Reviewer 2:

This study presents an overview of the impact of several grain shapes, the mixing state of light absorbing impurities and sub-grid topographic effects on the surface energy and water cycles in the Tibetan Plateau using ELM. The authors illustrate that non-spherical shapes and sub-grid topographic effects impact the surface energy and water balance considerably during spring, while the impact of the mixing state of light absorbing impurities is smaller. The manuscript is well written and the topic is relevant. The impact of the mixing state of light absorbing impurities and topographic effects, and to a lesser degree also grain shape, is often overlooked in ESMs and climate models. This manuscript thus provides a necessary overview of the importance of these processes for such models.

We appreciate your insightful comments and suggestions. We have revised the manuscript carefully.

The following comments should help with solving the remaining issues, with, for example, P1 L1 meaning page 1, line 1.

General comments

The comparison with satellite observations is limited to the control run only and could be expanded to some of the other experiments as well. It would be especially interesting to see how well ELM performs for the 'combined effect' experiment. Also, if the authors could make a figure showing the difference between model and observations could help visualizing the results.

As suggested, we have now added a comparison of the original (ELM_Control) and improved versions (ELM_New) against remote sensing data. In this revised manuscript, we used 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 the two remote sensing datasets (Figures R1). ELM_New reduces the underestimations of snow cover fraction at different elevation gradients and the area-weighted average values of snow cover fraction in ELM_Control (Figures R2 and R3). Compared with the mean value of the two

MODIS data, 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 (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.

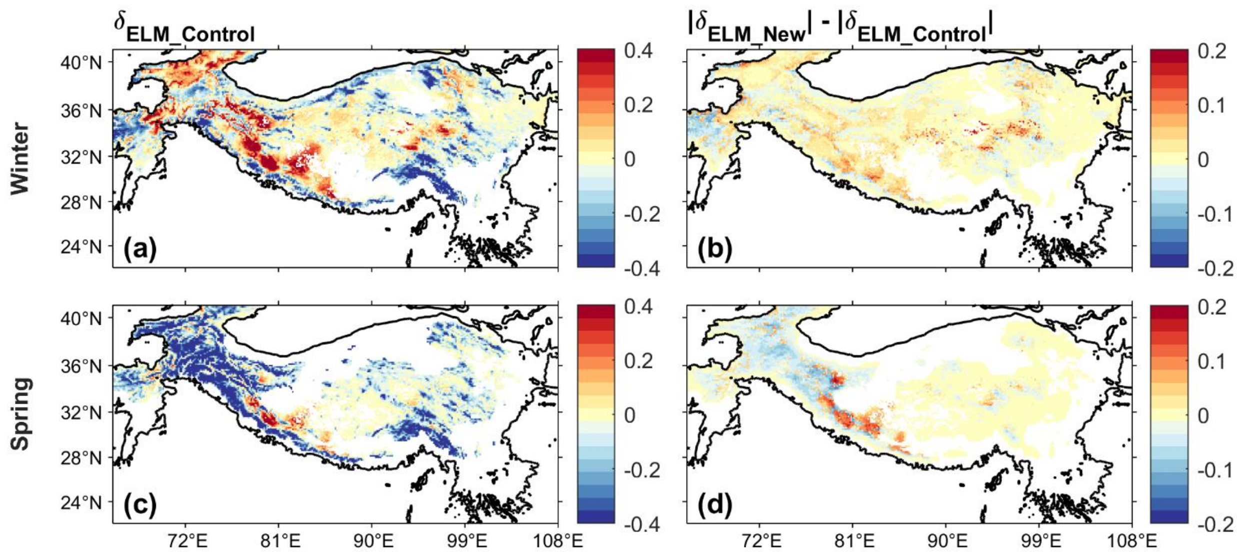

Figure R1: (a,c) The f_{sno} bias ($\delta_{ELM\_Control}$) of ELM_Control compared to the mean value of STC-MODSCAG and SPIReS, and (b,d) the difference ($|\delta_{ELM\_New}|-|\delta_{ELM\_Control}|$) between the absolute values of the biases of ELM_New (δ_{ELM_New}) and ELM_Control ($\delta_{ELM\_Control}$)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

