Anonymous Referee #1

Review of manuscript: “acp-2015-661”

The paper isolates and quantifies the scattering effect of ice hydrometeors in predominantly ice clouds on measured microwave brightness temperatures at the Summit station in Greenland. The scattering signatures are also compared with those obtained from a radiative transfer model.

I found the paper very interesting and well written. Here are a few minor points that in my opinion necessitate more discussion.

Pettersen *et al.*: Thank you for the time spent on your thoughtful review and questions and comments. We are glad that you find the work interesting. We will attempt to address your points below (R# is the reply to the comment and M# is the changes made to manuscript if applicable):

1) In Fig. 2, 4, and 5 the plot bar with the number of counts is missing. It could also be expressed as a percentage of the total number of observations. I think it will show that the number of cases where the ice signature is detectable in the 90 GHz channel are very limited. Therefore I don’t think the ice effect will alter the overall statistics of the retrieval performance. Of course if one is analyzing specific cases it is important to correctly model the propagation by including the effect of ice.

R1) We agree that the number of cases where the ice effect causes an issue with the retrievals is small and should not alter the overall climatological statistics of the PWV and LWP. We attempt to stress this point in the conclusion section (see page 19, lines 20 – 23). However, if one subsamples only the precipitating ice cases the retrievals values may be an issue.

We agree that plotting Figures 2 and 5 with a percentage (normalized) colorbar is useful (see new Figure 2 and 5 at the end of this document as well as in the revised manuscript). Figure 4 shows the response of only the low frequency MWR channels to the correction and has color contours with a count threshold described in the caption so we prefer to leave this figure as is.

M1) Please see new Figures 2 (page 27) and 5 (page 30) in the manuscript with colorbars of percentage normalized counts. Edited captions of both figures (see Page 27, lines 5 – 6 and Page 30, lines 6 – 7).

2) Was the same dataset used In Fig. 2 (a,b) and Fig. 4 (c,d)? Fig. 2 shows a maximum Zpath ~ 10^5 while in Fig. 4 is $6x10^4$. Or may be it was just truncated in Fig. 4?

R2) Yes, the same dataset was used in Figures 2 and 4. Figure 4 the y-axis is purposely truncated to highlight the change in slope from the correction in the low Z_{PATH} cases – the cases with lower ice optical depth where the low frequency MWR channels are insensitive to the ice. We added a note about the truncation of the y-axis in the Figure 4 caption.

M2) Clarification of the y-axis limits in Figure 4 caption (Page 29, lines 6 – 7).

3) In my personal opinion Fig. 3 is not really necessary for the understanding of the effect of ice in the retrieval. However I'll leave this to the author to decide.

R3) We are happy to hear that the text explanation of the LWP and PWV correction was clear (we thought that was a difficult point to explain), so thank you for this comment. We would prefer to leave the figure in the paper, as we believe that this correction is perhaps non-intuitive for readers less familiar with these types of retrievals and the figure may aid in understanding the correction.

4) In Fig. 5 what is the range of brightness temperatures for these cases where Zpath > ~10^4?

R4) This is a good point to highlight and is illustrated somewhat clearer in Figure 6: For Z_{PATH} of ~10^5 mm^6/m^2: in the 90 GHz channel the range of BTs is about 2 – 7K. For the 150 GHz channel, the range of BTs is about 10 – 30K. And for the 225 GHz channel, the range of BTs is about 20 – 50K. We do say in the text: "At the highest observed Z_{PATH} values (about 10^5 mm^6/m^2 and larger), BTs are enhanced by about 7 K in the 90 GHz channel and 30 K and higher in the 150 GHz channel" (see Page 16, lines 5 – 6), but this only references the maximum BTs. We clarified this language to stress that there are a range of BTs for a given Z_{PATH}.

M4) Clarified comments, see Page 16, lines 5 – 6.

5) In Fig. 5 it seems that all measured BT's have a positive bias with the model, which is independent of the presence of ice and may be due to (may be?) calibration. Is this a clear-sky bias? For example if I look at the 150 GHz frequency it seems that until Zpath < ~ 10^4 all observations lay around ΔTb ~+2 K +/- 2 K. It may be visually helpful to subtract this bias so that the plots are centered around zero when there is no ice effect.

