

Interactive comment on “The impact of Saharan dust and black carbon on albedo and long-term glacier mass balance” by J. Gabbi et al.

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We thank Anonymous Referee #2 for the helpful and constructive comments which greatly helped to improve our manuscript. The major issue was to extend and clarify the sections about the sensitivity study and the radiative forcing as also demanded by Anonymous Referee #1. We followed this suggestion. Furthermore, we have included comments about the findings of Painter et al., 2013 in the Discussion-section in order to emphasize the significance of our results. And finally, we have added the study region to the title as suggested.

In the following we address the referee comments point by point. The comments of the referee are listed according to the review letter (*italic*). For each comment, an explanation of the change we made is given (normal type style). The revised version

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of the text is given in smaller script size and quotation marks.

Comments of Anonymous Referee #2

General comment 1

There are revisions that would improve this paper. 1) Given than the impurity concentrations, mass balance, and atmospheric forcing measurements did not come from the same location, and some highly simplifying assumptions were made, it is good a sensitivity study was carried out- but I found this section to be too brief, lacking in detail, and would benefit from expansion and clarity.

We agree on referee's concern and have expanded and clarified the section about the sensitivity analysis for providing the reader with more detailed information. As this point was also raised by the other referee, see answer to general comment #1 of Anonymous Referee #1.

General comment 2

2) The location of the study should be added to title as the relative ratio of dust to black carbon estimated from the core measurements is specific to the Swiss Alps, and would not be the same for glaciers in say, the Himalaya, or the Andes.

The title was changed as suggested.

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See answer to general comment #5 of Anonymous Referee #1.

General comment 3

3) I found it very interesting that the impact on mass balance attributed to BC deposition falls within the mass balance impact in the Alps by BC in the 1900's put forth by Painter et al., 2013, a paper which suggested that black carbon was the driver behind the retreat of glaciers in the Alps at the end of the Little Ice Age. The results presented here helps to validate the claims made by this earlier paper, and the relevance of this paper could be greatly expanded by tying back the results of this study (to those in Painter et al., 2013) in the conclusion.

According to the suggestion of the referee, we included a paragraph which links our results with the findings of Painter et al., 2013. We added this section to the Discussion-section in order to explain the differences/similarities between these two studies in more details.

Page 15/16, Lines 471–485

"[...] Painter et al. (2013) suggested that the rapid retreat of Alpine glaciers at the end of the Little Ice Age was forced by increasing BC concentration due to industrialisation. They found BC-induced mass balance anomalies in the order of $-500 \text{ mm w.e. yr}^{-1}$ for the ablation area, which is similar to our results for the accumulation area (-180 to $-300 \text{ mm w.e. yr}^{-1}$) despite the different modelling approaches. While Painter et al., (2013) used a sophisticated radiation model (SNICAR, Flanner et al., 2007) to derive BC radiative forcing and in turn equivalent changes in air temperature and mass balance, we used a simple broadband albedo parameterisation in combination with a mass balance model. However, Painter et al. (2013) assume 10 to 20 times higher BC concentrations than reported by the ice core data in order account for altitudinal differences between the high-altitude ice core sites and the ablation area. In our study, we do not alter atmospheric deposition rates (see Section 5.4), but, contrary to Painter et al. (2013),

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account for changes in the BC surface concentration due to melt and accumulation processes as well as to removal by melt water. As a result, we obtain similar BC concentrations in the surface layer on average and thus, a comparable impact of BC on glacier mass balance. The general agreement of our assessment with that by Painter et al. (2013) indicates the highly relevant role of BC in shaping changes in glacier mass balance over the last century.”

General comment 4

4) Don't be afraid of commas! I found many long sentences in this manuscript that could be clarified with the use of a few commas.

We have checked the manuscript and have inserted commas where needed to make the text easier to understand.

General comment 5

5) Description of radiative forcing calculations needs to be broadened/clarified.

Done.

See answer to general comment #4 of Anonymous Referee #1.

Line by line comments

Comment 1

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Page 1134, Line 4: Remove “Saharan” qualifier here, it unnecessarily specific for the abstract

Done.

Page 1, Lines 2–4

“[...] Here, we investigate the long-term effect of snow impurities, i.e. mineral dust and black carbon (BC), on albedo and glacier mass balance.”

Comment 2

Page 1134, Abstract: Consider including impact on mass balance.

According to the referee’s suggestion we have added the impact of dust/BC on the mass balance to the abstract.

Page 1, Lines 9–13

“[...] Compared to pure snow conditions, the presence of Saharan dust and BC lowered the mean annual albedo by 0.04–0.06 depending on the location on the glacier. Consequently, annual melt was increased by 15–19% and the mean annual mass balance was reduced by about 280–490 mm w.e.”

Comment 3

Page 1135, Line 6: Consider changing “involving” to “perturbing”.

We changed “involving” to “resulting in” to make it clearer.

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Page 2, Lines 27–30

"[...] Snow impurities are mainly retained at the surface during conditions of melt and surface concentrations might be enhanced by up to one order of magnitude resulting in a pronounced melt amplification (Sterle et al., 2013)."

Comment 4

Page 1135, Line 13: Long-range transported crustal impurities accounts for 2/3 of the dust... where does the rest come from? Local landscape?

Yes. Around two thirds of the total are long-range transported crustal impurities and about one third has a local origin. We have added this information to provide more clarity.

Page 2, Lines 33–36

"[...] Analyses of firn cores from high-alpine sites, resolving the signal of the continental background aerosols, indicated that long-range transported crustal impurities account for about two thirds and local impurities for about one third of the total mineral dust deposited (Wagenbach and Geis, 1989)."

