Response to interactive comments from Referee #1

The referee is thanked for the careful reading of and constructive comments to the manuscript. The referee's comments are repeated below in italic font. The responses to the comments are shown in roman font.

Comments

- *The introduction does not mention a word on the importance of ice in volcanic clouds. While satellite measurements can be affected by under or overlying meteorological clouds, ice can also be present within the volcanic cloud (see e.g. Durant et al, 2008 for the main sources of water/ice in volcanic clouds). The fact that ash can act as CCN and that ice can coat ash particles should also be mentioned. In the satellite era there have been many other eruptions which where characterized by ice rich plumes. The literature on this topic should be thoroughly summarized and cited. Some entry points:*

  Rose, W. I.; Delene, D. J.; Schneider, D. J.; Bluth, G. J. S.; Krueger, A. J.; Sprod, I.; McKee, C.; Davies, H. L. & Ernst, G. G. J. Ice in the 1994 Rabaul eruption cloud: implications for volcano hazard and atmospheric effects Nature, 1995, 375, 477-479

  Rose, W. I.; Bluth, G. & Watson, I. Ice in volcanic clouds: When and where? Proc. of the 2nd Int. Conf. on Volcanic Ash and Aviation Safety, OFCM, Washington, D. C., Session 3, 61, 2004

  Durant, A.; Shaw, R.; Rose, W.; Y.Mi & Ernst, G. Ice nucleation and overseeding of ice in volcanic clouds J. Geophys. Res., 2008, 113, D09206

  The introduction has been rewritten and ice in volcanic clouds discussed, including referencing of the literature above and other papers.

- *First sentence of Section 3, repeat use of "polar orbiting" (typo)*

  Corrected.

- *Section 3.2 The numbers on the effect of SO2 on the DBT seem inconsistent: 0.13 DU: 0.31K, 10 DU -0.99K, 100 DU: -0.47K. Two problems: (i) These differences should grow monotonously as the amount of SO2 increases. (ii) They should become more and more positive (as BT1097.25 becomes smaller and smaller)*

  There is an error in the manuscript. The background BTD_I should be -1.05. This has been corrected.

- *Figure 3. The behavior for an ice cloud top temperature of 18 km is odd, the DBT first increases, seems to reach a local maximum around 0.1 g/cm3 and then decreases again. Could you show example spectra?*

  The spectra at 18 km used to calculate the BTD_I in the right panel of Fig. 3 of the manuscript is shown in Fig. A1. The BTD_I has a local maximum for an ice water

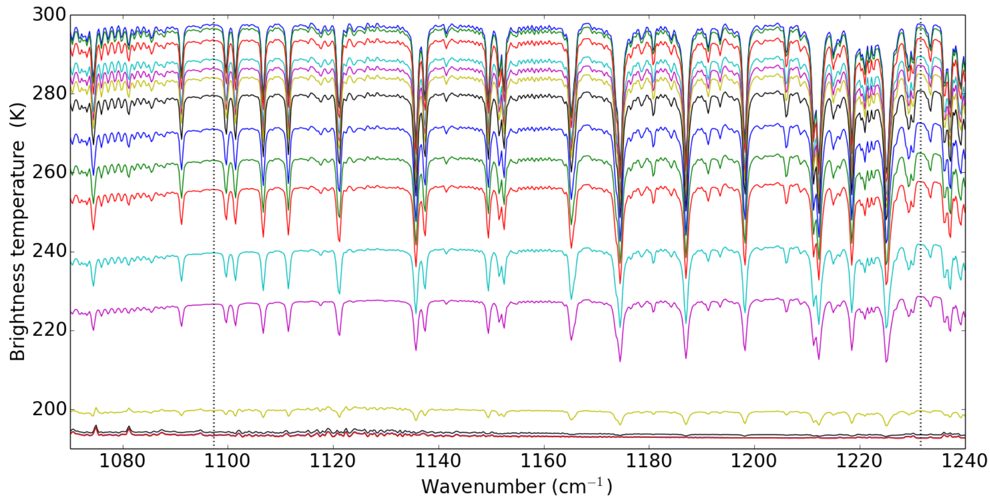

Figure A1: Brightness temperature spectra for an ice cloud at 18 km. The ice water content of the ice cloud was 0.001 (uppermost line), 0.002, 0.005, 0.01, 0.0125, 0.015, 0.02, 0.03, 0.04, 0.05, 0.075, 0.1 , 0.2, 0.3, 0.4, 0.5, and 1.0 (lowermost line) g/m^3. The dotted vertical lines are at 1097.25 and 1231.5 cm^{-1}.

  content of about 0.075 g/m^3 as shown in the right panel of Fig. 3 of the manuscript.