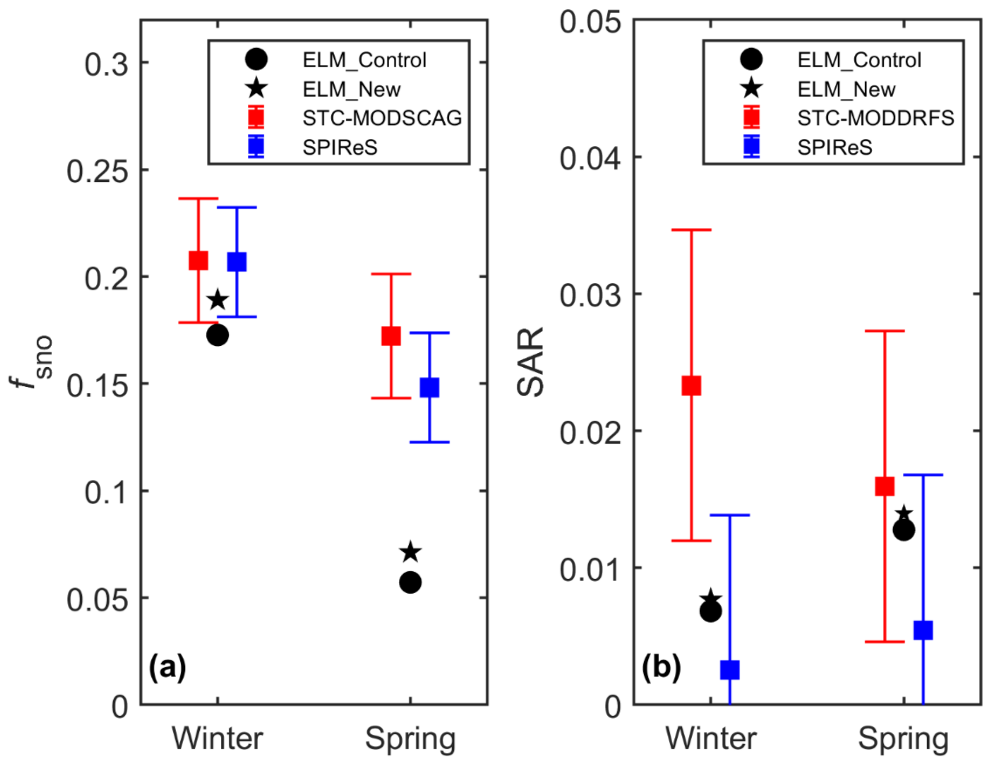

Figure R2: The area-weighted average of (a) f_{sno} and (b) SAR induced by LAPs for winter and spring from ELM, STC-MODSCAG/STC-MODDRFS, and SPIReS. The bar width represents the uncertainty bounds of STC-MODSCAG and SPIReS from Bair et al. (2021a). This figure corresponds to the Figure 3 in the revised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

