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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Snow cover sensitivity to black carbon deposition in the Himalaya: from atmospheric and ice core measurements to regional climate simulations" *by* M. Ménégoz et al.

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We thank the first referee for its useful and thorough reviews. Our replies to its comments follow below. In addition to this response, we submit a revised version of our manuscript, with the main modifications underlined in yellow, that can be downloaded on the discussion website (see the supplementary piece).

Response to the first anonymous Referee:

The first referee mentioned one critical point: "The most problematic issue with this study is that simulated BC concentrations in snow are about 60 times larger than the ice

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core measurements, bringing into serious question the accuracy and usefulness of the simulated impacts of BC on snow cover. The model bias is not even mentioned in the abstract, nor is there any attempt to correct for the bias and produce more believable results."

We agree with the first referee that there are strong differences in BC concentrations in the snow between our simulations and the ice core samples. Section 3.3 of our paper is dedicated to the different points that may explain these differences. The two main ones are: 1) the altitude difference between the grid cell (5552 m) and the ice core site (6400 m); and 2): the choice of the snow depth when analysing the BC concentration in the snow that strongly affects the simulated values. Concerning the first point, we argue that the BC concentration in snow that we simulated is not representative for high elevations areas (> 6000 m a.s.l.), but is more realistic for middle altitude (< 6000 m a.s.l.) seasonally snow-covered areas. This assumption is in agreement with results reported by Kaspari et al. (ACPD, 2013) who recently measured the BC concentration in the snow of the Mera Glacier: they found BC concentrations in snow sampled at 5400 m higher by a factor 180 to the values that they obtain at 6400 m (which are similar to the ice core used for our study, described in Ginot et al., 2013). Unfortunately, the low altitude samples were collected in exposed crevasse walls, which make the high-detected BC concentrations potentially overestimated in comparison with the concentrations in the undisturbed snowpack. Nevertheless, the factor 60 that we found in our simulation appears plausible and the mean of BC in snow that we simulated (201 μg kg-1) seems realistic, at least compared to the observation of Kaspari et al. (2013) that reach 180 μg kg-1. However, as suggested by referee #1, we propose to describe in detail the uncertainties and the limits of our study, both in the body and in the abstract of the revised version of our paper:

Abstract: "We applied a climate-chemistry global model to evaluate the impact of black carbon (BC) deposition on the Himalayan snow cover from 1998 to 2008. Using a stretched grid with a resolution of 50 km over this complex topography, the model

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reproduces reasonably well the remotely sensed observations of the snow cover duration. Similar to observations, modelled atmospheric BC concentrations in Central Himalaya reach a minimum during the monsoon and a maximum during the post- and pre-monsoon periods. Comparing the simulated BC concentrations in the snow with observations is more challenging because of their high spatial variability and complex vertical distribution. We simulated spring BC concentrations in surface snow varying from tens to hundreds of μg kg-1, higher by one to two orders of magnitude than those observed in ice cores extracted from Central Himalayan glaciers at high elevations (> 6000 m a.s.l.), but typical for seasonal snow cover sampled in middle elevation regions (< 6000 m a.s.l.). In these areas, we estimate that both wet and dry BC depositions affect the Himalayan snow cover reducing its annual duration between one and eight days. In our simulations, the effect of anthropogenic BC deposition on snow is quite low over the Tibetan Plateau because this area is only sparsely snow covered. However, the impact becomes larger along the entire Hindu-Kush, Karakorum and Himalayan mountain ranges. In these regions, BC in snow induces an increase of the net shortwave radiation at the surface with an annual mean of 1 to 3 W m-2 leading to a localised warming between 0.05 and 0.3 °C." We suggest to add the following statement in our paper to emphasis that our simulations are more representative of snow cover physics occurring at middle altitude than at high altitude:

Section 3.3, point (1): "This assumption is confirmed by Kaspari et al. (2013) who determined the BC concentration in snow sampled at different altitudes between the Mera Col (6400 m) and the Mera La (5400 m). At the Mera La, located at an elevation similar to our model grid cell, they measured an average of the BC concentration in snow reaching 180 μg.m-3 (considering the first 3 meters under the surface) with extreme values exceeding 3500 μg.m-3 in particularly polluted layers. According to their study, snow is more polluted by a factor of 180 between their low altitude site (5400 m) and their high altitude site (6400 m). Our simulation provides values of BC in snow ranging between 50 and 500 μg.m-3 in the Nepalese Himalaya (Figure 3a). It is therefore representative of BC concentrations in snow observed in middle altitude areas (<6000 m),

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and not of those measured at high altitude sites (>6000 m)."

Section 3.3, point 2: "However, we assume this hypothesis to be realistic for snow covered areas located under 6000 m, since Kaspari et al. (2013) observed at the Mera La particularly polluted snow layers, with a BC concentration exceeding 3500 μg.m-3, higher than the maximum that we simulated in the whole Himalayan region (Figure 3a)."

