclei (CCN~~)~~)-related inverse relationship between CDNC and NMD strengthened when the data were stratified by LWC. Some of this variation is due to changes in cloud base height below SPL. While there was a weak inverse correlation between LWC and IWC in the data as a whole, a stronger relationship was demonstrated for a case study on 9 February~~ 9,~~ 2014 during IFRACS. A minimum LWC of 0.05 g m^{-3} showed that the cloud was not completely glaciated on this day. Erosion of the droplet distribution at high IWC was attributed to the Wegener-Bergeron-Findeisen process ~~although~~as the high IWC was ~~caused~~accompanied by a 10~~-~~-fold increase in Ni. A relationship~~ found~~ between large cloud droplet concentration (25-35 µm) and small ice particles (75-200 µm) under cold (<-~~12~~8 °C) ~~and~~but not warm (>-8 °C) conditions during IFRACS suggests primary ice particle production by contact or immersion freezing. ~~Such a relationship under warm conditions could be indicative of biological ice nuclei. There was no direct evidence of secondary ice production.~~ The effect of blowing snow was evaluated from the relationship between wind speed and Ni and by comparing the relative (percent) ice particle PSDs at high and low wind speeds. These were similar, contrary to expectation for blowing snow. However, the correlation between wind speed and ice crystal concentration may support this explanation for high crystal concentrations at the surface. Secondary processes could have contributed to high crystal concentrations but there was no direct evidence to support this. Further experimental work is needed to resolve ~~this issue~~these issues.

1 Introduction

Aerosols and their effects on cloud microphysical properties have been shown to alter precipitation formation and distribution over complex terrain (e.g., Pruppacher and Klett, 1997; Borys et al., 2003; Rosenfeld and Givati, 2006; Lowenthal et al., 2011; Saleeby et al., 2013). Higher concentrations of cloud condensation nuclei (CCN) produce more numerous but smaller cloud droplets (Twomey et al., 1984; ~~Pen1g~~Peng et al., 2002; Lowenthal et al., 2002). This leads to decreased riming efficiency and a decrease precipitation on the windward slope (Borys et al., 2000, 2003) and has been shown to redistribute precipitation over mountain barriers in modeling studies (Saleeby et al., 2009, 2013).

There are numerous studies and reviews of ice nucleation theory, measurements and modeling (Vali, 1996, 1999; Diehl et al., 2006; Hoose and Möhler, 2012; Moreno et al., 2013; Murray et al., 2012; Knopf and Alpert, 2013; Kanji et al., 2017; Knopf et al., 2018). In mixed-phase cloud (MPC~~,~~), a small fraction of aerosols can act as heterogeneous ice nucleating particles (INP) and produce ice through four known freezing modes: deposition, immersion, condensation, and contact freezing. ~~Deposition freezing occurs when water vapor deposits directly onto an INP and generally occurs at temperatures below other heterogeneous freezing modes (Lohmann and Diehl, 2006). Contact freezing occurs when an INP comes into contact with a supercooled cloud droplet and initiates freezing. Immersion freezing and condensation freezing are more difficult to differentiate. Immersion freezing occurs when a supercooled cloud droplet forms, grows on an INP, and then freezes. Condensation freezing occurs when water vapor condenses onto an INP and forms a haze a droplet which freezes.~~

~~However, recent work in Arctic MPC showed that ice was observed only after a liquid cloud layer had developed and found no evidence of condensation freezing (de Boer et al. 2011). The relative efficiencies of contact and immersion nucleation are discussed by Pitter and Pruppacher (1973), Lohmann and Diehl (2006) and Nagare et al. (2016).~~ Contact freezing has been found to occur at higher temperatures than immersion freezing for a given INP (Pitter and Pruppacher 1973; Lohmann and Diehl, 2006; Nagare et al., 2016). Biological INP have been found to produce ice at relatively higher temperatures than non~~-~~biological INP (Levin and Yankofsky, 1964; Du et al., 2017).

Secondary ice production (SIP) processes ~~are~~were reviewed by Field et al. (2017). Sullivan et al. (2018) modeled SIP by rime splintering (Hallett-Mossop process), droplet shattering, and collisional breakup with ice particle enhancement depending on temperature, updraft velocity, and INP concentration. Rime splintering is thought to occur when a ~~supercooled~~super-cooled droplet with a diameter larger than ~25 µm freezes onto an ice particle or other surface and shatters at temperatures between -8 and -3 °C (Hallett and Mossop, 1974; Mossop, 1985). Keppas et al. (2017) found evidence for rime splintering in warm (-6 to 0°C) frontal clouds. Here, "lolly pop" shaped crystals formed by riming of columnar crystals by droplets larger than 100 µm were associated with high concentrations of small columnar crystals. Rangno and Hobbs (2001) concluded that shattering of freezing droplets ~~(>~~larger than 50 µm~~)~~ could have accounted for high observed ice particle concentrations in Arctic stratus.

At mountaintop observatories, ice crystal concentrations frequently exceed aircraft measurements by an order of magnitude or more (~~Roger~~Rogers and Vali, 1987; Geerts et al., 2015; Lloyd et al., 2015; Beck et al., ~~2017~~2018). Lloyd et al. (2015) considered blowing snow, rime splintering, and detachment of surface frost (Bacon et al., 1998) as sources of high ice particle concentrations at the ~~Jungraujoch~~Jungfraujoch Sphinx Observatory (JFJ). They ultimately favored the latter mechanism by process of elimination, albeit with no direct evidence. In contrast, Beck et al. (~~2017~~2018) suggested that the enhanced ice crystal concentrations at ~~mountaintops are~~the Sonnblick Observatory

(SBO) were due to blowing snow, turbulence near the mountain surface, or convergence of ice crystals near mountaintop due to orographic lifting.

Several studies have shown a link between cloud droplet size and ice particle concentrations (e.g. Hobbs and Rangno, 1985; Rangno and Hobbs, 2001; Lance et al. 2011; de Boer et al., 2011). Hobbs and Rangno (1985) found a strong relationship between the width of cloud droplet spectra and ice particle concentrations in cumuliform and stratiform clouds where cloud top temperature ranged between -36 and -6°C. Lance et al. (2011) found higher concentrations of ice particles larger than 400 µm in clean Arctic clouds with larger droplets sizes than in polluted Arctic clouds with smaller but more numerous drops.

~~The aforementioned~~Previous studies have furthered ~~the~~our understanding of precipitation ~~processes~~formation and distributions in complex terrain from dynamical and microphysical perspectives but ~~due to the lack of data, were~~have been unable to establish a link between ~~the~~ cloud microphysics aloft and at the surface. Rogers and Vali (1987) observed cloud microphysics at ~~both~~ the Elk Mountain Observatory (EMO) located in the Medicine Bow Mountains of Southern Wyoming and from the University of Wyoming Queen Air (UWQA) aircraft. Comparisons between crystal concentrations at EMO and on the UWQA routinely showed higher crystal concentrations at the surface. The authors attributed ~~the~~ higher surface concentrations to an unspecified process of ice crystal ~~generation~~production in ~~supercooled~~super-cooled orographic clouds in contact with snow-covered mountain surfaces. However, blowing snow can also introduce the potential for artifacts in observed ice crystal concentrations at mountaintop locations (Roger and Vali, 1987; Geerts et al., 2015).

The Storm Peak Lab Cloud Property Validation Experiment (StormVEx) was conducted from 15 November ~~15,~~ 2010 to 25 April ~~25,~~ 2011 at ~~DRI's~~the Desert Research Institute's (DRI) Storm Peak Laboratory (SPL) to produce a correlative data set *to validate cloud retrievals using in-situ measurements at SPL* (Mace et al., 2010; *Matrosov et al., 2012).* The Isotopic Fractionation in Snow (IFRACS) study was conducted at SPL from 20 January ~~20~~ to 27 February ~~27,~~ 2014 to explore the impacts of microphysical processes in wintertime orographic clouds on the water isotopic composition of falling snow (Lowenthal et al., 2016; Moore et al., 2016). This paper examines microphysical properties of wintertime orographic MPC at SPL using data collected during *StormVEx and IFRACS. A large record of concurrent measurements of ice and ~~supercooled~~super-cooled liquid water was ~~generated.~~produced by these studies. These data enable exploration of statistical relationships among microphysical properties ~~in a statistical sense~~, the temporal variation of cloud properties over ~~a 3 year period~~two winters at this site, the relationship between the ice and liquid phases, and ice ~~formation~~production mechanisms. Potential measurement artifacts due to instrumental characteristics and blowing snow are evaluated.*

2 Methods

Storm Peak Laboratory (SPL, 3210 m ASL; 40.456570°N, 106.739948°W) is located on the summit of Mt. Werner in the Park Range near Steamboat Springs, Colorado (Wetzel et al., 2004). In wintertime, SPL is in snowing, ~~supercooled~~super-cooled liquid cloud roughly 25% of the time (Borys and Wetzel, 1997). ~~Snow storms~~Storms occur roughly weekly under a variety of synoptic conditions (Rauber and Grant, 1986; Rauber et al., 1986; Borys and Wetzel, 1997). As noted by Lowenthal et al. (2016), given sufficient moisture during winter, a cloud forms and produces persistent snowfall at SPL. Winds are generally from the west or northwest during snowfall events. Cloud and snowfall can be inhibited ~~due to~~by blocking ~~by~~from the Flat Top Range (maximum elevation 3768 m ASL) under flow from the southwest.

Cloud microphysical ~~measurements~~properties were ~~made using~~measured with the same instruments during StormVEx and IFRACS. The cloud probes were mounted on a rotating wind vane (to orient them into the wind) located on the west (upwind) railing of the roof approximately 6 m above the snow surface (Fig. 1). Cloud droplet number concentrations (CDNC) and particle size distributions (PSDs) from 2-47 µm were measured with an aspirated ~~Droplet~~Particle Measurement ~~Technologies,~~Systems (PMS), Inc. (Boulder, CO~~) SPP~~), FSSP-100 forward scattering spectrometer probe~~.~~ that was electronically modified by Droplet Measurement Technologies (DMT), Inc. (Boulder, CO). Liquid water content was calculated from the ~~SPP~~FSSP-100 PSDs. During IFRACS, the ~~SPP~~FSSP-100 inlet was equipped with a "scarf tube", which narrows and accelerates the flow in the sample volume to 25 m s^{-1} according to ~~the manufacturer.~~PMS. The ~~face velocity~~air speed at the center of the inlet was measured at 9.4 m s^{-1}, which corresponds to a velocity of 26.7 m s^{-1} in the sample volume. The scarf tube was removed during StormVEx such that the ~~face velocity~~air speed at the inlet should have been the same as that in the sample volume. ~~There~~Attempts were ~~attempts~~made to measure the ~~face velocity~~air speed at the inlet during StormVEx but these were inconsistent. Therefore, StormVEx ~~SPP~~FSSP-100 concentrations were ~~recalculated~~calculated using the face velocity of 9.4 m s^{-1} measured during IFRACS.

