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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 are grateful for the thorough review by Anonymous Referee #1 on our manuscript and the suggestions for improving it. The main concern was to broaden and clarify the sections about the sensitivity study and the radiative forcing which we have done accordingly. We thank the referee for the hint that the mass absorption coefficient of BC is not in accordance with the applied albedo parameterisation proposed by Gardner and Sharp (2010). We have changed the value of the mass absorption coefficient and have updated the modelling results accordingly. Finally, we have changed the title of the paper 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 changes applied is given (normal type style). The revised version of the text is given in smaller script size and quotation marks.

Comments of Anonymous Referee #1

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.

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 26, 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 ($\mathrm{SSA_{initial}}$, $\mathrm{SSA_{min}}$, 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 ±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 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$_{\text{min}}$ 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.**"

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
Impurity model			
Dust input	$\mathrm{g\,kg^{-1}}$	22.3	17.8 - 26.8
BC input	$\mathrm{g\,kg^{-1}}$	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
SSA model			
SSA$_{\text{initial}}$	$\mathrm{m^2\,kg^{-1}}$	73.0	58.4 - 87.6
SSA$_{\text{min}}$	$\mathrm{m^2\,kg^{-1}}$	8.0	6.4 - 9.6
C_1	$10^{-3}\,\mathrm{mm^3\,d^{-3}}$	1.1	0.88 - 1.32
C_2	$10^{-5}\,\mathrm{mm^3\,d^{-3}}$	3.7	2.96 - 4.44
Snow density model			
a_t	$^\circ\mathrm{C\,mm^{-1}}$	0.033	0.0264 - 0.0396
c_1	$\mathrm{m^2\,h^{-2}\,kg^{-1}}$	0.001	0.0008 - 0.0012
k_0	$\mathrm{m^3\,kg^{-1}}$	0.021	0.0168 - 0.0252
k_1	$^\circ\mathrm{C^{-1}}$	0.08	0.064 - 0.096
F_C	-	0.02	0.016 - 0.096
c	$\mathrm{m^{-1}\,h^{-(d-1)}}$	1.0	0.8 - 1.2
d	-	1.25	1.0 - 1.5

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 contributions 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 492–494

"[. . .] 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 introduce larger uncertainties.

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.

Page 11, Lines 311–314
"[. . .] The melt parameters, TF and SRF, and the accumulation parameter, c_{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."

General comment 3
The black carbon mass absorption coefficient assumed in this study (7.5 m^2/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 m^2/g at a wavelength of 0.4μm. 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 m^2 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 216–220
"[. . .] 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 m^2 g^{-1} and 0.56 m^2 g^{-1}, respectively (Alfaro et al., 2004; Kaspari et al., 2014)."

General comment 4
The methodological description for calculating radiative forcing needs more detail. 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 14/15, 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, W m^{-2}) was calculated based on the change in melt rate, ΔM (m/s), caused by the presence/absence of mineral dust and/or BC in snow:

$$\mathrm{RF} = \Delta \mathrm{Q_M} = \Delta \mathrm{M}\,\mathrm{L_f}\,\rho_\mathrm{W} \quad (1)$$

where Q_M ($\mathrm{W\,m^{-2}}$) is the energy consumed by melt, L_f (333'700 $\mathrm{J\,kg^{-1}}$) the latent heat of fusion and ρ_W (1'000 $\mathrm{kg\,m^{-3}}$) 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 $\mathrm{W\,m^{-2}}$ due to Saharan dust, whereas at the stake close to the equilibrium line the radiative forcing was +0.6 $\mathrm{W\,m^{-2}}$. 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 $\mathrm{W\,m^{-2}}$ 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 $\mathrm{W\,m^{-2}}$ and for Saharan dust of 3.0–3.7 $\mathrm{W\,m^{-2}}$ compared to pure snow at the upper stake, and 12.9–15.9 and 4.7–6.3 $\mathrm{W\,m^{-2}}$ at the lower stake, respectively. At the daily scale, maximum modelled radiative forcing was 15–42 $\mathrm{W\,m^{-2}}$ for Saharan dust and 43–66 $\mathrm{W\,m^{-2}}$ 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 $\mathrm{W\,m^{-2}}$ (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 $\mathrm{W\,m^{-2}}$, 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 $\mathrm{W\,m^{-2}}$ 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 $\mathrm{W\,m^{-2}}$, 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."

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."

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."

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 13–16
"[. . .] 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."

Comment 3
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 46–49
"[. . .] Along with the beginning of the industrialisation global BC emissions sharply increased and continued to rise into the 21th 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)."

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 62–66
"[. . .] Using a unique 100-year record of seasonal glacier mass balances, ice core records of past atmospheric deposition of Saharan dust and BC and a sophisticated modelling approach, we examined to 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."

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.

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?

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

Page 5, Lines 136–137

”[. . .] 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.”

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 angels 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 8, Lines 220–221

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

Comment 8
Page 1143, Equation 6: Is Delta R_opt a rate (e.g., mm/day)? Please include units for this term.

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

Page 8, Lines 228–234, 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, ΔR_{opt} ($\mathrm{mm\,d^{-1}}$), is calculated as

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

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

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.

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)

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

Comment 11
Page 1152, Lines 6-9: Please clarify this sentence.

We have rephrased this sentence.

Page 14, Lines 414–420
"[. . .] 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)."

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.

Page 30, Caption Fig. 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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