

Response to: Interactive comment on "Saharan dust events in the European Alps: role on snowmelt and geochemical characterization" by Biagio Di Mauro et al.

Reviewer: Dr. Marion Greilinger

Authors responses are in *italic*, Reviewer's comments are in **bold**. Line and figures numbers refer to the track-changes version of the manuscript.

Review of:

Title: Saharan dust events in the European Alps: role on snowmelt and geochemical characterization

My recommendation

Major revisions due to general and specific comments listed below.

The authors investigate the input of mineral dust (MD) on the geochemistry as well as the impact on snowmelt in the Aosta Valley, Italy at 2160m a.s.l. within the accumulation periods 2013/14, 2014/15 and 2015/16. The study investigate the evolution of snow melt off via in-situ observations, digital images, AWS data and modelling. Besides the investigation of a snow darkening index representative for MD on the snow surface, a geochemical characterization from MD affected and non-affected snow was presented as well. Authors observed a shortening of the snow season, concluding that MD accelerate snow melt-out dates.

The addressed topic is of interest for the Cryosphere community, but also for the climate modelling (e.g. surface albedo feedback) and remote sensing community (e.g. validation and calibration of satellite images).

Dear Dr. Greilinger, thank you for the positive evaluation of the manuscript. We have carefully considered each of the Reviewer's comments and suggestions. The Reviewer will find below the responses to general and specific comments.

General comments:

My major concern is the structure and the "red line" throughout the manuscript. The manuscript suffers from many repetitions and the text does not account to the corresponding headline. Therefor it is very hard to read and needs a lot of scrolling to other passages to follow the "story" behind. It would be of much help for the reader and hence also of much more interest if this would be revised and shortened rigorously (therefore major revisions). Authors should think of splitting the results from the discussion into separate section. The manuscript might get ab bit more reader-friendly. Besides, citations seem to be sometimes randomly used whereas they are missing at points were there should be a quote. Authors should cite from recent to past or vice versa, but consistently throughout the manuscript. Details on the general comments raised above can be found in the specific comments below.

We removed repetitions along the manuscript, and we shortened it as suggested also by the other reviewer. Many paragraphs were moved in order to render the manuscript more fluid and reader-friendly. We carefully revised the citations in the manuscript. Regarding Section 3, we prefer to keep the results and discussion tied together in our paper.

Specific comments:

P1 L18 change "snowpack in a..." to "snow packs at a..."

We modified accordingly

P1 L28 ff Aren't these the results from the comparison of Crocus model results without impurities vs. observations? Otherwise to which reference do the values of 38 days etc. refer?

Yes, they are referred to the comparison between the snow depth from the model without impurities and the observed one. The sentence now reads:

"In our case study, the comparison between modeling results and observation showed that impurities deposited in snow anticipated the disappearance of snow up to 38 days for the 2015/2016 season that was characterized by a strong dust deposition event, out of a total 7 months of typical snow persistence"

P1 L34 Include also the importance on snow albedo feedback

We modified accordingly, the sentence now reads:

"We conclude that the effect of the Saharan dust is to anticipate the snow melt-out dates through the snow-albedo feedback. This process is known to have a series of further hydrological and phenological feedback effects, that should be characterized in future research"

P2 L7 remove sentence "These phenomena..."

We removed the sentence.

P2 L13 "...dust lowers THE snow albedo..."

We modified accordingly.

P2 L16 ff Which citation refers to which statement? One reference used twice in one sentence - maybe rewrite the sentence

We merged all the references at the end of the sentence, since they are all referring to the effect of dust on snow in Western US.

P2 L22 remove "s" from "centurys"

The spelling is already corrected.

P2 L30 maybe also include Greilinger et al here

We added this reference.

P2 L34ff remove "of the planet", change "Thanks to.." to "Due to.."

We prefer to keep the sentence as it is: "Even though the Alps are located at a distance of about 3000 km from the largest desert of the planet". In

the following sentence, we replaced "thanks to" with "due to" according to your comment.

P2 L40 "...precipitation and HENCE dust scavenging..."

We modified accordingly.

P3 L40 define LAPs here

We already defined the acronym LAPs in pg2 ln14. We added here which kind of LAPs were considered in the study (mineral dust and black carbon). The sentence now reads:

"[...] which can incorporate the effect of LAPs (mineral dust and black carbon) in snow [...]"