Ice particle PSDs were measured with a DMT CIP (Cloud Imaging Probe [25-1600 µm]) optical array probe (OAP) with 64 size channels and a resolution of 25 µm. ~~The cloud probes were calibrated and serviced prior to each field campaign.~~ An array diode is triggered when a particle obscures >50% of the incident laser energy on the diode. During IFRACS, an Applied Technologies, Inc. (ATI) (Longmont, CO) SATI 3~~-~~axis sonic anemometer supplied the wind speed along the horizontal axis of the CIP probe. For aircraft measurements, this is referred to as true air speed (TAS). This terminology is adopted to refer to horizontal air speed. During StormVEx, a Lufft Ventus UMB 2~~-~~axis sonic anemometer was substituted for the ~~Applied Technologies, Inc.~~ATI instrument after 8 February ~~8,~~ 2011. Data were collected at 1 Hz. The cloud probes ~~and sonic anemometers~~ were ~~mounted on a rotating wind vane (to orient them into the wind) located on the west (upwind) railing of the roof approximately 6 m above the snow surface.~~ calibrated and serviced at DMT prior to each field campaign.

The 2~~-~~D CIP images from StormVEx and IFRACS were processed using the Optical Array Shadow Imaging Software (OASIS) program developed at the University of Manchester (Crosier et al., 2011; Lloyd et al., 2015) and marketed by DMT (http://www.dropletmeasurement.com/optical-array-shadow-imaging-software-oasis). The CIP depth of field was corrected as a function of particle size (Baumgardner and Korolev, 1997). Ice particle shattering on the probe tips was found to be insignificant based on particle ~~interarrival~~inter-arrival time (Field et al., 2006). This is consistent with relatively low wind ~~speed~~speeds at the surface compared with aircraft speeds (~100 m s^{-1}). Concentrations in the first two CIP channels ~~(<~~(nominally smaller than 62.5 µm) were ignored because of sizing uncertainties (Korolev et al., 1998: Strapp et al., 2001) and because some of these particles are likely to be cloud droplets in ~~mixed phase clouds (~~MPC~~)~~. The total CIP concentration excluding the first two channels is referred to as Ni. The center~~-~~in approach, which includes particles that obscure an end diode, was used to identify particles and estimate the sample volume (Heymsfield and Parrish, 1978). Particle size was described as the area equivalent diameter, i.e., the diameter of a circle with the same area as the particle, as determined from the number of shadowed pixels and the probe resolution. Ice water content (IWC) was estimated by OASIS using the approach of Brown and Francis (1995). This estimate is uncertain because mass- dimensional relationships vary significantly with ice particle habit, riming extent, aggregation, and temperature (Mitchell, 1996; Schmitt and Heymsfield, 2010).

In aircraft studies, the volume of air sampled by cloud probes is ~~related~~proportional to TAS. At aircraft speeds, particles are sampled along the horizontal axes of and perpendicular to the sample area of the cloud probes. This is not necessarily the case with ground based sampling, even when the probes are mounted on a wind vane such as those used at SPL or JFJ, where cloud probes were mechanically oriented into the wind based on sonic anemometer measurements (Lloyd et al., 2015). If the particle trajectory is not as described above, the particles can appear misshapen but not necessarily miss sized according to the area equivalent diameter. CIP data used in the following analysis were constrained as follows: 1) 1~~-~~-second TAS >1 and <20 m s^{-1}. A lower limit is needed to ensure that particles ~~traverse~~traversed the CIP diode array as close to horizontally as possible. Note that the updraft near the mountain tends to impart a horizontal trajectory on falling ice particles (Borys et al., 2000). An upper limit is needed to guard against contamination by blowing snow. During StormVEx and IFRACS, snow and ~~supercooled~~super-cooled cloud water samples were collected in bags and on cloud sieves (Borys et al., 2000). Such sampling is not practical at wind speeds above 15 m s^{-1}, where snow may blow out of the bags and the cloud sieves may become overloaded. For the January and February period during StormVEx, TAS was >20 m s^{-1} during ~~only~~ 34/492995 (0.007%) of ~~seconds when the~~1-second CIP ~~measured particles.~~measurements. The corresponding frequency during IFRACS was 3663/338230 (1.1%). Five~~-~~-minute average temperature, pressure, and humidity were measured by the SPL weather station. Water vapor concentration and isotopic composition were measured during IFRACS with a Picarro L2130-i water vapor isotopic analyzer (Lowenthal et al., 2016).

3 Results and Discussion

The full StormVEx program lasted nearly 6 months, from November~~,~~ 2010 through April~~,~~ 2011, while IFRACS was designed as a 6 week field project in January and February~~,~~ 2014. During IFRACS, the Picarro analyzer began collecting data on 20 January ~~20~~, however, the weather was clear until 27 January ~~27~~ (Lowenthal et al., 2016). For a consistent comparison between the two studies, StormVEx data are limited to January and February~~,~~ 2011. Cloud probe measurements were made on 30 days during StormVEx and 15 days during IFRACS. Measurement periods during StormVEx were intended for comparison with ground~~-~~-based remote sensing instruments. The probes were turned on when it started snowing but were not necessarily turned off if SPL was not in MPC. Measurements during IFRACS were started only when SPL was in MPC to sample liquid and ice for isotopic analysis. While there were twice as many sampling days during StormVEx, the CIP probe measured particles for 101.4 and 77.2 hours during StormVEx and IFRACS, respectively. The 1~~-~~-second data were averaged to 1~~-~~-minute with a 75% (at least 45 seconds) data completeness requirement. To ensure that the measurements represented MPC, only seconds when Ni was >0, LWC was >0.01 g m^{-3} and CDNC was ~~>~~≥10 cm^{-3}, were included. With these constraints, there were 49.2 and 43 hours of concurrent MPC measurements during StormVEX and IFRACS, respectively.

3.1 ~~SPP~~FSSP-100 and CIP Particle Size Distributions

Average PSDs calculated from concurrent 1~~-~~-minute average ~~SPP~~FSSP-100 and CIP measurements are shown in Figs. ~~1a~~2a and ~~1b~~2b for StormVEx and IFRACS, respectively. The average PSDs were similar in the two studies. Corresponding averages of 1~~-~~-minute CIP and ~~SPP~~FSSP-100 concentrations are summarized in Table 1~~. Table 1~~, which shows that LWC and CDNC were similar in the two studies~~, although average~~. Average IWC during IFRACS was twice that during StormVEx. Small (75-200 µm, referred to as Conc75-200) and large (>400 µm) ice particle concentrations were also higher during IFRACS. The average LWC at SPL was more than an order of magnitude lower than LWC observed in the Sierra Nevada (1.5 g m^{-3}) and Cascade (2 g m^{-3}) mountains, respectively (Lamb et al., 1976; Hobbs, 1975). The ratios of average Conc75-200 to average Ni were 91 and 83% during StormVEx and IFRACS, respectively. Based on their coefficients of variation, liquid cloud properties (CDNC and LWC) were much less variable than Conc75-200, large ice particles, and Ni at SPL.

While the first CIP channel, nominally 12.5-37.5 µm, lines up with the ~~SPP~~FSSP-100 PSD at ~25 µm in both studies (Fig. ~~1~~2), concentrations of ~~SPP~~FSSP-100 particles larger than 25 µm undershot the CIP PSD during StormVEx~~ but not ~~, and to a lesser extent, during IFRACS. ~~Concentrations~~The FSSP-100 reported non-zero concentrations of ~~droplets~~particles larger than 25 µm ~~were significantly lower~~for 14 and 56% of 1-second measurements during StormVEx~~. The~~ and IFRACS, respectively. During these periods, average CDNC, LWC, and were similar, i.e., 200 cm^{-3}, 0.105 g m^{-3}, and 9.1 µm, respectively, during StormVEx, and 210 cm^{-3}, 0.103 g m^{-3}, and 9.2 µm, respectively, during IFRACS. Average TAS was 6.1 m s^{-1} during StormVEx and 6.0 m s^{-1} during IFRACS. At an ~~SPP~~FSSP-100 sampling flow ~~rate~~speed of 9.4 m s^{-1} at the inlet and an average TAS of ~6 m s^{-1}, sampling is ~~anisokinetic~~super-isokinetic, leading to ~~oversampling of smaller droplets. Ideally, the~~under-sampling of larger droplets. Gerber et al. (1999) demonstrated inertial enhancement of large drop concentrations in the aspirated FSSP fitted with a flow ~~through the SPP-100 sample tube should increase as the square of the radius inside the~~ accelerator (scarf tube~~. However, the behavior of the flow at the leading edge of~~). Thus, the loss of large droplets caused by super-isokinetic sampling may have been partially offset by inertial concentration of large droplets by the scarf tube ~~could be turbulent, resulting in entrainment of larger particles. This~~during IFRACS. However, it is ~~consistent with the PSDs shown in Fig. 1 and the slightly lower LWC and mean diameter (NMD) during StormVEx (Table 1).~~difficult to see how under-sampling would have totally eliminated large droplets when they were present.

Spherical liquid drops and~~ irregular~~ ice particles can be distinguished with image analysis, however, this is only possible for particles with area equivalent diameters larger than about 110 µm for the CIP with 25 µm resolution (Crosier et al., 2011). ~~To determine whether the CIP measured liquid droplets in MPC, the~~The average of ~~the~~ 1~~-~~-second CIP PSDs in mixed~~-~~-phase (wet) cases were compared with dry cases when Conc75-200 was >0 and LWC was zero [no particles detected by the ~~SPP~~FSSP-100]). Figure ~~2~~3 shows the ratio of the average of 1~~-~~-second wet to average dry CIP concentrations as a function of size for StormVEx and IFRACS. In both studies, the ratio was elevated in the first CIP channel only. The ratio decreased significantly and was flat between the ~~third~~3rd and ~~eighth~~8th CIP channels, i.e., Conc75-200. ~~Thus~~This suggests that on average, the CIP measurements were only affected by cloud droplets~~ only~~ in the first CIP channel.