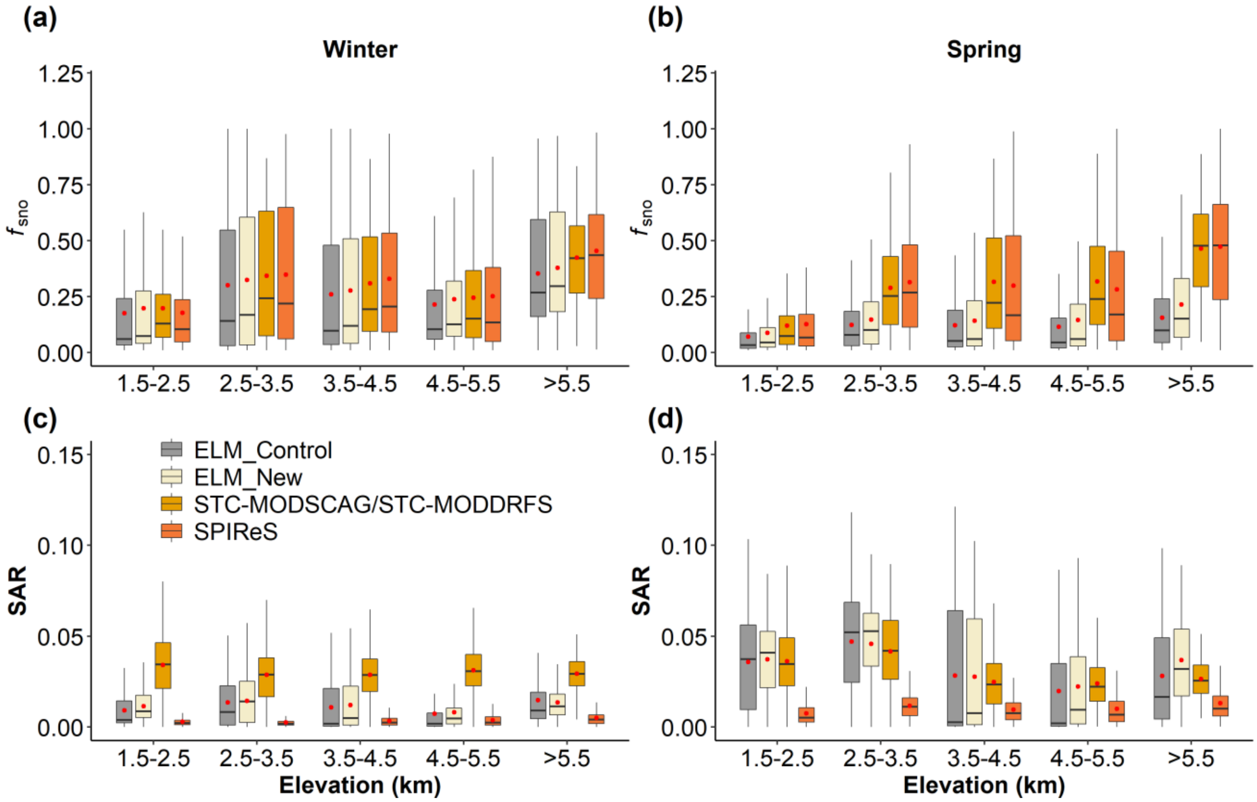

Figure R3: Statistical distributions of (a,b) f_{sno} and (c,d) SAR induced by LAPs under different elevation ranges for winter and spring from ELM, STC-MODSCAG/STC-MODDRFS and SPIReS. This figure corresponds to Figure 4 in the revised manuscript.

It is not clear to me what grain size is chosen in this study and why. Furthermore, it is also good to notice that a homogeneous snow grain size that does not vary in time, as is employed in ELM if I am not mistaken, could have a significant impact on the results. Wet and dry snow metamorphism, refreezing and the presence of slush or ice can all impact the grain size and albedo. This may explain for a large part the differences observed with remote sensing observations. Similarly, it is not clear to me what concentrations of LAPs are chosen.

In this study, the snow grain size is not a prescribed parameter. SNICAR-AD can mechanistically simulate the snow aging process, i.e., the evolution of the snow grain size, by considering the dry snow metamorphism, liquid water-induced metamorphism, refreezing of liquid water, and addition of freshly-fallen snow (Flanner et al., 2007). Besides, SNICAR-AD in ELM can also prognostically simulate the change of LAP concentrations in different layers (Flanner et al., 2007). After LAPs are deposited from the atmosphere, LAPs are redistributed based on meltwater drainage through the snow column and snow layer combination and subdivision. Thus, both the LAP concentration and snow grain size in the ELM simulations vary with space and time. We clarified these points above in Line 133-134 of the revised manuscript.

This study investigates several grain shapes. It is not clear to me, however, why these grain shapes are chosen in particular. Are these grain shapes often occurring on the Tibetan Plateau? If the authors could show that these shapes are relevant, it would strengthen the results of this study. Also, what grain shape will you assume in the final ELM version?

