

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

**J. Gabbi et al.**

gabbij@vaw.baug.ethz.ch

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Dear Dr. Radic,

We would like to thank the two reviewers for their reviews, which helped improving the manuscript. The major issue of both referees was to clarify and broaden the sections about the sensitivity analysis and the radiative forcing. We have done so and have added a table with the parameter ranges used in the sensitivity analysis as suggested by anonymous referee #1. Furthermore, we have adjusted the title of our manuscript as proposed by the two reviewers. Anonymous referee #1 pointed out that the used mass absorption coefficient of black carbon is not in accordance with the applied albedo parameterisation. In response, we have changed the value of the mass absorption

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coefficient and have updated all results accordingly. Anonymous referee #2 proposed to refer to the study of Painter et al. (2013), who suggested that black carbon forced the end of the Little Ice Age, in order to expand the relevance of this paper. We have added an additional section to the discussion-part of the paper where we discuss in detail the findings of Painter et al. (2013) and compare them with our results.

In the following we address the referee comments point by point. The comments of the referees are listed according to the review letter (*italic*). For each comment, an explanation of the changes applied is given (normal type style). The revised version of the text is given in smaller script size and quotation marks.

We are confident that the changes have resulted in an improved manuscript.

Kind regards,

Jeannette Gabbi and the co-authors

### **Comments of Anonymous Referee #1**

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#### *General comment 1*

*More detail should be included on the sensitivity studies described in Section 5. It was not clear exactly how each of the parameter changes should influence the simulated mass balance, and interpretation of this part of the study could be improved with more discussion on these parameter changes. It would be helpful to include a table listing the ranges of parameter values that were applied in the sensitivity studies.*

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We agree with the reviewer's concern and have extended and specified the section about the sensitivity analysis to provide more clarity. More detailed information on the effect of the individual parameters on the mass balance is included in the revised version of the manuscript. Furthermore, the interpretation of this part is broadened. As suggested we added a table showing the parameter ranges used in the sensitivity analysis.

**Pages 16/17, Section 5.2 & Page 27, Table 1**

"In order to assess the sensitivity of the model results to the chosen input parameters, we performed a sensitivity analysis. Four parameters of the snow impurity model were examined: (1) removal rates of BC by melt water, (2) fraction of Fe which is presented as Fe-oxides, (3) the proportion of haematite and goethite in the Fe-oxides, and (4) the ratio of the MAC of BC vs. MAC of Fe-oxides. In addition, another four parameters of the SSA model ( $SSA_{\text{initial}}$ ,  $SSA_{\text{min}}$ ,  $C_1$ ,  $C_2$ ) and six parameters of the snow density model ( $a_t$ ,  $c_1$ ,  $k_0$ ,  $k_1$ ,  $F_C$ ,  $c$ ,  $d$ ) were investigated. **Furthermore, we also assessed implications of deviating atmospheric deposition rates of mineral dust and BC on the mass balance as the ice core data is taken from another site (see Section 5.4).** The parameters of the melt and accumulation model were not included in the sensitivity analysis because they were directly constrained by the continuous seasonal mass balance measurements at the study sites. The sensitivity of the parameters was assigned by varying each parameter by 5% intervals around to the chosen value in a range of  $\pm 20\%$ , keeping all other parameters constant. **Tab. 1 shows the used parameter ranges.** According to Anslow et al. (2008) we defined the sensitivity of a parameter as the slope around the origin of the curve defined by the percentage change in the parameter value and the percentage change in the resulting model variable (mass balance in our case). **For example a sensitivity of 0.5 designates that an arbitrary percentage change in the parameter value involves a half as large percentage change in the mass balance. A positive sensitivity means that an increase in the parameter value leads to an increase in the mass balance, a negative sensitivity that an increase in the parameter yields a decrease in mass balance.**

Results of the sensitivity analysis are shown in Fig. 9. The mass balance was most sensitive to the amount of snow impurities and the parameters of the snow density model while the parameters of the SSA model were clearly less relevant. In contrast to the input quantity of BC, mineral dust had a less pronounced impact on modelled mass balance. A change of 10% in the BC concentration in precipitation led to a 5.8% change in mass balance, whereas the same change in the mineral dust concentration in

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**Table 1.** Parameters of the impurity, the SSA and the snow density model and the corresponding parameter ranges ( $\pm 20\%$ ) applied in the sensitivity analysis.