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Average Conc75-200 was higher under wet than dry conditions: 78 versus 49 L^{-1} during StormVEx and 118 versus 21 L^{-1} during IFRACS. ~~This could be an indication of liquid mediated ice production (Rangno and Hobbs, 2001; de Boer et al., 2011; Lance et al., 2011). Note that average~~Average TAS under wet and dry conditions were similar, i.e., 5.9 and 6.5 m s^{-1}, respectively, during StormVEx and 5.9 and 5.2 m s^{-1}, respectively, during IFRACS. ~~There is an apparent inconsistency in this analysis, which is that when particles are counted in the first CIP channel under "dry" conditions, they should also be measured by the SPP-100.~~ The ~~average concentrations in the first CIP channel under "dry" conditions were 0.32 and 0.06 cm^-3 during StormVEx and IFRACS, respectively. These values can be inaccurate because of sizing uncertainty in the first two CIP channels. The actual concentration of particles in CIP channel 1 under "dry" conditions may also be below the limit of detection of the SPP-100. The~~potential impact of ice particles on ~~SPP~~FSSP-100 measurements cannot be observed directly with these instruments. ~~Taken at face value~~However, the magnitude of the ratio of wet/dry concentrations in CIP channel 1 ~~places an upper limit on~~constrains the effect of ice particles on the ~~SPP~~FSSP-100 measurements. ~~On average, droplets were 34 times more abundant than~~ The relative fraction of crystals in ~~the 12.5-37.5 µm size range while the corresponding~~ CIP channel 1 can be estimated from the ratio ~~during StormVex was only~~ of wet/dry in CIP channel 1 to the average of the ratios of wet/dry in CIP channels 3-8, where droplets were absent and where the ratios of wet/dry were constant. These values, 2.3 and 6 for StormVEx and IFRACS, respectively, imply that 43% (1/2.3) and 16.7~~.~~% (1/6) of particles in CIP channel 1 were ice crystals during StormVEx and IFRACS, respectively. Because of the sizing uncertainty for particles which triggered a single diode (CIP channel 1) it is impossible to know precisely which FSSP-100 channels were impacted by ice crystals.

The distributions of Conc75-200, wind speed and temperature as a function of wind direction during StormVEx and IFRACS are summarized in Table 2. During StormVEx, mostly all of these cases were on 22 January 22 2011. The 5-minute average wind direction was exactly the same (351.9º) for 3.5 hours. It is not likely that a 5-minute average value could be the same to a tenth of a degree for two consecutive 5-minute periods, much less eighteen. During IFRACS, many of the NNW wind directions exhibited the same value for thirty minutes or more. The reason is that the wind vane can become iced by riming and doesn't move. The data were screened for repeated 5-minute wind speeds and these were eliminated. This reduced the number of 1-minute observations by 2 and 4.7% during StormVEx and IFRACS, respectively.Winds were from the NW sector ~75.3 and 57% of the time during StormVEx and IFRACS, respectively. There was one 5~~-~~-minute period during IFRACS when the wind direction was 11 degrees. High Conc75-200 were seen in the NW sector in both studies but the highest concentrations were seen in the NNW sector, albeit at low frequency. When segregated by wind direction, there was no relationship between Conc75-200 and temperature or wind speed in either study.

3.2 ~~Supercooled~~Super-cooled Liquid Cloud Microphysics

In non~~-~~-precipitating warm clouds, an increase in CCN should increase CDNC while decreasing droplet size at constant LWC (Albrecht, 1989). Smaller drops may inhibit collision coalescence and precipitation and increase LWC (Zheng et al., 2010). Borys et al. (2000) demonstrated a direct relationship between clear air equivalent sulfate concentration (a surrogate for pre cloud CCN) and CDNC and an inverse relationship between CDNC and droplet size (NMD) in

MPC at SPL. In such clouds, the droplet distribution may be impacted by riming of ice particles and by transitions between the liquid and ice phases. Figure ~~3~~4 presents the relationship between 1~~-~~-minute droplet NMD and CDNC in MPC during StormVEx (Fig. ~~3a~~4a) and IFRACS (Fig. ~~3c~~4c). The relationship is stronger when the data are stratified by LWC. The average NMD and CDNC were calculated for each of the four ranges of LWC in Fig. ~~3~~4 and are plotted in the figures as a function of LWC. NMD and CDNC increased monotonically with LWC in both studies. This is consistent with enhanced growth of droplets as cloud base drops below SPL. However, for CDNC to increase with LWC, either the supersaturation must increase or CCN aerosols must become entrained in the cloud between cloud base and SPL. Figures ~~3b~~4b and ~~3d~~4d present average ~~SPP~~FSSP-100 PSDs for low (0.05-0.1 g m^{-3}) and high (0.2-0.3 g m^{-3}) LWC, corresponding to Figs. ~~3a~~4a and ~~3c~~4c, respectively. The distributions are shifted to larger sizes at high LWC and the increase in CDNC is evident for droplet sizes larger than 10 µm. Note that the shift in the PSDs to larger sizes at high LWC stops at about 35 µm, i.e., the concentration of very large drops is higher at low LWC. ~~This could indicate a preferential loss of very large drops to riming at high LWC.~~

3.3 Relationship between LWC and IWC

As noted above with respect to Table 1, liquid cloud microphysical properties at SPL were less variable than those of the ice phase. One reason for this is that the ice phase is impacted by processes occurring upwind and at higher altitude. Lowenthal et al. (2011; 2016) estimated that most of the snow mass was formed within 1 km above SPL. This does not preclude ice nucleation at higher altitudes, as small, freshly nucleated crystals contribute little to IWC. Even though riming occurs, most efficiently for large droplets, it is not apparent from ~~Figs. 1 and 4~~Fig. 2 that the liquid cloud was impacted by the ice phase. Indeed, the Pearson and Spearman Rank (non~~-~~-parametric) correlations between all concurrent 1-minute average IWC and LWC were only -0.18 and -0.10, respectively, during StormVEx and -0.13 and -0.16, respectively, during IFRACS. The effect of outliers, characteristic of skewed distributions, is reduced with the non~~-~~-parametric statistic. Henceforth, the Spearman Rank correlation is displayed in parenthesis after the Pearson correlation. Scatter plots of IWC versus LWC ~~(not~~are shown~~) resemble a solid cluster of points filling a right triangle.~~ in Figs. 5a and 5b for StormVEx and IFRACS, respectively. The edge ~~(hypotenuse)~~ in the data suggests that there were periods when IWC and LWC were more strongly ~~anticorrelated.~~anti-correlated. If only days with at least 2 hours of valid, 1~~-~~-minute average data are considered, there were 4 out of 11 and 3 out of 11 days during StormVex and IFRACS, respectively, where the Pearson and Spearman Rank correlations between IWC and LWC were less than -0.5.

A sampling day during IFRACS with relatively high average IWC (0.23 g m^{-3}) and LWC (0.182 g m^{-3}) was identified for closer examination. Figure ~~4~~6 presents time series of 1~~-~~-minute average IWC and LWC on 9 February ~~9,~~ 2014. In this case, the correlation between IWC and LWC was -0.59 (-0.60), suggesting interaction between the ice and liquid phases. The minimum 1-minute average LWC was 0.05 g m^{-3}~~, i.e., the cloud at SPL was never fully glaciated~~ and there were no “dry” (LWC=0) 1-second sample periods on this day. To contrast periods with high and low IWC, average ~~SPP~~FSSP-100 PSDs were calculated for ~~the~~a High-Ice period between 12:45 and 13:17 MST (Fig. ~~4~~6) and for ~~minutes~~Low-Ice periods outside of that interval with the additional constraint that the LWC/IWC ratio was greater than 2. These PSDs are presented in Fig. ~~5.~~7. Figures 8a and 8b present CIP images from the High- and

Low-Ice periods, respectively. Note the relatively higher concentration of "dots" in Fig. 8b (Low-IWC, High-LWC). These represent cloud droplets that occluded a single CIP diode. The average IWC and LWC were 0.72 and 0.088 and 0.054 and 0.25 g m^{-3} for the ~~high~~High- and ~~low IWC~~Low-Ice periods respectively. The average IWC and LWC during the ~~high IWC and high LWC~~High-Ice periods were 3.7 and 1.98 times higher, respectively, than the study wide averages (Table 1). Compared with the ~~low IWC~~Low-Ice period, the ~~high IWC SPP~~High-Ice FSSP-100 PSD displays a marked loss of particles with diameters between ~5 and 23 µm. The corresponding loss of liquid water was 0.181 g m^{-3} (Fig. ~~5~~7). The most obvious explanation is evaporation of droplets (Wegener-Bergeron-Findeisen process). The loss of LWC is much lower than the more than order of magnitude difference in IWC for the two cases.

The ~~increase in IWC~~High-Ice period is ~~due to~~characterized by an order of magnitude higher Ni concentration ~~at high IWC~~ (525 L^{-1}) compared ~~to low IWC (~~with 50 L^{-1}~~)~~. during the Low-Ice period. The correlation between IWC and Ni was 0.98 (0.98). ~~At the same time, the concentration of large droplets (25-35 µm, CDNC25-35) was higher at high IWC (976 L^{-1}) than at low IWC (422 L^{-1}). This could imply a link between ice production and the presence of large cloud droplets (Hobbs and Rangno, 1985; de Boer et al., 2011; Lance et al., 2011).~~

There were no relationships between LWC or IWC and either temperature or water vapor concentration, which were relatively invariant, i.e., -5.4±0.3 °C and 8064±204 ppmv, respectively. ~~The correlations between TAS and MTAS (maximum 1 second TAS) and IWC were 0.46 (0.42) and 0.66 (0.60), respectively. The correlations between TAS and MTAS and Ni were 0.42 (0.38) and 0.62 (0.56), respectively. The higher correlations for MTAS suggest that the high IWC (Ni) period could have been influenced by blowing. Average TAS and MTAS during the high and low IWC periods were 8.3 and 16.6 and 5.6 and 8.9 m s^{-1}, respectively. A difference of 2.7 m s^{-1} in TAS between the high and low IWC periods is unlikely to have caused the 10-fold increase in Ni during the high IWC period. However, the near doubling of average MTAS to ~17 m s^{-1} during the high IWC period suggests that the large increase in Ni could have been related to blowing snow.~~

