Interactive comment on “The origins of ice crystals measured in mixed phase clouds at High-Alpine site Jungfraujoch” by G. Lloyd et al.

Anonymous Referee #1

Received and published: 16 July 2015

Review of “The origins of ice crystals measured in mixed phase clouds at High-Alpine site Jungfraujoch” by G. Lloyd et al.

This manuscript details observations of mixed phase cloud and aerosol properties taken over a high mountain site in Switzerland in order to further our understanding of what microphysical processes contribute to ice formation in mixed phase clouds. I think this is a great article highlighting important research, but I do have a few ideas that should be considered in order to improve the manuscript. I will list my major comments on the paper here:

1. While the introduction goes into great detail about the various studies that have observed mixed phase clouds using a mountain observatory, there is no material that leads the reader into what the broad motivation of the study is. Why is it important to study aerosol effects on mixed phase clouds in the first place? Doesn’t it have to do with how, in general, how models do not resolve these processes very well? What sort of sensitivity do commonly model out parameters (like radiative forcing, etc.) have to the mixed phase cloud properties? Why should we care about the scales of the transitions between phases? I also would suggest splitting up the two paragraphs into even smaller paragraphs as I found Section 1.1 hard to follow in general.

Author Response: We have now included more information about the motivations for the work in section 1.1 and changed the section title to help focus it on the motivations. The paragraphs have also been restructured to make it easier for the reader.

2. While the discussion go into a great deal of discussion of how much processes that affect changes in the ice crystal concentrations could affect the IMF values, there is little to no discussion of how processes related to changes in the liquid droplet properties could also affect the IMF outside of stating that LWC could increase or decrease. Do the authors have any insight as to what processes could contribute to the changes in LWC?

Author Response: Lines 330-331 now highlight the possible controls on the liquid droplet properties. These include cloud base height, temperature and depth of cloud. Changes in LWC due to these parameters would then feed into the LWC and impact the IMF values.

3. The authors rule out the possibility of the Hallett-Mossop process simply because “However, temperatures at JFJ were generally colder than in the H–M zone, and ice concentrations as a function of temperature (Fig. 5a and b) did not show any 15 significant increase at higher temperatures.” However, the authors also mention a peak in IWC at -8 C during 2013, and I do see a peak in ice concentration at about 75/L at this temperature range in Figure 5a. Given these increases in IWC and ice crystal concentration at these temperatures, it does make me wonder if the H-M process is occurring at this temperature range. Did the authors check the CPI imagery for the presence of graupel along with splinters?

Author Response: Although there were some limited periods when the temperature was close to the H-M temperature zone we are confident this process is not producing the high concentrations of ice observed. One of the reasons for this is the concentrations of ice that are often 100s and sometimes over 1000 L^{-1} are higher than have been observed in natural free floating clouds observed in other studies. We also didn't see any graupel in the CPI imagery that might facilitate the process.

Farrington et al. (2015) compared model simulations using WRF with the microphysics measurements during INUPIAQ and found that the times when rime-splintering could explain observed concentrations at JFJ were very limited. Fig. 7 in this paper highlights the point well.

Full reference: Farrington, R. J., Connolly, P. J., Lloyd, G., Bower, K. N., Flynn, M. J., Gallagher, M. W., Field, P. R., Dearden, C. and Choularton, T. W.: Comparing model and measured ice crystal concentrations in orographic clouds during the INUPIAQ campaign, Atmos. Chem. Phys. Discuss., 15(18), 25647–25694, doi:10.5194/acpd-15-25647-2015, 2015.

The decrease in CDP droplet concentration along with the increase in LWC in Figures 6a and c lend me to think that there are large enough droplets to form drizzle and splinters, as well as there being enough LWC present for significant riming for 2013. However, I don't see these same trends for 2014. Have the authors checked the mean droplet spectra from the CDP for T > -10 C from 2013 and 2014 to see if it is the case that there are more large drops in the H-M temperature range?

Author Response: Although we did not look at CDP spectra exclusively for temperatures > - 10 °C we did check the size distributions for the whole campaign finding droplet sizes measured by the CDP were generally < ~ 35 µm. We also didn't see any evidence of drizzle during the campaign periods.

