Reviewer 1:

The mixing state of LAPs in snow has large impacts on LAP-induced snow albedo reduction and surface radiative forcing (RF). However, most land surface models assume that snow grain shape is spherical and LAPs are externally mixed with the snow grains. On this background, the authors improved the snow radiative transfer model in the land model (ELM v2.0) of the Energy Exascale Earth System Model version 2.0 (E3SM v2.0) by considering non-spherical snow grain shapes (i.e., spheroid, hexagonal plate and Koch snowflake) and internal mixing of dust-snow and systematically evaluates the impacts on surface energy and water balances over the Tibetan Plateau (TP). In general, this study is well written and can advance understanding of the role of snow grain shape and mixing state of LAP-snow in land surface processes and offer guidance for improving snow simulations and RF estimates in Earth system models under climate change. I think this manuscript can be accepted if address the following questions.

We appreciate your comments and suggestions, and we have revised the manuscript accordingly.

1. The authors spent much of this manuscript on comparing the modeling results with remote sensing snow data under the control simulation using the previous settings, which was not the main concern of this manuscript. This analysis only demonstrated the capability of the original land model in snow cover fraction or SAR simulation, but can not reflect the improvement of your work. So, I suggest the results based on the original land model and your improved version can be simultaneously compared with remote sensing data to highlight the improvement of your simulation.

As suggested, we have now added a comparison of the original (ELM_Control) and new versions (ELM_New) against remote sensing data. In this revised manuscript, we used the new versions of STC-MODSCAG/STC-MODDRFS and SPIReS data. The results show that ELM_New has smaller biases of snow cover fraction than ELM_Control in spring, compared to two remote sensing data (Figures R1). More specifically, ELM_New reduces the underestimations of snow cover fraction at different elevations and the area-weighted average values of snow cover fraction in ELM_Control (Figures R2 and R3). Compared to the mean value of the two MODIS datasets, ELM_New reduces 0.014 (13.6%) of the bias of

ELM_Control in the area-weighted average f_{sno} for spring (Figure R2a). However, both ELM_Control and ELM_New show large differences in the spatial distribution of LAP-induced SAR, compared to the two remote sensing datasets, which are also quite different from each other (Figure R3c-d). We have added the corresponding results in Line 282-326 of the revised manuscript. We also updated the corresponding contents in the abstract, discussion and conclusions of the revised manuscript.