The three non-spherical shapes chosen in this study are the typical snow grain shapes that have been previously used to capture the major morphological characteristics of observed snow grain structures in the real snowpack (Dominé et al., 2003; Erbe et al., 2003; Liou et al., 2014). Moreover, the simulated snow albedo with the assumptions of the three non-spherical snow shapes showed better agreement with the observations (He et al., 2018). However, note that there are very limited field observations of snow grain shapes over the Tibetan Plateau, which prevents an accurate prescription of snow shape in ELM. Therefore, we have conducted sensitivity analyses to quantify the impact and uncertainty caused by these three non-spherical snow grain shapes. Only four typical types of snow grain shapes are included in the analysis, but the real snow grain shape is more complicated and irregular (Kokhanovsky et al., 2005). We clarified in Line 68-74, 171-174 and 538-539 of the revised manuscript.

The hexagonal plate shape has been used as the default snow grain shape in the standalone version of SNICAR-AD v3 (Flanner et al., 2021). However, which snow grain shape should be prescribed in ELM still needs further investigation and analysis.

In the manuscript, the authors show that the impact of TOP on the results is quite large and larger than the impact of the mixing state. This is in my opinion an important result of this work and should get more attention. It should get mentioned in the abstract and the conclusions as one of the main results. The impact of the mixing state of LAPs should not be overexaggerated in the abstract and conclusions as well.

We have documented the TOP parameterization and its impacts on the energy budget and snow processes in a previous study (Hao et al., 2021), so we have mainly investigated the interactions between the improved snow radiative transfer model and sub-grid topographic effects (TOP) in this work to minimize repetition. 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. The individual contributions of non-spherical snow shapes, mixing states 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. We added the finding about the TOP effects in the abstract (Line 35-38), discussion (Line 464-474) and conclusions (Line 556-559) of the revised manuscript. We also changed the expression (e.g., avoid the use of such expression 'large impacts') to avoid overexaggerating the impacts of mixing state of LAP-snow.

Specific comments

P1 L18: "The mixing state of LAPs in snow also has large impacts…". In the manuscript you show that the impact of the mixing state is considerably smaller than compared to grain shape and TOP. So please rephrase.

We deleted 'large' in this sentence of the revised manuscript.

P1 L27: Please format units like W/m^2 with negative exponents, i.e., $W\ m^{-2}$, throughout the manuscript.

As suggested, we have reformatted the units throughout the manuscript.

P3 L42: Please provide the definition of albedo here as well.

We have replaced "albedo" with "broadband albedo", which is defined as the ratio of reflected to the incident radiative flux at the surface over the entire solar spectrum. We have added this definition in Line 45-46 of the revised manuscript.

P3 L44: 'Sky conditions' is unclear

Snow albedo is affected by the atmospheric conditions which determine the direct-to-diffuse ratio of incoming radiation. Thus we have replaced "sky conditions" by "atmospheric conditions" in Line 48 of the revised manuscript to be more clear.

P3 L67: Define the asymmetry factor.

Asymmetry factor represents the average cosine of the scattering phase angle and determines the fractions of backscattered and forward-scattered light. We have added this explanation in Line 159-160 of the revised manuscript.

P3 L69: Define the single-scattering albedo.

Single-scattering albedo describes the probability that a photon experiencing an extinction event is scattered as opposed to absorbed. We have added this explanation in Line 156-157 of the revised manuscript.

P4 L75: In my opinion, more should be said about the physical processes that make the albedo drop because of dry and wet deposition. So why is there a difference between the impact of dry deposition and wet deposition. Also, do you expect dry or wet deposition to be most relevant for the Tibetan Plateau?

We have revised this sentence as "The mixing state of LAPs in snow (i.e., external mixing and internal mixing) has large impacts on α_{sno}" in Line 79-81 of the revised manuscript. The dry and wet depositions of LAPs can affect the mixing state of LAPs in snow and thus snow albedo. Such information is provided by the predefined aerosol deposition data or the atmospheric aerosol model. We clarified these in Line 215 of the revised manuscript.

P4 L102: haven't --> have not

Done.

P6 L140-141: " 1) SZA dependence of surface irradiance". This is a bit confusing, it suggests that you have implemented a new routine for SZA dependency, but if I understand it correctly, it is part of the SNICAR-AD model. Please clarify.