R5) You are correct that this is a clear-sky bias. An analysis of observed minus computed downwelling radiance in clear sky scenes shows a seasonal dependence to this bias (with the mean bias over the annual cycle being about zero), but that the magnitude of the bias is always smaller than the radiometric uncertainty of the observation. However, since our analysis uses data from primarily the summer season, this results a positive bias in these channels. We are unable to determine if this (small) bias in the channels is due to calibration uncertainty in the radiometer or forward model error. In the lower frequency channels (23.84 and 31.40 GHz) it is negligible (see Figure 2a and b). In the 90, 150, and 225 GHz the clear-sky bias is ~0.5, 1.3, and 1.9K, respectively. Since this is a systematic bias within the radiometric uncertainty, we would prefer to keep the figure as is and not subtract out the bias. We prefer to leave the figures plotted as is, but added a comment about the clear sky bias in the caption.

M5) We added detail about the clear sky bias in the caption for Figure 5 (see Page 30, lines 12 – 16).

6) Referring to my previous comments, in Fig. 6 however the ΔTbs appear unbiased. Is this just a visual effect?

R6) We believe that this is a visual effect, because in Fig. 6 the points are colored by the average Z_{PATH} within the bin, not the number of points within the bin. Therefore the clear-sky biased "bullseye" is not obvious in the figure. The same BT difference data is used in these multi-frequency plots, but the occurrence is not shown.

7) In Fig. 5 It appears that there is a non-linear increase of ΔTb when Zpath > 10^4. In other words Zpath saturates around 10^5 but ΔTbs keep increasing. For example at 90 GHz when Zpath is near its maximum ΔTb can be anywhere between 5 and 15 K. Is this effect due to differences in the vertical distribution of the hydrometeors?

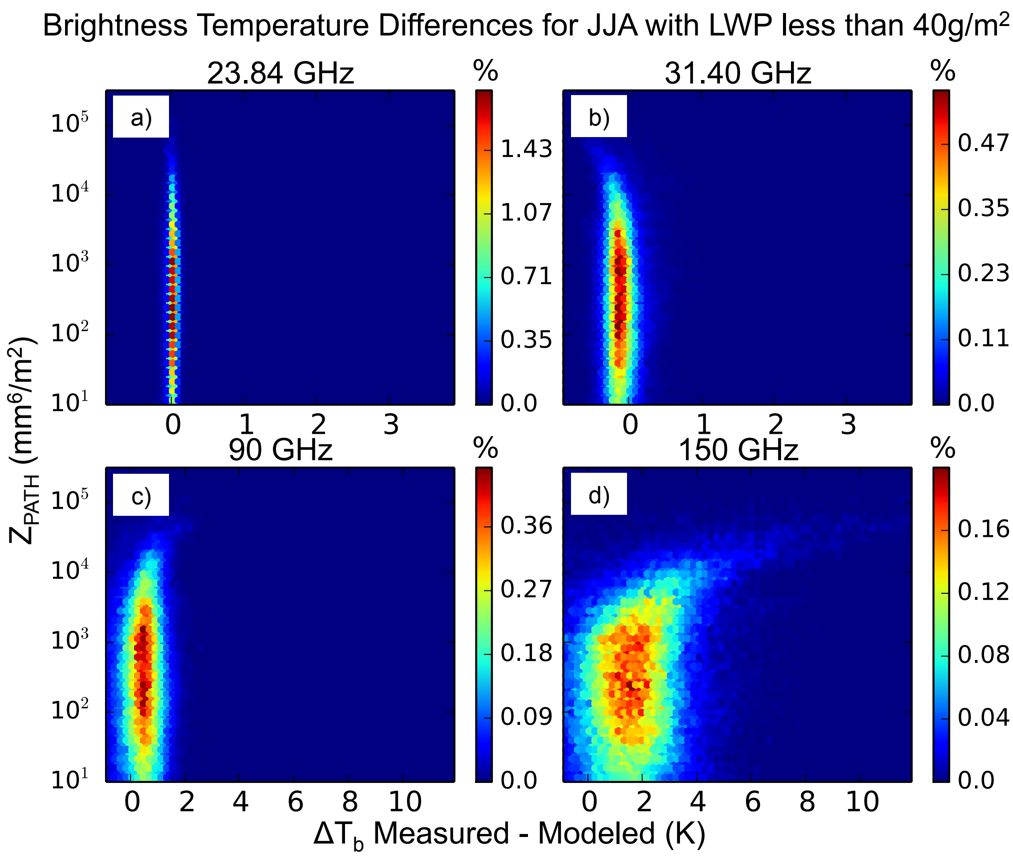
R7) We think this is a very reasonable hypothesis, however to try verify this using models, we need accurate particle size distributions representative of Summit, Greenland. The large range in the passive microwave signature is likely more related to variations in the ice crystal habits and particle size distribution, rather than the vertical distribution on its own. The ice crystal sizes and habits change as they move vertically in the column (due to cloud dynamics, growth processes, etc.), so these effects are difficult to model and beyond the scope of this work.