3.4 Liquid Mediated Ice Production

In this section, the hypothesis that ice production in MPC at SPL ~~is~~was related to large droplet concentration is examined ~~(Hobbs and Rangno, 1985; Lance et al., 2011). To reiterate, Fig. 2 demonstrates that the CIP measured cloud~~. Large droplets ~~in the first but not higher channels. Noting that particles were measured by the CIP in channel 1 under dry conditions, the ratio of wet/dry concentration in CIP channel 1 constrains the effect of ice particles on the SPP-100 measurements. During StormVEx, a wet/dry a ratio of ~4 suggests that ~20% of~~are defined as CDNC25-35 ~~could have been ice particles. During IFRACS, a wet/dry ratio of 34 suggests that the effect of ice particles on~~ with diameters between 25 and 35 µm. Because of the paucity of CDNC25-35 ~~was negligible.~~
concentrations >0 during StormVEx, the analysis is confined to IFRACS. Thirty-second averages were calculated for periods with CDNC25-35 >0 and Conc75-200 >0 using the 75% data completeness criterion. The relationships between ~~1 minute~~30-second average CDNC25-35 and Conc75-200 were examined under cold (<-~~12~~8 °C) and warm (>-8 °C) conditions. This is intended to distinguish cold and warm primary or secondary (e.g., Hallett-Mossop rime splintering) ice production processes. Figures ~~6a~~9a and ~~6c~~9b present relationships for ~~StormVEx~~IFRACS under cold and warm conditions, respectively ~~and Figs. 6b and 7d present the corresponding relationships for IFRACS.~~. The

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average temperatures for ~~all 1 minute averages (Table 1) during StormVEx and IFRACS~~the cold and warm periods were -~~12~~11.2±1.5 and -5.8±~~2~~0.8 ~~and -8.2±3.6~~ °C, respectively. Figure ~~6a~~9a shows a moderate relationship (r=0.~~57~~72 [0.~~45~~73]) between CDNC25-35 and Conc75-200 at cold ~~temperature during StormVEx~~temperatures but no ~~direct~~ relationship at warm ~~temperature~~temperatures (r~~=-0.10 [-~~=0.~~45]). Note that this is based on relatively few (29) data points. During IFRACS (Fig. 6b), there was a strong relationship (r=~~161 [-0.~~90 [0.88]) at cold temperature but a weaker one (r=0.42 [0.53]) at warm temperature (Fig. 6d). Figure 6d suggests that the warm data points followed two trends, one similar to the cold points in Fig. 6b and the other similar to the flat distribution of warm points in Fig. 6c.~~165]).

~~Temperatures at SPL during StormVEx and IFRACS were less than -15°C only 9% of the time and thus small crystals could not have nucleated homogeneously or by deposition.~~ Given the relationships between large droplet and small ice crystal concentrations, is the temperature range at SPL consistent with immersion and/or contact freezing? This appears to be the case at colder temperatures (<-~~12~~8 °C) at SPL for contact freezing, as seen in Figs. 7 and 13 in Moreno et al. (2013) and for immersion freezing, particularly for biological INP (Levin and Yankofsky, 1964; Du et al., 2017; Kanji et al., 2017). ~~The large droplet – small crystal relationship was considerably noisier during StormVEx (Fig. 6a) than IFRACS (Figure 6c). This could reflect contamination of CDNC25-35 by ice particles or a problem with the measurement of large droplets during StormVEx (discussed above). The relationship is ambiguous at warmer temperatures. Temperatures were >-8 °C on 3 out of 30 sampling days (2.7% of sample minutes) during StormVEx and 9 out of 15 sampling days (54% of sample minutes) during IFRACS. Assuming that biological INP are more prevalent under warmer conditions (Stopelli et al., 2015), the direct relationship during the warm IFRACS sampling periods is consistent with contact or immersion freezing involving biological INP. Bowers et al. (2009) observed biological INP at SPL which froze at temperatures ≥ 10 °C in the immersion mode.~~ The lack of a relationship at warm temperatures would appear to preclude secondary ice formation by the Hallett-Mossop process. As noted above, the FSSP-100 cannot distinguish liquid droplets from ice crystals. It possible that the relationship between CDNC25-35 and Conc75-200 represents an autocorrelation between two segments of the ice crystal distribution. Two factors argue against this: 1) Figure 3 suggests that ice particles are 6 times more prevalent than droplets in the large droplet size range; and 2) the relationship doesn't exist at >-8 ºC. Higher resolution instruments, such as the holographic imagers used by Beals et al. (2015) and Beck et al. (2018) should be used to address this issue.

~~Secondary ice production (SIP) mechanisms have been extensively reviewed (e.g., Field et al., 2017). Sullivan et al. (2018) modeled SIP by rime splintering, droplet shattering, and collisional breakup. Rangno and Hobbs (2001) concluded that shattering of large droplets (>50 µm) upon freezing could have accounted for high observed ice particle concentrations in Arctic stratus. While there is no evidence of droplets this large at SPL, they could be present upwind and above SPL. Keppas et al. (2017) concluded that rime splintering occurred in warm (-6 to 0 °C) frontal clouds. "Lolly pop" shaped crystals were taken as evidence of riming of columnar crystals by droplets larger than 100 µm. Neither "lolly pops" nor droplets this large have been observed in MPC at SPL. Lloyd et al. (2015) considered blowing snow, rime splintering, and detachment of surface frost (Bacon et al., 1998) as sources of high ice particle concentrations at JFJ. They ultimately favored the latter process, albeit with no direct evidence. There is also no~~

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~~evidence regarding surface frost splinters at SPL. Rime splintering could have been responsible for the relationship between CDNC25-35 and Conc75-200 during IFRACS under warm conditions although it is not clear why this wouldn't also have been the case during StormVEx. Perhaps there were too few warm 1 minute periods during StormVEx to establish a meaningful relationship. For rime splintering to account for a relationship between CDNC25-35 and Conc75-200, the rime mass fraction as well as the number of splinters produced by each rimed droplet would have to be consistent. This is farfetched.~~

3.5 Blowing Snow

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Blowing snow can cause significant artifacts in ice crystal measurements at surface locations. Rogers and Vali (1987) found higher ice crystal concentrations at the Elk Mountain Observatory compared with those observed aloft on the University of Wyoming Queen air but discounted blowing snow as the explanation for this difference. Lloyd et al. (2015) concluded that high ice crystal concentrations at JFJ were not caused by blowing snow. Geerts et al. (2015) compared CIP concentrations (≥75 μm) at SPL with those measured aboard the University of Wyoming King Air (UWKA) during the Colorado Airborne Multiphase Cloud Study (CAMPS) when the aircraft was in the vicinity of SPL. Concentrations were considerably higher at SPL when the maximum wind speed associated with 5~~ ~~-minute average measurements was above about 4 m s^{-1}. This was attributed to blowing snow. However, a valid comparison between aircraft and surface measurements depends on the assumption that both platforms measure the same ice crystal population. This would require establishing crystal trajectories from a point upwind aloft to a point downwind at the surface. Even if a direct link between the PSDs aloft and at the surface could be demonstrated, the falling crystal PSD is likely to be modified by depositional growth at ice supersaturation in the low level liquid cloud, riming and aggregation, or sublimation in subsaturated regions. ~~The ice crystal PSD measured at the surface can also be enhanced by ice production near the surface, as discussed above, secondary ice production, or blowing snow~~ Beck et al. (2018) reported a large increase in Ni when the maximum wind speed increased from 14-16 to ≥16 m s^{-1} at the Sonnblick Observatory in Rauris, Austria when winds were from the south.

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~~Beck et al, (2017) conducted ice particle measurements at various heights on a 10 m tower at the Sonnblick Observatory (SBO) in Rauris, Austria. They suggested that during cloud free periods, a rapid decrease in ice crystal concentration with height could be explained by blowing snow. However, the wind speeds during those periods were around 17 m s^{-1}, which is significantly higher than the 1 minute average wind speeds in the SPL analysis. In contrast, when SBO was in liquid cloud, a consistent decrease in ice crystal concentration with height on the tower was not observed. Rather, varying vertical profiles of crystal concentration were attributed to advection of ice crystals in a turbulent layer above the snow surface or enhancement of ice crystal concentration due to a convergence zone of ice crystals at the mountaintop associated with orographic flow over the barrier.~~

~~Correlations between 1 minute average TAS and Conc75-200 during StormVEx and IFRACS were 0.38 (0.36) and 0.54 (0.47), respectively. These moderate correlations could be taken as evidence for blowing snow. Note that the corresponding correlations in the 1 second data were lower, i.e., 0.23 (0.25) and 0.14 (0.22), respectively. The lower correlations in the 1 second~~ Figure 10a plots the 1-second maximum TAS during a 1-minute period (MTAS) and the corresponding 1-minute average TAS (Fig. 10b) against 1-minute average Ni for High-Ice, Low-Ice, and all other (Intermediate-Ice) periods on 9 February 2014. MTAS was highly correlated with TAS [0.90 (0.90] over the course of the day. The highest Ni correspond to the highest MTAS (and TAS) and *visa versa*. Average MTAS was 16.6±2.4, 8.9±2.0, and 11.3±2.8 m s^{-1} during High-, Low-, and Intermediate-Ice periods, respectively. This could imply that high Ni resulted from blowing snow when the winds were higher in the early afternoon. However, contrary to results reported by Beck et al. (2018), there was no step function in Ni corresponding to a threshold in MTAS. Further, there appears to be an inverse relationship between 1-minute MTAS and 1-minute Ni, especially for the High- and Low-Ice regimes. Beck et al. (2018) noted that a correlation between MTAS and blowing snow could be reduced if the averaging time was too long or obscured because of an [indeterminate] lag between the arrival of the gust and the particles that may have been lofted by it. Beck et al. (2018) suggested using an averaging time of 10-15 seconds. Figure 11 plots 15-second average (using the 75% data completeness criterion) MTAS against Ni for the High-Ice, Low-Ice, and Intermediate-Ice periods on 9 February 2014. Figure 11 shows that while both MTAS and Ni varied considerably in each case, there was no apparent wind speed threshold and the correlations between MTAS and Ni were actually negative under High- and Low-Ice conditions. These results are not consistent with the blowing snow hypothesis.

