Anonymous Referee #1

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The authors conducted a theoretical investigation of dust-snow internal mixing and its effects on dust-induced snow albedo reduction. The dust-snow internal mixing has not been quantified by many previous studies, and the present study could potentially increase our understanding of its impact. This manuscript is suitable for this journal and is generally well structured in terms of language. However, I do have one major concern related to the method used in this study. Please see my comments below for details.

R: Thanks for the valuable comments, we have addressed all comments very carefully as detailed below.

Major Comments:

1. My major concern is that the effective medium approximation used by the authors cannot be applied to dust in snow due to the much larger dust size than black carbon (e.g., Bohren, C. 1986: Applicability of effective-medium theories to problems of scattering and absorption by non-homogenous atmospheric particles, J. Atmos. Sci., 43, 468–475). This has also been discussed in detail in Section 2.1 of Flanner et al. (2012, ACP doi:10.5194/acp-12-4699-2012).

R: Although previous literature indicated that the effective medium approximation cannot be applied to dust in snow due to the much larger diameter of dust particles than black carbon (Bohren 1986; Flanner et al., 2012), there are still some studies to solve optically effective complex refractive index of dust composite aerosols based on the effective medium approximation (Cremonesi et al., 2020; Zhang et al., 2020). Besides, we acknowledge that the effective medium approximation used in this study can create some errors for the albedo calculation of dust/snow internal mixing. Therefore, we carefully evaluate the accuracy of our results by comparison to more rigorous calculations found in He et al. (2019), which can be seen in Figure R1 (i.e., Figure 11 in the revised manuscript). More details can be found in Page 19, Lines 1-12 in the revised manuscript as follows.

"In this study, the application of the effective medium approximation greatly simplifies the complexity of snow radiation transfer calculation for dust–snow internal mixing, and the effect of non-uniform distribution of dust in snow grains on snowpack optical properties are explicitly quantified for the first time. However, it is worth noting that this method has its limitation when applying to large particles (e.g., dust) in snow (Bohren 1986; Flanner et al., 2012), which can create some errors for the albedo calculation of dust–snow internal mixing. To verify the credibility of our results, we carefully make a comparison with the more rigorous calculations found in He et al. (2019), which used the geometric-optics surface-wave approach (GOS) to consider the impact of dust–snow uniform internal mixing on snow albedo reduction. As shown in Figure 11, the results show that the enhancement ratio of snow albedo reduction (1.28) due to dust–snow internal mixing (relative to external mixing) is slightly higher than the value (1.16) reported by He et al. (2019), and this deviation is comparable to that caused by snow nonsphericity (He et al., 2019). Therefore, we indicated that the effective medium approximation used in this study is reasonable and reliable."

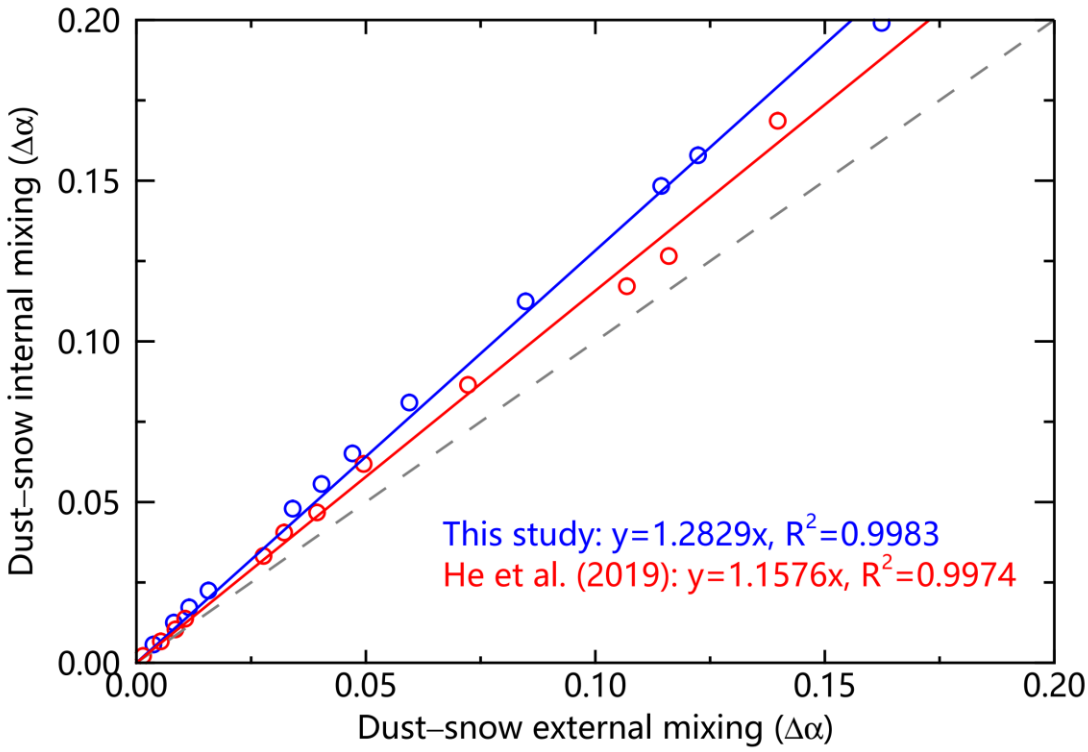

Figure R1. Comparisons of snow albedo reduction ($\Delta\alpha$) under the cloudy sky caused by dust-snow uniform internal mixing (y-axis) and external mixing (x-axis) for this study (blue) and He et al. (2019) (red).

