Referee #1

"The manuscript investigates the effects of snow grain shape and BC-snow mixing sates on the snow albedo and surface radiative forcing over the Tibetan Plateau. To achieve the goal, the authors improve the SNICAR model parameterization by introducing nonspherical snow grain shape and BC-snow mixing states based on their previous work, and the parameterization is systematically compared with observations of both pure and polluted snow. Furthermore, the BC observation in the TP is well reviewed, and the uncertainties related to the snow shape and BC-snow mixing are studied. The topic is interesting and important for snow albedo studies, and the manuscript is well organized and written. It can be published on ACP after minor revision."

We thank the reviewer for his/her constructive comments and suggestions, which help to improve the manuscript. Below is a point-by-point response to the comments.

Specific Comments:

1. Title: The title of the manuscript is not very clear, and the main focus of the paper cannot be clearly obtained through the title. The snow grain shape effects are not related to the BC.

Response: Thank you for the comments. First, we would like to clarify that the snow grain shape effects are closely related to BC impacts on snow albedo. As we showed in this work (and our previous study, He et al. 2018a JGR), spherical snow grains lead to stronger BC-induced albedo reductions than nonspherical snow grains if other conditions/variables are the same. Both snow shape and aerosol-snow mixing state are important to BC-snow albedo effects. In fact, one of our highlights in this work is that the combination of snow grain shape and BC-snow mixing state shows an important interactive effect on BC-induced albedo reduction. Second, the focus of this paper is to assess the uncertainty in BC-induced snow albedo reduction over the Tibetan Plateau caused by snow grain shape and BC-snow mixing state using an improved SNICAR model, which is consistent with the current title. Thus, we think the current title can reflect the focus of the paper and we choose not to change it. Please note that we also put some efforts in describing and evaluating the implementation of new aerosol-snow parameterizations into SNICAR in this paper, because this is the modeling basis for quantifying snow albedo uncertainties over the Tibetan Plateau, which does not deviate from the paper focus.

2. Line 278-287: There are significant uncertainties on BC MAC. The difference between He et al. (2017b) and Bond and Bergstrom (2006) can be simply explained by natural variations. However, the authors made unrealistic adjustment on BC density and size. Is

this really necessary, and how would a different MAC in the model influence the final results?

Response: Thank you for the comments.

First, we agree that the differences in BC MAC between He et al. (2017b) and Bond and Bergstrom (2006) could be due to natural variations/uncertainties. In fact, BC MAC could vary from ~2 to ~15 m^2 g^{-1} due to uncertainties in particle density, size, structure, and refractive index. However, based on a comprehensive review of observations, Bond and Bergstrom (2006) recommended a value of 7.5 m^2 g^{-1} at 550 nm to best represent BC MAC, which has been widely adopted in previous studies (e.g., Aoki et al., 2011; Flanner et al., 2007, 2009). Thus, to reduce the potential uncertainty from BC MAC in this work, we have chosen to use the value recommended by Bond and Bergstrom (2006).

Second, to achieve the recommended BC MAC, we adjusted the BC density to be 1.5 g cm^{-3} and BC size to be a lognormal distribution with a geometric mean diameter of 0.06 μm and a geometric standard deviation of 1.5. We would like to clarify that these values are reasonable for BC particles. (1) In fact, a BC density of 1.5 g cm^{-3} has been widely used in previous studies (e.g., Flanner et al. 2007; Aoki et al., 2011), as indicated in the manuscript. Bond and Bergstrom (2006) suggested that the measured void-free BC usually has a density of 1.7–1.9 g cm^{-3} but the density can be lower for BC with voids. Long et al. (2013) further showed that ambient BC particle density can vary from 1.2 to 1.8 g cm^{-3}. (2) The BC size used in this work is also within the observed ranges. Bond et al. (2006) showed that the observed BC geometric mean diameter varies from 0.01 to 0.15 μm near combustion sources, while the observed geometric standard deviation varies from 1.2 to 2.0 for BC either near combustion sources or in continental plumes.

Third, if using a smaller BC MAC (e.g., 6.8 m^2 g^{-1} at 550 nm as used in He et al. 2017b), the BC-induced snow albedo reduction would be smaller, compared with current estimates using a value of 7.5 m^2 g^{-1}. The quantification of MAC effects on snow albedo reduction is beyond the scope of this study and will be investigated in future work.

