Dear Reviewer,

thank you for taking the time to review our manuscript. Your feedback is greatly appreciated and was helpful in improving the quality of this research. We value your constructive criticism and thoughtful comments, which have helped to identify areas that require further clarification and refinement.

We carefully considered your suggestions and incorporated them into the revised manuscript to address the issues raised, as specified below (referee comments in black; our answers in blue).

Comments of Reviewer #2

I think the previous two reviewers had very nice summary and evaluation of the manuscript. I agree with a lot of their comments. Overall I think this is a very rigorous study of the IR based retrieval of cloud properties and it is worthy of publication. On the other hand I think the manuscript needs some modification and revision before it can be finally accepted for publication.

First of all the manuscript reads more like a shortened Ph.D./MS. thesis than a scientific paper. It is way too long and hard to get insightful/meaningful results without having to go through many unnecessary parts. For example, the section 2 "physics background" should be significantly shortened if not removed completely as it is about something that is from textbook and well known. Similarly, I'm not sure if the Appendix A is needed either. In any case, I would suggest finding all possible ways to make the paper succinct.

Thank you for this feedback, it is very valuable to know. We have made several changes to the manuscript to shorten it and make the messages and results clearer.

We have significantly shortened section 2 "Physical Background" and moved the explanations of the single scattering properties to the appendix. Although much of the physical background is well known, we believe it is valuable to keep the parts which are most essential for understanding the content of the paper for readers less familiar with the subject.

We agree that the content of Appendix A (Mathematical Framework of Radiative Transfer) is well known and not essential for understanding our study. We have removed it as suggested.

We have also shortened the results sections (sections 5 and 6) to make them more concise. The largest changes have been made to Section 6.1 to avoid redundancy with Section 5 and to make its messages clearer. The shortened version of Section 6.1 is shown in the response to Major Comment 2 from Reviewer #1.

The discussion of "disentangling the roles of cloud absorption and scattering" is interesting. However, it is based on the assumption that scattering is completely ignored in the IR cloud remote sensing, which is rarely the case in recent studies. As mentioned by the first reviewer, a popular method is the so-called beta ratio method, which was first proposed Parol et al., 1991 and then improved and used in many follow up studies (e.g., Pavolonis 2010, Heidinger et al. 2010; Heidinger et al., 2015;). The beta ratio method is based on the so-called similarity principle that takes into account the strong forward scattering of cloud particles in radiative transfer. I think it is important to point this out (with proper reference) and discuss it against Eq. (6).

Sorry for the confusion: We did not want to give the impression that scattering is ignored in IR cloud remote sensing - IR retrievals are often based on RT calculations (e.g. look-up tables), which usually also simulate scattering. Our intention in studying the different roles of absorption and scattering is to better understand the underlying physics of how these processes contribute to the BTD values. We believe that this aspect is not often studied in detail and we want to contribute to a better explanation of why the BTDs show certain behavior. We do not assume that Eq. (6), which only considers absorption, is the basis for recent IR retrievals. Eq. (6) is only intended to demonstrate the BTD nonlinearity effect in its simplest form.
To make it very clear that scattering is usually not ignored in IR remote sensing, we rewrote two sentences in the introduction:

"Radiative transfer through clouds and the atmosphere is complex, with many parameters that can in principle influence satellite observations. Although radiative transfer models are capable to correctly account for all of these quantities, the relative importance of these parameters is often not fully understood."

"In addition, the origin of the dependence of BTDs on cloud thermodynamic phase, as observed in satellite measurements and radiative transfer results, is not fully understood. Although phase retrievals are usually based on accurate radiative transfer calculations that take into account all radiative effects, it is argued that variations in the refractive indices of ice and water across the infrared window cause the BTDs to be sensitive to cloud phase (Finkensieper et al. 2016, Key et al. 2000, Baum et al. 2000, Baum et al. 2012)."