Examining all available data~~ suggest that if surface snow had been resuspended by the wind, it would have occurred at some distance upwind of the building.~~, Table 3 presents average Conc75-200 over ranges of TAS ~~and CDNC25-35~~ during StormVEx and IFRACS. Conc75-200 increases monotonically, if not linearly, with ~~both~~ TAS ~~and CDNC25-35~~ in both studies. ~~Finally, relationships between Conc75-200 and TAS, CDNC25-35, and temperature were examined using stepwise and non parametric regression. The results are shown in Table 4. The higher a variable's contribution (partial r square) to the model r square, the greater its importance as an explanatory variable. For StormVEx, TAS had the highest partial r square, followed by CDNC25-35 and Temp, whose contribution was negligible. However, for IFRACS, CDNC25-35 was the primary contributor to r square, followed by TAS and Temp (also negligible). The relatively~~If it is assumed that smaller ~~contribution of CDNC25-35 to the variance of Conc75-200 during StormVEx could be due to a measurement problem, as discussed above. Indeed, average CDNC25-35 concentrations during StormVEx and IFRACS were 47 and 231 L^{-1}, respectively, while total CDNC were similar (Table 1).~~

~~Smaller~~ crystals should be lofted more efficiently ~~lofted~~ from the snow surface and remain suspended farther downwind than larger ones (Schmidt, 1982~~). Thus,~~), blowing snow should result in a relative enrichment of small crystals in the CIP PSD, independent of absolute concentration. Average 1-minute CIP PSDs were calculated, normalized to average Ni, and expressed as percentages. These are presented for high (8-12 m s^{-1}) and low (1-~~4 m s^{-1}) TAS in Figure 7. Contrary to expectation for blowing snow, there is little difference between the relative PSDs at low and high TAS up to approximately 200 and 300 μm during StormVEx and IFRACS. The cumulative increase in small particles and corresponding decrease in large particles at the point where the high and low TAS PSDs cross was 7% in both studies. This small enhancement of small particles at high TAS cannot~~3 m s^{-1}) TAS in Figure 12. During StormVEx, Conc75-200 was 83 and 93% of Ni at low and high TAS, respectively. The corresponding percentages during IFRACS were 79 and 87%, respectively. The relative enrichments of Conc75-200 at high TAS, i.e., 10 and 8%, during StormVEx and IFRACS, respectively, are consistent with expectations for blowing snow. However, these percentages cannot explain the large differences in the absolute concentrations of Conc75-200 at high and low wind speeds, which are factors of 4.5 and 6.5 during StormVEx and IFRACS, respectively (Table 3). They also do not explain the large differences between surface and aircraft measurements observed by Rogers and Vali (1987) and Geerts et al. (2015). ~~However, it could be due to an equivalent loss~~Correlation of ~~large particles through collisional breakup. Increased turbulence should enhance collisional breakup of~~ wind speed with crystal concentrations does not necessarily imply blowing snow. In mountain clouds, ice crystal concentrations vary with synoptic and orographic dynamics. Stronger uplift nucleates more crystals ~~by increasing collision frequency (Vardiman, 1978; Lohmann~~upwind and above the mountain barrier as droplets continue to grow and temperatures decrease (e.g., Neiman et al., ~~2016). Combining data from both studies, the~~ 2002; Stoelinga et al., 2013). The correlations between ~~u (~~1-minute average TAS~~)~~ and ~~σ_u and between w and σ_w~~vertical velocity were 0.~~76~~75(0.~~75~~72) and 0.~~71~~66(0.~~73),~~67) during StormVEx and IFRACS, respectively~~, i.e., there was more turbulence at higher TAS.~~ .

3.6 Secondary Ice Production

Secondary ice production (SIP) mechanisms have been extensively reviewed (e.g., Field et al., 2017). Sullivan et al. (2018) modeled SIP by rime splintering, droplet shattering, and collisional breakup. Rangno and Hobbs (2001) concluded that shattering of large droplets (>50 µm) upon freezing could have accounted for high observed ice particle concentrations in Arctic stratus. While there is no evidence of droplets this large at SPL, they could be present upwind and above SPL. Keppas et al. (2017) concluded that rime splintering occurred in warm (-6 to 0 °C) frontal clouds. "Lolly pop" shaped crystals were taken as evidence of riming of columnar crystals by droplets larger than 100 µm. Neither "lolly pops" nor droplets this large have been observed in MPC at SPL. Lloyd et al. (2015) considered blowing snow, rime splintering, and detachment of surface frost (Bacon et al., 1998) as sources of high ice particle concentrations at JFJ. They ultimately favored the latter process, albeit with no direct evidence. There is also no evidence regarding surface frost splinters at SPL. Snow was continually falling during measurement periods at SPL leaving no undisturbed icy surface to accumulate frost. Rime splintering (Hallett-Mossop) is thought to occur at temperatures above -8 ºC. During StormVEx, average Conc75-200 was 13.6 and 89 L^{-1} at temperatures warmer than -8 ºC and colder than -12 ºC, respectively. The corresponding average TAS were 5.8 and 5.2 m s^{-1}, respectively. During IFRACS, average Conc75-200 was 95 and 116 L^{-1} at temperatures warmer than -8 ºC and colder than -12 ºC, respectively. The corresponding average TAS were 6.1 and 4.9 m s^{-1}, respectively. While rime splintering may have occurred, it was not the dominant ice formation mechanism.

4 Conclusions

Studies of mixed~~-~~-phased orographic clouds (MPC) were conducted at the Storm Peak Laboratory (SPL) in northwestern Colorado in January and February during StormVEx (2011) and IFRACS (2014). In total, the data represent ~92 hours when SPL was immersed in ~~supercooled~~super-cooled liquid cloud and it was snowing. On average, liquid cloud PSDs, CDNC, NMD, and LWC were similar between years while Ni and IWC were 48 and 114% higher, respectively, during IFRACS. Average wind speeds were similar (~ 6 m s^{-1}) in both studies while average temperatures were colder during StormVEx (-12.8 °C) than IFRACS (-8.2 °C). ~~Supercooled~~Super-cooled

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liquid cloud properties at SPL were consistent between the two studies. The microphysical properties of ice particles were more variable as they depend on the structure of the cloud above and upstream of SPL.

The inverse relationship between cloud droplet size (NMD) and concentration (CDNC) is related to CCN at SPL (Borys et al., 2000). This relationship is stronger when the data are stratified by LWC. Both CDNC and NMD increase with increasing LWC, demonstrating droplet growth and enhanced activation of or entrainment of CCN below SPL. Future studies at SPL would benefit from direct measurement of cloud base height. There was a weak relationship between LWC and IWC for all data (the correlation was -0.18 (-0.10) and -0.13 (-0.16) during StormVEx and IFRACS, respectively), however, a stronger inverse relationship was evident on several days during each study. This was demonstrated for a case on 9 February~~ 9,~~ 2014, where the correlation between IWC and LWC was -0.59 (-0.60). During a period of maximum IWC on this day, the droplet PSD showed a significant loss of liquid water and a decrease in droplet concentration compared to periods with low IWC and high LWC. As there was an order of magnitude increase in the ice crystal concentration (Ni) between the ~~high~~High- and ~~low IWC~~Low-Ice periods, the loss of LWC was likely due to crystal growth at the expense of evaporating droplets (Wegener-Bergeron-Findeisen process).

~~Relationships~~A relationship between large cloud droplets (CDNC25-35) and small ice crystals (Conc75-200) ~~suggest~~during IFRACS suggests that droplet freezing (contact or immersion) was involved in ice production at SPL. This relationship was only evident ~~during StormVEx only~~ at temperatures below -~~12 °C. During IFRACS, relationships were seen under cold (<-12 °C) and warm (>-~~8 °C~~) conditions. Warmer temperatures during IFRACS could have been associated with an increase in biological aerosols which have been shown to be effective immersion and contact INP at warmer temperatures than inorganic INP.~~. There ~~is~~was no evidence that secondary ice production mechanisms such as rime splintering, large droplet freezing, or frost splintering influenced Conc75-200 at SPL. It is unclear how these processes could have produced the observed ~~correlations~~correlation between large droplet and small ice crystal concentrations.

Blowing snow can significantly impact surface ice crystal concentrations ~~at the surface~~ and has been invoked to explain large differences between surface and aircraft ice crystal measurements. The potential effect of blowing snow on ice crystal measurements at SPL was evaluated ~~based on~~from two perspectives. On 9 February 2014 during IFRACS, 1-minute average Ni increased with both 1-minute average TAS and the 1-second maximum TAS (MTAS), although there was no threshold wind speed or step function in Ni. However, during High-Ice and Low-Ice periods, there was an inverse correlation between 15-second average Ni and MTAS over a wide range of MTAS. This is not consistent with blowing snow. For the ~~assumption~~entire data set, Ni also increased with wind speed. To test the hypothesis that ~~blowing~~this was caused by blowing snow, it was assumed that blowing snow should preferentially enhance the relative abundance of small crystals (Conc75-200) in the ~~ice crystal~~CIP PSD. Comparison of the relative (expressed as percentages of ~~the total~~Ni) ice crystal PSDs at high (8-12 m s^{-1}) and low (1-~~4~~3 m s^{-1}) TAS showed that Conc75-200 was enriched by 8-10% at higher TAS. However, this level of enrichment cannot explain the factor of 4.5-6.5 higher Conc75-200 at high TAS at SPL or previously reported orders of magnitude differences between surface and aircraft measurements. ~~While the temperature dependent relationships between CDNC25-35 and Conc75-200 suggest~~Stronger dynamics, especially orographic and/or convective uplift, also contribute to ice production ~~by droplet freezing, moderate correlations and a statistical dependence of Conc75-200 on TAS can be taken as evidence of~~

~~blowing snow.~~upwind and above the mountain. It is possible that both primary production and blowing snow were active at SPL. These results highlight the need for targeted experiments to quantify the contributions of blowing snow to ice crystal concentrations at mountaintop locations. They also demonstrate the limitations of instrumentation such as the FSSP-100 and CIP (2-D optical array probe) for distinguishing liquid droplets from small ice crystals in mixed-phase cloud. Higher resolution instruments are required for this purpose.

Data Availability

Data are available at: https://www.dri.edu/doug-lowenthal-research-reviews

Author Contribution

DL was a principal investigator on IFRACS~~.~~ and is Professor Emeritus at DRI. AGH is the director of the Desert Research Institute's Storm Peak Laboratory. AGH and GM were principal investigators on StormVEx. RD was a graduate student at DRI who worked on the IFRACS field experiment and used the results in his Master's thesis. IM is the site manager at Storm Peak Laboratory. RB is Professor Emeritus at DRI and worked on the IFRACS field experiment.