The original SNICAR-AD model assumes that clear-sky irradiance does not change with SZA. In the new version (i.e., SNICAR-AD v3), clear-sky irradiances are calculated for the full range of SZA (0–89° at 1° resolution) for each profile. We incorporated this new improvement in our ELM model. We clarified this in Line 151 of the revised manuscript.

P6 L144: There are six types of atmospheric profiles now included, but are clouds considered as well or is it only for clear-sky conditions? As clouds alter the spectral distribution of irradiance and limit direct radiation, it often has quite a large impact on the broadband albedo.

All of the six types of atmospheric profiles consider the clear-sky and cloudy conditions (see Table 1 in Flanner et al. (2021) for details). We clarified this in Line 152 of the revised manuscript. Spectral irradiances associated with clear-sky or cloudy atmospheres are selected internally in the SNICAR-AD model to match the specific conditions of direct or diffuse incident light.

P6 L147: Assuming that you will introduce the single-scattering albedo and asymmetry factor earlier, please also define the extinction cross section.

We replaced ‘extinction cross section’ with extinction efficiency. Extinction efficiency is the sum of scattering efficiency and absorption efficiency and represents the light attenuation ability of the particle. We added this explanation in Line 157-158 of the revised manuscript.

P6 L160: Why do you choose to investigate these three non-spherical grain shapes?

The three non-spherical shapes are typical snow grain shapes used to approximately represent the observed snow grains in the real snowpack (Dominé et al., 2003; Erbe et al., 2003; Liou et al., 2014), which capture the major morphological characteristics of observed snow grain structures. Moreover, the simulated snow albedo with the assumptions of the three non-spherical snow shapes showed better agreement with the observations (He et al., 2018). We clarified these in Line 68-74, 171-174 and 538-539 of the revised manuscript. Please see our response to the third question from Reviewer #2 for more details.

P7 L171: “… and Rs is the specific-projected-area-equivalent radius.” This has already been said and can be removed here.

We have edited the text as suggested.

P7 L181: “…where ω_{dust} and ω_p are single-scattering albedo of pure snow and dirty snow…”. I suppose it is vice versa? i.e., ω_p is for pure snow?

Yes. We have modified it.

P9 L228: A dot is missing after the citation.

We have fixed the citation.

Table 1: What impurity concentration do you assume?

We do not make any assumption about the impurity concentration. SNICAR-AD can prognostically simulate the evolution of the snow grain size and LAP concentration via deposition and redistribution. We clarified it in Line 133-134 of the revised manuscript.

P10 L237: *u*m --> μm

We have edited the text as suggested.

P10 L44: Why do you choose this simulation to be the control simulation? Is this the most realistic one? Please explain.

Generally, the use of "control" implies the original configuration, before any 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). In the revised manuscript, we compared both ELM_Control and ELM_New with MODIS snow data. We clarified this in Line 224-225 of the revised manuscript.

P10 L257-260: Could you elaborate a bit more on ANOVA? Also, what do you mean with 'maximum absolute relative difference' and 'mean absolute relative difference'?

ANOVA compares the means between different groups and determines whether they are statistically significantly different from each other. The maximum absolute difference is calculated as the maximum of the absolute value of the difference between two cases. The maximum relative difference is calculated as the maximum of the absolute value of the relative difference between two cases. The mean absolute difference is calculated as the mean of the absolute value of the difference between two cases), and mean relative difference is calculated as the mean of the absolute value of the relative difference between two cases. We clarified these in Line 268-276 of the revised manuscript.

Fig. 2: For areas in the east, it is hard to see if there is a low snow cover or no snow at all. This can be solved by providing a separate color for no snow cover. Furthermore, The figure might be easier to read if discrete colors are used.

We masked the areas with low snow cover smaller than 0.01 as below. We also used the discrete colors for all spatial maps of the revised manuscript. We have also updated all other spatial maps to use discrete colormaps.