Parameter	Unit	Value	Range
<b>Impurity model</b>			
Dust input	$\text{g kg}^{-1}$	22.3	17.8 - 26.8
BC input	$\text{g kg}^{-1}$	23.2	18.6 - 27.8
BC removal rate	%	20	16 - 24
Fe in FeO	%	54.5	43.6 - 65.4
MAC FeO/BC	-	0.082	0.066 - 0.099
<b>SSA model</b>			
$SSA_{\text{initial}}$	$\text{m}^2 \text{kg}^{-1}$	73.0	58.4 - 87.6
$SSA_{\text{min}}$	$\text{m}^2 \text{kg}^{-1}$	8.0	6.4 - 9.6
$C_1$	$10^{-3} \text{mm}^3 \text{d}^{-3}$	1.1	0.88 - 1.32
$C_2$	$10^{-5} \text{mm}^3 \text{d}^{-3}$	3.7	2.96 - 4.44
<b>Snow density model</b>			
$a_t$	$^{\circ}\text{C mm}^{-1}$	0.033	0.0264 - 0.0396
$c_1$	$\text{m}^2 \text{h}^{-2} \text{kg}^{-1}$	0.001	0.0008 - 0.0012
$k_0$	$\text{m}^3 \text{kg}^{-1}$	0.021	0.0168 - 0.0252
$k_1$	$^{\circ}\text{C}^{-1}$	0.08	0.064 - 0.096
$F_C$	-	0.02	0.016 - 0.096
$c$	$\text{m}^{-1} \text{h}^{-(d-1)}$	1.0	0.8 - 1.2
$d$	-	1.25	1.0 - 1.5

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precipitation only resulted in a 1.6% change in mass balance. The reason for this difference in sensitivity is the stronger absorption of solar radiation by BC compared to mineral dust. An even higher sensitivity could be assigned to the removal efficiency of BC with melt water. **A 10% change in the BC removal rate leads to a 1.5 times larger change in the mass balance.** This is particularly important since the removal rates are subject to considerable uncertainty (see Section 5.5). **Hence, the removal of BC by melt water seems to be the most critical point of the simulation and strongly controls the impact of BC on the long-term glacier mass balance.** Besides the impurity model, also the performance of the density model affected the simulations. In particular, parameter  $k_0$  (Eq. 11), describing the density change due to compaction, and the outflow parameter  $d$  (Eq. 10) were found to have sensitivities that are comparable to those of the input concentration of BC (Fig. 9). **The higher the values of the density parameters,  $k_0$  and  $d$ , the faster is snow compaction. More efficient compaction in turn entails higher impurity concentrations in the surface snow layer and thus enhanced melt rates. The parameters of the SSA model show the lowest sensitivity and therefore are less relevant for the results. The two parameters,  $SSA_{\min}$  and  $SSA_{\text{initial}}$  (Eq. 5), are the most sensitive ones. An increase in the two parameter values leads to a depletion in pure snow albedo which slightly diminishes the impact on snow impurities. However, this effect is small compared to the other uncertainties."**

*Specific questions related to these studies are: In the runs with altered concentrations of BC and dust within precipitation, was the total aerosol deposition conserved and the ratio of wet to dry deposition altered, or was the total aerosol deposition altered? (The latter case would presumably produce disagreement with the ice core data).*

Indeed, the total aerosol deposition was deliberately altered in order to show the effect of a potential over- or underestimation of dust/BC concentrations as the ice core data is not collected at the study site, but on another glacier in the Swiss Alps (see Section 5.4). The high spatial variability in atmospheric deposition rates of mineral dust and mainly BC makes it likely that dust/BC deposition on Claridenfirn probably slightly deviate from the ice core data. For this reason the amount of dust/BC was changed in the sensitivity analysis.