P4 L11ff "...was installed in 2009 measures air temperature (HMP45, Vaisala Inc.) and snow height (ultrasonic sensor SR50A, Campbell Scientific Inc.)."

We prefer to keep the sentences separated, since the AWS measures a variety of variables described below in the paragraph (not only air temperature and snow depth).

P4 L18 - P5 L2 belongs to introduction

We shortened the paragraph and we used it to introduce the use of digital images in the methodology section. The sentence now reads:

"In recent years digital images analysis was applied to the monitoring of vegetation phenology (Julitta et al., 2014; Migliavacca et al., 2011; Richardson et al., 2007), landslides, glaciers (Jung et al., 2010) and snow (Corripio, 2010; Dumont et al., 2011; Hinkler et al., 2010; Parajka et al., 2012). Regarding the two latter, using digital cameras researchers successfully retrieved snow albedo and snow cover in alpine areas."

P5 L3 Include new subsection 2.2 RGB images or digital images or similar

We introduced a new section:

"2.2 Digital images analysis"

P5 L6 rephrase "...and the same view scene was repeatedly captured" What would you like to say?

We meant that the camera is fixed, and the same scene is repeatedly photographed. The sentence now reads:

"and the same scene was repeatedly photographed"

P5 L7 ..."format WITH a resolution of..AND three-color channels (red, green, blue)..."

We modified accordingly.

P5 L9 Just as suggestion, it is always nice to refer to UTC. If you use local time, please specify time zone.

We used local time, that is in "UTC+1". We added this information in the manuscript:

"The images were collected from 10 am to 5 pm (local time: UTC+1), with an hourly temporal resolution."

P5 L16 "Following Di Mauro et al. (2015) and Ganey et al. (2017) SDI was correlated...distribution of deposited impurities ~~from space~~ ..."

Actually, in Di Mauro et al. 2015 we developed the regression models from field spectral data and radiative transfer modeling to link SDI and mineral dust concentration in snow. Then Di Mauro et al. 2017, and Ganey et al. 2017 used the index for mapping different kind of impurities from space. For these reasons, we prefer to keep the sentence in its original form.

P5 L17 What do you mean with "and from hypospectral imagery of ice cores"?

In Garzonio et al. 2018, we calculated the index from hyperspectral images acquired on an ice core drilled in the Alps for representing a time series of impurities deposition on a glacier. The high spectral resolution of these images allowed the calculation of different spectral indices.

For clarity, we replaced "imagery" with "images".

P5 L24 "using THE SURFEX..."

We modified accordingly.

P5 L25 "...estimation AS WELL AS numerical..."

We modified accordingly.

P5 L28 "...and mass transfer between the snowpack and the atmosphere as well as the snowpack and the ground..."

The model simulates also energy and mass transfer within the snowpack, the sentence now reads:

"Snow dynamics are represented as a function of energy and mass-transfer within the snowpack, between both the snowpack and the atmosphere, and the snowpack and the ground below"

P5 L31 "...snow properties, LAPs concentrations and..."

We modified accordingly.

P5 L33 "...and accounts for...and impurities such as dust and black carbon."

We modified accordingly.

P5 L34 "...TARTES was used to calculated SDI..." How was this done?

SDI was calculated using the formulation proposed in Di Mauro et al. 2015. The sentence now reads:

"Snow spectral albedo simulated with TARTES was used to calculate SDI (using the formulation proposed in Di Mauro et al. 2015), and it was compared with SDI calculated from the digital camera"

P6 L15 "...a few meters apart from the AWS."

We modified accordingly.

P6 L16 "...from a pit at depths of..."

The sentence now reads:

"For each snow pit, we collected a surface samples at 0 cm, and three samples at depths equal to 20, 40, and 60 cm from the surface"

P6 L18 remove "successive"

We modified accordingly.

P6 L20 "...particles between 2 and 60µm (equivalent spherical diameter)."

For clarity, we prefer to keep this sentence in its original form.

P6 L22 reference why you use 2.5G/cm³, Why exactly this number?

This is the common value used since the very early studies about the atmospheric mineral dust content extracted from ice cores (Hänel, 1968; Royer et al., 1983). It is slightly lower than the average continental crust density (that is about 2.9 g cm⁻³), since it was assessed that the mineral assemblage that characterize mineral aerosols is lighter than the average continental one (Hänel, 1968).

We deem that, in the manuscript, the reference to Ruth et al. 2008 is exhaustive.