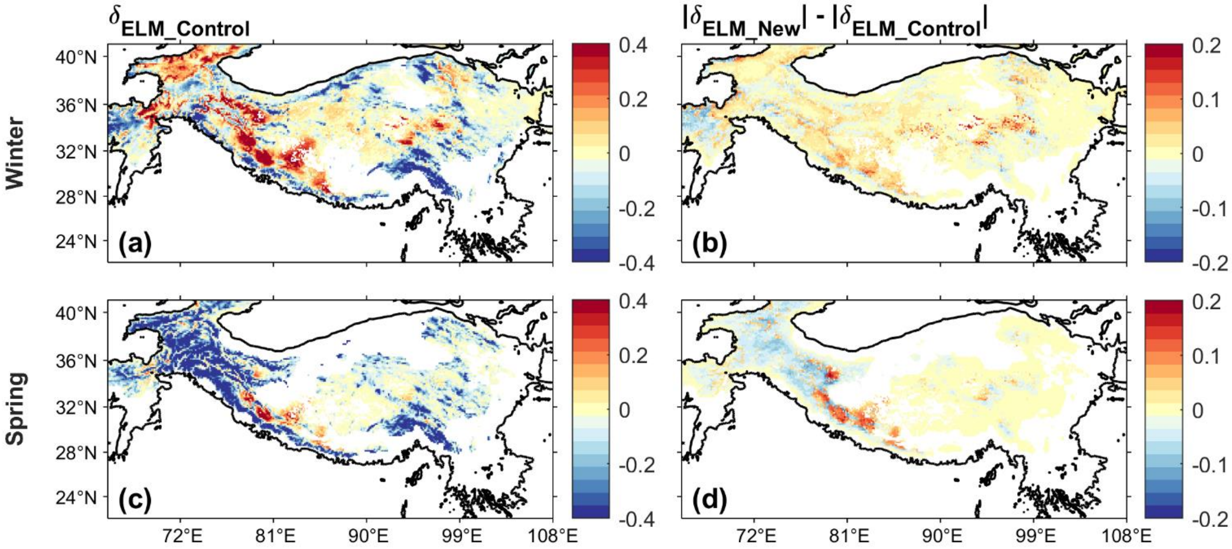

Figure R1: (a,c) The f_{sno} bias ($\delta_{\mathrm{ELM\_Control}}$) of ELM_Control compared to the mean value of STC-MODSCAG and SPIReS, and (b,d) the difference ($|\delta_{\mathrm{ELM\_New}}|-|\delta_{\mathrm{ELM\_Control}}|$) between the absolute values of the biases of ELM_New ($\delta_{\mathrm{ELM\_New}}$) and ELM_Control ($\delta_{\mathrm{ELM\_Control}}$) for winter (a-b) and spring (c-d). The negative values (blue color) in (b,d) show that ELM_New has a smaller bias than ELM_Control. The areas with f_{sno} smaller than 0.01 are masked. This figure corresponds to Figure 2 in the revised manuscript.

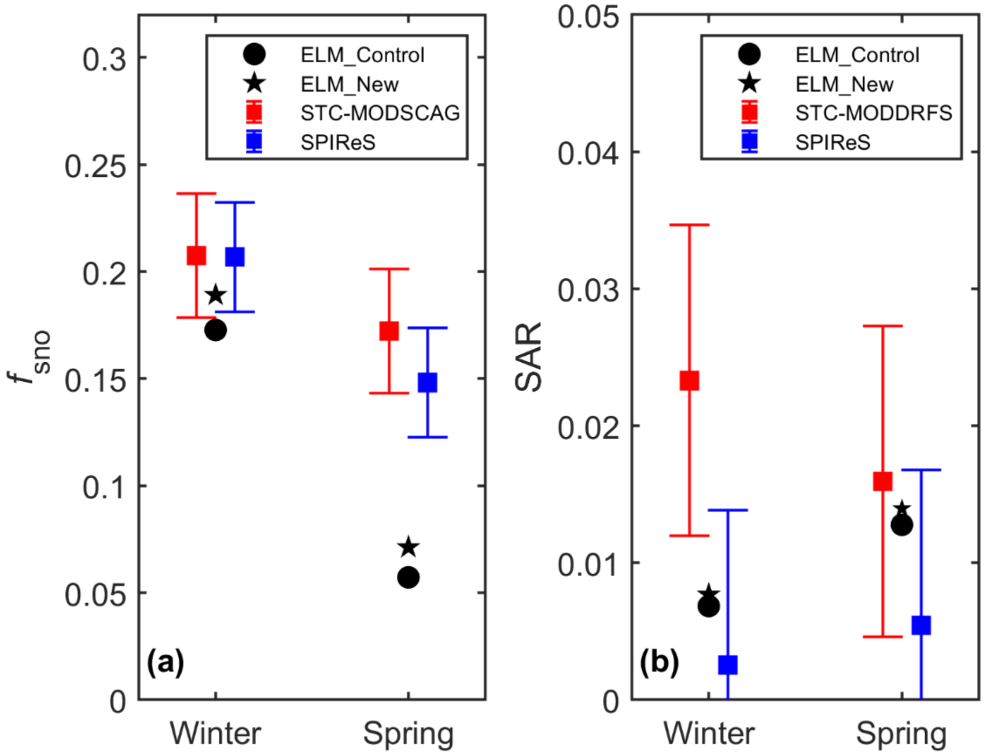

Figure R2: The area-weighted average of (a) f_{sno} and (b) SAR induced by LAPs for winter and spring from ELM, STC-MODSCAG/STC-MODDRFS, and SPIReS. The bar width represents the uncertainty bounds of STC-MODSCAG and SPIReS from Bair et al. (2021a). This figure corresponds to Figure 3 in the revised manuscript.