- *Section 4.1: please give a bit more explanation on how the ice cloud RT simulation was done, so that the reader can catch the gist without having to consult other papers. Without having read the paper, the title of the Key et al. reference seems to suggest that paper deals with shortwave radiation.*

  The work of Key et al. (2002) indeed only the covers shortwave. In the latest release of the libRadtran package (Emde et al., 2015) the Key et al. (2002) parameterization has been extended to the thermal range to 100 cm^{-1} based on single scattering data provided by P. Yang and on the size distributions from J. R. Key. This has been clarified in the manuscript.

- *Please give some references on high resolution RT simulations of ash/ice clouds: E.g. for ash*
  Newman, S. M.; Clarisse, L.; Hurtmans, D.; Marenco, F.; Johnson, B.; Turnbull, K.; Havemann, S.; Baran, A. J.; OSullivan, D. & Haywood, J. A case study of observations of volcanic ash from the Eyjafjallajkull eruption: 2. Airborne and satellite radiative measurements J. Geophys. Res., 2012, 117, D00U13

E.g. for ice
Wang, C.; Yang, P.; Platnick, S.; Heidinger, A. K.; Baum, B. A.; Greenwald, T.; Zhang, Z. & Holz, R. E. Retrieval of Ice Cloud Properties from AIRS and MODIS Observations Based on a Fast High-Spectral-Resolution Radiative Transfer Model J. Appl. Meteor. Climatol., Journal of Applied Meteorology and Climatology, American Meteorological Society, 2012, 52, 710-726

The mentioned references and descriptions have been added to section 4 of the revised manuscript. In addition the recent work by Ishimoto et al. (2016) has been referenced.

- *Figure 4: the examples, although instructive could be chosen much better, and although it is a bit of work, I highly recommend the following changes:*

  - *I would suggest removing either B or C since they are very similar*
  - *I would suggest adding a spectrum where there is a non-saturated ice cloud, so that the reader can see what the spectral signature looks like in the infrared (a saturated ice cloud is basically a black body)*
  - *I would suggest adding a spectrum of pure ash. It might be difficult to find a 100ice free observation in the eruption of Kelut, but it would be worth showing the one with the least amount of ice, so that the "pure" ash signature can be seen. In this way, both signatures (ash+ice) can be recognized in the ash+ice spectra.*
  - *Following these suggestions there would be 5 spectra: ash, ash+ice, ice, clear, and saturated ice. Naming these spectra as such would also make the manuscript easier to read (A/B/C is not very telling).*

  The examples have been updated based on the suggestions above as follows:

  - Example B has been removed.
  - A non-saturated ice cloud example has been added.
  - Unfortunately no pixels with pure ash is identified with the method used. The Ash (A) example contains the largest ash loading detected and has been kept.
  - Thus, 5 spectra are used as examples: Thick ash and ice, thin ash and ice, ice cloud, saturated ice cloud and cloudless. Renaming of the examples have been made throughout the manuscript. Table 1 and Figs. 1, 2, 4, 6 and 7 have been updated to reflect this change.

- *The look-up-table strategy that is applied here for the retrieval has been applied before for hyperspectral retrievals. Some example should be given to show that this is not a new method. E.g. Peyridieu, S.; Chédin, A.; Capelle, V.; Tsamalis, C.; Pierangelo, C.; Armante, R.; Crevoisier, C.; Crépeau, L.; Siméon, M.; Ducos, F. & Scott, N. A. Characterisation of dust aerosols in the infrared from IASI and comparison with PARASOL, MODIS, MISR, CALIOP, and AERONET observations Atmos. Chem. Phys., 2013, 13, 6065-6082*

Thank you for this reference. The paper by Peyridieu et al. (2013) have been referenced and briefly discussed in section 4.2 in the revised manuscript.

