Reply on Anonymous Referee #1 (AMT-2017-50)

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1 Introduction

The comments of the reviewer have been helpful to improve the manuscript. Especially the question on the dependence of solar zenith angle on the retrieval results and the missing comparison with in situ measurements provided more understanding of the retrieval algorithm and of the radiative effects between clouds and surface.

The detailed replies on the reviewers comments are given below.
The reviewers comments are given bold while our replies are written in regular roman letters. Citations from the revised manuscript are given as indented and italic text.

Detailed Replies

1. The authors used the solar zenith angle of 63° to describe the dependence of the retrieval of cloud optical properties on snow surface albedo grain size. A note on how it would change with a different solar zenith angle would be useful for completeness. His note would also be useful in section 4.2.

The solar zenith angle of 63° was used because of the two case studies presented in the manuscript. We now did rerun the sensitivity study for solar zenith angles of 45° and 80°. It was found that the uncertainties in retrieved τ due to a wrong assumption of the grain size do not significantly change with solar zenith angle. However, for low Sun, $\theta = 80°$, the bias in retrieved $r_{\mathrm{eff,C}}$ was slightly reduced, while for $\theta = 45°$, the uncertainties of the retrieved $r_{\mathrm{eff,C}}$ are increased (see Figure 1). This can be explained by the probability that photons interact with the surface. This is lower for high solar zenith angle. We added this general dependency on solar zenith angle to the revised manuscript:

> *The numbers presented here, were obtained for a solar zenith angle of $\theta_0 = 63°$. For simulations with different solar zenith angles, similar grain size effects are observed. In general, the magnitude of the grain size effect of τ does not significantly change with θ_0. However, for low Sun, large θ_0, the grain size effect on the retrieved $r_{\mathrm{eff,C}}$ was slightly reduced, while for higher Sun, small θ_0, the effects increase. This is caused by the increased probability that radiation interacts with the surface in case of decreasing solar zenith angle.*

The snow grain size effect on retrieved τ does not depend on the solar zenith angle, while the effect on $r_{\mathrm{eff,C}}$ is larger for a higher Sun.