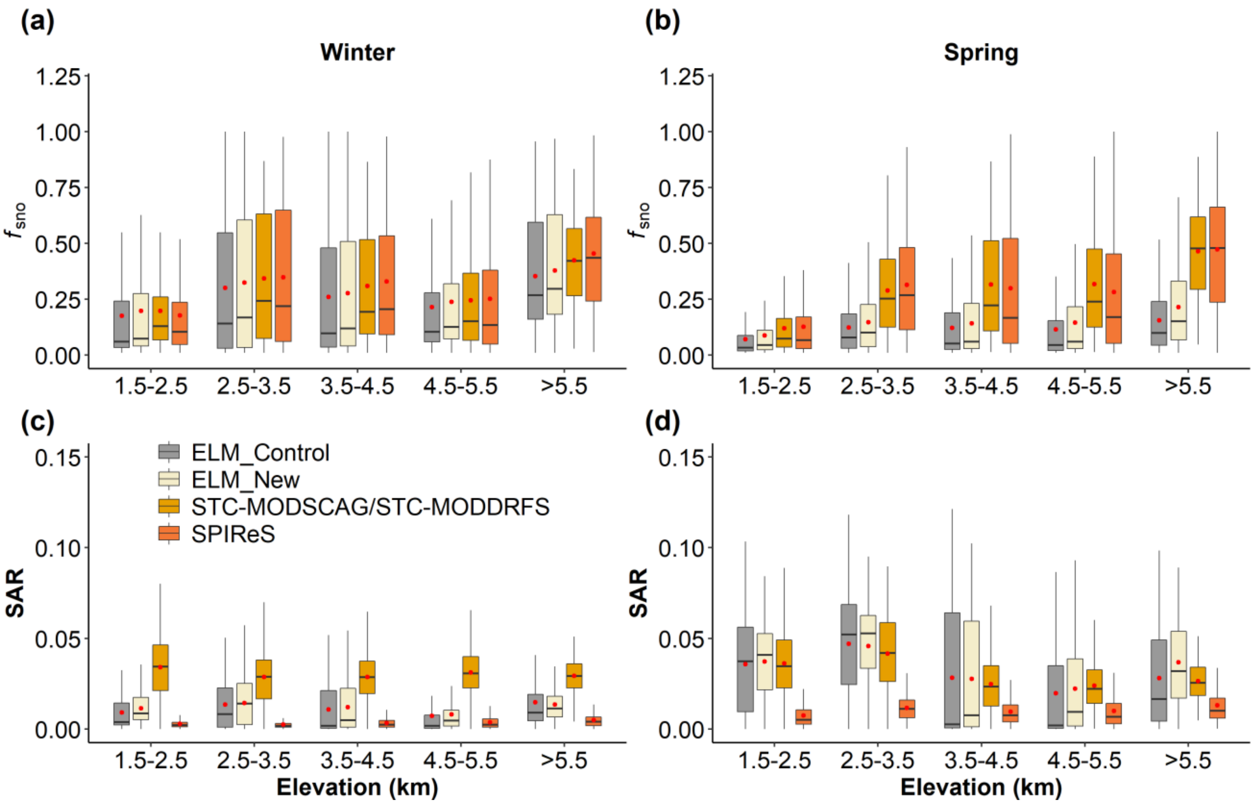

Figure R3: Statistical distributions of (a,b) f_{sno} and (c,d) SAR induced by LAPs under different elevation ranges for winter and spring from ELM, STC-MODSCAG/STC-MODDRFS, and SPIReS. This figure corresponds to Figure 4 in the revised manuscript.

2. In the Abstract, the authors said "Compared with two remote sensing ……, the control ELM simulation with the default settings of spherical snow grain shape, internal mixing of BC-snow, external mixing of dust-snow and without TOP can capture the overall snow distribution reasonably." So my question is what is your contribution? From your abstract, I can not find better simulation results after improving these snow microphysics properties. I think the authors should highlight the advances in reproducing the satellite observations after the improvements.

As mentioned in our responses to Q1, we have added a comparison of ELM_Control and ELM_New against the MODIS data in the revised manuscript and found that with the new model features, the simulation of snow cover fraction is generally improved. However, large biases remain in the LAP-induced SAR and large differences are noted between two remote-sensing products.