Furthermore, we agree that the beta ratio method is very interesting and has many strengths. We have added a note in the introduction of our manuscript that beta ratios are another popular approach to cloud phase retrievals. However, we believe that a detailed discussion of beta ratios is beyond the scope of this study, which is explicitly focused on BTDs and their sensitivities. We added the following to our manuscript:

"Finally, we note that besides BTDs, there are other popular methods for retrieving cloud phase and other cloud properties, such as β ratios (Parol et al., 1991; Pavolonis, 2010; Heidinger et al., 2015). While this study is specifically aimed at BTDs, understanding the effects of different cloud properties on the radiative transfer through clouds is also useful to better understand the physics underlying β ratio retrievals."

While the manuscript covers most of the important aspects of the IR based retrieval of cloud properties, an important missing is the impacts of cloud microphysics. A good paper on this topic is Zhang et al (2010). I think it would make the study stronger if you can add some study/discussion to about this effect, perhaps along with the discussion on the effects of cloud geometrical thickness.

If we understand correctly, you are suggesting a discussion on the impact of vertical inhomogeneity of microphysical parameters on BTDs since this is the topic of the Zhang et al. (2010) paper and the impact of cloud microphysics (ice habit, Reff) is already included in our manuscript. We agree that this is a very interesting topic and that an additional discussion of the effects of vertical inhomogeneity would make the study more complete. We have therefore added a sensitivity analysis of the BTDs to the vertical inhomogeneity of R_{eff} (see figure below) and added it to the discussion of the effects of cloud geometric thickness in the Appendix, as suggested:

"Figure E2 shows the sensitivity of the BTDs to vertical inhomogeneity of R_{eff}. To model this inhomogeneity and capture its basic effects on BTDs we use a simple setup of clouds with a total geometric thickness of 2 km, consisting of two 1 km thick layers (layer 1 on top, layer 2 at the bottom, specified in the subscripts). Both layers have the same optical thickness, $\tau_1 = \tau_2 = \tau/2$. Cloud layer 1 has a $R_{eff,1}$ which is either equal, smaller or larger to layer 2, $R_{eff,1} \lesseqgtr R_{eff,2}$ (case A, B or C), such that the average $\overline{R_{eff}}$ is the same for all three cases (case A: $R_{eff,1} = R_{eff,2} = \overline{R_{eff}}$; case B: $R_{eff,1} = 0.8\,\overline{R_{eff}} < R_{eff,2} = 1.2\,\overline{R_{eff}}$; case C: $R_{eff,1} = 1.2\,\overline{R_{eff}} > R_{eff,2} = 0.8\,\overline{R_{eff}}$). Hence, in case A, the R_{eff} is homogeneous; in case B and C it is inhomogeneous. This model of vertical inhomogeneity is of course very simplified, but it is useful for calculating a rough estimate of the magnitude of inhomogeneity effects and for understanding the underlying physics.
Overall, the sensitivity to vertical R_{eff} inhomogeneity is comparatively small ($\lessapprox 0.5$ K). The effects of the vertical R_{eff} inhomogeneity on the BTDs are due on the one hand to its effects on the transmittance of the surface radiance and on the other hand to its effects on the emittance of the cloud itself. Zhang et al. (2010) show (for ice clouds) that the nonlinear dependence of the optical properties on R_{eff} leads to an increased weighting of small particles in the signal of the transmitted radiance. This leads to larger BTDs for cases where the cloud is (partly) composed of particles smaller than the average (the inhomogeneous cases B and C), where transmittance is the dominant process (small τ). However, as can be seen in Fig. E2 for small τ ($\lessapprox 2$), this effect is very small compared to other dependencies, since the cloud transmittance in the infrared window depends mainly on τ and less on the details of the vertical R_{eff} profile of the cloud (Zhang et al., 2010). On the other hand, when the cloud emittance dominates for increasing τ, the signal from the particles at the bottom of the cloud is (partially) absorbed by the top cloud layer. The BTD signal is then dominated by the R_{eff} of the top cloud layer ($R_{eff,1}$). This makes a difference mainly for small R_{eff} values (see min $\overline{\mathrm{R}_{\mathrm{eff}}}$ curves in Fig. E2), as the BTDs depend non-linearly on R_{eff} (see Fig. 7). Figure E2 shows that these effects on cloud emittance (dominant for large τ) lead to larger overall effects on the BTDs compared to the effects on transmitted surface radiance (dominant for small τ)."