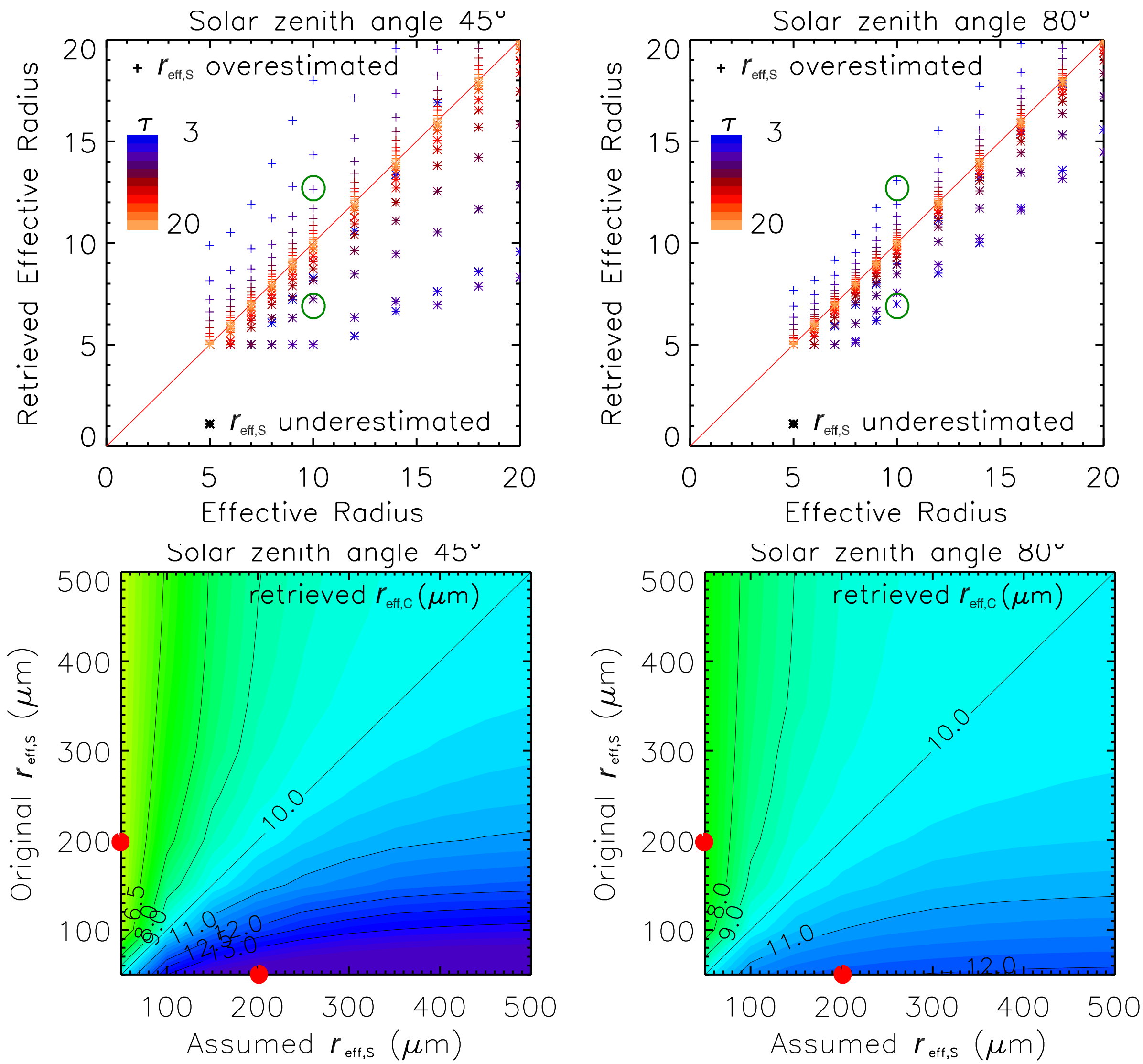

Figure 1. Comparison of retrieval uncertainties for solar zenith angle of 45° (left panels) and 80° (right panels). Upper plots show the comparison of synthetically retrieved $r_{\mathrm{eff,C}}$ with the original parameter value. Calculations in the upper panels are performed for assuming a larger snow effective grain size of $r_{\mathrm{eff,S}} = 200\,\mu\mathrm{m}$ instead of the original $r_{\mathrm{eff,S}} = 50\,\mu\mathrm{m}$ (crosses) and a smaller snow effective grain size of $r_{\mathrm{eff,S}} = 50\,\mu\mathrm{m}$ instead of the original $r_{\mathrm{eff,S}} = 200\,\mu\mathrm{m}$ (asterisks). In the lower panels all combinations of assumed and original $r_{\mathrm{eff,S}}$ are analyzed for a specific cloud of $\tau = 4$ and $r_{\mathrm{eff,C}} = 10\,\mu\mathrm{m}$.

Additionally, we used the new simulations to estimate the sensitivities of the spectral reflectivity to the three cloud and snow parameter for different solar zenith angles. Not significant differences were found in the spectral separation of the sensitivities. Figures 3 and 1 show the calculated standard deviations and principle component weighting for solar zenith angle of 45° and 80°. The wavelength dependent sensitivities of the cloud reflectivities did change only minor still allowing a separation of the three parameters by measurements at different wavelengths. Similarly, the retrieval grid of the forward simulations was only shifted to one or another direction. The orthogonality and potential ambiguities are almost unchanged. In the revised manuscript we added:

The results are presented for a solar zenith angle of $\theta_0 = 63°$ but are applicable to larger and smaller θ_0.

Although the retrieval was applied to cases with a specific solar zenith angle only, radiative transfer simulations showed that the spectral sensitivities used in the retrieval algorithm are similar in case of smaller or larger solar zenith angles.

2. Section 2.2 is slightly difficult to follow, please refine descriptions.

We reordered some passages in order to improve the readability. See marked up manuscript for all changes.

3. The use of percentages to denote uncertainty is slightly ambiguous and should be better defined.

Yes, we agree, percentages can be difficult to interpret. Therefore, we added how the percentage have to be read. In addition, the correct values are always given when percentages are used.

... the snow grain size effect, expressed by the percentage deviation of the retrieved from the original true value, ...

4. The use of the mean standard deviation per respect to a variable seems to be quite novel. Maybe more description is needed, especially to address the possible covariability of some parameters (i.e. sigma_tau is most variable when there is a high reff_c).