In our model we do not differentiate between dry and wet deposition as the contri-

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butions of dry deposition seems to be negligible (Schwikowski et al., 1995). This assumption is supported by the observation that Saharan dust containing layers in ice/firn cores generally have a thickness of several centimeters which indicates that Saharan dust was deposited during snow fall events. Furthermore, there is evidence that Saharan dust depositions in the Alps coincide with warm fronts causing precipitation (Schwikowski et al., 1995). For these reasons, we assume that all dust/BC is deposited by wet deposition. Hence, we do not consider the type of deposition in our sensitivity analysis.

We will include a table with the parameter ranges (see above) to clarify this issue. Furthermore, we reworded the corresponding sentence to make it clearer.

**Page 16, Lines 505–508**

"[...] Furthermore, we also assessed implications of deviating atmospheric deposition rates of mineral dust and BC on the mass balance as the ice core data is taken from another site (see Section 5.4).

*Secondly, how does variability in the ratio of haematite to goethite impact the simulations? In section 3.1.1 it is mentioned that these minerals have different absorption characteristics, but it seems that a single absorption coefficient is applied to all iron oxides. Is it merely through differences in the molecular weight of the two minerals that different haematite/goethite ratios impact the simulations?*

This is correct. The absorption coefficient was the same for both minerals, haematite and goethite, and only the molecular weight of the two minerals is responsible for the difference in the absorption. We do not consider different mass absorption coefficients for haematite and goethite because there are several other simplified assumptions in the calculation of the dust absorption involved (e.g. the constant ratio of haematite/goethite and a fixed amount of Fe encompassed in iron oxides) which

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introduce larger uncertainties.

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*General comment 2*

*One of the stated motivations for conducting this analysis at Claridenfirn is that there are 100 years of mass balance measurements at this location. It would therefore be helpful to include a comparison of the simulated and measured glacier mass balances, e.g., added to Figure 7. Was this excluded because the parameterization was heavily tuned to match the observations, and therefore the simulated and observed mass balances are essentially identical? If so, this should be stated more clearly. It is a bit unsettling that the parameters of the mass balance model were adjusted for each year of simulation (as indicated in section 3.5), though at least the ratio of weights applied to temperature and insolation was held constant throughout the simulation. Does the simulation that includes both black carbon and dust produce the best agreement with measured mass balance?*

As suspected by the referee, the observed and simulated mass balance are essentially identical as we have used the seasonal mass balance measurements to calibrate the melt and accumulation parameters for each year in order to reconstruct the mass balance evolution as accurately as possible. We decided to calibrate the accumulation and melt parameters annually in order to receive the “true” sequence of melt and accumulation events and its effect on the dust and BC concentration in the surface snow. Thus, we make optimal use of the long-term direct measurements to constrain our model. We added some further explanation about this issue to make it clearer. With this modelling setup it is thus not possible to answer the question if simulations including mineral dust and BC agree better with observations than simulations without snow impurities.

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**Page 10, Lines 314–318**

“[...] The melt parameters, TF and SRF, and the accumulation parameter,  $c_{\text{prec}}$ , were calibrated for each year individually by means of the seasonal balance measurements. This annual calibration ensures that simulated mass balances coincide with observations in order to extract an accurate sequence of melt and accumulation events controlling the surface concentrations of light-absorbing impurities.”