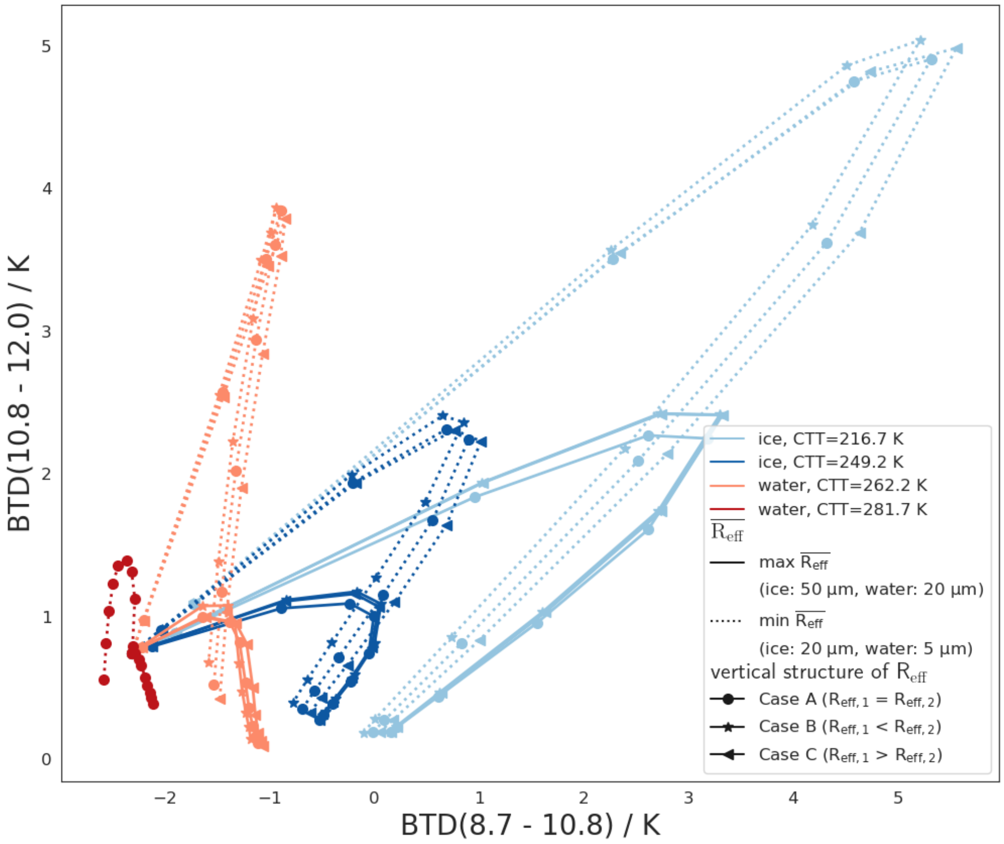

Figure E2. Same as Fig. 11, but for fixed ice crystal habit (ghm) and vertical inhomogeneity of R_{eff} (in different markers): the cloud consists of two layers (layer 1 on top, layer 2 at the bottom, specified in the subscripts), each with geometric thickness of 1 km and the same layer optical thickness, $\tau_1 = \tau_2 = \tau/2$. Cloud layer 1 has a $R_{eff,1}$ which is either equal, smaller or larger to layer 2, $R_{eff,1} \lesseqgtr R_{eff,2}$ (case A, B or C), such that the average $\overline{R_{eff}}$ is the same for all three cases (case A: $R_{eff,1} = R_{eff,2} = \overline{R_{eff}}$; case B: $R_{eff,1} = 0.8\,\overline{R_{eff}} < R_{eff,2} = 1.2\,\overline{R_{eff}}$; case C: $R_{eff,1} = 1.2\,\overline{R_{eff}} > R_{eff,2} = 0.8\,\overline{R_{eff}}$). No R_{eff} inhomogeneity is shown for the case of liquid clouds with CTT = 281.7 K, since their CTH is at an altitude of 1 km, leaving room for only one cloud layer.

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