Reviewer #1:

The authors present a study on the impact of different climate forcers on the regional climate of the Tibetan plateau. They used the CESM1 global model coupled to an aerosol scheme representing different types of aerosols like BC, dust, sea salt, sulfate and coupled to the CLM4 land surface scheme for the representation of snow and snow processes. The authors looked at the specific roles of CO_2, BC in the atmosphere and in the snow, and sulfate in the atmosphere on the warming over the Tibetan plateau in the recent decades. They concluded that the simulations represent well the observed decrease in snow cover. They also state that BC plays a more important role in the observed warming over the Tibetan plateau compared to the global mean of the warming effect of BC. This stronger impact of BC, thus, contributes to the stronger-than-average increase of temperatures in the studied region.

While the presented results and conclusions are possibly justified based on the results of the simulations, I find that a major and indispensable step in the model validation is missing: It remains unclear how well the snow cover itself concerning parameters like extent, duration, or melting date is represented in the global model. It further remains unclear how well the BC in snow concentrations are simulated. For validation purposes the authors only show observed and simulated trends of the snow cover. Since these patterns are similar the authors assume that the model well represents the impact of a changing snow cover. In my opinion this conclusion is not justified based only on the presented data and further validation of the model is needed. Therefore, I recommend major revisions before a potential publication of the manuscript in ACP.

Response: Thanks for reviewing our paper. We agree that more model validation regard to snow cover climatology should be provided. We now added an additional supplement figure and many discussions in the text for this purpose. Please see the detailed responses below.

Comments: The authors need to define the meaning of the parameter “snow fraction”. For a full description of the snow cover multiple parameters are needed like snow height, SWE, snow cover extent, snow cover duration, snow melt-out dates, and so on. It remains unclear what parameter is used. Since the observations are based on remote sensing data, I assume that the snow fraction is related to snow cover extent? But what trend is shown in Figure 1? The trend in the maximum snow covered area or the period with snow cover? This needs to be specified.

Response: The data shown in Fig 1 is "Snow Cover Extent". We now clarify in the method section that we used "NOAA Climate Data Record of snow cover extent (Robinson et al., 2012)." The figure legend and caption of Fig 1 is modified to be "snow cover extent"). We also clarify in the Fig 1 caption that " The trend is calculated based on snow cover extent data in the entire period. " The model output of "snow fraction" refers to the same variable and that naming convention is retained in the manuscript.

It is well known that global models tend to overestimate the snow cover of the Tibetan plateau. One potential reason is that the blocking effect for the moisture transport crossing the Himalayas is too small due to the coarse resolution of the global models. As a result the precipitation over the Tibetan Plateau is overestimated. This limitation can partly be overcome with models using higher spatial resolutions (e.g. Ménégoz et al., 2013). By the way, how well are the high altitude regions represented in the used global model? The authors explicitly state that the observed warming has been important in high altitude regions. A spatial and temporal overestimation of the snow cover over the Tibetan Plateau in general will certainly lead to an overestimation of the snow-related effects. Therefore, it is crucial to validate the simulated snow cover using observations. Validating the model with simulated and observed trends can only be a second step.

Response: We now compare the simulated and observed present-day temperature, precipitation, and snow cover fraction in revised Figure S2.

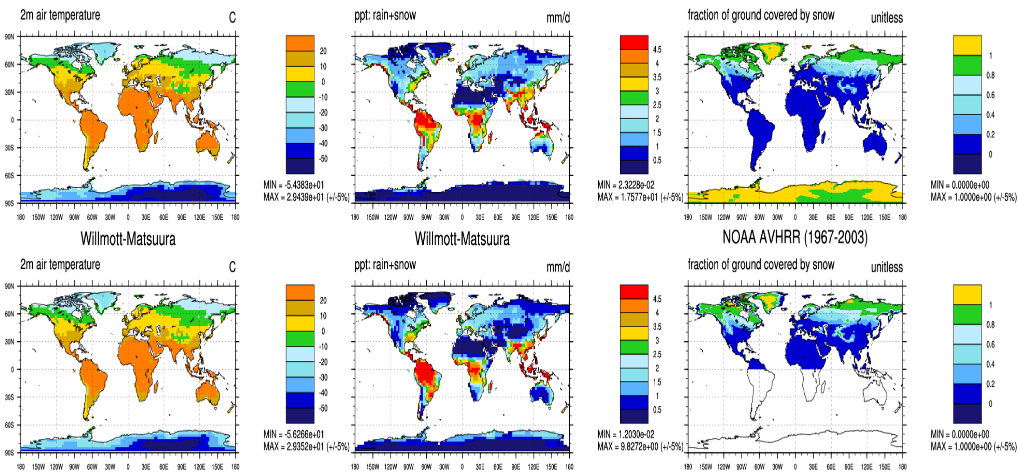

Fig S2. (Left) climatological surface air temperature (ºC) in the model simulation in the top panel, and observed surface air temperature in the bottom panel. (Middle) total precipitation (rain and snow fall) (mm/day) (Right) snow cover fraction. The model results in the top row are the 1981-2005 averages of the transient simulations under all radiative forcing. The temperature and precipitation observations are from updated dataset of Willmott and Matsuura (2001). The snow cover observations are from NOAA AVHRR as compiled by Robinson et al., (2012). In terrain-complex regions (such as North American Rockies, South American Andes and Tibet Plateau), the model tends to overestimate the precipitation and consequently snow cover, a bias commonly found in global climate model with coarse resolutions (Ménégoz et al., 2013). More detailed land model evaluations can be found in Lawrence et al., (2011).