-Hänel, 1968: The real part of the mean complex refractive index and the mean density of samples of atmospheric aerosol particles

-Royer et al., 1983: A 30000 year record of physical and optical properties of microparticles from an East Antarctic ice core and implications for paleoclimate reconstruction models

-Ruth, U., Barbante, C., Bigler, M., Delmonte, B., Fischer, H., Gabrielli, P., Gaspari, V., Kaufmann, P., Lambert, F., Maggi, V., Marino, F., Petit, J.-R., Udisti, R., Wagenbach, D., Wegner, A. and Wolff, E. W.: Proxies and Measurement Techniques for Mineral Dust in Antarctic Ice Cores, Environ. Sci. Technol., 42(15), 5675-5681, doi:10.1021/es703078z, 2008.

P6 L25-P7 L17 could be shortened, many passages not necessary. It is the Data and methods section!

As suggested also by the other Reviewer, these paragraphs were moved to Section 3.3

P7 L23 "...in 'strong' events with dust deposition fluxes...and 'weak' events with lower concentrations."

We modified accordingly.

P7 L36-P8 L2 removes paragraph, it is the Data and methods section!

We removed lines 36-38 pg. 7 as suggested also from the other Reviewer. We prefer to keep here the other sentence since it describes Figure 2, which is a Result.

P7 L10 remove first sentence

We removed the sentence accordingly.

P7 L11 "...variables observed at Torngon station and simulated with the Crocus model using..."

We modified accordingly.

P8 L15 "In Figure 3d ..."

We modified accordingly.

P8 L16ff Remove sentences "Strong and weak..." as well as "ALADIN CLiamte..."

We modified accordingly.

P8 L17 You found a good agreement between the qualitative information, but how about the quantitative?

For this preliminary comparison between NMMB/BSC-dust and ALADIN we were interested in the agreement of the timing of dust events. Results showed that both models predicted at least two strong events in the same periods (February 2014, and April 2016). Several weaker events were also detected by both models. A quantitative evaluation of this comparison is actually out of the scope of our manuscript.

P8 L27 Please be more explicit why results before explain the large different in snow melt out dates.

We now added this sentence to better explain the higher concentration simulated in surface snow:

"This can be due to the longer duration of the dust event in April 2016, and may also explain the large change (38 days) in the snow melt-out dates observed in the data"

P9 Figre3 I personally have difficulties to read and interpret Figure 3d and especially Figure 3e. Maybe explain in more detail in the text (and/or legend) what is the shaded area and what is the colored (reddish, yellowish) area?

We added further details in the legend of Figure 3, now it reads:

"Figure 3 a)-b)-c): time series of albedo, snow water equivalent (SWE), and snow depth (SD) measured with the AWS and simulated with Crocus model including and excluding the impact of LAPs. SWE data are missing in December 2013 because of problems with the power supply. d): dust fluxes simulated with ALADIN (maroon bars, note that the scale is inverted), and strong (large stars), and weak (small stars) dust events simulated with NMMB/BSC-Dust. e): dust concentration ($\mu\text{g/g}$) in the snowpack (yellow to black palette) simulated with Crocus and superimposed on the snow depth profile (grey shaded area). f): surface concentration (averaged over the first 10 cm) of dust simulated with Crocus."

P9 Table1 It would be also nice to show the correlation with the Crocus model without impurities

We added this information. We now created a Figure (i.e. Figure 4) for comparing R^2 and RMSE for Crocus simulation accounting and not accounting for the impact of LAPs. Here the new figure:

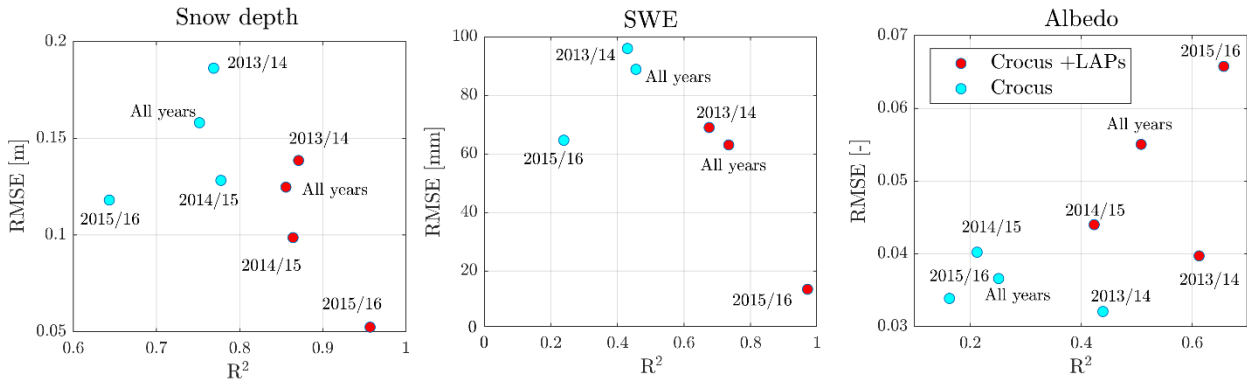


Figure 4 Comparison between snow depth (SD), snow water equivalent (SWE) and albedo observed from the AWS station in Torgnon and simulated with Crocus accounting and not accounting for the impact of LAPs on snow

Furthermore, we realized that that was an error in the time series of snow albedo in Figure 3 of the manuscript. We now corrected the series. Here the new Figure 3:

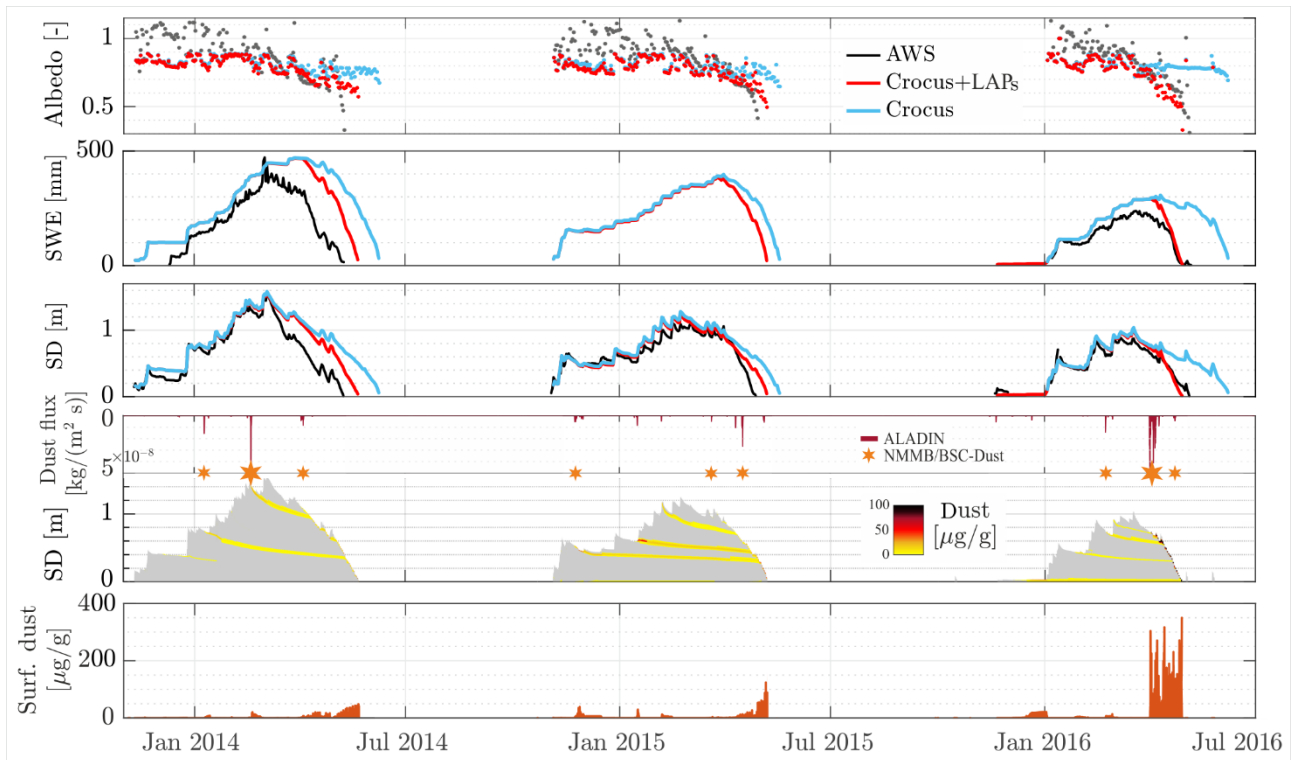


Figure 3 a)-b)-c): time series of albedo, snow water equivalent (SWE), and snow depth (SD) measured with the AWS and simulated with Crocus model including and excluding the impact of LAPs. SWE data are missing in December 2013 because of problems with the power supply. d): dust fluxes simulated with ALADIN (maroon bars, note that the scale is inverted), and strong (large stars), and weak (small stars) dust events simulated with NMMB/BSC-Dust. e): dust concentration ($\mu\text{g/g}$) in the snowpack (yellow to black palette) simulated with Crocus and superimposed on the snow depth profile (grey shaded area). f): surface concentration (averaged over the first 10 cm) of dust simulated with Crocus.