The mean standard deviation was used to provide an efficient way to identify wavelengths that are sensitive to a single cloud or snow parameter. Therefore, we aimed to include all simulations. E.g., for each cloud, a standard deviation of all simulations with different $r_{\mathrm{eff,S}}$ was calculated. $\sigma_{r_{\mathrm{eff,S}}}$ is then derived by averaging these standard deviations for all different clouds. It is right, that for a selection of the set of simulated clouds or snow grain sizes different numbers might be obtained. With the intention to provide a simple retrieval algorithm based on measurements at three wavelength, we did not extended this analysis into more detail. In addition, we finally selected wavelengths corresponding to MODIS bands. A limitation to only a few spectral band will limit the results of a more detailed study investigating the spectral sensitivities for different sub-samples of cloud and snow parameters. To point the use of the mean standard deviations more clearly we added the following sentences in the manuscript.

E.g., for each cloud, a standard deviation of all simulations with different $r_{\mathrm{eff,S}}$ was calculated. $\sigma_{r_{\mathrm{eff,S}}}$ is then derived by averaging these standard deviations for all different clouds.

Similarly, the use of sub samples of the full cloud and snow parameter range investigated here might change the derived values.

5. Description of the identification process of when the retrieval of snow grain size and cloud property fails would be a useful addition to this paper.

In the manuscript, we mentioned, that the retrieval may fail if mixed-phase clouds are present. In that case "fail" does not mean, that the algorithm may stop at some step and does not provide a results. "Fail" refers to wrong results which may be far off the real snow or cloud properties. For mixed-phase clouds, also the cloud ice crystals will absorb the solar radiation at similar wavelengths as snow; the spectral signatures of cloud and snow properties might be merged stronger than for liquid clouds. Therefore, the retrieved snow grain size might be biased by the cloud ice ($r_{\mathrm{eff,C}}$), and vice versa. Still the retrieval would provide a results but this might be wrong. To clarify this, we changed the manuscript to:

In this case, the retrieval may provide unrealistic cloud properties as the ice crystals absorb solar radiation at similar wavelengths as the snow surface does.

6. The retrieval is applied to data over land although no mention of that in the description of the retrieval methodology description.

Yes, for Case I, the retrieval was also applied for snow covered land surface. These data are only presented in the maps of Figure 8. The time series in Figure 6 does not include the full flight track, as mentioned in the manuscript. However, the application of the retrieval to land surfaces of sufficient snow cover is justified, as the surface below a snow layer does not effect the snow albedo, when the snow layer exceeds a thickness of about 10 cm or more. In the revised manuscript we added a note, that the retrieval was also applied to snow covered land surfaces.

Note that here a longer time series is shown than presented in Figure 6. This includes areas with snow covered land surfaces, for which the retrieval can be applied assuming that the snow layer is sufficiently thick and the snow albedo is not affected by the underlying surface (Warren, 2013)

7. A note on the availability of surface or in situ measurements for the 2 cases would be helpful.

Measurements of snow grain size on the sea ice have not been conducted during the campaign. Therefore, no reference is available. However, airborne cloud microphysical measurements have been obtained during the flight. Having only one aircraft, Polar 5, the in situ and remote sensing measurements had to be performed subsequently. For both investigated examples, Case I and II, the remote sensing flight legs were flown first. About one hour later the in situ measurements were obtained on the same flight leg. These measurements were included in the revised manuscript and compared to the retrieval results. The following sections have been added:

Cloud microphysical in situ measurements on board of Polar 5 were use to validate the retrieved $r_{\mathrm{eff,C}}$d. A Cloud Droplet Probe (CDP) provided size resolved cloud particle concentrations in the size range from 2.5 μm to 46 μm and *corresponding $r_{\mathrm{eff,C}}$ (Klingebiel et al, 2015). Using only one aircraft, the in situ and remote sensing measurements had been performed subsequently. For both investigated Cases I and II, the remote sensing flight legs were flown first. Roughly one hour later the in situ measurements were obtained at the same location following the flight track of the remote sensing sequence. Due to the stable meteorological conditions, changes of the cloud properties with time are expected to be small which allows a comparison of in situ and remote sensing data. A reference to validate the retrieved snow grain size is not available because no ground-based measurements on the sea ice have been conducted during VERDI.*

In situ cloud microphysical measurements of $r_{\mathrm{eff,C}}$ had been obtained along the same flight track about one hour after the remote sensing measurements. At cloud top, two derived vertical profiles show $r_{\mathrm{eff,C}}$ between 6 μm and 7.5 μm, which is in the range of the retrieval results.

The in situ microphysical measurements cover two cloud profiles along the same flight track, one observed above open ocean and one above sea ice. Both profiles showed no difference with $r_{\mathrm{eff,C}}$ of about 9 μm at cloud top, which are higher compared to Case I and in agreement with the retrieval results.

8. The conclusion is well written, especially with the inclusion of the bullet points.

Thanks!