Also, if the H-M process is operating for the clouds in 2013, but not in 2014, do the authors have any insight as to why? If there is an active H-M process occurring, it may be worth adding a couple of figures to that effect. This also affects section 6.4 which talks about riming on mountain surfaces.

Author Response: The H-M process will operate to some degree in mixed phase clouds that span the appropriate temperature range. This happens in 2013 but not in the colder conditions prevailing in 2014

4. Whenever they can, the authors should replace statements like "several hundred" with more exact values in order to make the paper more quantitative. A good example of this is in the fourth conclusion.

Author Response: We have altered this in the conclusions and also in the main text to refer to a more exact number of cloud events that were analysed. (e.g. Line 220)

Minor comments:

Section 4. Paragraph 1. The way this is written, it is hard to identify the high and low pressure systems since most of the text in the first paragraph does not refer to Figure 3 until the very last sentence. This should be rewritten to guide the reader through Figure 3, and it should definitely introduce Figure 3 before describing the synoptic features.

Author Response: The figure is now introduced earlier in this section (line 205).

Section 5.1. Line 2. Missing period.

Author Response: We couldn't find a missing period, but did find a double space that has been corrected (Line 226).

Section 5.1. Lines 19-20. Do you think the Hallet-Mossop process could cause this? This is related to major comment 3.

Author Response: We would also expect to see a trend to reducing liquid water content values if the H-M process was producing splinters that were depleting the liquid droplets.

Section 6.1. Lines 8-11. Could you quote Korolev et al.'s exact frequencies they found?

Author Response: The data presented in Korolev's work is now stated (Line 314).

Section 6.1. Second to last paragraph. There are dendrites present in Figure 14, so I do not think you can say that the fragile habits typically associated with mechanical breakup are not present. Does this affect your conclusion that "there is currently no evidence in the literature that this mechanism would be capable of producing the ice crystals concentrations observed."

Author Response: The CPI imagery presents some of the typical pristine ice habits that we would see. Around -15 °C these often consisted of plates and sectored plates. Although there is some evidence that the sectored plates were developing a more complex structure, possibly becoming more dendritic, we found little evidence of fully developed fragile ice. As we cannot completely rule out some dendritic ice we have changed the wording of the sentence (Line 356).

Section 6.4. This is related to major comment 3. I don't think you have adequately shown that there is no link between the concentration of small ice crystals and the number of droplets or liquid water content at temperatures around -5 C, especially since the data during 2013 suggest an enhancement of LWC and ice crystal concentration that corresponds with a decrease in droplet concentration for temperatures around -5 C. Have you checked for the presence of riming in the CIP imagery for 2013 at around -5 C?

Author Response: The ice particle images do show some evidence of riming whenever supercooled liquid water is present. We do not rule out the H-M process occurring in these clouds. The key point is that the highest ice particle concentrations occur in clouds where H-M is not operating as they do not span the appropriate temperature range.

Interactive comment on "The origins of ice crystals measured in mixed phase clouds at High-Alpine site Jungfraujoch" by G. Lloyd et al.

D. Baumgardner (Referee)

darrel.baumgardner@gmail.com

Received and published: 8 September 2015

This study of the microphysics of mountaintop clouds presents a number of interesting aspects of possible sources of high concentrations of small ice crystals. Although I tend to agree with their general conclusions, that the most likely explanation of these high concentrations are from surface sources, I am reluctant to recommend publication in ACP until a more rigorous analysis is presented of the expected uncertainties in the measurements, particularly those that are associated with determining the ice fraction. I was disappointed that with as many instruments that are being implemented in this study, the results that are presented are mostly from only the CDP and the 2D-S.

The problem that I have with the way the data are presented is that the CDP measure- ments are always described as "droplet" measurements. This automatically assumes that all the cloud particles < 50 um are water droplets but in fact, there is no justification for this.

Author Response: We are confident that the particles measured by the CDP are overwhelmingly water droplets this is discussed in more detail below.

Secondly, there is no discussion of how many pixels are needed to determine the "roundness" of an image from the 2D-S and what is the accuracy of this derived separation between liquid and ice.