- *The channels selection: 37 channels mostly between 750 and 1250 makes sense, however, the part most sensitive to "only-ash", namely 1070-1250 cm-1 has only 3 channels, and thus the spectral range 750-1000 cm-1 with 34 channels will dominate the retrieval. This can be seen very clearly in Figure 6, where the "ash only" fit shows huge residuals around 1200. To make the retrieval representative for the entire spectral range 750-1250, the RMSD formula could be replaced by a weighted RMSD, where more weight is attributed to the channels above 1070 cm-1. The effect on the retrieval results of the unbalanced number of points left and right to the O3 band should be commented on, and preferably retrieval tests should be made. It could very well be that by assigning due weight to the part 1070-1250 cm-1 would result in much more ash being retrieved.*

  This is an interesting comment. The analysis has been redone using a weighted root-mean-square with equal weights assigned to the 750-1000 cm^{-1} and 1070-1250 cm^{-1} wavenumber regions. As can be seen in Figs. A2 and A3, the weighted RMSD is slightly larger then the un-weighted RMSD shown in Figs. 8 and 9 of the manuscript. For the two ash and ice case pixels the brightness temperatures for the wavenumber used to calculate the un-weighted and weighted RMSD is shown in Fig. A4. For the thin ash and ice case the differences in RMSD are small, while for the thick ash and ice case the weighted RMSD agree better for the 1070-1250 cm^{-1} region and worse for the 750-1000 cm^{-1}, as expected.

  The weighted RMSD is briefly discussed in the revised manuscript, and the un-weighted data analysis kept.

- *In Table 1, there is a retrieved reff of 4 micron - at the edge of the look up table. This is an indication that the range of reff of the look up table should be expanded. In this context, please also see Stevenson, J. A.; Millington, S. C.; Beckett, F. M.; Swindles, G. T. & Thordarson, T. Big grains go far: understanding the discrepancy between tephrochronology and satellite infrared measurements of volcanic ash Atmos. Meas. Tech., 2015, 8, 2069-2091*

  In the revised manuscript the largest effective radius in the LUT as been increased to 10 μm. Affected Tables and Figures have been updated accordingly. With a geometric standard deviation of 2.0 also larger ash particles than 10 μm are included the simulated spectra. Big grains may travel far, but as acknowledged by Stevenson et al. (2015), they are generally not detectable by infrared methods.

- *End of section 5, discussion of figure 11. The RMSD is generally larger for the ice only case. Should it not always be the case, by definition? Since the ice only case is a subset of the ash+ice case (i.e. there should not be as single point below the diagonal in figure 11).*

  If there is both ash and ice in the measured spectra then the RMSD should always be larger for the ice only case. If there is only ice in the measured spectra this may not necessarily be the case.