9. P.2 line 33, exact meaning of sentence not clear, please define what is an improvement of uncertainty by 20%, is it an uncertainty range that is 20% less, or that is it 20% smaller compared to the retrieved value.

Yes, by using "improve by 20 %" the meaning was not sufficiently clear. Indeed, Rolland and Liou (2001) calculated the percentage reduction the the uncertainties range. The absolute reduction differs for different clouds. Therefore, the relative numbers are given. We rephrased the sentence to:

Rolland and Liou (2001) showed that the retrieval uncertainties of thin cirrus can be reduced by 20 % for optical thickness and by 45 % for ice crystal effective radius when a reasonable estimate of the surface albedo is applied.

10. Fig. 2 could be made clearer if the optical thickness and cloud particle effective radius were put directly on the figure. At least an indication of the low end of the optical thickness and effective radius would be needed.

We added such labels in the revised figure.

11. P.5 line 5, cloud reflectivity is also impacted at wavelengths lower than 1000 nm, the word ‘only’ is erroneous in this case, maybe use a less strict word.

Yes, "only" is not true. We changed the sentence to:

The simulations illustrate that τ impacts γ_λ primarily at wavelengths larger than 1000 nm where the snow albedo is lower than 0.8, while lower wavelengths are less sensitive to τ.

12. P.6 line 9, Sentence slightly difficult to follow.

That's true, the sentence was way to long. We split now and rephrased to:

> *For liquid water cloud retrievals obtained over snow surfaces with unknown grain size, the snow grain size effect on uncertainties of retrieval results was quantified. Therefore, synthetic measurements obtained from the retrieval forward simulations as introduced in Section 2.1 are applied. For each synthetic measurement defined by* τ, $r_{\mathrm{eff,C}}$, *and* $r_{\mathrm{eff,S}}$ *a set of retrieval assuming different values of effective snow grain sizes were performed.*

13. P.6 line 12 Please elaborate or define more clearly 'retrieval forward simulation'

The forward simulations of the retrieval are introduced in Section 2.1. We added this reference here.

> *Therefore, synthetic measurements obtained from the retrieval forward simulations as introduced in Section* **??** *are applied.*

14. P. 8 line 15, typo, should read 'In cases where liquid water clouds are...'

Has been corrected in the revised version.

15. Fig. 4 – consider only showing the absolute value of the PCA spectra, for easier comparison to the mean standard deviation values.

Yes, we already thought about that, but concluded that the sign of the PCA weightings should not be neglected as it is a valid information. On the other hand, the magnitude itself is important to compare the different principle components. Therefore, we adjusted the plot and showed only absolute values. Original negative weightings are plotted as dashed lines to indicate the sign. However, this new plot looks to busy and we think the main information is lost due to the different line styles. We therefore, would like to keep the original version, but included the alternative version here in the replies (Figure 2).