Section 4: "As stated in Section 3.3, we simulated relatively high BC concentrations in snow, representative of those observed at intermediate altitudes (< 6000 m). The snow cover variations that we simulated are therefore representative of these areas, whereas the much lower values observed by Ginot et al., (2013) and Kaspari et al. (2013) suggest the BC forcing to be weaker at higher altitude (> 6000 m). Maskey et al. (2011) pointed out that the areas located higher than 6000m concern only 1% of the mountainous regions (> 3000m) in Nepal, a characteristic applicable to the whole Himalayas. Thus, the largest areal extent of snow cover area lies in the elevation zone between 3000m and 6000m, where snow is more likely polluted. Our simulation is representative of intermediate altitude areas, where snow cover is not continuous from one year to another. It cannot be used to assess the "snow darkening effect" at regions higher than 6000m."

Concerning the vertical profile of BC in snow (point 2), we suggest to add a statement in the conclusion, pointing out that it would be difficult to perform model sensitivity experiments facing the complexity of the vertical distribution of BC in snow: "In addition, field campaigns dedicated to observe the vertical profile of BC in the snowpack are helpful to improve our understanding of the snow darkening effect: Kaspari et al. (2013), observed a highly variable BC concentration in snow sampled on the Mera Glacier, as they measured concentrations varying from two orders of magnitude between the upper (6400 m a.s.l.) and the lower (5400 m. a.s.l.) parts of the glacier. According to their study, the BC concentration varies from $\sim$10 to thousands μg.kg-1 in a vertical profile sampled at 5400 m. To our point of view, it is difficult to validate the ability of coarse gridded models to simulate the BC concentration in the snow as it strongly

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depends on the snow depth considered both in simulations and observations. Further observations of BC in snow could help to force models with realistic vertical profiles of BC in snow. Nevertheless, we assume that our study is based on BC concentrations typical for seasonal snow cover at middle elevation areas (< 6000 m. a.s.l.) and are not representative of permanently snow covered areas located at high elevations (> 6000 m a.s.l.). We estimate that the BC deposited on the mountains of the Hindu Kush-Karakoram-Himalayas decrease the snow cover duration by one to eight days per year."

Minor comments:

* As recommended we need to temper the sentences pointing out the performances of our model to simulate the atmospheric BC concentration:

-> In the abstract: "As in local observations, modelled atmospheric BC concentration in mountainous areas reaches a minimum during the monsoon and a maximum during the post and pre-monsoon periods."

-> In the conclusion: "Even with some differences induced by local atmospheric processes not described by our large-scale model, this one reproduces the seasonal variations of the atmospheric BC concentrations observed in the Mount Everest region with maximum values occurring in the post and pre-monsoon period."

* Radiative impacts of dust: "The snow albedo changes induced by dust deposition, well known to minimize the forcing of BC in snow (e.g. Ginot et al., 2013, Kaspari et al. 2013) is also taken into account in both simulations."

* Section 2.1: As recommended we suggest to add in a revised version some details about the aerosol emission inventory, which does not include interannual variations: "All the experiments were conducted with the present-day global aerosol emission inventory described in Lamarque et al. (2010), a decadal resolved inventory made for the Coupled Model Inter-comparison Project Phase 5 (CMIP5, CLIVAR special issue,

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2011)."

* p.31019, line 19: As explained by Marinoni et al. (2010) and as recommended by Petzold et al. (2002), Bonasoni et al. (2010) used a mass absorption efficiency equal to 6.5 m2 g−1 to convert measured aerosol absorption coefficient to equivalent BC concentration. The very good correlation between EC and equivalent BC (R2=0.94), obtained by totally independent methods confirms the fact that, despite the presence of high levels of dust, MAAP absorption measurements are primarily influenced by BC. Note that these experimental precisions are note quoted in our revised version of the manuscript. We would like to add only the reference to Marinoni et al. (2010) who detailed the experimental protocol followed to measure atmospheric BC at the NCOP observatory.

* p.31020, line 11: This 19.8 m core was sub-sampled with a mean resolution of 6.6 cm (the size of the samples varying between 4 and 16 cm), resulting in ∼30 samples per year.