We find that at global scale the agreement between model simulation and observation are reasonably good. However, as correctly pointed out by the reviewer, the precipitation over the Tibet Plateau tends to be overestimated by the model (Fig S2b) and therefore the snow cover is biased high in the model (Fig S2c), especially for winter season by 30-40%. We now note this model caveat in Section 3 when discussing the snow retreat trend, and we comment that future models using higher spatial resolutions (e.g. Ménégoz et al., 2013) will potentially improve the model fidelity. However, we still claim that as a global climate model used for climate attribution purpose, our current model outperforms several previous coarse-resolution models. For example, contrasting our Fig S2(c) to Fig 2 of Qian et al. (2011) which used a previous generation CAM3 with 2.8 degree, one can easily see

that the major biases in the interior of Tibet Plateau are significantly improved and the maximum snow cover along the mountain ranges are now better represented in our model.

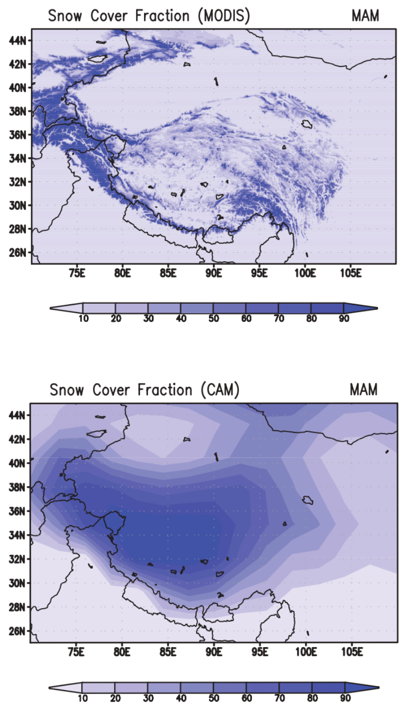

Fig. 2. Snow Cover Fraction (SCF) averaged for March-April-May (MAM) over Tibetan Plateau, (top) MODIS and (bottom) Model.

Fig 2 of Qian et al. (2011)

Qian, Y., Flanner, M. G., Leung, L. R. and Wang, W.: Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate, Atmos. Chem. Phys., 11, 1929–1948, doi:10.5194/acp-11-1929-2011, 2011.

We copied the discussion in Section 3 here for reviewer's reference. "Menon et al. (2010) attempted to simulate the snow reduction trends during 1990s but the spatial distribution of the observed trend was not well captured mainly due to the coarse resolution of the model. Qian et al. (2011) also acknowledged their model's limitation in representing the snow cover climatology and therefore may have biases in estimating BC impact on snow. It is well known that global models tend to overestimate the snow cover of the Tibetan Plateau, and one potential reason is that the blocking

effect for the moisture transport crossing the Himalayas is too small due to the coarse resolution of the global models and too much snowfall is simulated (Ménégoz et al., 2013). This limitation can partly be overcome with models using higher spatial resolutions. The modelling work presented here is a major step forward in terms of spatial resolution (about 1º by 1º), as opposed to earlier studies [2.8° by 2.8° in Flanner et al. (2009) and Qian et al. (2011); and 4° by 5° in Menon et al. (2010)], which helps better resolving the complex topography in this region. As a result of increased spatial resolution and also the improved land scheme, the biases in snow cover simulation is significantly reduced from its earlier model versions [Lawrence et al., (2011), also contrast Fig. S2c with Fig. 2 of Qian et al., (2011)]. However, we note that the precipitation over the Tibet Plateau is still overestimated (Fig S2b), and future studies, especially using regional climate models with even higher resolutions, are needed to improve the fidelity of model simulations of snow pack and glaciers over this topography-complicated region."

The impact of a changing snow cover and the involved feedback mechanisms are very complex and depend on many parameters: timing of the melt-out dates, incoming solar radiation, latitude, altitude, and possibly others. These parameters all influence the derived radiative forcing. For example, Jacobi et al. (2015) showed monthly averages of the radiative forcing related to the presence of BC in snow in the Himalayas. It can be assumed that if the melt-out dates are wrongly simulated the same shift in the melting of the snowpack can lead to an incorrect radiative forcing because it will not be similar for different months. Again, a correct model response regarding the impact of a changing snow cover can only be expected if the snow cover is correctly represented.