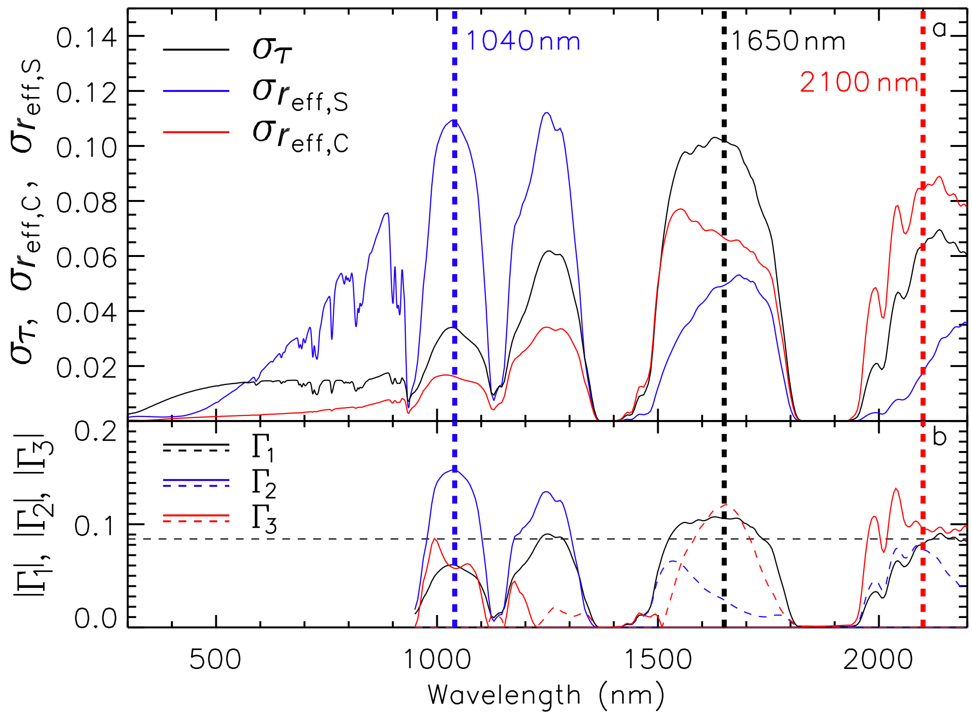

Figure 2. Mean standard deviations of spectral cloud reflectivity σ_τ, $\sigma_{r_{\mathrm{eff,C}}}$, and $\sigma_{r_{\mathrm{eff,S}}}$ with respect to a single cloud or snow parameter τ, $r_{\mathrm{eff,C}}$, and $r_{\mathrm{eff,S}}$ calculated for the sets of radiative transfer simulations (panel a). The absolute values of the first three spectral weights Γ_1, Γ_2, and Γ_3 of a principle component analysis are given in panel b. Dashed lines indicate negative values, solid lines positive values of Γ_1, Γ_2, and Γ_3.

16. Typo P.12, line 10, 'too weak' instead of 'to week', sentence would benefit from being more precise.

Has been corrected in the revised version.

17. Typo P.12, line 13 'ice floes' instead of 'ice flows'

Has been corrected in the revised version.

18. P.12, line 16, revise sentence for the use of the word 'also'

Has been corrected in the revised version to:

> *A surface with a high albedo always enhances the upward radiance above a cloud even in the case of optically thick clouds.*

19. Comment, Section 5, the radiometric uncertainties quoted for the ratios seem large considering the calibration uncertainty partially cancel.

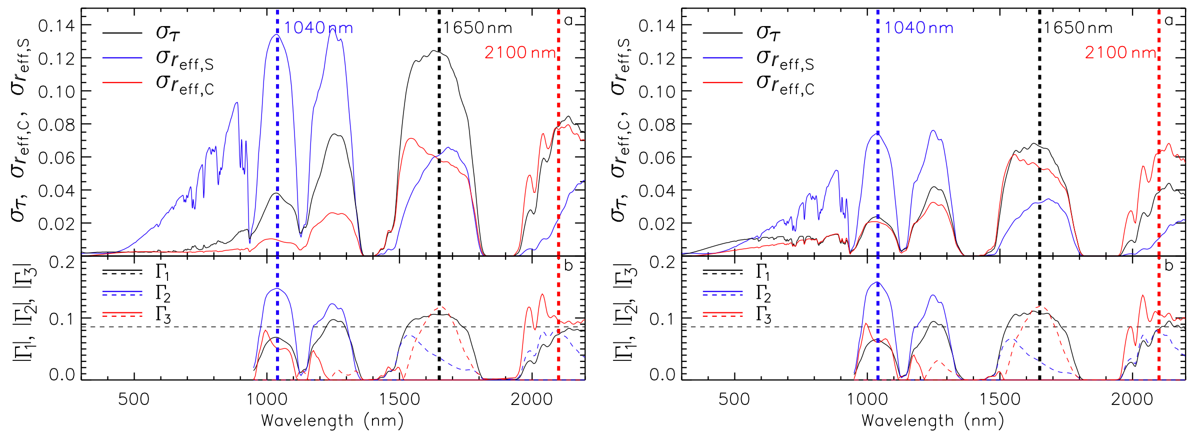

Figure 3. Same es Figure 2 but for solar zenith angle of 45° (left) and 80° (right)

We carefully calculated the uncertainties of the ratios by considering the uncertainties of the individual radiance measurements. Apart from the radiometric calibration which cancels out for the ratios, the largest contribution to the high uncertainties results form the signal to noise ratio. The noise and dark signal of the spectrometers differ between the two spectrometer types operated in SMART and also within the spectrometer spectral range. Especially the measurements at 2100 nm wavelength are almost at the end of the spectrometer photo diode array where the sensitivity strongly decreases. Therefore, the signal to noise ratio of R_3 is quite large. In addition, the radiance is lower at larger wavelengths and even lower in the absorption bands used for the retrieval. These low radiances reduce the signal to noise ratio compared to shorter wavelengths covered by the same spectrometer. This effect can easily lead to uncertainties ranging above 10%.