Reviewer 3:

This study incorporates several new features into the representation of snow albedo in the E3SM model, including non-spherical snow grains, internally-mixed dust and black carbon within ice grains, and sub-grid topographic effects. The study assesses the impacts of these improvements on the simulated snow cover and surface energy budget, including impacts of individual effects as well as the combined effects of all model changes operating simultaneously. Overall, the paper is well-organized and very well-written. I have only a few minor comments, and I recommend that the manuscript be published after these are addressed.

Thank you for these useful comments and suggestions. We have revised the manuscript carefully.

Minor comments:

Section 4.3: In the sensitivity studies that apply internal mixing of LAPs, are all of the particles assumed to be internally-mixed, or only the proportion of deposited aerosol that was simulated to be internally-mixed? (And is that proportion actually simulated? My understanding is that the MAM aerosol model simulates the mixing state of aerosols, so that information could, in principle, be utilized, but it is not clear that such information is being extracted and utilized in the model experiments). Either way, please expand the discussion on this issue, including any implications for the magnitude of impact assessed in the sensitivity studies.

In this study, we performed sensitivity analyses using offline ELM simulations in which predefined aerosol dataset for dust and black carbon (BC) was used. The dust particles in ELM are assumed to be either internally-mixed (Sph_BCInt_DExt_PP) or externally-mixed with snow (Sph_BCExt_DExt_PP). The aerosol dataset includes deposition rate of both hydrophobic BC and hydrophilic BC. This study assumes that hydrophobic BC is all externally mixed with snow, while hydrophilic BC can be all externally-mixed (Koc_BCExt_DExt_PP) with snow or internally-mixed (Sph_BCExt_DInt_PP) with snow. We have clarified these details in Line 209-227 of the revised manuscript.

Indeed, in reality, both the snow grain shape and mixing state of LAP-snow are spatially-inhomogeneous and time-varying (Räisänen et al., 2015). For instance, dust may be partially internally and externally mixed with snow grains and simply assuming external mixing of dust-snow could underestimate the dust effects, while assuming fully dust-snow internal mixing will overestimate the dust effects (Shi et al., 2021). We added these discussions in Line 538-542 of the revised manuscript.

Currently, the four-mode version of Modal Aerosol Module (MAM4) assumes the internal mixing of aerosol particles (BC and dust) in the same size bin and external mixing between different size bins within the atmosphere. For the interactive atmosphere-land simulations using the current E3SM, the mixing state of aerosols in MAM4 is used to inform the partitioning of hydrophobic and hydrophilic BC in the deposition fluxes to land surface. However, the mixing between BC and dust components, BC-snow, or BC-dust is not considered. Besides, land-atmosphere interaction is neglected by performing offline ELM simulations in this study. Further investigation is needed to couple the atmosphere model with the MAM scheme and ELM to share more information about the mixing state of LAP-snow and LAP-LAP. We stated these limitations in Line 542-543 of the revised manuscript.

line 115: "... control ELM simulation with the default settings..." - Please clarify whether the default settings are the old or new default settings, i.e. with or without all of the changes described in this study. The use of "control" would generally imply the original configuration, before cay changes are implemented.

The control simulation with the default settings in the original ELM is named ELM_Control, while the case with all the added parameterizations is named ELM_New (Table 1). We clarified this in Line 224-225 of the revised manuscript.

Line 318: "... because LAP-induced SAR is larger in spring ..." - While the model SAR is definitely larger in spring than winter, it is not totally clear from Figs 3 and 4 that the *observed* SAR is larger in spring. (And I am surprised that it is not, given the likelihood of melt-induced

surface accumulation during spring and higher frequency of springtime dust storms in this region). Please comment on this.

We have clarified that spring has larger LAP-induced SAR in the ELM simulations to avoid misunderstanding in Line 334-335 of the revised manuscript. We also stated the difference between the model-based and MODIS-based results and discussed the uncertainties of both model simulations and MODIS retrievals. The model simulations depend on the prescribed aerosol deposition data, while the MODIS retrievals depend on the quality of observed reflectance and algorithm assumptions. Only limited field measurements showed that the snowpacks in the Indus Basin are clean in winter (Negi et al., 2010). More field measurements over the TP are needed to evaluate the model simulations and MODIS retrievals to advance our understanding of the snow darkening effects of LAPs on snow and their spatial and seasonal variations. The ongoing and upcoming hyperspectral satellites such as PRISMA (PRecursore IperSpettrale della Missione Applicativa) mission, the Surface Biology and Geology (SBG) led by NASA and the Copernicus Hyperspectral Imaging Mission for the Environment (CHIME) led by European Space Agency (ESA) will be promising for improving the remotely sensed estimates of LAP-induced SAR. Long-term field measurements of snow grain characteristics, α_{sno} and LAP concentrations over the TP are needed to evaluate the model simulations and advance our understanding of snow grain shape and mixing state effects. We added these discussions in Line 509-533 of the revised manuscript.

Line 394: "Overall, the effects of mixing state of dust-snow are smaller than the effects of mixing state of BC-snow." - Why? Please explain.

We found that both the effects of the mixing state of dust-snow and BC-snow vary with space (Figure 12 in the revised manuscript). In fact, the effects of mixing state of LAP-snow depend on the specific LAP concentration for the target pixel. This sentence may mislead the readers and thus we have deleted it in the revised manuscript.

Line 511: "... but the real snow grain shape may be more complicated and irregular..." - I think you can safely say that the real snow grain shape *is* more complicated and irregular.

Agree. Done.

References

Negi, H. S., Singh, S. K., Kulkarni, A. V., & Semwal, B. S. (2010). Field-based spectral reflectance measurements of seasonal snow cover in the Indian Himalaya. International Journal of Remote Sensing, 31(9), 2393-2417.

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Räisänen, P., Kokhanovsky, A., Guyot, G., Jourdan, O., and Nousiainen, T.: Parameterization of single-scattering properties of snow, The Cryosphere, 9, 1277-1301, 2015.