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*General comment 3*

*The black carbon mass absorption coefficient assumed in this study ( $7.5 \text{ m}^2/\text{g}$ ) is inconsistent with that assumed by Gardner and Sharp (2010) in their parameterization of albedo. They state that the maximum mass absorption coefficient of BC is  $6.8 \text{ m}^2/\text{g}$  at a wavelength of  $0.4 \mu\text{m}$ . This is relevant for the determination of a BC-equivalent dust concentration, which is based on the ratio of mass absorption coefficients of BC and iron oxides. This determination should be made consistently with the assumed absorptivity of BC in the Gardner and Sharp (2010) albedo model. This issue may not have a large impact on the results, but should be fixed or at least addressed.*

We thank the referee for the hint. We changed the value of the mass absorption coefficient to  $6.8 \text{ m}^2 \text{ g}^{-1}$  and updated the model results accordingly. As already mentioned by the referee the results are only marginally affected by this change.

**Page 7, Lines 218–221**

“[...] In order to model the effect of mineral dust on snow albedo, the mineral dust (i.e. Fe oxides) was converted to optically equivalent concentrations of light-absorbing carbon using mass absorption coefficients (MACs) of BC and Fe oxides of  $6.8 \text{ m}^2 \text{ g}^{-1}$  and  $0.56 \text{ m}^2 \text{ g}^{-1}$ , respectively (Alfaro et al., 2004; Kaspari et al., 2014).”

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*General comment 4*

*The methodological description for calculating radiative forcing needs more detail.*

C643

*This calculation appears to be based on melt production and is therefore different from other, commonly used (e.g., IPCC AR5) definitions of radiative forcing. If the radiative forcing is derived in terms of the amount of energy used to melt snow, it may underestimate the true radiative forcing, which also operates during the pre-melt season. Implications of such differences in methodology for comparisons with other studies should also be mentioned.*

We calculated the radiative forcing based on the melt production as supposed by the referee. According to the referee's suggestion we added more information about the calculation of the radiative forcing and included also comments about the differences to other studies.

#### **Pages 14–16, Section 5.1**

"Converting changes in annual mass balance caused by absorption of dust/BC into the energy consumed for melt allowed calculating the radiative forcing of snow impurities. The radiative forcing (RF,  $\text{W m}^{-2}$ ) was calculated based on the change in melt rate,  $\Delta M$  (m/s), caused by the presence/absence of mineral dust and/or BC in snow:

$$\text{RF} = \Delta Q_M = \Delta M L_f \rho_w \quad (1)$$

where  $Q_M$  ( $\text{W m}^{-2}$ ) is the energy consumed by melt,  $L_f$  ( $333\,700 \text{ J kg}^{-1}$ ) the latent heat of fusion and  $\rho_w$  ( $1\,000 \text{ kg m}^{-3}$ ) the density of water. Changes in melt rates are equal to changes in mass balances as presented in Section 4.2.2. For the measurement site in the accumulation area we found a mean radiative forcing over the 100 year period of  $+0.3 \text{ W m}^{-2}$  due to Saharan dust, whereas at the stake close to the equilibrium line the radiative forcing was  $+0.6 \text{ W m}^{-2}$ . In contrast to Saharan dust, the radiative forcing of BC over 1914–2014 was about seven times larger, and was  $+2.0$  and  $+3.3 \text{ W m}^{-2}$  on average for the two sites. In the summer months, July and August, when melting is strongest, the radiative forcing for BC reached values of  $8.7$ – $9.7 \text{ W m}^{-2}$  and for Saharan dust of  $3.0$ – $3.7 \text{ W m}^{-2}$  compared to pure snow at the upper stake, and  $12.9$ – $15.9$  and  $4.7$ – $6.3 \text{ W m}^{-2}$  at the lower stake, respectively. At the daily scale, maximum modelled radiative forcing was  $15$ – $42 \text{ W m}^{-2}$  for Saharan dust and  $43$ – $66 \text{ W m}^{-2}$  for BC.

