Reviewer#2

This study performed WRF-Chem high-resolution (~12km) model simulations coupled with the SNICAR model to resolve BC/dust-snow interactions and associated albedo reductions. The model results are evaluated with a suite of observations for snow properties and aerosol conditions. The authors further illustrated the effect of model resolution by comparing with a quasi-global WRF-Chem simulation. This study highlights the importance of model resolution and aerosol-snow interactions in modeling the Tibetan Plateau hydroclimate. The manuscript is generally well-organized and well-written. I have a few comments and suggestions to help improve the manuscript.

Response: We are thankful to the reviewer for the positive comments and helpful suggestions. We have addressed all the suggestions and our point-by-point responses for the specific comments are mentioned below in blue color.

The subsequent modifications and additions in our revised manuscript against each comment are shown in red color.

1. When evaluating modelled LAP concentration in snow, did the authors average the LAP concentrations throughout all the snow layers (up to 5) in the model? Or did the authors only look at specific snow thickness (e.g., top 10 cm) in the model? The observed LAP in surface snow may have different sampling thicknesses/depths. More clarifications could be useful. Similar clarifications should also be provided for snow grain size calculations and evaluation.

Response: In our study, simulated values of LAP concentration and snow grain size from the topmost snow layer are compared to the observed values.

In Figure 7, we show the comparison of simulated annual mean LAP values (circle) and simulated range of midday mean LAP values (box plot) against a range of annual mean LAP measurements from literature (obtained from more than one study over each location). The top layer estimates of LAP in snow depends on meltwater flushing, new snowfall and associated top layer evolution (Flanner et al., 2007, 2012; Oleson et al., 2010). Thus, the snow layer corresponding to LAP concentrations varies daily. At the same time, the corresponding range in measurements (annual mean LAP values) used here (except Pamirs) is in principle representative of different years and different snow depths over a location. We agree with the reviewer that the observed LAPs in surface snow have different sampling depths. To minimize the influence of snow sampling depth variation, we have only used the data from literature which are observed as snow surface measurement or from snow pits having thickness less than 15 cm. Additionally, as our model grid size has spatial resolution of 12 km, it is reasonable to believe that other factors like meteorology conditions, AOD distribution, microphysical parameterizations of LAP-snowmelt association and macrophysics of the simulated snow packs can impose greater biases to our simulated annual mean LAP concentration compared to this discrepancy in snow sample depth. The satellite based observations of snow grain size from

STC-MODSCAG data is representative of the snow surface layer. Therefore, we have used the corresponding model values from top snow layer in snow grain size comparisons.

We have added the following discussions on this uncertainty in the methodology section of revised manuscript and also modified Figure 7 caption for better clarity.

Line numbers: 203-207

Note that the number of snow layers and thickness of top snow surface layer are predicted in the CLM model. Fresh snowfall and melting continuously affect the model surface snow layer thickness (3 cm or less). Therefore, LAP concentrations within each snow layer depend on meltwater flushing, new snowfall and associated top layer evolution (Flanner et al., 2007, 2012; Oleson et al., 2010).

Line number: 376-385

We have used more than one study to have a range of annual mean LAP values over each location so in principle the observations are representative of different years and different snow depths over the same glacier (with an exception over Pamirs). Moreover, simulated annual mean LAP concentration only from the topmost snow surface layer is compared to the observed surface snow LAP in snow concentration, which introduce differences in the snow sample depth used for the evaluation. However, to minimize the influence of snow sample depth variation, we have only used data in the literature which are observed as snow surface measurement or from snow pits having a thickness less than 15 cm.
Line number: 351

Simulated SGS values from the topmost snow surface layer is compared to the MODSCAG SGS retrievals.

2. Introduction (Lines 112-114): For the authors' information, there are a number of valuable recent global modeling studies on the LAP-induced snow albedo effect over the Tibetan Plateau which could be included here as references (e.g., Kopacz et al. 2011 ACP, https://doi.org/10.5194/acp-11-2837-2011; He et al. 2014 GRL, https://doi.org/10.1002/2014GL062191; Zhang et al. 2015 ACP, https://doi.org/10.5194/acp-15-6205-2015).

Response: We thank the reviewer for this information. We have included these and other latest studies in our revised manuscript. The modified text is at Lines 112-117.

Many of these studies used online global model simulations at coarse spatial resolutions of ~50-150 km (Flanner and Zender, 2005; Ming et al., 2008; Qian et al., 2011; Kopacz et al., 2011; Zhang et al., 2015). Other studies employed offline simulation of the snow albedo effect using measured or modelled concentrations of deposited LAP in surface snow or estimated from atmospheric loading and ice cores (Yasunari et al., 2013; Nair et al., 2013; Wang et al., 2015; He et al., 2014; Santra et al., 2019).

3. Line 343: It is a little weird to identify April-June as the summer season. How about using "pre-monsoon" season?

Response: We have replaced "summer" with "pre-monsoon" in the revised manuscript.

4. Is there any specific reason to select 2013-2014 water year as the simulation period? Is it because the availability of observations?

Response: In the NASA's HMA project, the water year 2013-2014 is identified as a good water year for study. Therefore, we selected this year for satellite retrieval and model simulations.

5. Another important uncertainty factor the authors did not mention is the snow grain shape effect. Recent studies have shown significant effects from nonspherical snow grain shapes on snow albedo and BC/dust-induced albedo reduction (e.g., Liou et al. 2014 JGR, https://doi.org/10.1002/2014JD021665; Dang et al. 2016 JAS, https://doi.org/10.1175/JAS-D-15-0276.1; He et al. 2017 JC, https://doi.org/10.1175/JCLI-D-17-0300.1). I suggest including some discussions on this aspect. Also, did the authors assume spherical snow grains in their model simulations? This should be clarified in the model description.