Response: We agree with these comments that radiative forcing due to BC in snow is also sensitive to the simulated snow cover in the background. We incorporated some more discussions on this in Section 4 as follows: "In addition to the uncertainty in BC loading, the forcing magnitude is also sensitive to model parameterization (Yasunari et al., 2013), and also the simulated background snow cover because the wrongly simulated melting dates of the snowpack can lead to an incorrect radiative forcing (Jacobi et al., 2015). Therefore, both in-situ (Wang et al., 2013; Zhao et al., 2014) and

laboratory measurements (Hadley and Kirchstetter, 2012) are needed to constrain model parameterizations of BC in snow."

I am also surprised to note that the simulated radiative forcing is larger for the reduction of the snow albedo due to the presence of BC compared to the radiative forcing caused by the earlier melting of the snowpack. This is opposite to results of many previous studies concerning light-absorbing impurities in snow (e.g. Flanner et al., 2007; Painter et al., 2007; Jacobi et al., 2015). Is this difference related to an overall limited representation of the snow cover in the model?

Response: Thanks for pointing out this discrepancy. We have checked the numbers in the model output again, and indeed the positive surface forcing initially due to BC deposition (Fig S4(b), calculated from the fixed SST simulation) is somewhat larger than the consequent snow-melting induced surface forcing (calculated from the fully coupled simulation). One caveat for our calculation of surface forcing due to BC deposition that it may be partially contaminated by the snow loss as the snow is already melting in the first five year of the simulation. We further clarify this issue in the caption of Fig S4 as follows "The change of surface albedo in (a) is calculated using the five years of atmosphere-only simulation in which BC emission is increased. Therefore, the albedo change largely represents the surface darkening due to BC deposition, although we cannot completely rule out the associated melting during this period. As a result, the actual radiative forcing at the surface due to BC in snow should be smaller than that in (b)."

We are currently incorporating a more proper radiation diagnostic procedure as in SNICAR without causing any fast feedback such as snow melting, which is similar to the one we used for calculating atmospheric forcing of various species. This will help better quantifying the BC surface darkening forcing from BC atmospheric heating. The relative contribution of the two is a future research topic of ours.

What are the simulated BC in snow concentrations? Do they correspond to observations? I admit that the available data are scarce, but still the few observations give an order of magnitude for the BC in snow in the Himalaya/TP region. If in the simulations the BC in snow concentrations are incorrect, but the simulated trends in the snow cover as well as in the albedo are correct, this would in my opinion suggest that the model sensitivity is incorrect.

Response: Due to accessibility to the original model output and the in-situ observation data, we were unable to perform this model validation step directly. A recent study (Zhang et al., 2015) used the same atmospheric and land snow model (but driven by realistic meteorological field in the year of 2000). They showed that simulated BC concentration is significantly larger than that from in situ sampling (Table S3 in Zhang et al., 2015), but suggested that the positive bias is smaller than what's previously reported in Ménégoz et al., (2014). However, as discussed in Ménégoz et al., (2014), they argue that "the spatial variations in BC deposition, can strongly affect the accuracy and representativeness of BC-in-snow measurements for the purpose of evaluating global models" and that "global models with coarse grid resolution cannot accurately represent elevation of sampling sites".

We now acknowledge these issues in the Section 5 related to the surface darkening effects as follows:" However, we note that model estimates of radiative forcing due to BC deposition on snow have large uncertainty. Using the same atmospheric and land model (but driven by realistic meteorological field in the year of 2000), Zhang et al., (2015) showed that simulated BC concentration in snow is biased high with respect to in situ sampling. Although the large spatial variations in BC deposition can affect the representativeness of BC-in-snow measurements for the model evaluation purposes, this potential model bias should be kept in mind."

The reviewer's concern on the fidelity of BC concentration in snow is a valid point. Although we have made previous efforts to constrain BC atmospheric radiative forcing in the model using satellite and ground radiometer measurements (Xu et al., 2013), the improvement on the accuracy of BC concentration in snow and a proper accounting of its radiative effect is a future research direction for us.

Zhang, R., Wang, H., Qian, Y., Rasch, P. J., Easter, R. C., Ma, P.-L., Singh, B., Huang, J., and Fu, Q.: Quantifying sources, transport, deposition, and radiative forcing of black carbon over the Himalayas and Tibetan Plateau, Atmos. Chem. Phys., 15, 6205-6223, doi:10.5194/acp-15-6205-2015, 2015.

SO4 should be substituted by either “sulfate” or SO2− 4. There are no SO4 emissions. The authors probably refer to emissions of SO2?

Responses: Thanks. We now define the acronym "SO4" for "sulfates" at its first occurrence, and this is consistent in the text and all figures. You are right about the emission. We now clarify in the method section that " The forcings were imposed by instantaneously increasing the emissions of BC, or the emission of SO_4's precursor sulfur dioxide, or by increasing CO_2 concentration to present-day level (400 ppm)."

References

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Painter, T.H., A.P. Barrett, C.C. Landry, J.C. Neff, M.P. Cassidy, C.R. Lawrence, K.E. McBride, and G.L. Farmer, Impact of disturbed desert soils on duration of mountain snow cover, Geophys.Res.Lett. 34, L12502, doi: 10.1029/2007GL030284, 2007.

Response: Thanks very much for providing those helpful suggestions on references. They are now cited in the paper.