Competing Interests

The authors declare that they have no conflict of interest.

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Table 1. Average of concurrent 1-minute CIP and ~~SPP~~FSSP-100 measurements during StormVEx and IFRACS. The values in parentheses are the coefficients of variation.

	CIP						~~SPP~~FSSP-100					
	Conc75-200[a] (L^{-1})	Large[b] (L^{-1})	Ni[c]	Conc75-200/ Ni (%)	Large/ Ni (%)	IWC[d] ($g\ m^{-3}$)	CDNC[e] (cm^{-3})	LWC[f] ($g\ m^{-3}$)	NMD[g] (µm)	~~TAS~~TAS[h] ($m\ s^{-1}$)	Temp. (°C)	~~N[h]~~N[i]
StormVEx	88	2.4	95	91	3.7	0.090	211	0.117	9.2	6.1	-12.8	2955
	(116)	(129)	(132)			(118)	(54)	(63)	(22)	(30)	(22)	
IFRACS	123	5.9	141	83	7.2	0.193	199	0.126	10.1	6.0	-8.2	2580
	(146)	(112)	(142)			(109)	(73)	(54)	(27)	(35)	(44)	

[a]CIP concentration from 75-200 µm

[b]CIP concentration ≥400 µm

[c]CIP concentration ≥75 µm

[d]Ice water content

[e]Cloud droplet number concentration

[f]Cloud liquid water content

[g]Cloud droplet number-weighted mean diameter

~~[h]Number~~[h]TAS is the horizontal wind speed

[i]Number of 1-minute observations in the average

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Table 2. Frequency distribution of Conc75-200, wind speed, and temperature as a function of wind direction.

	StormVEx				IFRACS			
Wind Direction (degrees)	Conc75-200 (L^{-1})	Wind Speed ($m\ s^{-1}$)	Temp.[a] (°C)	~~Frequency[b]~~#[b] ~~(%)~~	Conc75-200 (L^{-1})	Wind Speed ($m\ s^{-1}$)	Temp. (°C)	~~Frequency~~# ~~(%)~~
>0-30	-	-	-	-	27	~~6.~~3.9	-10.6	~~0.194~~5
>180-210	18.2	~~5.7~~8.3	-9.3	~~1.2~~36	~~28~~27	~~5.0~~4.9	-9.~~6~~2	~~4.7~~114
>210-240	~~73~~67	~~5.2~~6.0	-10.7	~~9.0~~252	56	~~7.~~5.3	-9.9	~~22.4~~560
>240-270	~~79~~77	6.9~~.1~~	-11.7	~~14.5~~420	~~72~~68	~~8.9~~6.1	-6.9	~~15.6~~387
>270-300	~~92~~91	~~5.7~~6.1	-13.5	~~58.8~~1728	~~146~~149	~~8.3~~6.5	-8.~~1~~0	~~29.1~~724
>300-330	66	~~3.4~~5.0	-13.2	~~15.1~~446	~~190~~191	6.~~7~~2	-7.5	~~23.0~~590
>330-360	~~460~~150	~~7.8~~6.2	-	~~1.4~~11	~~231~~165	~~7.~~6.5	-6.7~~.9~~	~~5.0~~79
			~~10.7~~11.3					

[a]Temperature based on 5~~-~~-minute average measurements.

~~[b]Based on the number of minutes in Table 1.~~

[b]There were 2893/2955 and 2459/2580 1-minute measurements when the wind vane was not frozen during StormVEx and IFRACS, respectively.

Table 3. Relationships ~~among~~between TAS~~,~~ and small ice crystal concentrations (Conc75-200 ~~(small crystals), and CDNC25-35 (large droplets~~) during StormVEx and IFRACS. r is the Pearson (Spearman Rank) correlation.

	StormVEx		IFRACS	
TAS	Conc75-200	N	Conc75-200	N
(m s^{-1})	(L^{-1})		(L^{-1})	
1-3	39	51	46	~~111~~110
3-5	51	928	49	~~800~~801
5-8	84	1463	112	1258
8-12	175	513	301	382
12-16	-	-	616	29
r	0.38 (0.36)		0.54 (0.47)	

	~~StormVEx~~		~~IFRACS~~	
~~CDNC25-35 (L^{-1})~~	~~Conc75-200 (L^{-1})~~	~~N~~	~~Conc75-200 (L^{-1})~~	~~N~~
~~0-25~~	~~70~~	~~1369~~	~~24~~	~~488~~
~~25-50~~	~~117~~	~~407~~	~~41~~	~~501~~
~~50-100~~	~~172~~	~~216~~	~~62~~	~~434~~
~~100-500~~	~~223~~	~~202~~	~~154~~	~~775~~
~~500-2000~~	~~228~~	~~17~~	~~379~~	~~339~~
~~>2000~~	~~-~~	~~-~~	~~480~~	~~21~~
~~r~~	~~0.24 (0.33)~~		~~0.61 (0.68)~~	

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~~**Table 4**. Results of stepwise regression[a] of Conc75-200 on the explanatory variables TAS, CDNC25-35, and temperature (Temp). Variables are entered according to their contributions to the model r square. Partial r square are shown for each variable. Pr>F is the probability that the estimated contribution to the model is random. Importance[b] is a metric of the non parametric regression procedure which is analogous to the partial r square.~~

	~~StormVEx~~		~~IFRACS~~	
	~~Partial r-square~~	~~Importance~~	~~Partial r-square~~	~~Importance~~
~~TAS~~	~~0.188~~	~~100~~	~~0.131~~	~~44~~
~~CDNC25-35~~	~~0.051~~	~~63~~	~~0.31~~	~~100~~
~~Temp~~	~~0.0014~~	~~5.7~~	~~0.035~~	~~21~~

~~[a]Stepwise regression was done using the REG procedure with forward selection in SAS 9.4.~~

~~[b]Non parametric regression was done using the ADAPTIVEREG procedure in SAS 9.4.~~

Figure 1. Recent picture of SPL probe stand with in and FSSP-100 in foreground, CIP in background, and sonic anemometer on top (left panel). View facing west over the railing (right panel).

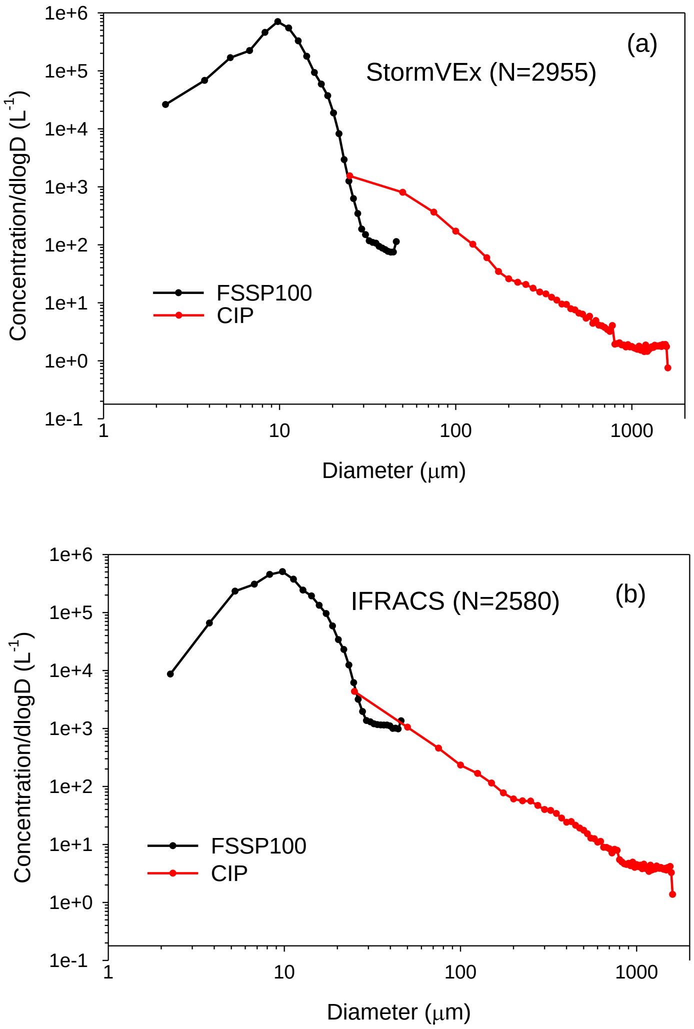

Figure 2. Average of concurrent 1-minute FSSP-100 and CIP particle size distributions (PSDs) from StormVEx (a) and IFRACS (b).

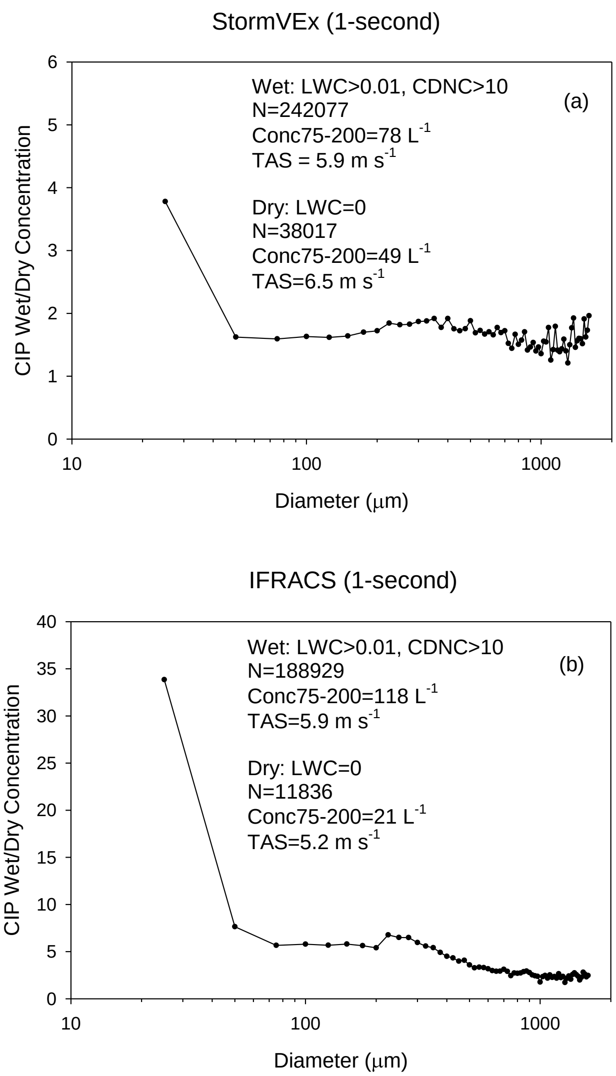

Figure 3. Ratio of average mixed-phase (LWC>0.01 g m^{-3}, CDNC>10 cm^{-3}) to dry (LWC=0) PSDs for StormVEx (a) and IFRACS (b).