Although model improvements are generally small or mixed, a main contribution of this study is to advance understanding of uncertainties in snow albedo modeling and their impacts on energy budget and water cycle by systematically evaluating the impacts of non-spherical snow grain shape and internal mixing of LAP-snow across the full range of f_{sno} on surface energy balance and water cycles over the Tibetan Plateau (See Figures 10 and 11).

3. The two used remote sensing data of ASR have larger differences themselves, so I wonder whether it is appropriate to use these two data in comparing with your simulations. Maybe only using MODSCAG/MODDRFS data is better from your results.

The two remote sensing datasets (i.e., STC-MODSCAG/STC-MODDRFS and SPIReS) are based on different models/algorithms (Bair et al., 2021) and no study, to our knowledge, has evaluated the relative accuracy of these datasets due to limited field measurements in the Tibetan Plateau. A comprehensive evaluation of the two remote sensing products based on field measurements is needed to determine the accuracy of each product, which is beyond the scope of this study. Thus, we used both STC-MODSCAG/STC-MODDRFS and SPIReS to provide an observational bound for comparison with the SAR estimates of ELM. We also discussed the uncertainties of both remote sensing data and ELM simulations in Line 509-534 of the discussion part of the revised manuscript.

4. From the results, I found the snow grain shape and TOP have larger impacts on snow cover fraction or SAR simulation, while the impact of mixing sate is relatively lower. So my question is why you spent most of your content on snow grain shape and mixing sate, but the impact of TOP was only simply discussed in the last Section 4.4.

This work aims to improve the snow radiative transfer model in ELM v2.0 by accounting for non-spherical snow grain shape and internal mixing of LAP-snow and systematically evaluate their impacts on surface energy balance and water cycle over the Tibetan Plateau. Thus, we focused on the impacts on the non-spherical snow grain shape and mixing state of LAP-snow. Indeed, apart from snow grain shape and mixing state of LAP-snow, topography also changes the apparent surface albedo and solar radiation absorbed by the surface, and in turn affects snow dynamics. Compared to ELM_Control, the individual contributions of non-spherical snow shape, mixing state of LAP-snow, and local topography to the change of snow and surface fluxes have different signs and magnitudes, and their combined effects may be negative or positive due to complex and non-linear interactions among the factors. Considering that we have already documented the TOP parameterization and its impacts on energy budget and snow processes in another published GMD paper (Hao et al., 2021), we mainly investigated the interactions between the improved snow radiative transfer model and sub-grid topographic effects (TOP) in this work to minimize repetition. We added the finding about the TOP effects in the abstract (Line 35-38), discussion (Line 464-474) and conclusions (Line 556-559) in the revised manuscript.

5. When discussing the impacts on water cycles, the authors only spent little content while this part was very important. In addition, this is no figure in the manuscript in this part. I think more discussions are needed because the impact of snow grain shape and mixing state of LAP-snow on SAR or RF have been fully discussed in previous studies while the impact on water cycles is little mentioned.

The revised manuscript includes one table to present the impacts on energy budget and water cycle. Considering that Figures R4 and R5 below show the important impacts of snow grain shape on surface energy balance and water cycle, we have transferred them from the supplementary materials of the original manuscript to the main text of the revised manuscript. We also added more analysis and discussion on the impacts on energy and water cycles under different snow cover fractions and more mechanistic explanations in Line 403-435 of the revised manuscript.