At a global scale, the mean radiative forcing from BC in snow is reported to be in the range of  $0.02$ – $0.08$

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$\text{W m}^{-2}$  (Bond et al., 2013; IPCC, 2013). During boreal spring, when the snow-albedo feedback is maximal, the radiative forcing of mineral dust and BC over Eurasia is higher and amounts to  $1.2$  and  $2.7 \text{ W m}^{-2}$ , respectively (Flanner et al., 2009). For snow-covered surfaces of the Tibetan Plateau the radiative forcing of BC reaches values of up to  $5$ – $25 \text{ W m}^{-2}$  in springtime (Flanner et al., 2007; Kopacz et al., 2011; Qian et al., 2011). Similar peak values are found for desert dust in the mountain snow cover of the Colorado River Basin ( $25$ – $50 \text{ W m}^{-2}$ , Painter et al., 2007; Skiles et al., 2012). In general, radiative forcing of BC found for Claridenfirn is at the lower end of the range of values obtained for Colorado or Tibetan Plateau. Regarding mineral dust, the effect is also clearly stronger on the Colorado Plateau than in the Alps. In terms of maximum daily radiative forcing, values obtained for Claridenfirn are of similar magnitude as for other regions. However, radiative forcing reported in other studies is not directly comparable to the results of this study as dust/BC sources and the temporal dynamics of melting are different. Furthermore, radiative forcing of some of the above-mentioned studies was calculated by directly accounting for the change in the energy fluxes, rather than using the change in melt rates due to light-absorbing impurities as in our approach. Hence, the radiative forcing reported here represents a lower limit as the radiative impact in the pre-melt season is not taken into account."

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#### **General comment 5**

*I suggest modifying the title to indicate that the study focuses on Swiss or Alpine glaciers, or even specifically to the Claridenfirn. The current title implies a general study of glacier impacts associated with BC and dust, but the analysis is really quite specific to the Swiss Alps.*

We agree with the referee's suggestion and have changed the title accordingly.

#### **Page 1, Title**

"The impact of Saharan dust and black carbon on albedo and long-term mass balance of an Alpine glacier."

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C645

## Minor comments

### Comment 1

Page 1134, Line 10: “employed to assess dust/BC-albedo feedback” - To many, “albedo feedback” implies feedback between the atmosphere and land surface, which is not assessed here. The meaning of “feedback” in this context should be clarified.

We have rephrased the corresponding sentence.

### Page 1, Lines 7–9

[...] A combined mass balance and snow/firn layer model was employed to assess the effects of melt and accumulation processes on the impurity concentration at the surface and thus on albedo and glacier mass balance.”

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### Comment 2

Page 1134, Line 16: “dust-enriched layers” - Should this be “dust and BC-enriched layers”?

Right! We have replaced the term “dust-enriched layers” with “dust and BC-enriched layers” where required throughout the whole manuscript.

### Page 1, Lines 14–17

[...] The upper site has experienced mainly positive mass balances and impurity layers were continuously buried whereas at the lower site, surface albedo was more strongly influenced by re-exposure of dust and BC-enriched layers due to frequent years with negative mass balances.”

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### Comment 3

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Page 1135, Line 26: “Since mid-20th century BC concentrations started to decrease and have stabilised over the last few decades (Bond et al., 2007)” - Although European emissions have declined during the past few decades, Figure 6 of Bond et al. (2007) indicates that global BC emissions have continued to rise. It wasn't clear if this passage was meant to refer to global or European emissions.

We agree with the referee that this statement is confusing and have clarified the sentence.

### Page 2, Lines 47–50

[...] Along with the beginning of the industrialisation global BC emissions sharply increased and continued to rise into the 21st century. In the European region BC concentrations started to decrease since mid-20th century and have stabilised over the last few decades (Bond et al., 2007).”

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### Comment 4

Page 1136, Line 16: “we examined the dust/BC-melt feedback” - Again, please clearly define this feedback. Here, I believe it refers to enhanced melt induced by BC/dust, which in turn increases the surface layer concentration of BC/dust and thereby further increases melt.

We have rephrased this sentence according to the referee's suggestion.