Minor Comments:

1. Page 2, Line 10: "absorption coefficient". Did the authors mean the absorption coefficient of snow-dust mixture?

R: To avoid potential ambiguity, the sentence has been revised as "… absorption coefficient and albedo of dust-contaminated snowpack …".

2. Abstract: The authors assumed spherical snow grains and semi-infinite snowpack in their calculations. These need to be mentioned in the abstract to avoid potential confusion.

R: Added as suggested (See Page 2, Line 6 in the abstract).

3. The authors assumed spherical snow grains in this study. But it would be good to discuss the role of snow grain shape in the introduction, because recent studies showed that snow nonsphericity can interact with LAP-snow mixing, which leads to weaker LAP-induced albedo reduction for nonspherical snow shapes than snow spheres (e.g., Dang et al., 2016 JAS: doi:10.1175/JAS-D-15-0276.1; He et al., 2018b JGR, doi:10.1002/2017JD027752). The snow shape can have nontrivial impacts on dust-snow albedo reduction.

R: More descriptions have been added to investigate the role of snow grain shapes in the introduction (See Page 4, Line 2-5).

4. The authors used the effective medium theory to handle dust-snow internal mixing. However, as mentioned in my major comment, this method has its limitation when applying to large particles (e.g., dust) in snow. Some other studies (e.g., Liou et al., 2014, JGR doi:10.1002/2014JD021665; He et al., 2019, JAMES doi:10.1029/2019MS001737) have used another geometric-optics surface-wave

approach to deal with dust-snow internal mixing. These two are the pioneering studies investigating dust-snow internal mixing effects, and need to be discussed in the introduction. Particularly, the authors also need to highlight the difference or novelty of the study compared with these recent studies (e.g., new method, new perspective, etc.?). In the results or discussion section, it is good to also discuss the difference in the results from the present study and the previous study (e.g., He et al., 2019 JAMES) in terms of the impact of dust-snow internal mixing. It would be interesting to see if the results are consistent or not based on two different methods.

R: We have added more contents to analyze the related studies about dust-snow internal mixing effects from Liou et al. (2014) and He et al. (2019) (see Page 4, Lines 23-28).

"Liou et al. (2014) is the pioneer to investigate the dust-snow internal mixing effects based on the geometric-optics surface-wave approach. Subsequently, He et al. (2019) used the same method to explicitly quantify the combined effects of dust-snow internal mixing and snow grain nonsphericity on snow optical properties, thereafter, develop a set of new dust-snow parameterizations for land/climate modeling applications."

Besides, we highlighted that the method used in this study greatly simplifies the complexity of snow radiation transfer calculation, and evaluated the effect of non-uniform distribution of dust in snow grains on snowpack absorption coefficient and albedo for the first time. Furthermore, we also carefully access the accuracy of our results by comparison to more rigorous calculations found in He et al. (2019). As shown in Figure R1, the results show that the enhancement ratio of snow albedo reduction (1.28) due to dust–snow internal mixing (relative to external mixing) is slightly higher than the value (1.16) reported by He et al. (2019), and this deviation is comparable to that caused by snow nonsphericity (He et al., 2019). Therefore, we indicated that the effective medium approximation used in this study is reasonable and reliable. More details can be found in p. 19, lines 1-12:

"In this study, the application of the effective medium approximation greatly simplifies the complexity of snow radiation transfer calculation for dust–snow internal mixing, and the effect of non-uniform distribution of dust in snow grains on snowpack optical

properties are explicitly quantified for the first time. However, it is worth noting that this method has its limitation when applying to large particles (e.g., dust) in snow (Bohren 1986; Flanner et al., 2012), which can create some errors for the albedo calculation of dust–snow internal mixing. To verify the credibility of our results, we carefully make a comparison with the more rigorous calculations found in He et al. (2019), which used the geometric-optics surface-wave approach (GOS) to consider the impact of dust–snow uniform internal mixing on snow albedo reduction. As shown in Figure 11, the results show that the enhancement ratio of snow albedo reduction (1.28) due to dust–snow internal mixing (relative to external mixing) is slightly higher than the value (1.16) reported by He et al. (2019), and this deviation is comparable to that caused by snow nonsphericity (He et al., 2019). Therefore, we indicated that the effective medium approximation used in this study is reasonable and reliable."

5. Page 5, Lines 13-14: Please rephrase this sentence. Did the authors mean 20cm and 3cm of snow depths?

R: This sentence has been rewritten as follows.

"For fairly pure snow, semi-infinite means about 20 cm in the VIS and 3 cm in the near-infrared (NIR) regions of snow depths, respectively."

References:

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