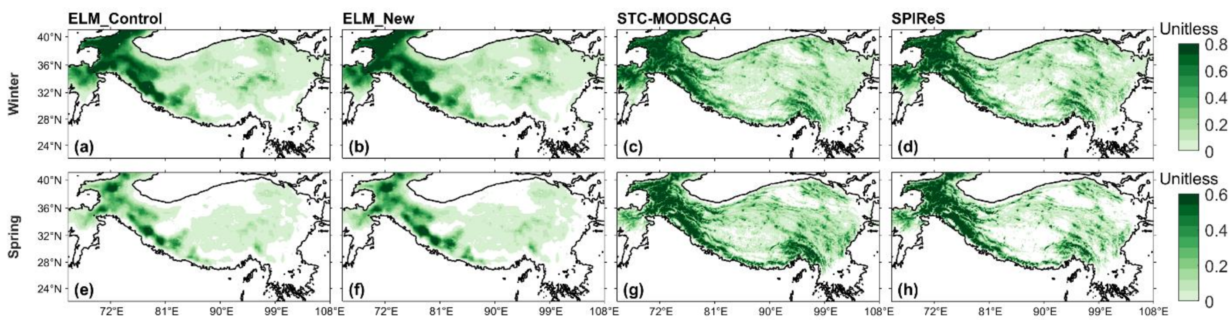

Figure R4: Spatial distributions of f_{sno} estimated from (a,e) ELM_Control, (b,f) ELM_New, (c,g) STC-MODSCAG/ STC-MODDRFS and (d,h) SPIReS for winter (a-d) and spring (e-h). The areas with f_{sno} smaller than 0.01 are masked. This figure corresponds to Figure S2 in the revised manuscript.

Fig 3 and all other boxplots. Please also state that what is on the x axis; i.e., that fsno and SAR as a function of elevation are shown.

We have made the suggested change.

Fig. 4: Same as Fig 2. Also, 'Same as Figure 3' is written, while it is the same as Fig. 2

We have made the suggested change.

P11 L277: "… although their spatial patterns are similar." This is somewhat hard to see in the figures. A figure with the difference between ELM and the observations could help with that.

We added such a figure as Figure R1 in the revised manuscript. This figure shows that ELM_Control overall overestimates snow cover fraction for winter, but underestimates snow cover fraction in spring. ELM_New reduces the bias of snow cover fraction in spring compared to ELM_Control.

P12 L290: "The difference may be due to the overestimation of snow grain size…". Can you explain a bit more why this may be the case? As grain size has a strong impact on the albedo, modelling this incorrectly could lead to large differences with observations, potentially overshadowing any grain shape or mixing state effects. It seems to me like it may have a large impact on the results here and should be mentioned.

Indeed, snow grain size has large impacts on the snow albedo. Figure R5 shows the spatial patterns of snow grain size of ELM and MODIS data. Clearly ELM overestimates snow grain size compared to MODIS data, which is also identical to the results in (Sarangi et al., 2020). The overestimation of snow grain size in ELM may account for the difference between MODIS and ELM. Besides, both the impacts of non-spherical snow grain shape and mixing states are sensitive to snow grain size (He et al., 2018a). However, there are large uncertainties in modeling the snow aging processes to represent the evolution of snow grain size in ELM (Figure R5), which needs further improvements. We added this figure and the corresponding analysis in Line 302-303 and 462-463 of the revised manuscript.