### Page 3, Lines 63–68

[...] Using a unique 100-year record of seasonal glacier mass balances, ice core records of past atmospheric deposition of Saharan dust/BC and a sophisticated modelling approach, we examined the contribution of light-absorbing impurities to glacier melt for (1) a site with accumulation conditions over the entire period, where dust is predominately buried by winter snow, and (2) a site at the glacier's equilibrium line involving a re-exposure of buried dust and BC layers at the surface in years with negative mass balance.”

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*Comment 5*

*Page 1138, Line 17: "... an annual cycle of BC concentrations in the atmosphere" - This seems like a useful way of deriving seasonal variations in BC deposition from annually-resolved ice core data, but I wonder if the seasonal cycle of BC deposition could have been different 100 years ago, e.g., due to more generation of BC for winter heating purposes. It would be interesting to include a sensitivity study that varies the seasonal cycle of BC deposition. I would not consider this critical for the paper, though, so I leave it up to the authors.*

The referee mentions an interesting point. In fact, BC emissions over populated regions are generally higher in winter than in summer (Herich and Hüglin, 2013). However, variations in BC depositions at high altitude sites are not driven by the seasonal cycle of BC emissions in lower regions, but by changes in atmospheric stability (Baltensperger et al., 1991). Only in summer polluted air masses from the lowlands are transported upwards by thermal convection. In winter, the high-altitude sites are above the mixing layer and are generally not reached by the polluted air masses (Baltensperger et al., 1991). This can also be observed for sulfate, an anthropogenic pollutant, which is also mainly emitted in winter and is transported primarily in summer by thermal convection to high-altitude sites (Schwikowski et al., 1999). Accordingly, we suppose that the seasonal pattern of BC emission has not changed much over the last century. For this reason, we decided not to test the sensitivity of the annual BC cycle.

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*Comment 6*

*Page 1139, Line 11: "... the ratio of haematite to haematite plus goethite" - Is this the mass ratio of minerals, or the mass ratio of Fe within the minerals?*

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It corresponds to the mass ratio of minerals. We have added this information to the manuscript.

**Page 5, Lines 138–140**

"[...] According to Shi et al. (2011) the mass ratio of the mineral haematite to the minerals haematite plus goethite for Saharan dust is 0.42 on average."

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*Comment 7*

*Section 3.3: Does the albedo model provide diffuse or direct-beam albedo? If the latter, how was solar zenith angle incorporated into the model? Please include more detail on this.*

The model, as applied in our study, provides direct-beam albedo. The albedo model of Gardner and Sharp (2010) offers the possibility to account for variations in the solar zenith angle. However, the effect of the solar zenith angle on the albedo is largest at high solar zenith angles i.e. in the early morning or evening and in winter when melt rates are low. Furthermore, the model runs on a daily basis. For this reason we do not account for the solar zenith angle on the albedo calculation. We now provide this information in the manuscript.

**Page 7, Lines 222–223**

"[...] The direct-beam albedo of the impurity-loaded snow is then obtained as  $\alpha = \alpha_{SSA} + d\alpha_C$ . The effect of the solar zenith angle on the albedo is not considered as the model runs on daily basis."

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*Comment 8*

C649

Page 1143, Equation 6: Is Delta  $R_{opt}$  a rate (e.g., mm/day)? Please include units for this term.

The unit of Delta  $\Delta R_{opt}$  is indeed  $\text{mm d}^{-1}$ . There is an error in the unit of the empirical coefficients  $C_1$  and  $C_2$ . Instead of  $\text{mm d}^{-1}$  the unit should be  $\text{mm}^3 \text{d}^{-1}$ . We added the unit of  $\Delta R_{opt}$  and changed the units of the empirical coefficients accordingly.

**Page 8, Lines 231–238, Equation 6**

"[...] The approximation by Brun (1989) is used to simulate the evolution of snow grains under wet conditions with respect to the liquid water content of the snowpack. The growth of the optical radius of snow,  $\Delta R_{opt}$  ( $\text{mm d}^{-1}$ ), is calculated as

$$\Delta R_{opt} = \frac{C_1 + C_2 \cdot \theta^3}{R_{opt}^2 \cdot 4\pi}, \quad (2)$$

where  $C_1 = 1.1 \times 10^{-3} \text{ mm}^3 \text{ d}^{-1}$  and  $C_2 = 3.7 \times 10^{-5} \text{ mm}^3 \text{ d}^{-1}$  are empirical coefficients and  $\theta$  is the liquid water content in mass percentage. The SSA decrease is more pronounced when  $\theta$  increases."