P9 L12 "...8.5µm for snow samples collected at 20cm and 40cm depth, instead..."

We modified accordingly.

P9 L15 Remove the sentence "At the bottom.."

We modified accordingly.

P9 L16 Authors say that results are comparable with other studies. Please give some numbers what others found, not only the citation.

We added the size distribution found by the referenced studies. Now the sentence reads:

"Dust size distributions are compatible with other measurements of dust enclosed snow and ice in the Alps (3-5 μm , Maggi et al., 2006), and in Caucasus (1.98-4.16 μm , Kutuzov et al., 2013). Differences between our samples and these studies may be ascribed to the different altitude of the samplings."

P9 L17 "Samples shown in.."

We modified accordingly.

P10L8 - P11L27 Please work through the whole section. Parts of the text are already mentioned before, conclusions drawn here are not obvious for the reader. Where exactly do I see the marked change in snowmelt rate and the induced earlier snowmelt in Figure 3e? Here you also mention already some conclusions. It is the Results and discussion section!

In these paragraphs, we present a focus on the 2015/2016 season. So, we briefly resume the role of dust on snow in this season. We removed some repetitions in the text. The marked change in snowmelt rate is clearly visible from the drop of snow depth in Figure 6. We removed the repetition in the following sentence. The sentence now reads:

"[...] a marked change in snowmelt rate is observed from the snow depth series around the 20th of April (Figure 6)."

P13 Figure5 "...data are also shown (black line)."

We modified accordingly.

P13 L10 "In the upper part of Figure 6 ..."

We modified accordingly.

P14 L1 "In the lower part of ..."

We modified accordingly.

P14 L5 Why are you sure that the red line is IN the pit? Couldn't this be also a shadowing effect of e.g. an uneven surface? Why should the February event be visible only in the area of the pit?

We just provided a possible interpretation of that pattern in the snow pit. The February event may be visible only in that area because it was then buried from new snow during the season. We modified the sentence, that now reads:

"This can be possibly associated with the precedent 'weak' depositions from February and March, which were concentrated in a thin snow layer by melting during early spring"

P14 L14 Which non-linear model? Explain and describe the model of Di Mauro et al. 2015 shortly.

We added further details on the nonlinear model that we used. Now the sentence reads:

"Using this information, we inverted the nonlinear (rational) model developed in Di Mauro et al. (2015) that links mineral dust concentration and SDI values, and we obtained an estimated dust concentration equal to $56 \mu\text{g}_{\text{dust}} \text{g}^{-1}_{\text{snow}}$."

P14 L24-L31 repetition and extensive discussion (maybe start a separate discussion section related to the sections in the results.

We removed repetitions from this paragraph.

P14 L32- P15 L2 Belongs to the introduction

We removed part of this text, since the issue was already present in the introduction section

P15 L3-L7 is an outlook, move to summary

We believe that this outlook sentence is better suited for this section, because it is meant to put our results in the broader context of long-term monitoring of dust and black carbon depositions.

P15 L8-L18 another discussion block

As we stated in the answer to your general comment, we prefer to keep the results and discussion tied together.

P15 L20-L26 move to introduction

We prefer to keep these introductory sentences in this chapter. They are important for putting into context the geochemical characterization of dust.

P15 L27 "The analysis of the elemental composition allowed..."

We modified accordingly.

P15 L28 Is the threshold of definition of major and minor components referring to > or < than 1% of the average crust composition set by the authors? Reference?

This definition is widely used in the geochemistry scientific community, and it can be found in any geochemistry textbook (e.g. Geochemistry, W.M. White, Wiley-Blackwell). The definition is already reported in the manuscript at pg 18 ln 10.