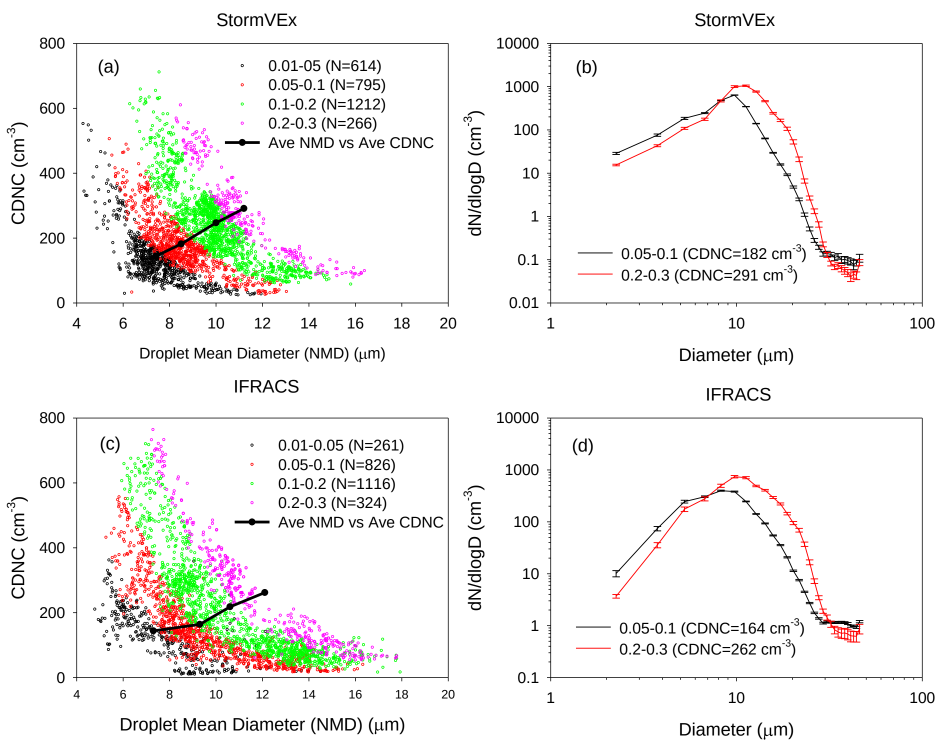

Figure 4. Relationships among 1~~-~~minute average mean cloud droplet diameter (NMD~~),~~) and concentration (CDNC), ~~and~~ segregated by liquid water content (LWC, ~~μg m^{-3})~~g m^{-3}), as shown by colors in the legend, during StormVEx (a) and IFRACS (c). Corresponding average PSDs for low (0.01-0.05 g m^{-3}) and high (0.2-0.3 g m^{-3}) LWC are shown in Figs. ~~3b and 3d~~4b and 4d. The error bars in Figs. 4b and 4d are standard errors.

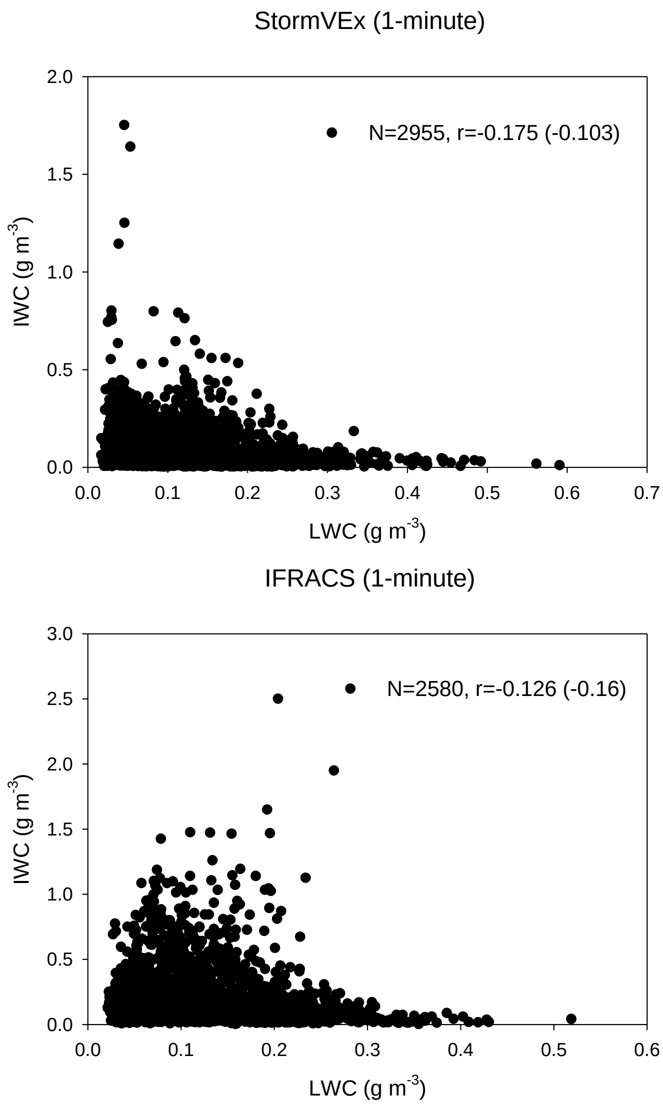

Figure 5. Relationships between LWC and IWC during StormVEx (a) and IFRACS (b).

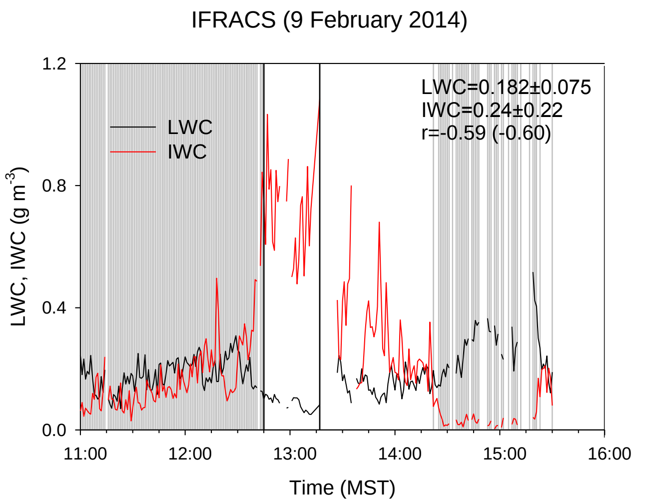

Figure 46. Time series of LWC and IWC on 9 February ~~9,~~ 2014 during IFRACS. The High-IWC period is from 12:45 – 13:17 MST. The Low-IWC periods are indicated by the shaded areas.

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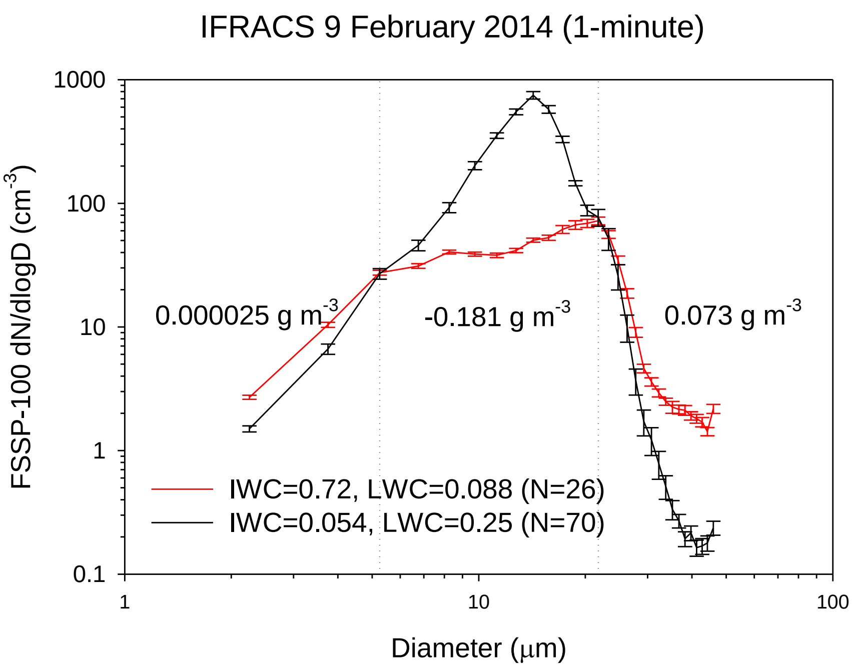

Figure 7. Average PSDs for high (1245-1317 MST) and low (<1245 or >1317 MST and LWC/IWC>2) IWC periods in Fig. ~~4~~6. The values in the middle of the plot are the differences between the high (red) and low (black) cumulative LWC in the three sections of the distributions defined by the vertical dotted lines. The error bars are standard errors.

(a) (b)

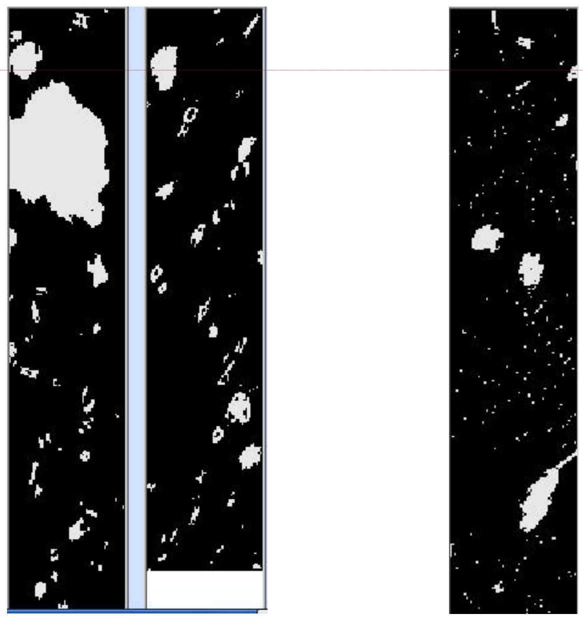

Figure ~~6~~8. CIP images from 9 February 2014: (a) 13:12:19 MST, High-Ice and low LWC, and (b) 12:29:09 MST, Low-Ice and high LWC. The vertical bars contain all of the images sampled in 1-second. The width of each bar corresponds to 1600 µm.