Author Response: We used 20 pixels (about 60 um) the more pixels used the more certain one is of the classification of the particles but clearly using a higher number of pixels raises the minimum size that can be classified. The CDP gave a clear well-formed spectrum of particles below 35 um in size we are confident (see below) that these are water droplets.

The images show that large particles are all irregular ice crystals, there is no evidence of large water droplets in the 2D-S.This is confirmed by the holography system (see below) where no water droplets larger than 40 um are detected. Hence we are confident that the vast majority of the liquid water is in the small droplets measured by the CDP. This is supported by analysis of the images from the CPI part of the 3VCPI probe.

This information is now included in the paper (Lines 188-192)

A separate paper with a detailed inter-comparison between all the microphysical instruments is being prepared.

Similarly the use of holography to differentiate liquid and ice is not sufficiently described or justified.

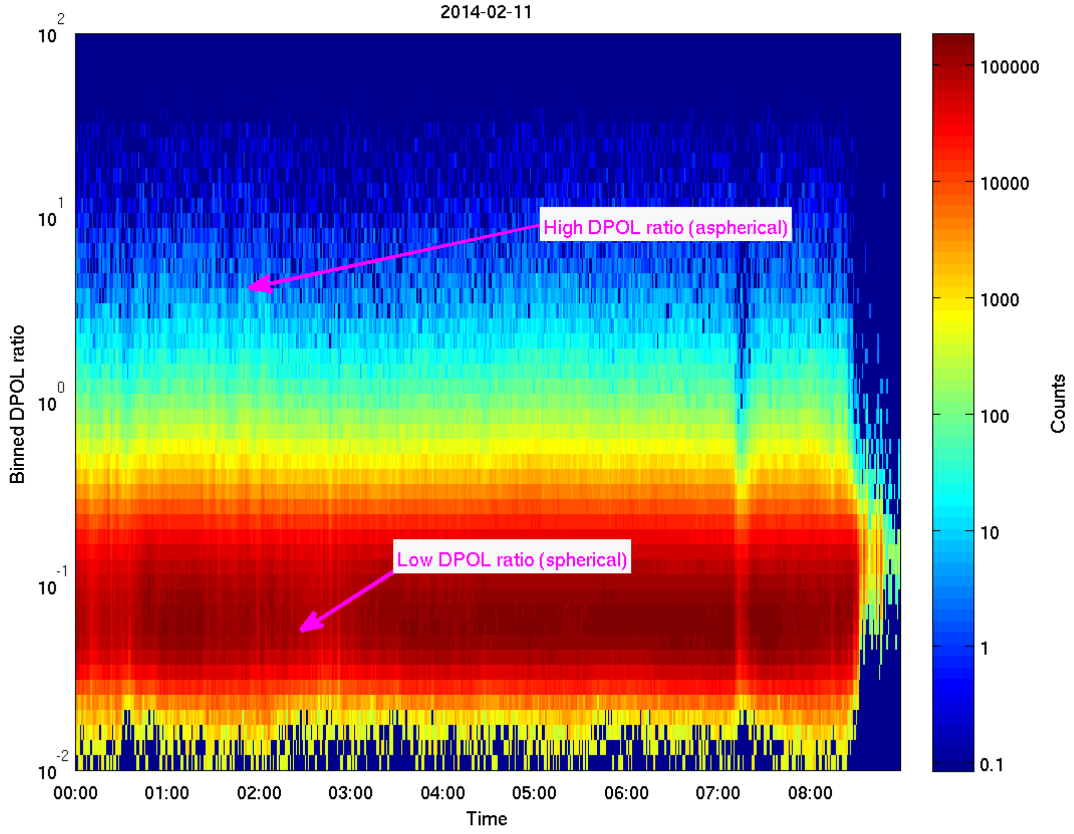
Author Response: This has been expanded on in the paper (lines 152-153 and 161-163). GIPFELHOLO images > 40 µm were inspected manually to determine whether they were ice or liquid. HOLIMO II uses a supervised learning algorithm to classify cloud particles larger than 20 µm to distinguish between ice and liquid.