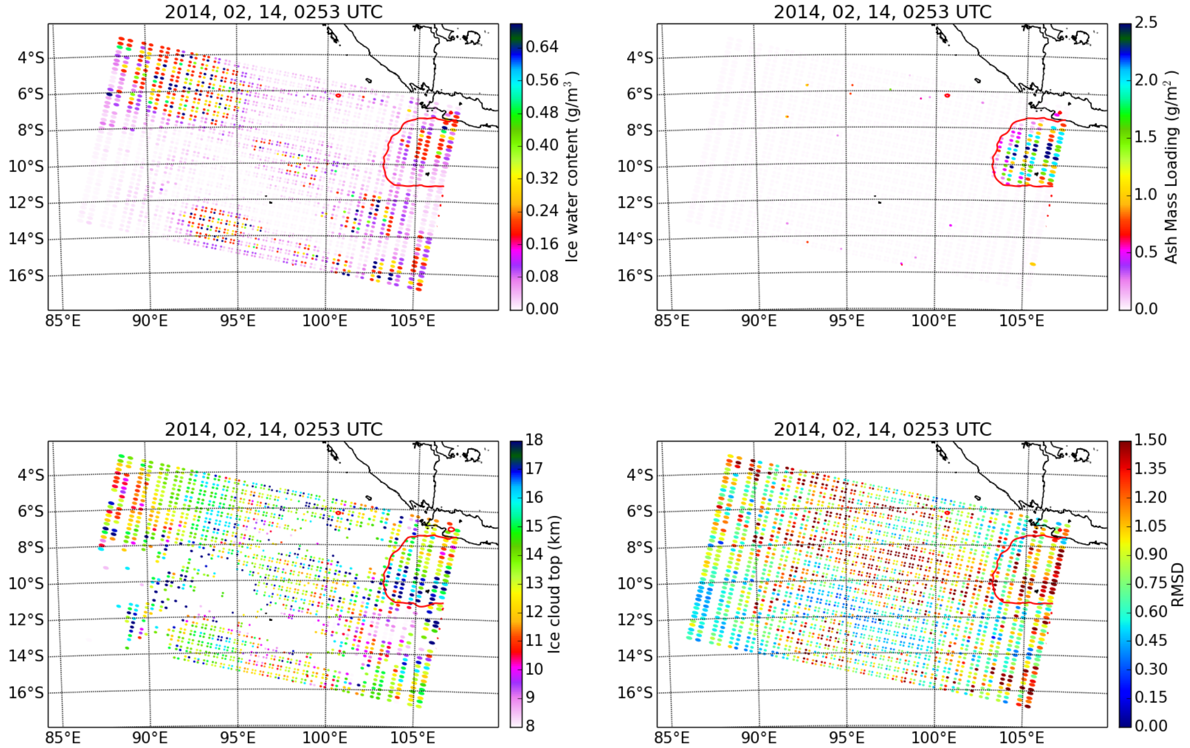

Figure A2: (Upper left panel) The estimated ice water content. (Upper right panel) The estimated ash mass loading. (Lower left panel) The estimated altitude of the ice cloud top height for ice clouds with ice water content >0.01 g/m^2. (Lower right panel) The weighted root mean square difference (RMSD) of the simulated-measured spectra. The red contour line delineates the area identified as ash. Data from 14 Feb 2014, 0253 UTC. To be compared with Fig. 8 in the manuscript.

- *Figure 8/9. Discussion/interpretation/comparison is much too short. I.e. How do these retrievals compare with previously published results (Kristiansen et al. 2015)? How much ash/ice total mass within the volcanic plume was measured? How does this compare to other ice/ash retrievals in the literature (from this and other eruptions)?*

  A discussion of Figs. 8 and 9 have been included.

- *The paper focuses on the technical / radiative transfer aspects of the problem, but more interpretation of the results would be highly welcome. E.g. at the end of the discussion it is pointed out that there is no correlation between retrieved ash/ice loadings - does this mean that the ice is not of volcanic origin? From the retrieval plots it seems that the retrieved altitude for the ice does reach 18 km. How common is it to have ice clouds at that location at such a high altitude? Some comparison with Calipso could help to increase confidence in the presented data.*