To clarify, we have included the aforementioned discussions in the track-change manuscript (Lines 292–302) as follows:

"We should note that BC MAC could vary significantly in reality (e.g., from 2 to 15 m^2 g^{-1} at 550 nm) due to uncertainties from particle density, size, structure, and refractive index (Bond and Bergstrom, 2006). Thus, we use the recommended value (7.5 m^2 g^{-1}) derived from a comprehensive review of measurements to reduce the potential uncertainty from BC MAC in this study. Compared with the current estimates, using a smaller BC MAC (e.g., 6.8 m^2 g^{-1} at 550 nm as used in He et al. 2017b) would lead to weaker BC-induced snow albedo reductions, the quantification of which, however, is beyond the scope of this study and will be investigated in future work. In addition, the adjusted BC density and size used in the present study are still within the observed ranges, with 1.2–1.9 g cm^{-3} for densities (Bond and Bergstrom, 2006; Long et al., 2013) as well as 0.01–0.15

μm and 1.2–2.0 for geometric mean diameters and standard deviations (Bond et al., 2006), respectively."

3. Table 1: The authors made some assumptions to evaluate the new parameterization, and Table 1 list most parameters for comparison with observations. The detailed assumptions should be indicated in the manuscript, e.g., which parameters are assumed, and which parameters are observed. Meanwhile, are the parameters adjusted to match the observations, or realistic parameters that are picked independent of observations lead to the great agreement.

Response: Thank you for the comments. We would like to clarify that all the parameter values are picked based on the corresponding observed/realistic values in each case when the observations are available. We did not adjust model parameters to match observations. Even for the assumed parameter values indicated in Table 1, we did not tune the values to match observations. Instead, we adopted either commonly used values or observed values from other studies. Following the reviewer's comment, we have included the detailed assumptions and clarifications in the track-change manuscript as follows:

Lines 332-346: *"To conduct reasonable comparisons, we used the observed snow density, grain size, thickness, snowpack layer, direct/diffuse radiation, solar zenith angle, and underlying ground albedo in model simulations for each case (see Table 1 and Figure 6 for details), except for underlying ground albedos in the Brandt et al. (2011) and Painter et al. (2007) cases and the grain size of the second snow layer in the Brandt et al. (2011) case because of unavailable measurements. Thus, we assumed black underlying grounds (albedo = 0) in the two cases, which has negligible effects on albedo estimates due to thick snow optical depths. In the Brandt et al. (2011) case, we further assumed an effective radius of 500 μm (typical for aged snow) in the second snow layer to make it optically semi-infinite, which is consistent with the observed condition."*

Lines 386-395: *"Similar to Section 3.4.1, we used the observed BC concentration in snow, snow density, grain size, thickness, snowpack layer, direct/diffuse radiation, solar zenith angle, and underlying ground albedo in model simulations for each case (see Table 1 and Figure 7 for details), except for the snow density in the Pedersen et al. (2015) case and the underlying ground albedo in the Meinander et al. (2013) case because of unavailable measurements. Thus, we assumed a typical fresh snow density of 150 kg m^{-3} in the former case and a black underlying ground (albedo = 0) in the latter case. Compared with assuming a black underlying ground, we find that using a non-black underlying ground albedo typically observed over the Tibet (Qu et al., 2014) only leads to very small (<5%) relative differences in albedo calculations in the Meinander et al. (2013) case."*

4. Figure 6: It seems that most observations give an albedo slightly less than 1 around 400nm, whereas most model results overestimate the albedo. Is there any explanation?

Response: Thanks for pointing it out. The slight but systematic model overestimates at around 400 nm (shown in Fig. 6) are probably due to the uncertainty of ice refractive indices. Based on a recent study (Picard et al., 2016), the ice refractive indices (Warren and Brandt, 2008) used in this study may result in too weak snow absorption around 400 nm and hence lead to albedo overestimates, compared with observations. We have included the following discussions in the track-change manuscript (Lines 368–380):

"We note that model results in all cases show slight but consistent albedo overestimates around 400 nm compared with observations (Fig. 6), probably due to the uncertainty of ice refractive indices. In this work, we used ice refractive indices from the most widely-used database (Warren and Brandt, 2008) obtained from measurements in the Antarctic, which shows a very low ice absorption coefficient around 400 nm. However, based on more recent measurements in Antarctic snow, Picard et al. (2016) found a much higher ice absorption coefficient around 400 nm than that from Warren and Brandt (2008), which suggested that the uncertainty in ice visible absorption is probably larger than generally appreciated. Therefore, the weak snow absorption caused by refractive indices used in this study could lead to the overestimates in modeled albedo around 400 nm."

5. Figure 8: The effects on the snow albedo and surface radiative effects are illustrated in the figure. The two variables are closely related, and, from the figure, it seems that there is a strong correlation between them.

Response: Yes, the BC-induced snow albedo reduction is closely correlated with the surface radiative effects. This is because the regional mean surface radiative effect is computed by multiplying the regional mean snow albedo reductions with the regional mean surface downward solar fluxes (from MERRA-2 reanalysis data). As shown in Table S2 (in the supplement), the mean surface downward solar fluxes across different Tibetan sub-regions are similar during the same season, which leads to the strong correlation between snow albedo reductions and surface radiative effects across the sub-regions as shown in Fig. 8.