8) The author identifies the selected clouds as precipitating, however it is not clear how the hydrometeors are modeled in the radiative transfer model in section 5.4. It seems that in the model the hydrometeors are located in the cloud and the ice is assumed to be cloud ice content with no precipitating ice content. In other words, how is the profile of ice mixing ratio defined? Could it be that if the hydrometeors are entirely located in the cloud it may take a higher IWP to produce the same brightness temperature of a precipitating cloud? I think that the vertical distribution of the scattering hydrometeors will have a major effect on the model result as it appears to be based on Fig. 5 (see comment #7).

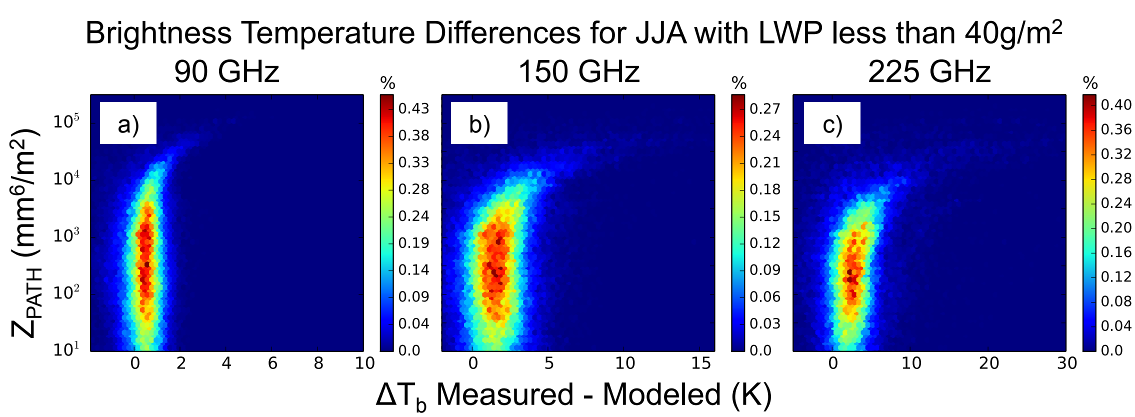
R8) This is a good point: we make no distinction between precipitating ice and cloud ice in this study and have clarified this in Section 5.4. The Field *et al.*, 2007 size distribution is temperature dependent, so it forces a particular relationship between the Z_{PATH}, passive microwave signature, and the IWP. If the microwave extinction optical depth is held fixed, then the calculated IWP does tend to increase as the temperature drops, because of the shifting of the Field *et al.*, 2007 size distribution towards smaller particles, though that relationship may not hold for all temperatures and ice crystal habits.

M8) See Page 18, lines 8 – 10.

New Figure 2 – with colorbars expressed as a percentage of total number of observations for each MWR Channel:



New Figure 5 – with colorbars expressed as a percentage of total number of observations for each HFMWR Channel:



Anonymous Referee #2

Received and published: 30 December 2015

This study explains the radiometric signatures observed across a wide range of frequencies (~20 - 225 GHz) and by both active (cloud radar) and passive (microwave radiometer) sensors. To make everything physically consistent, the authors have to improve (modify) existing liquid water retrieval algorithms to account for the influence of ice at high frequencies. By identifying the major contributors to the observed signatures, I think that this study laid the groundwork for future use of all these radiometric data in cloud ice/liquid water retrievals. Therefore, I think this study is valuable and should be published.

Pettersen *et* al.: Thank you for the time and effort spent reviewing the manuscript. We are glad you find the work to be valuable and appreciate your thoughts and comments and will do our best to address them below (R# is the reply to the comment and M# is the changes made to manuscript if applicable):

But I do have the following comments, and would like the authors to address them.

C1) First, reading the paper, I could not find at what level the "liquid water cloud" was placed when the radiative transfer simulations were conducted, and how its relative position to the profile of ice (dBZ) will alter the conclusions. For example, for high dBZ cases, most of ice should be close to surface, whether the liquid water is placed below or above the major portion of the ice in the vertical should change the downwelling brightness temperatures at high frequencies. Did the authors ever do any sensitivity test to see how big this effect is?