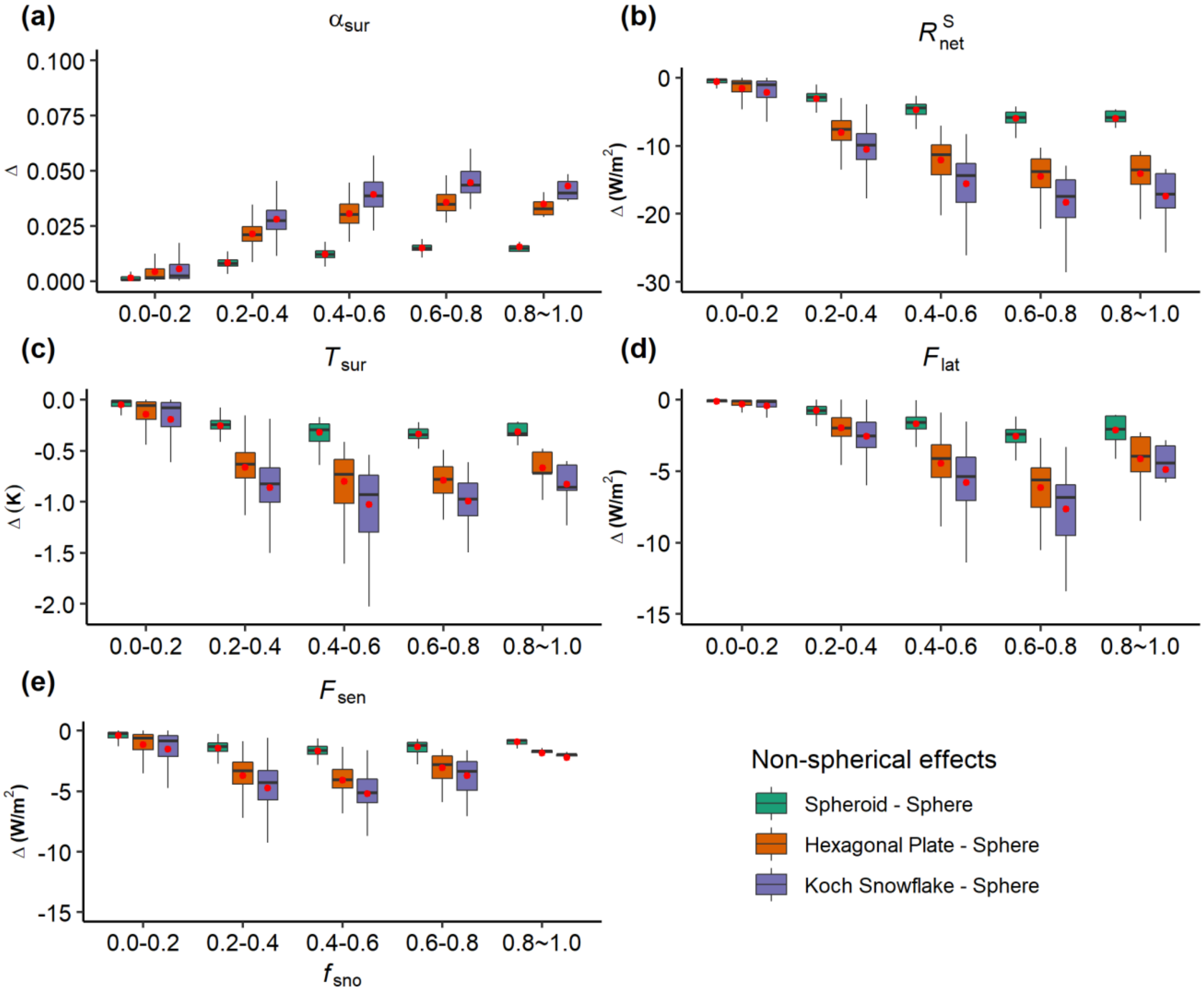

Figure R4: The boxplots of the differences (Δ) in surface energy budget terms: (a) surface albedo (α_{sur}), (b) net solar radiation (R^s_{net}), (c) surface temperature (T_{sur}), (d) latent heat flux (F_{lat}) and (e) sensible heat flux (F_{sen}), between different snow grain shapes: spheroid – sphere, hexagonal plate – sphere and Koch snowflake – sphere under different snow cover fractions (f_{sno}) for spring. See Table 2 for the specific calculation methods. This figure corresponds to Figure 10 in the revised manuscript.