* p.31020, line 26: How does the model deposition in this gridcell compare with that in the gridcell of the actual ice core site? We suggest to add these two statements in Section 3.2 to answer this question: "The altitude of the model grid cell containing the Mera Glacier reaches only 3000 m a.s.l., an altitude too low to simulate a continuous seasonal snow cover in winter/spring. Therefore, we used for our comparison the neighbouring grid cell located 50 km further north at an altitude high enough (5552 m a.s.l.) to conserve a continuous seasonal snow cover in the simulations." "Note that the BC deposition rates simulated in the grid cell really containing the Mera Glacier are 30% higher than those simulated in the grid cell that we used for our comparison. Such difference is due to the altitude of this grid cell, lower by 2500 m than those of its neighbour, and therefore much more exposed to the transport of pollutants emitted at the foothills of the Himalayas. With a mean altitude of 3000 m, i.e. ∼3400 m lower than the real altitude of the drilling site, it would be definitely impossible to compare the observations with the values simulated in this grid cell. Nevertheless, our climate model

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has a too coarse resolution to simulate the local aerosol deposition, and the final goal of such comparison is to discuss the seasonal variations and the order of magnitude of the BC regionally deposited in snow-covered areas, both in local observations and in regional simulations."

p. 31023, line 14: BC -> aerosol

p. 31023, line 15-19: How large is the observed vertical gradient in BC, and how much of the model bias can therefore be explained with the 1000m difference in model/observation altitude? We suggest to add the following statement in Section 3.3: "In the grid cell used for our comparison, the ratio between the BC atmospheric concentrations simulated at the surface (5552 m) and those modelled at 6500 m varies between 5 and 10 over the period 1998-2008."

p. 31023. Bullet 2: Do you simulate BC concentrations in the bottom model snow layer as well as the top layer? If so, it seems that you could conduct a more realistic comparison with measurements by incorporating simulated BC amounts throughout the snow column. We simulated BC concentrations in the bottom snow layer as well as in the top layer. They are systematically very low in comparison with the surface values. However, we prefer to consider the surface values for comparisons with observations since this is the surface snow that mainly drives the snow albedo. In addition, as explained in Section 3.3 (point 2) the depth of snow samples used for BC in snow measurements is quite variable depending on the measuring protocol. Within the shallow ice core itself, the length of sub-samples was highly variable, ranging from 4 to 16 cm. This point is likely to impact artificially the value of the observed BC concentration in the snow. In addition, the samples extracted from the ice core were affected by post-depositional processes depending how long they were exposed at the surface, whereas our model simulates a real time BC concentration at the surface. Finally, it seems more appropriate to us to keep the raw snow depth values both for models and observations, and explain the difficulty to choose a coherent snow depth to compare modelled BC concentrations values with the observed samples.

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p. 31025, line 5: We suggest to correct the following statement: “Kaspari et al. (2011) measured average rBC concentration in snow of 0.7 μg kg-1 for the recent period using an SP2.”

p. 31025, line 4: "because" was the wrong word: "We simulate high amounts of BC and dust wet deposition in the region of the Mera Glacier, while dry deposition represents locally only 11 % of the total simulated deposition (Table 2).”

p. 31027, line 13: sentence to be reformulated: "The pronounced spatial heterogeneity of precipitation in the Himalayas (Ménégoz et al., 2013b) certainly induce large spatial variations of BC wet deposition, which may explains parts of the difference between the observations of BC in snow performed by Ginot et al. (2013), Ming et al. (2008) and Kaspari et al. (2011, 2013).”

Section 4: How, precisely, is snow cover duration calculated? : We suggest to add a new statement in the revised paper: "We computed the difference between the two simulations to estimate the snow cover duration change induced by BC in snow. The snow cover duration is defined as the number of days per year with a snow water equivalent higher than 0.01 mm.”

Section 4: We found no impacts of BC deposition on the snow cover duration over the Tibetan Plateau in our simulation. This result is not an artefact induced by the way of computing the snow cover duration. We suggest to add the following explanation in our revised manuscript: Âń Two reasons explain that snow cover duration is not reduced by BC deposition over the Tibetan Plateau: (i) The Tibetan Plateau is lengthily snow-covered only during the winter (DJFM), when solar radiation is low and when aerosol transport from the Indian plains is limited as temperature are low, atmosphere is highly stable and Westerlies very strong (Ménégoz et al., 2013b). (ii) During spring, summer and fall, the Tibetan Plateau is more affected by BC deposition, but snow covers the surface only during brief periods, too short to allow post-depositional processes to accumulate BC at the surface of the snow cover.”

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p. 31028, line 20: Is this increase in net solar energy an annual-mean? For more clarity, this statement can be reformulated as following: "In the regions where the BC deposition on snow induces a decrease of the snow cover duration, we found a positive increase in the annual net surface solar radiation that spatially varied between 1 and 3 Wm-2 on average over 1998-2008".

p. 31028, line 24: "Similarly" need to be removed. Figure 3: The red contouring will be changed in the revised version. We suggest to add in the caption the following statement: "Wind fields have been nudged toward the ERA-Interim reanalysis (see details in Section 2.1)."

We now quote the paper of Qian et al (2011) insisting more on the uncertainties of our modelling study in the main parts of the manuscript as well as in the abstract.

Additional references:

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Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/13/C12583/2014/acpd-13-C12583-2014-supplement.pdf

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