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**Comment 9**

Page 1144, Line 1: I think  $C_1$  should be  $10^{-3}$  rather than  $10^3$ .

This is correct. We have changed the unit accordingly.

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**Comment 10**

Section 4.2: Please clarify whether the calculated albedo reductions are relative to pure snow, or relative to snow only without BC (in the case of dust estimates) or without dust (in the case of BC estimates)

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We have added the missing explanation (see Section 4.2 in the revised manuscript).

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**Comment 11**

Page 1152, Lines 6-9: Please clarify this sentence.

We have rephrased this sentence.

**Page 13/14, Lines 421–429**

"[...] However, changes in mass balance cannot be directly deduced from average dust concentrations because (1) the impurity concentration and albedo changes are not linearly related and thus a higher impurity concentration might lead to smaller changes in albedo, and (2) during years with high melt rates also other particulate impurities accumulate at the surface which limits the total impact of Saharan dust on surface mass balance. Thus, despite the exceptionally high surface concentration in 2007, the change in mass balance is only slightly larger than in years with lower surface concentrations as for example in the deposition intense year 2000 (Fig. 8a and c)."

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**Comment 12**

Figure 6: If this shows an absorption optical depth, as indicated in the caption, over what thickness of snow/ice is it derived from? Optical depth is usually calculated over the entire column. The quantity shown in this figure needs to be defined more clearly.

The absorption/optical depth is calculated as the product of the mass absorption coefficient of dust/BC and the loading in the surface snow layer i.e. the mass of dust/BC in the top 2 cm. We added this information to the caption of Figure 6.



"Figure 6 Mean annual absorption (optical depth) of mineral dust and BC over the period 1914– 2014 for (a) the upper and (b) the lower stake. The optical depth is calculated as a product of the mass absorption coefficient of BC/Fe oxides and the corresponding loading in the snow surface layer (top 2 cm)."

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## Comments of Anonymous Referee #2

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### *General comment 1*

*There are revisions that would improve this paper. 1) Given that 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.

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

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*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 484–499**

"[...] 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), 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."

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*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.

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*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*

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

Done.

C655

**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."

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*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."

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*Comment 3*

*Page 1135, Line 6: Consider changing "involving" to "perturbing".*

We changed "involving" to "resulting in" to make it clearer.

**Page 2, Lines 29–31**

"[...] 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)."

C656

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*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 34–37**

"[...] 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)."

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*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 43–45**

"[...] BC has become a focus of interest as it has been identified recently as one of the major contributors to global climate change (Ramanathan and Carmichael, 2008; Bond et al., 2013 )."

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*Comment 6*

C657

*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 56–58**

"[...] 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)."

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*Comment 7*

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

We have split this sentence.

**Page 3, Lines 68–71**

"[...] 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."

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*Comment 8*

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

C658

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

**Page 3, Lines 84–85**

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

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*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 113–116**

"[...] 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)."

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*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).*

We have added the missing information to the corresponding paragraph.

C659

**Page 5, Lines 132–135**

"[...] 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."

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*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 293–294**

"[...] 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)."

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*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.

**Page 12, Lines 374–378**

C660

"[...] 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."

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*Comment 13*

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

Done.

**Page 12, Lines 380–381**

"[...] 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."

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*Comment 14*

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

We have reworded this sentence.

**Page 12, Lines 385–386**

"[...] 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.*

C661

We have rephrased this sentence.

**Page 13, Line 400–401**

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

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*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 470–472**

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

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*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.

**Page 15, Lines 477–479**

"[...] 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."

C662

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*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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C663

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