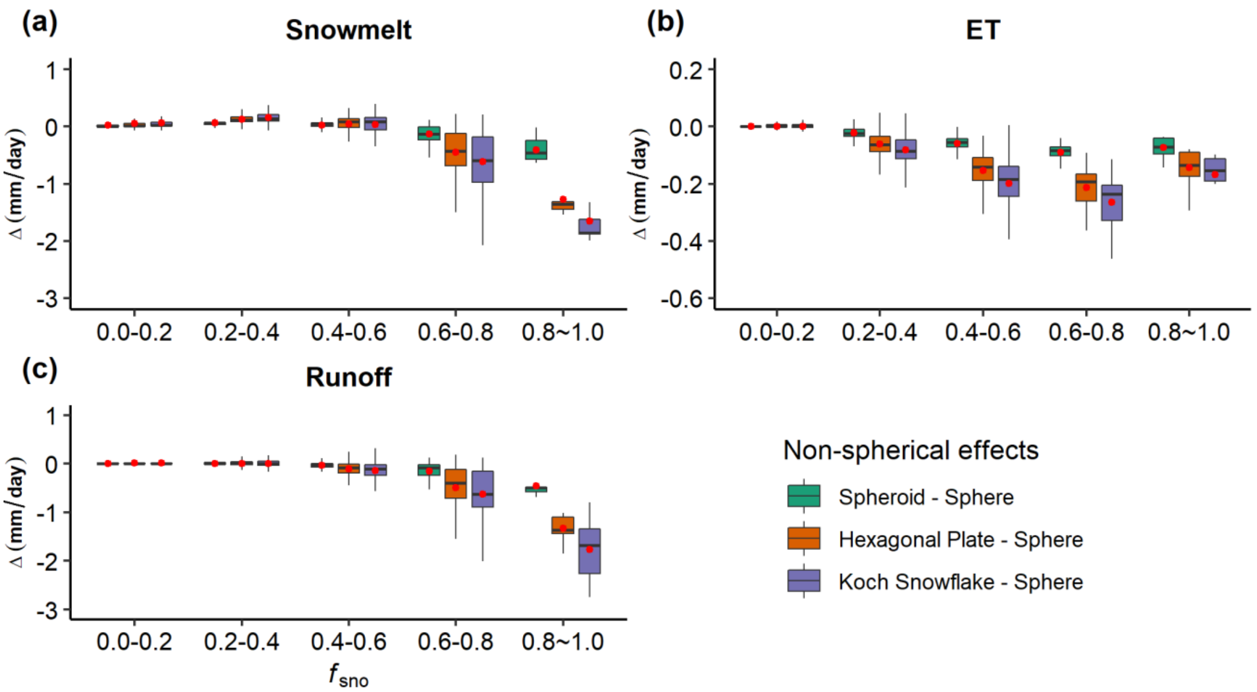

Figure R5: Same as Figure S4, except for hydrological terms: (a) snowmelt, (b) ET, and (c) runoff. This figure corresponds to Figure 11 in the revised manuscript.

6. In the Discussion, the authors spent much time on discussing why the snow cover was underestimated in spring. As mentioned in the Discussion, the underestimation may be caused by the use of a constant snow accumulation ratio, empirical snowmelt shape factor, and the complex vegetation-snow interaction processes of snow interception and dynamical removal from canopy. So I think this was not closely related to the contributions of this manuscript. While the discussions from Lines 468-517 are the main limitations in your work and the directions the future work moves on. I suggest the authors can discuss the limitations in the first place, then simply discuss the underestimation.

We followed this suggestion to revise the discussion Section 5 of the revised manuscript. We first discussed the main contributions of this work on the impacts of snow grain shapes and mixing states of LAP-snow, compared with the existing studies and stated the limitations and prospects for further improvements of snow albedo parameterizations. We further discussed the uncertainties of ELM simulations compared to the remote sensing data and the existing issues of both ELM and remote sensing data.

References

Bair, E. H., J. Dozier, C. Stern, A. LeWinter, K. Rittger, A. Savagian, T. Stillinger, and R. E. Davis (2022), Divergence of apparent and intrinsic snow albedo over a season at a sub-alpine site with implications for remote sensing, The Cryosphere, 16(5), 1765-1778, doi: 10.5194/tc-16-1765-2022.

Hao, D., Bisht, G., Gu, Y., Lee, W. L., Liou, K. N., and Leung, L. R.: A parameterization of sub-grid topographical effects on solar radiation in the E3SM Land Model (version 1.0): implementation and evaluation over the Tibetan Plateau, Geosci. Model Dev., 14, 6273-6289, 2021.