Comment 5

Page 1135, Line 22: Consider including Bond et al., 2013 as a reference in addition to Ramanathan and Carmichael, 2008 (DOI: 10.1002/jgrd.50171).

The suggested reference was added.

Page 2, Lines 42–44

"[...] BC has become a focus of interest as it has been identified recently as one of the major contributors

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to global climate change (Ramanathan and Carmichael, 2008; Bond et al., 2013).”

Comment 6

Page 1136, Line 7: Consider including the region for the studies completed by Skiles and Painter (Colorado River Basin, Western US) as you do for the other cited studies.

We have added the study site for Skiles et al., 2012 and Painter et al., 2010.

Page 2/3, Lines 55–57

”[...] Investigations in the Colorado River Basin, Western US, show that the radiative forcing of mineral dust deposition may shorten the duration of snow cover by several weeks (Skiles et al., 2012) and also affects the timing and magnitude of runoff (Painter et al., 2010).”

Comment 7

Page 1136, Line 20: The sentence starting with “We have chosen...” should be restructured with commas, split into two sentence, or rewritten.

We have split this sentence.

Page 3, Lines 66–68

”[...] We have chosen Claridenfirn (Swiss Alps) for which the worldwide longest data series of seasonal glacier mass balance exist. This comprehensive data set enables an accurate and field data-based simulation of ablation and accumulation processes.”

Comment 8

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Page 1137, Line 9: Were density measurements made in the snow pits or with a SWE sampler?

The density measurements were made in the snow pits. This information has been added.

Page 3, Lines 82–83

"[...] Simultaneously snow density measurements in snow pits have been carried out."

Comment 9

Page 1138 (study site and data): Please clarify how black carbon is estimated after 2002 and dust after 2007.

We have added this missing information.

Page 4, Lines 112–114

"[...] For BC and mineral dust concentrations of the years 2002-2014 and 2007-2014, respectively, which are not covered by the ice core data, a mean concentration averaged over the entire period was assigned (Fig. 2a)."

Comment 10

Section 3.1.1, Lines 5–15: Consider clarifying here that study done by Kaspari et al., 2014 was carried out in the Himalaya, not the Alps. Also, this study used gravimetric mass for their analysis, but found that there is linear relationship between Fe concentration and gravimetric mass (using a very small set of samples).

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We have added the missing information to the corresponding paragraph.

Page 5, Lines 130–133

"[...] The absorption of mineral dust in the visible spectrum is highly sensitive to the content of iron oxides. Kaspari et al. (2014) determined light-absorption of mineral dust in snow and ice of a Himalayan glacier based on gravimetrically determined Fe concentrations. Accordingly, we used records of iron (Fe), provided by the ice core, to infer mineral dust concentrations."

Comment 11

Section 3.4, Lines 19–20: Reword this sentence. You used wet deposition in the model, this is fine, I suppose, but you should use caution in stating this is the predominant mechanism! This is not well known or well established. Dust deposition events in particular are almost pre-frontal, when wind speeds are high enough to transport dust from the source region.

We have rephrased the corresponding sentence.

Page 10, Lines 289–290

"[...] Mineral dust and BC entered the system by liquid or solid precipitation as wet deposition is expected to be the predominant mechanism (Raes et al., 2000; Koch, 2001)."

Comment 12

Section 4.1.3 Lines 1-5: Rewrite. Basically you are trying to say there was more dust, but black carbon is more absorbing, but your wording is confusing.

We have reworded this paragraph for clarity.

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Page 12, Lines 370–372

"[...] In contrast to BC, mineral dust concentrations at the surface were up to five times larger. However, as BC is much more absorptive than mineral dust (mass absorption coefficient about 10 times higher), the overall absorption by BC and dust are in a similar range."

Comment 13

Section 4.1.3, Line 9: "Absorbent" to "absorber".

Done.

Page 12/13, Lines 374–375

"[...] In all other years, the absorption of BC outweighed the absorption of mineral dust and over the entire period BC was clearly the dominant absorber."

Comment 14

Section 4.1.3, Line 9: The influence of BC is already stronger than dust. Reword.

We have reworded this sentence.

Page 13, Lines 379–380

"[...] If removal rates of BC and mineral dust would be in a similar range, the influence of BC on the absorption would be even larger."

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Comment 15

Page 1151, Lines 5–8: This sentence is circular and confusing – reword.

We have rephrased this sentence.

Page 13, Line 394

"[...] The overall impact of BC on the surface albedo was substantially higher than that of Saharan dust."

Comment 16

Page 1153, Line 22: is the mountain snow cover of the Colorado River Basin, not the 'Colorado Plateau', which is a desert.

Changed.

Page 15, Lines 459–461

"[...] Similar peak values are found for desert dust in the mountain snow cover of the Colorado River Basin (25–50 W m⁻², Painter et al., 2007; Skiles et al., 2012)."

Comment 17

End of Section 5.1: I think it would be sufficient to say the results are not directly comparable because dust/BC sources and melt dynamics are different. (I think you have an extra word "often" on the last line of page 1153).

We agree and have rephrased this sentence.

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"[...] However, radiative forcing reported in other studies is not directly comparable to the results of this study as dust/BC source and the temporal dynamics of melting are different."

Comment 18

Section 5.2: Can you give an overall estimate of uncertainty?

As there are many poorly constrained variables involved in our assessment it is not possible to provide one single value for the uncertainty. Basically, the uncertainty in the selected parameter values is largely unknown and could only be narrowed down based on highly challenging field and laboratory experiments. However, our sensitivity analysis covers all individual factors determining the final uncertainty in our results and indicates processes for which additional research is required.

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