P16 Table2 state somewhere in the legend or in the plot that SH1 is the dust affected and SH2 the clean snow! This would help the reader. Otherwise readers have to go back to the Methods section to check this. What are the value in the brackets? Why are some elements given in % mass fraction and others in $\mu\text{g}/\text{g}$? This makes it difficult to compare.

In the caption of Table 2 (that became Table 1 in the revised version of the manuscript) we added the information on SH1 and SH2, and the meaning of values in the brackets (that are measurements uncertainties). Furthermore, we converted all elements concentration to $\mu\text{g/g}$. Now the caption of Table 1 reads:

"The elemental composition of SH1 (snow sample containing mineral dust) and SH2 (clean snow sample). Data are expressed in terms of $\mu\text{g g}^{-1}$ and are referred to the mass of the extracted material, not to the considered snow volume. Values in brackets are measurement uncertainties. Normalized concentrations were calculated considering the Upper Continental Crust as a reference (Rudnick and Gao, 2003).

Regarding the description of errors, in the methods section we now added:

"For a complete description of the method, including the estimation of errors, see Baccolo et al. (2015, 2016)."

P17 L1 "Concentrations of major elements normalized to the upper continental crust composition are shown..."

We modified accordingly.

P17 L9 "...see in Figure 7c."

The comparison was made in each sub plot of Figure 8, not only Figure 8c.

P17 L13 For Fe this is even more than 30 times if I am not mistaken.

Actually, Fe is 222 times more concentrated in SH1 with respect to SH2 (40000 $\mu\text{g/g}$ for SH1, versus 180 $\mu\text{g/g}$ for SH2). For this reason, we wrote that the "absolute concentrations that are more than two orders of magnitude higher".

P17 L23 remove the sentence "This is related to..." This is discussed again few lines below

We modified accordingly.

P17 L27 remove "not with the first one"

We modified accordingly.

P17 L35 Actually it is not the Ca which is affecting the pH but the related Carbonate! Include here the Carbonate discussion from L23

We modified the sentence, that now reads:

"The Ca component of carbonates, beside affecting soil pH and improving soil structure, have important effects on ecosystem physiology (Schaffner et al., 2012)."

P17 L37 remove the bracket

We modified accordingly.

P17 L35-P18L3 maybe rephrase the whole paragraph, difficult to see what the authors like to say

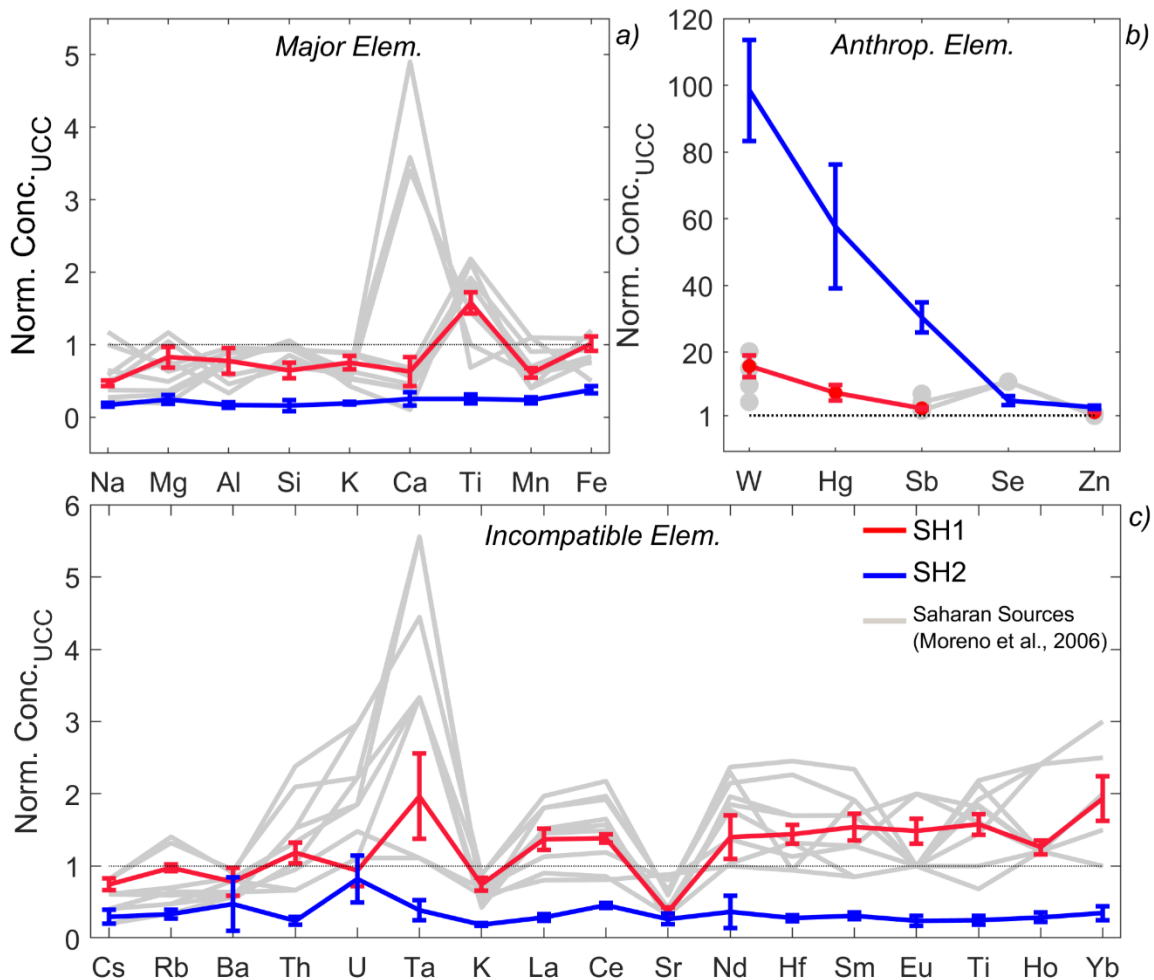
We rephrased the whole paragraph, shortening it. Now it reads:

"For both elements, SH1 shows notably higher concentrations (see Table 1). This requires more attention and further studies to understand the feedback of Saharan dust deposition on biogeochemistry of high-altitude ecosystems"

P18 Figure7 What is the y-axis in Figure 7b? Remove the sentence "They are intended here..." from the legend. Remove "..., presenting anomalously high normalized concentrations;" Remove everything after "...listed following..." What is meant with "incompatible elements (with respect to Fe)? Indicate here also the nomenclature of SH1 and SH2 to be consistent throughout the manuscript.

We added the legend in the y-axis of Figure 8b, and we removed the text from the caption. Regarding the "incompatible elements" you can find further details in the referenced papers (Sun and McDonough, 1989). We decided to keep the text regarding the element listing, since it is not straightforward for non-specialists. We also added SH1, SH2, and Saharan sources (Moreno et al. 2006) in the legend of figure 8.

Here the new Figure 8:



P18 L16 include sentence "They are..." already in the first sentence of the paragraph in line 13.

We modified accordingly.

P18 L23 Remove the sentence "Given the position..."

We modified accordingly.

P19 L1-L10 repetition to earlier passages

We shortened the paragraph, removing the repetition regarding anthropogenic activities in the Po valley.

P19 L12 What does this "incompatibility degree with respect to Fe" reveal? Why use this measure?

In Moreno et al 2006, this metric is used to characterize Saharan dust sources. In the manuscript, we already stated that this is useful understand the provenance and the geochemical signature of rock samples

P19 L13 Remove the sentences "As in the case..." until "low normalized concentrations." Repetition!

We modified accordingly.

P19 L33 The content of the next section is not a conclusion but a summary! Please stet the conclusion you draw based on your work more explicitly.

In Section 4 (Conclusion) we included a summary of the findings of our paper in which the conclusions are already clearly stated. In this section, we also provide some future perspectives in the growing body of research focusing on the role of impurities on snow.

P19 L38 "...11days, respectively."

We modified accordingly.

P20 L3 See also <http://www.aaqr.org/article/detail/AAQR-18-03-ACPM-0116> to confirm the Sahara dust event. Include citation.

We included this citation.

P20 L9 But the fingerprint of the local sources plays also a role. Please state this here in the text.

The sentence now reads:

"These results demonstrate that through an accurate geochemical characterization of dust deposited on the Alps, it is possible to identify the different Saharan sources involved in the single transport events, but the fingerprint of the local sources may play also an important role"

P20 L20 Maybe you find something in here <https://onlinelibrary.wiley.com/doi/abs/10.1034/j.1600-0889.49.issue1.4.x>

Thanks for the suggestion, we will take this into account for future analysis on the geochemistry of snow in the Alps.

Best regards,

Biagio Di Mauro and co-authors