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Interactive comment on "Enhanced light absorption and reduced snow albedo due to internally mixed mineral dust in grains of snow" *by* Tenglong Shi et al.

Anonymous Referee #4

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General comments

This paper reports a comparison of the impacts on snow albedo due to dust externally vs. internally mixed with snow, starting from idealized cases and then proceeding to estimates of albedo reduction based on actual measurements of dust concentration in snow at various geographical locations in the Northern hemisphere.

This topic is relevant for ACP and the paper is mostly well-written, but unfortunately there is one major concern (as also noted by the first reviewer). The Maxwell-Garnett approximation is applied to cases which are, in principle, much outside its region of validity. Theferore, I can recommend the publication of this paper only if the authors are able to use a more rigorous approach, or — at very minimum — to carefully evaluate the accuracy of their results by comparison to more rigorous calculations found in the literature.

Major comments

1. The use of the Maxwell-Garnett approximation to compute the effective refractive index (and subsequently the single-scattering properties) of snow grains containing mineral dust particles is physically questionable. The problem is that the Maxwell-Garnett approximation assumes that the inclusions are much smaller than the wavelength. In the case of dust particles, with an effective radius of $1.1\,\mu$m as considered here, this is definitely not the case (e.g., the effective size parameter $x = 2\pi r/\lambda$ exceeds 10 in the visible region).

Consequently, when comparing the effects of dust internally vs. externally mixed with snow, you are in fact comparing dust particles with different size: particles in the micrometer scale for external mixing, and (in principle) infinitesimally small particles for internal mixing.

2. Neither the introduction nor other parts of the paper discuss the present work properly in the context of previous studies that have considered internal mixing of dust within snow grains. These include, at least, the studies by Liou et al. (2014) and He et al. (2019), both of which appear in the reference list of the current paper (so the authors seem to be aware of their existence anyway).

These papers use a more rigorous approach (the geometric-optics surface-wave approach, GOS) and they also consider the impact of snow grain shape but not whether the dust particles are concentrated in the inner or outer parts of snow grains. Also note that the paper by He et al. (2019) employs the same size distribution for dust as the current paper. This should allow a comparison of the results of your approach with the GOS approach.

Minor comments

1. p. 5, line 27: There is an error in Eq. (3). It should be $\sigma_{ext} = \frac{1}{l_{tr}(1-g)} = \frac{3C_v}{2r_{ef}}$. See Eq. (18) in Kokhanovsky and Zege (2004). This is also obvious if you consider the units.

2. p. 9, lines 2–5: Was the effect of clouds included in the calculation of the solar spectrum? The reason why I'm asking is that the broadband albedo for pure snow in Fig. 10 (about 0.87) seems quite high (i.e., too high for cloud-free conditions, for $r_{ef} = 200\,\mu$m).

3. p. 10, line 17: "the order of magnitude of k_{ice} was comparable to k_{dust} at those wavelengths". This is not quite true, as the difference between k_{dust} and k_{ice} is still 2–3 orders of magnitude. It is just more than compensated by the much larger difference in ice vs. dust concentration.

4. p. 12, line 25: "monotonic dependence of σ_{abs}" on what? On $\overline{r_c}$ and $\overline{r_p}$?

5. p. 13, lines 12-14: The increase of forward scattering with size does not matter much in this case, in which the snow grains are well in the geometric optics regime. Rather, the decrease of albedo with r_{ef} is explained by the fact that the snow extinction (and also scattering) coefficient is inversely proportional to r_{ef}, so that for a given amount of dust, the single-scattering albedo of the snow-dust mixture is smaller for large snow

grains. To put it another way, for larger r_{ef}, solar radiation can penetrate deeper into snow, which increases the chances of absorption by dust.

6. p. 16, lines 11–25. This discussion on the impact of dust particle effective radius on the ratio of snow broadband albedo for internal vs. external mixing of dust is not valid, for reasons explained in the first major comment. The independence of single-scattering properties on dust particle size in the internally mixed cases is an artifact resulting from the use of the Maxwell-Garnett approximation, Eq. (8), which assumes that dust particles are very small compared to the wavelength.

7. p. 17, lines 25–27. The contrast in the effect of dust on snow albedo between fresh and aged snow is probably even more pronounced than indicated here, because snow grain effective radius r_{ef} is generally larger for aged snow than fresh snow. In the present calculations, a constant $r_{ef} = 200\,\mu m$ is assumed.

Technical and language corrections

1. p. 4, line 11: this should be “Tibetan plateau”?

2. p. 5, lines 13-14: This is not very clear. Is this what you mean? “...the snow layer can be generally considered semi-infinite in the VIS region if the snow depth is at least 20 cm, and in the near-infrared (NIR) if it is at least 3 cm.”

3. p. 5, line 17: this should be “Kokhanovsky”.

4. p. 10, line 14: “The wavelength of the valley k_{eff}.” Do you mean “the wavelength of the minimum of k_{eff}”?

5. p. 11, line 12: “can be regarded as a function of”. Simpler: “depend on”.

6. p. 11, lines 16–17: “σ_{abs} increased ... with $\overline{r_c}$ values of 1 to 0.7”. It would be clearer, and probably more correct, to say “...when $\overline{r_c}$ decreased from 1 to 0.7”. There are several other examples like this in the text.

7. p. 13, lines 3-4: “σ_{abs} was decreased by 28%, 32% and 32% ...”. I guess this refers to the difference in σ_{abs} between the uniform case $\overline{r_c} = 1$ and the case $\overline{r_c} < 0.75$, but it is not clear from the sentence. Please clarify.

8. p. 14, line 19: “...such that internal mixing declined more than external mixing”. Presumably this should be “...such that $\alpha_{integrated}$ declined more for internal mixing than external mixing”.

9. p. 15, lines 20–24: This sentence can be clarified. “For example, the difference in $E_{\alpha,integrated}$ between dust concentrations of 10 and 20 ppm was 0.011 for IDM (uniform) and 0.015 for IDM (central, $\overline{r_c} < 0.75$), while the corresponding differences between dust concentrations of 90 and 100 ppm were only 0.004 and 0.005”.

10. p. 18, line 25–28: This is rather cumbersome. Suggestion: “Therefore, assuming a completely external mixing of dust and snow grains will underestimate the effects of dust on snow albedo and radiative forcing in numerical models (...). Similarly, assuming completely internal mixing of dust and snow grains will overestimate the effects of dust ...”.

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