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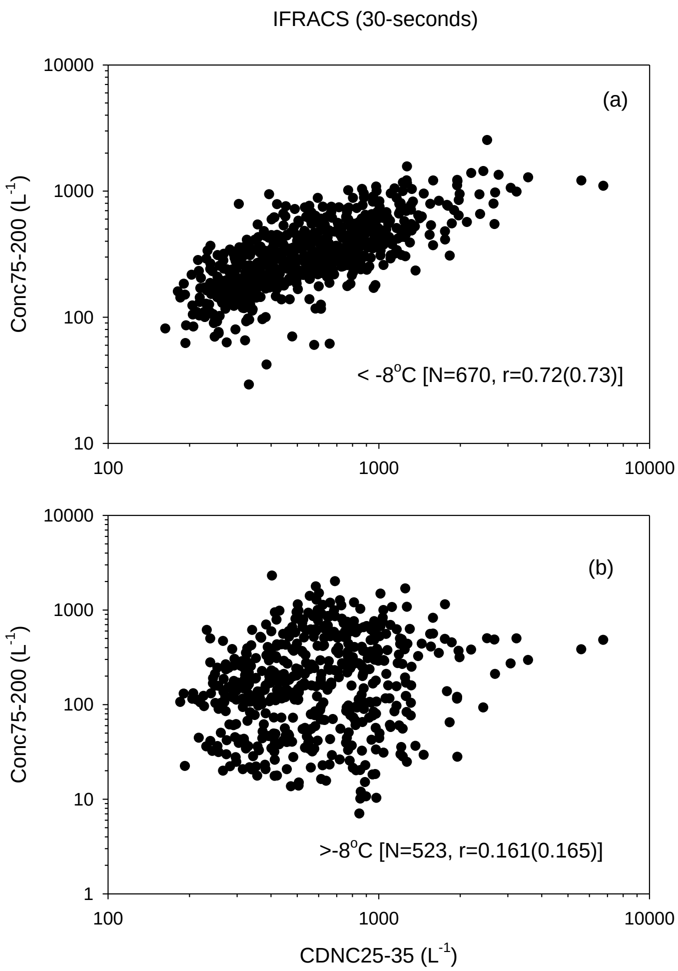

Figure 9. Relationships between ~~1 minute~~30-second average concentrations of large cloud droplets (~~25-35 μm,~~ CDNC25-35) and small ice crystals (Conc75-200) during ~~(a) StormVEx and (b)~~ IFRACS under cold conditions <~~12~~8 °C~~). Corresponding relationships under~~) and warm ~~(>~~ (<8 °C) conditions ~~are shown in (c) and (d).~~. Number of observations and Pearson (Spearman Rank) correlations are shown.

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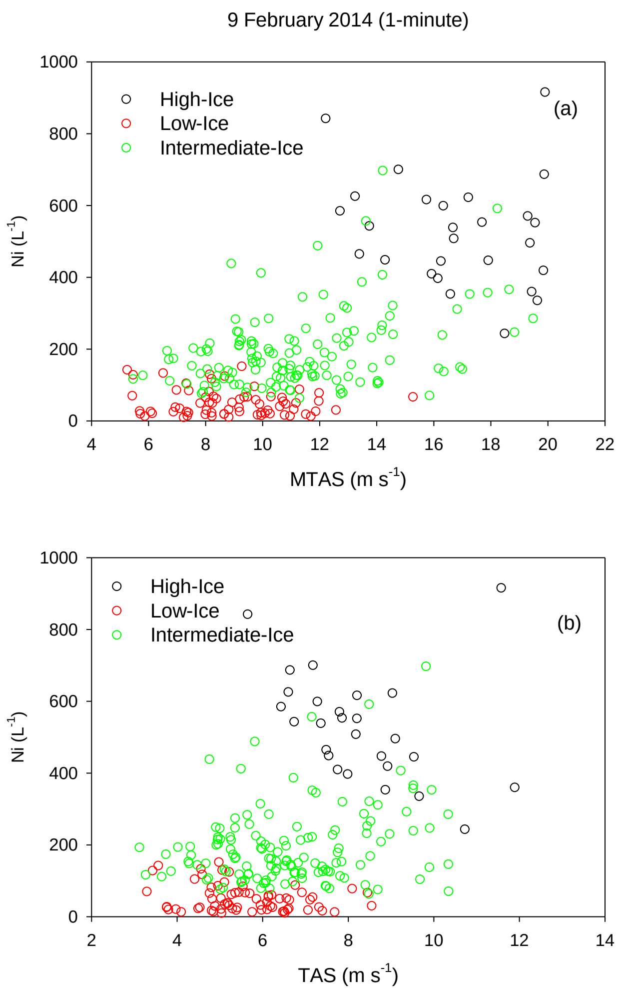

Figure 10. Relationships between 1-minute average TAS (a) and maximum 1-second TAS (MTAS) (b) and Ni for High-Ice, Low-Ice, and Intermediate-Ice (all other 1-minute periods) periods on 9 February 2014.

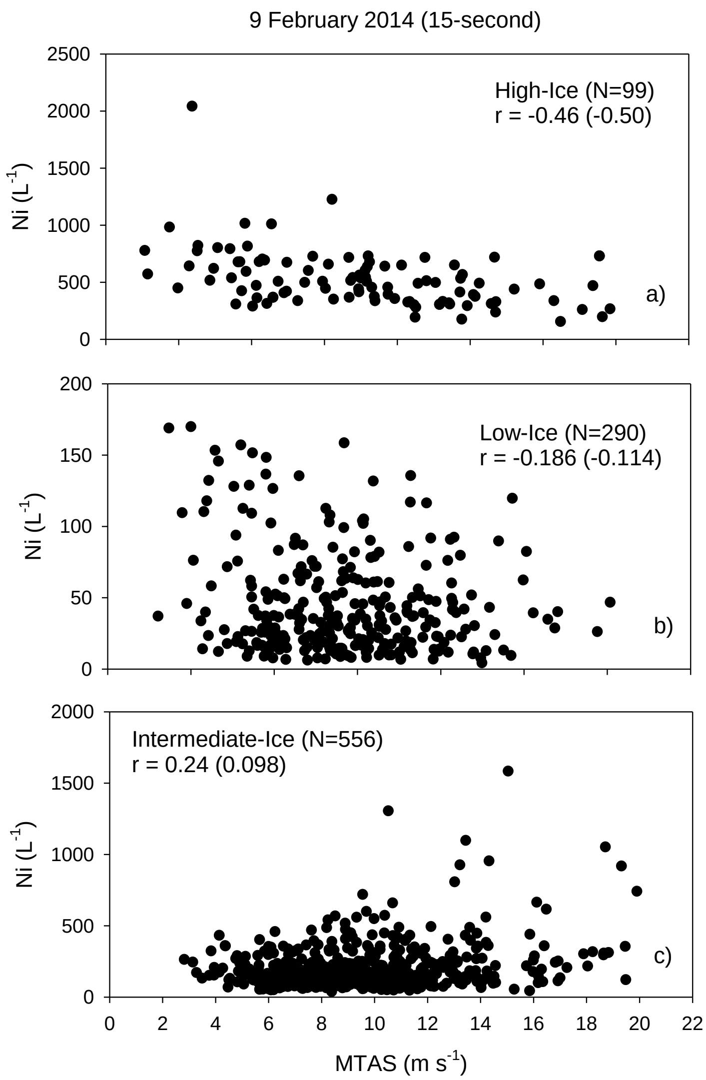

Figure 11. Relationships between 15-second average Ni and MTAS for High-Ice (a), Low-Ice (b), and Intermediate-Ice (c) periods on 9 February 2014.

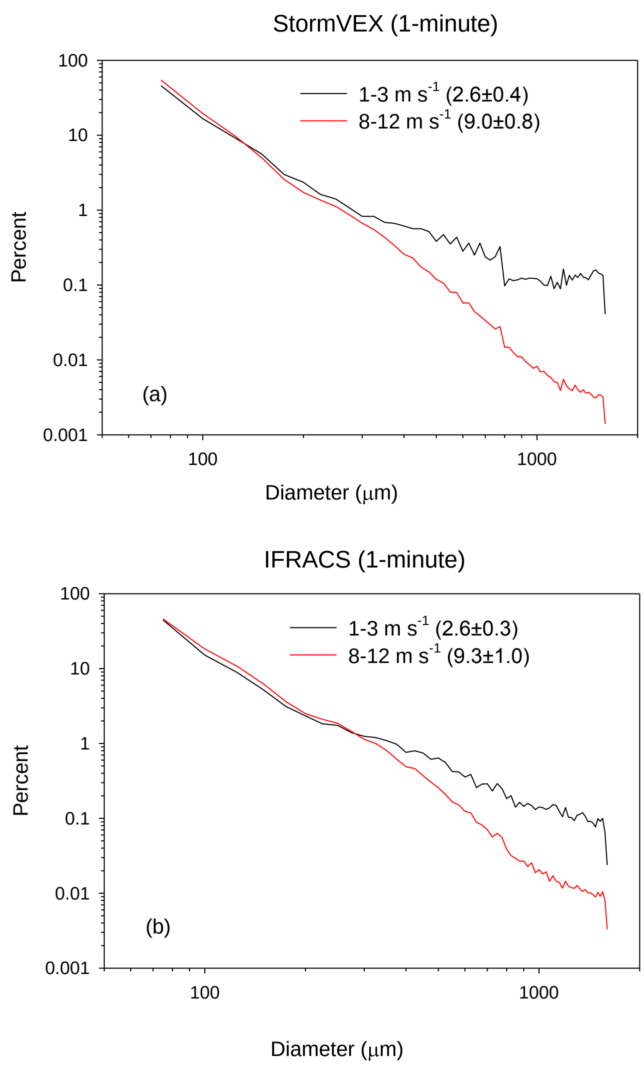

Figure 12. Averages of 1-~~-~~minute relative ~~(%)~~(% of Ni) CIP PSDs at low (1-~~4~~3 m s^{-1}) and high (8-12 m s^{-1}) TAS during StormVEx (a) and IFRACS (b). Average TAS are ~~given~~shown in parentheses.

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