R1) For the radiative transfer modeling used to isolate the ice signature from the MWR observations in this study, the cloud liquid water level is defined by the Ceilometer cloud base height (see Section 2.1.3). However, for the SOI simulations that included the ice scattering (see Section 5.4), we did not include the presence of cloud liquid water but only the scattering from the ice and emission from the atmosphere gases (see Page 18, line 10). We edited and added a clarifying note about this in first paragraph Section 5.4. Additionally, we did run sensitivity studies with cloud liquid water path typical of Summit (~40 g/m^2) and see insignificant difference in the simulated enhanced brightness temperature in the HFMWR: the highest Z_{PATH} values at Summit (10^5 mm^6/mm^2) decreased an approximate 1, 1.5, and 4% in the enhanced BTs in the 90, 150, and 225 GHz channels, respectively.

M1) We added a clarifying comment in Section 5.4 (see Page 17, lines 19 – 21).

C2) Second, in the paper, the authors mentioned that the TKC15 liquid water absorption model "improved convergence" in doing retrievals compared to other models. Since two* of the authors of TKC15 model are also co-authors of this paper, is it possible to give the readers more details on "how the improvements are"? I doubt that the other liquid water dielectric models (for example, the Rosenkranz 2015 model) are so different (therefore, switch to Rosenkranz 2015 model would not alter your result), but I could be wrong. But at least, the readers should be let known whether this uncertainty is a factor in explaining the observed signatures.

R2) *Quick correction before addressing the comment: one author of the Turner, Kneifel, Caddedu (2015) study is a co-author in this work (Dave Turner is a co-author; Stefan Kniefel's case study work from the Kneifel et al. (2010) paper was foundational to this study, however Kneifel is not a co-author).

This is a good point and the question of which liquid water absorption model is appropriate to use in this study was addressed in the responses to the initial Quick Reports. This study was originally submitted using the Liebe91 cloud liquid water model and a 4-channel LWP/PWV retrieval (23, 31, 90, and 150 GHz). This is what is currently available in the published LWP/PWV retrievals in the ICECAPS dataset in the ARM Archive. Reviewer 1 from the Quick Reviews of the manuscript suggested that Liebe91 was inaccurate and suggested several other cloud liquid water models. Since D. Turner is a co-author of the TKC15 study, which is particularly well suited to supercooled water studies, and had a model ready to try in our framework, it was logical to use the TKC15 cloud liquid water model with a 3-channel LWP/PWV retrieval (23, 31, and 90 GHz).

The TKC15 paper goes into detail with comparisons to many other cloud liquid water models, including the Rosenkranz 2015 model. Please see Figures 5 and 6 in TKC15 for specific cloud liquid water model comparisons: reference – doi:10.1175/JTECH-D-15-0074.1. We believe that these figures in TKC15 address your question with regard to comparison of the current cloud liquid water models. The comment about the "improved convergence" of the retrievals in this manuscript was specific to using the TKC15 versus Liebe91 cloud liquid water model. We have added clarification that in our study the improvement is only referring to the use of TKC15 over the Liebe91 as it is relevant since the currently published retrievals still use Liebe91.

M2) We clarified the comparison of Liebe91 and TKC15 in Section 2.1.2 (see Page 6, lines 23 – 26 and Page 19, lines 10 – 14).

C3) Lastly, the authors excluded cases with LWP greater than 40 g/m2 to minimize the influence by liquid water. Since the radiative transfer simulation includes liquid water clouds, why does this constraint have to be placed? Is it because the MWRRET retrievals are completely unreliable for those cases even with the correction proposed in this study? For precipitation studies, those excluded cases may be more important. The reviewer is wondering whether observed radiometric signatures for those high-LWP cases can be used for physical retrievals.