Response: Yes, we have assumed spherical shaped snow grains in the simulations. In agreement with this suggestion from the reviewer, we have revised our manuscript to include the references and a discussion on the uncertainties in simulated aerosol-induced snow albedo darkening due to snow grain shape assumption.

The modified text is added at Line number 734 in the revised manuscript is shown below.

Moreover, we have assumed spherical shaped snow grains in our simulations. Recently, microscopic level studies show that uncertainties associated with simplified snow grain shape treatment in model parameterization can solely contribute to large biases in SNICAR-$\Delta\alpha$ estimates and thus the LAP-snow albedo radiative and snow melt feedback processes (Liou et al., 2014; Dang et al., 2016; He et al., 2017).

6. It would be useful if the authors could add a section to discuss the uncertainties involved in this study for the estimates of aerosol-induced snow albedo effects. For example, uncertainties from overestimated fSCA and SGS, underestimated NSD, AOD biases, etc

Response: Following this suggestion from the reviewer, we have included a focused discussion on the uncertainties involved in simulated LAP-induced snow albedo darkening.

The modified text is added at Line number 720 in the revised manuscript is shown below.

As already discussed, the simulated fSCA values in WRF-HR are greater than observed fSCA from STC-MODSCAG for most of the winter season (Figure 4E). Specifically, the underestimation in WRF-HR simulated Δα values (Figures 9C and 9D) in winter over Karakoram, Hindu Kush and Himalayas is in agreement with corresponding overestimation of WRF-HR simulated fSCA values over these regions (Figure 2). STC-MODDRFS estimated Δα is based on surface reflectance, while Δα calculated by model involves the surface layer depth. The surface snow layer in SNICAR/CLM continuously evolves as fresh snowfall is added or with snow melting, so the LAP concentrations in the surface layer depend on new snowfall, meltwater flushing, and layer combination/division (Flanner et al., 2007; Flanner et al., 2012; Oleson et al., 2010). Therefore, more precipitation and more snow coverage in winter can be a primary factor causing the underestimation of annual mean LAP concentration and LAP-induced snow darkening. Secondly, the associated overestimation in simulated SGS during winter (Figure 4E) can also contribute to the lower Δα values simulated in WRF-HR because bigger snow grains in WRF-HR lead to lower clean albedo and thus smaller percentage reduction in albedo compared to STC-MODDRFS. Moreover, we have assumed spherical shaped snow grains in our simulations. Recently, microscopic level studies show that uncertainties associated with simplified snow grain shape treatment in model parameterization can solely contribute to large biases in SNICAR-Δα estimates and thus the LAP-snow albedo radiative and snow melt feedback processes (Liou et al., 2014; Dang et al., 2016; He et al., 2017). Thirdly, the fact that the persistent cloud cover over HMA during winter season can induces a lot of uncertainty in the STC-MODSCAG and STC-MODDRFS estimates, is also equally important.

At the same time, uncertainties regarding aerosol emission, transport and deposition to the snow layers are also significant. It is well known that the transport and deposition of black carbon from Indian landmass to Himalayas increases in the afternoon with the evolution of boundary layer over the IGP region (Dumka et al., 2015;Raatikainen et al., 2014). This feature is well simulated by the model (not shown). As STC-MODDRFS estimates are representative of 1000 LT, but simulated values are sampled in the midday (1000-1400 LT), positive biases in aerosol transport and deposition in snow packs (i.e. higher Δα values) might be simulated in WRF-HR runs, especially during pre-monsoon months. At the same time, GOCART dust emission parameterization (used here) is dependent on near surface wind speed. Previous studies have evaluated and illustrated inherent uncertainties in dust emission by this parameterization, mostly underestimation over Indian region (Dipu et al., 2013; Kumar et al., 2014). Thus, the uncertainty in local dust emission fluxes over HMA can also contribute to the biases in simulated Δα values. Also, large biases in LAP values may be simulated due to model uncertainties in enhanced wet scavenging fluxes in winter. An overestimation in LAP concentration can lead to an overestimation of snow darkening and melting, resulting in an underestimation of NSD (Figure S4). The large biases in Δα values (> 20 %) simulated by WRF-HR towards late spring could be attributed to both, underestimation in fSCA and overestimation of LAP concentration in the model.

Although a better quantification of these model biases requires evaluation against in-situ measurements, it is worth mentioning here that no in-situ measurements are available for a direct comparison of these high Δα values WRF-HR over W. Himalayas (Gertler et al., 2016). Nonetheless, the high values simulated during pre-monsoon are close to previously reported values over other HMA regions. Kaspari et al., (2014) used the offline SNICAR model to report that BC concentrations in pre-monsoon snow/ice samples at Mera Glacier were large enough to reduce albedo by 6-10% and the reduction in albedo was 40-42% relative to clean snow when dust is included in the calculation. Recently, Zhang et al. (2018) has combined a large dataset of LAP measurements in surface snow with the offline SNICAR model to illustrate that Δα can be >35% over Tibetan Plateau. Moreover, the composite effect of this discrepancy on seasonal/annual mean values is minimal as the snowpack is at its minimum near the end of pre-monsoon season. Similar high daily variability, huge radiative forcing values (LAPRF ~200 W/m^2) and sudden decline in snow depth in late pre-monsoon is also reported over upper Colorado river basin (Skiles et al., 2015; Skiles and Painter, 2017).