6. The manuscripts show significant influences of snow shape and BC-snow mixing on surface albedo. During the discussion, the albedo reductions, which are relatively small, are used to evaluate the influence. The surface albedos under different circumstances can directly compared to indicate the influences. Furthermore, considering the variations on the models and input parameters, the uncertainties on the albedo may be quite significant, and this may greatly influence the conclusions.

Response: Thank you for the comments. We agree that the present estimates of albedo reductions may be associated with uncertainties from various factors, including model and input parameters, which could affect the signal of BC-induced albedo reductions. Besides, in relatively clean areas, the BC-induced albedo reductions are small (e.g.,

<0.01), which may be comparable or even smaller than the uncertainty of surface/snow albedo under different conditions. Surface albedos obtained from remote sensing observations typically have errors of a few percent (*Warren*, 2013 JGR). However, in the polluted regions, the albedo reductions can be larger than 0.1, which provides strong and detectable signals. In this study, to reduce the uncertainty in albedo calculations, we have used observed values for model/input parameters in the estimates of BC-induced albedo reductions over TP when measurements are available. However, we do realize that there are still several important uncertainty sources and limitations in this study, including uncertainties from measurements, BC and snow grain properties, and complex snowpack processes, which have been discussed in the original manuscript (Lines 470–482). Here, we have further included discussions on the uncertainty issues mentioned by the reviewer in the track-change manuscript (Lines 533–536) as follows:

"These uncertainties associated with modeling and measurements may decrease the signal-to-noise ratio for the detection of BC effects on snow albedo, particularly in relatively clean regions with small BC-induced albedo reductions (e.g., <0.01). Thus, improved and robust estimates require both accurate snow albedo modeling and snowpack measurements."

7. The manuscript includes a lot of information and leads to a few quite important conclusions. The conclusion section seems simply a list of the work done and conclusions obtained. A lot of details are included in the section, but it is not well organized. It should definitely be re-organized to better summary the focus of the manuscript.

Response: Thank you for the comments. We have re-organized and refined the conclusion section to better summarize and highlight the focus of this study as follows (Lines 544–617):

" We implemented a set of new BC-snow parameterizations into SNICAR, a widely used snow albedo model, to account for the effects of snow nonsphericity and BC-snow internal mixing. We evaluated model simulations by comparing with observations. We further applied the updated SNICAR model with a comprehensive set of in-situ measurements of BC concentrations in the Tibetan Plateau (TP) snowpack (glacier) to quantify the present-day BC-induced snow albedo effects and associated uncertainties from snow grain shape and BC-snow mixing state.

Based on the SNICAR model updated with new BC-snow parameterizations, we found that nonspherical snow grains tend to have higher pure albedos but lower BC-induced albedo reductions compared with spherical snow grains, while BC-snow internal mixing substantially enhances albedo reductions relative to external mixing. Compared with observations, model simulations assuming nonspherical snow grains and BC-snow internal mixing perform better than those with the common assumption of snow spheres and external mixing. The results suggest an important interactive effect from snow *nonsphericity and internal mixing, and highlight the necessity of concurrently accounting for the two factors in snow albedo and climate modeling.*

We further applied the updated SNICAR model with comprehensive in-situ observations of BC concentrations in snow and snowpack properties over the TP to quantify the present-day (2000–2015) BC-induced snow albedo effects. We found that BC concentrations show distinct sub-regional and seasonal variations. The concentrations are generally higher in the non-monsoon season and low-altitudes (<5200 m) than in the monsoon season and high-altitudes (>5200 m), respectively. The spatiotemporal distributions of snow albedo reductions and surface radiative effects generally follow that of BC concentrations. As a result, the BC-induced mean albedo effects vary by up to an order of magnitude across different sub-regions and seasons, with values of 0.7–30.7 (1.4–58.4) W m^{-2} for BC externally mixed with fresh (aged) snow spheres.

Moreover, the BC-snow albedo effects over the TP are significantly affected by the uncertainty in snow grain shape and BC-snow mixing state. We found that BC-snow internal mixing enhances the mean albedo effects by 30–60% relative to external mixing across different sub-regions and seasons, while nonspherical snow grains reduce the albedo effects by up to 31% relative to spherical grains. These effects become comparably important with the snow aging/size effect over polluted areas. Therefore, the combined effects of snow grain shape and BC-snow mixing state can complicate the spatiotemporal features of BC-snow albedo effects over the TP, with significant implications for regional hydrological processes and water management.

In summary, this study points toward an imperative need for improved measurements and model characterization of snow grain shape and aerosol-snow mixing state in order to accurately estimate BC-induced snow albedo effects. In future work, we will incorporate the new features of the updated SNICAR model into land surface and climate models, including CESM-Community Land Model (CLM) for global modeling and WRF-Noah-MP for regional modeling, to account for the effects of snow grain shape and aerosol-snow mixing state and to assess the associated uncertainties and hydrological feedbacks in global/regional climate system.”