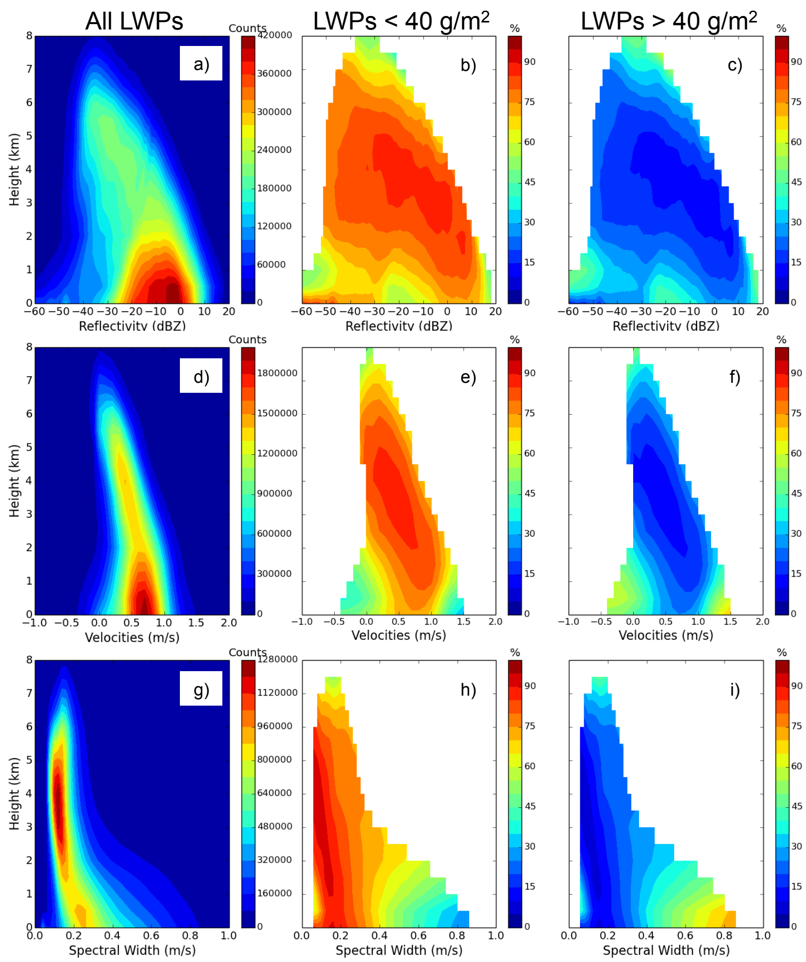
R3) The LWP constraint did not have to be placed, but it limits the analysis to cases where the separation of the ice and the cloud liquid water is simplified. Figure 1 shows CFADs of MMCR radar products for all cases and less and greater than 40 g/m^2. In Figure 1b (less than 40g/m^2) the reflectivity exhibits common ice hydrometeor characteristics and accounts for the majority of the cloudy cases for JJA at Summit. We inferred from these characteristics that we would still be examining a majority of the deep, ice cloud cases by limiting the LWP and aid in isolating the ice signature in the microwave. To better illustrate this point, we changed Figure 1 to show the percentage of the occurrence for the less than and greater than 40g/m^2 cases (see new Figure 1 at the end of this document).

This paper explores the first iteration of a process we hope to help separate out the ice from the cloud liquid water signal and going forward we will attempt to recover concurrent high LWP with high Z_{PATH} cases. In addition, with higher LWP, the optical thicknesses are less likely to be in the 'low optical depth' regime, which makes the passive microwave signatures more sensitive to details about the vertical distribution of the hydrometeors. Through this work we realized that the high Z_{PATH} and high LWP radiometric signals in the MWRs are difficult to disentangle and therefore we kept the 40g/m^2 threshold.

One note: we believe that the MWRRET LWP retrievals do a good job with greater than 40g/m^2 cases as long as the ice in the column has a low or moderate Z_{PATH} (i.e., less than ~10^4 mm^6/m^2). These high Z_{PATH} cases account for only 2% of the JJA data and thus the majority of high LWP retrieved by the MWR are likely accurate. However, if one examines only precipitating (snowing, high Z_{PATH}) cases at Summit, then the retrieved LWP values be affected by the radiometric signal by the ice in the column, regardless of the actual physical amount of LWP.

M3) New Figure 1, panels b, c, e, f, h, and i. (See Page 26). Explanation of Figure 1 revised in Section 3.1 (Page 9, line 26 – Page 10, line 14).

New Figure 1 –illustrates the different characteristics of MMCR properties when the LWPs are less than and greater than 40g/m^2 in terms of percentage of total counts:



Note to the Editor: After considering Comment 3 from Reviewer 2, we decided to recreate panels b, c, e, f, h, and i of Figure 1 in terms of percentage of LWP filtered observations by total observations. We believe that this illustrates the characteristics of the hydrometeors as related to the LWP more clearly.