It is my understanding that the CAS is actually a CAS-POL. If this is so, then there are already publications that show that it can be used to differentiate between liquid and ice in particles below 50 um, e.g. Baumgardner, D., R. Newton, M. Krämer, J. Meyer, A. Beyer, M. Wendisch, P. Vochezer, 2014: The Cloud Particle Spectrometer with Polarization Detection (CPSPD): A next generation open-path cloud probe for distinguishing liquid cloud droplets from ice crystals, Atmos. Res., 142, 2-14. This publication shows comparisons in mixed phase mountain clouds of measurements from several instruments and justifies using the polarization ratio as a means to estimate ice phase. Without this measurement, the current study has no accurate means to prove that the CDP is only measuring water droplets and this leads to an uncertainty in the IMF of as much as +/- 50-100%. This study is a very good opportunity to compare results from multiple instruments and better show the robustness of the conclusions that are drawn. Without a more extended error analysis and instrument intercomparison of size distributions and derived water contents (e.g. where is a CDP and PVM comparison?), the results that are presented cannot be properly interpreted within the expected uncertainties and the resulting conclusions remain on shaky ground.

Author Response: The CDP measurements were presented in preference to other instruments due to it being an open path instrument and not subject to inlet losses, however, as discussed below the LWC values from the CDP agreed well with the other instruments. Although the CDP does respond to ice the droplet concentrations reported by the instruments are often several 100 cm^{-3}. If there was significant misclassification of these particles as ice, of 50% for example, then it would suggest concentrations of small ice < 50 µm of 50,000 L^{-1}.

We have analysed polarisation data from the CAS for the time period shown in Fig. 7 to check for the possible presence of small ice crystals (figure below). The DPOL data suggests that particles in the CDP size range are liquid droplets with little evidence of aspherical ice particles. Using a depolarisation threshold ration of 0.5 for identifying ice then the CAS data suggest that approximately 1 particle in 10^4 over the CAS size range of up to 50 um. This suggests an upper limit of approximately 10 particles per litre of ice in this size range.

Reference to Baumgardner et al. (2014) has also been made in the manuscript as the measurements made by the CPSPD at mountain top site Zugspitze is relevant to the measurements made at JFJ (Lines 394-400).



We have compared the CDP with the PVM in 2013 and with an FSSP during 2014 (PVM was unavailable). This has been included in the manuscript (new fig. 7) and described in lines 261-264. We find good agreement between the CDP and these instruments, with the CDP tending to measure 10 % greater LWC values when compared to the PVM and FSSP. This small offset could possibly be explained by the CDP being an open path instrument and by uncertainties in defining the sample volumes of the probes.

Interactive comment on "The origins of ice crystals measured in mixed phase clouds at High-Alpine site Jungfraujoch" by G. Lloyd et al.

P. Vochezer

paul.vochezer@kit.edu

Received and published: 10 September 2015

I think the presented manuscript is a valuable documentation of cloud measurements on a mountain top station. I found the discussion of the different mechanisms that could lead to the high observed numbers of ice particles very elucidating. However the authors argue only in the case of blowing snow that this mechanism depends on wind velocity. I would expect each of the proposed processes to dependent on the wind velocity. Which are: The number of a lofted pre activated aerosol particles should increase with the wind velocity. Riming by super cooled droplets should increase with wind velocity. Furthermore the detachment of hoar frost should increase with wind velocity. How do the authors interpret their results with regards to this argumentation?

Author Response: These comments are valuable points. When analysing our data we found only a limited number of periods (Fig. 15) where ice crystal concentrations were related to the wind speed. These periods appeared to occur immediately following fresh snowfall that was presumably re-suspended by the wind into cloud. When considering the contribution from hoar frost we used a parameterisation of an aerosol flux from frost flowers that did have a wind speed dependency. However when applying this to concentrations in clouds measured at JFJ it was not very sensitive over the wind speed range impacting the JFJ. The figure below shows the number of ice crystals in cloud produced by the frost flower flux over an in-cloud fetch of either 1 or 2km. Over the range 2-15 m s^{-1}, which were typical wind speeds at JFJ, there is not a significant change in ice crystal concentrations. This is in contrast to blowing snow, which exhibits a much steeper rate of increase depending on the wind speed