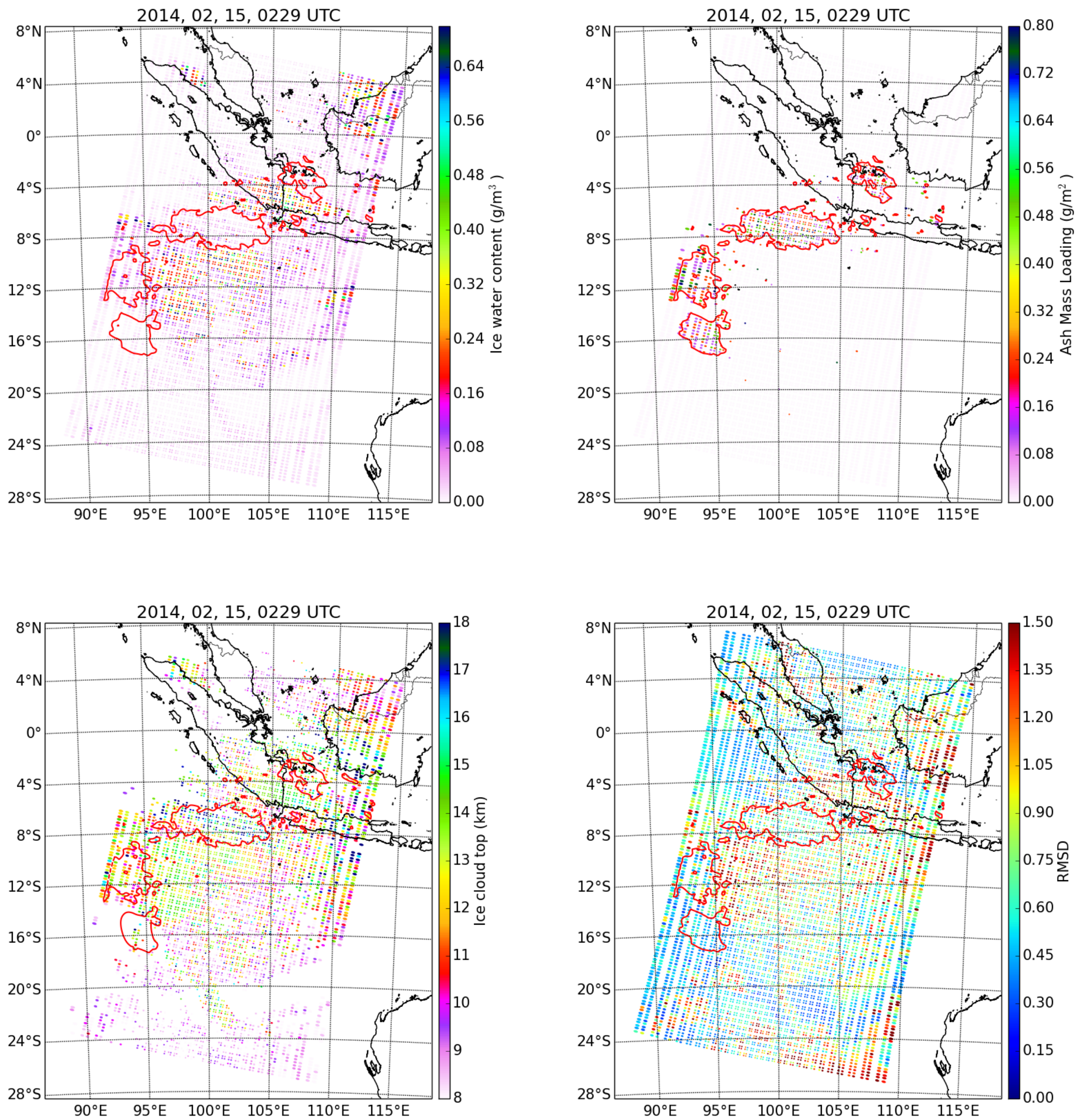

Figure A3: (Upper left panel) The estimated ice water content. (Upper right panel) The estimated ash mass loading. (Lower left panel) The estimated altitude of the ice cloud top. height for ice clouds with ice water content >0.01 g/m^2. (Lower right panel) The root mean square difference (RMSD) of the simulated-measured spectra. The red contour line delineates the area identified as ash. Data from 15 Feb 2014, 0229-0235 UTC. To be compared with Fig. 9 in the manuscript.

The discussion has been restructured and extended.

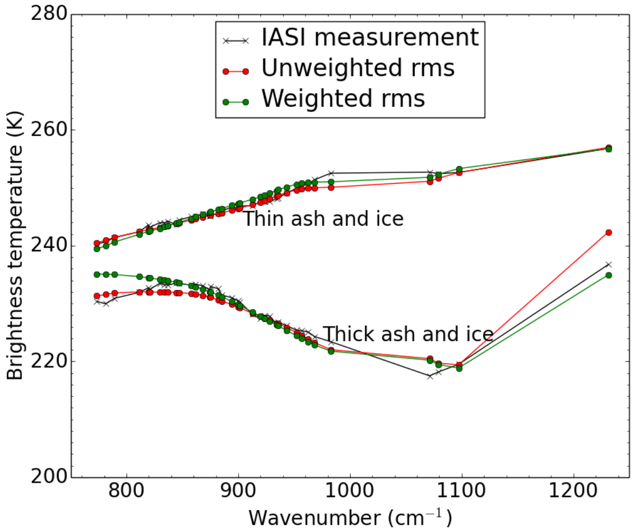

Figure A4: The brightness temperature for the pixels identified as ash in the right panels of Figs. 1 and 2. The brightness temperatures measured by IASI are shown only for points which are used to calculate the RMSD. The RMSD is calculated as in the manuscript, Eq. 1 and Fig. 6 (red lines) or using a weighted RMSD (green lines). Note that the lines connecting the points are drawn just for visualisation and do not represent the actual spectral behaviour between the data points.

Bibliography

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