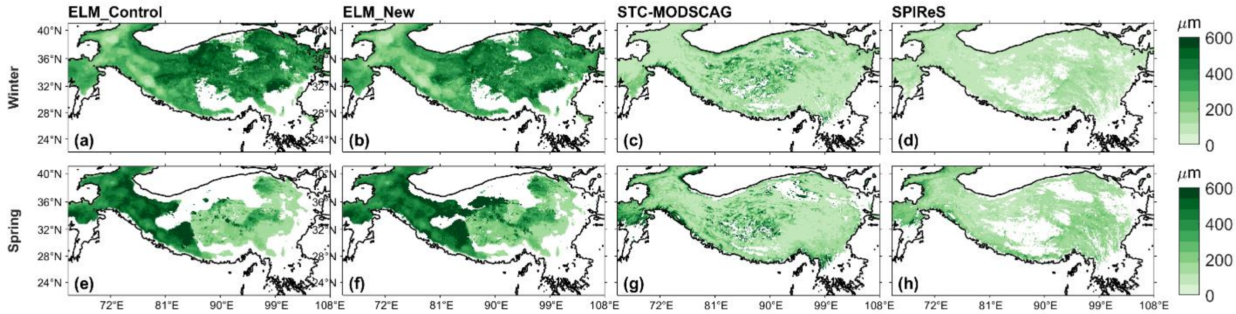

Figure R5: Spatial distributions of snow grain size estimated from: (a,e) ELM_Control, (b,f) ELM_New, (c,g) STC-MODSCAG/STC-MODDRFS and (d,h) SPIReS for winter (a-c) and spring (d-f). The areas with f_{sno} smaller than 0.01 are masked. This figure corresponds to Figure S3 in the revised manuscript.

P14 L316: "Western regions show larger RFs induced by all LAPs than the eastern regions". Looking at Fig. 2 there is almost no snow cover in the east, so logically barely any RF changes are visible there.

We masked the areas with low snow cover smaller than 0.01 to distinguish the snow-free regions. We also used the discrete colors for all spatial maps of the revised manuscript.

P14 L324: I assume you mean Table 3, not Table 1?

Modified.

P14 L328: "… which is identical to" --> which is similar to.

We have modified the text as suggested.

P15 L341: Are all shown changes in Fig. 6 significant? If not, please also illustrate significance on the maps.

Yes, all the differences in the six sub-figures of Fig. 6 are significant based on ANOVA ($p<0.05$). We clarified this point in Line 357-358 of the revised manuscript.

Caption of Fig. S4 and S5: I suppose you mean α_{sno} instead of A_{sno}?

We have modified the text as suggested.

Fig. 7: A bit confusing that the color scale is now inverted compared to Fig. 6. To help solve this confusion, please explicitly state in the manuscript that the differences are now negative.

We explicitly clarified in the captions of both Figures 6 and 7 in the revised manuscript.

P19 L389: "… has larger effects on F_{lat} than F_{sen}". Why?

Snow grain shape affects snow albedo and thus surface albedo, which further affects net solar radiation and thus surface energy balance. We clarified this mechanism in Line 406-409 of the revised manuscript. The non-spherical impacts on latent heat and sensible heat fluxes vary with space and are related to the relative magnitude of latent heat and sensible heat fluxes. We deleted this sentence to avoid misunderstanding.

P19 L391 - 392: "The differences in … than those for Koch snowflake shape". Can you explain why?. Similarly on P19 L395 – 396, please explain why you would expect a sign change.

Snow grain shape affects the differences in the energy balance terms between the internal and external mixing of LAP-snow, because non-spherical grains tend to have larger α_{sno} and could affect SAR induced by LAPs. We have rephrased the first sentence to clearly show the results and the corresponding explanation in Line 357-359 of the revised manuscript.

The mixing state effects on surface energy balance have an opposite sign compared to the non-spherical shape effects, because internal mixing leads to smaller snow albedo than external mixing, while non-spherical grain shape has large snow albedo than spherical grain shape. We added these explanations in Line 378-379 of the revised manuscript.

P21 L417 – 418: One of the figure references can be omitted.

We have deleted the first figure reference.

P23 L455 – 456: "… to the reported values in the existing study". What do you mean? It is not clear to me what the authors want to say here.

We have deleted this paragraph, considering that this part is not well related to this study.

P23 L459 – P24 L466: "However, different studies … or annual scales". I am not sure if I understand what you want to say with this part.

We have deleted this paragraph, considering that this part is not well related to this study.

P24 L470: "Mixing state of LAP-snow also has large impacts on SAR". Looking at the results of this manuscript, it looks like the impact is considerable smaller than the impact of grain shape and TOP. Please rephrase.

We have deleted 'large' in the manuscript.

References

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Erbe, E. F., Rango, A., Foster, J., Josberger, E. G., Pooley, C., and Wergin, W. P.: Collecting, shipping, storing, and imaging snow crystals and ice grains with low-temperature scanning electron microscopy, Microscopy research and technique, 62, 19-32, 2003.

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