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. Stanislav Kutuzov

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

The study "Saharan dust events in the European Alps: role on snowmelt and geochemical characterization" by Biagio Di Mauro and co-authors is dedicated to a very important topic of impacts of mineral dust on melting of snow in mountainous region. This research is based on observations over 3 years in high-altitude site in European Alps, AWS data and modelling. Additionally authors present a novel and relatively simple technique to monitor dust occurrence on snow. Results of the geochemical analysis of snow sample from one of the dust deposition events were also presented and compared to the chemistry of "clean" snow. Paper is well written and contains a comprehensive description of the research together with substantial literature review, results and discussion. I recommend this manuscript for publication after a minor revision.

Dear Dr. Kutuzov, 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.

As a general comment in my opinion text could be structured better. In many instances it goes beyond the topic and sometimes the discussion of the methods and results can be found all over the manuscript. Although it is important to mention relevant issues with the methods and data but it is expected that discussion of the results comes after the description of data and method. This complicates reading of the manuscript.

Authors did a great job reviewing a substantial number of previously published researches but the resulted introduction seems excessive and includes a number of repetitions. Some of the statements are repeated later as well. In some instances sentences located in different places are actually stating essentially similar findings and can be combined. I recommend shortening of the introduction and text generally by removing repetitions and information which is not directly related to the conducted research or discussion.

Thank you for this comment. Following your indications, we shortened the introduction and removed repetitions and information not directly linked to our research.

Some specific comments are listed below.

P.1 L.31-34 This was said in previous sentence. Listing of these feedbacks in abstract gives a wrong impression that all these feedbacks were assessed and evaluated here which is not the case. I suggest either to rephrase and generalise or simply to drop it.

We removed from the abstract the sentences regarding the specific feedback effects of the anticipated snowmelt induced by dust depositions. The sentence now reads:

"We conclude that the effect of the Saharan dust is to anticipate the snow melt-out dates, that is known to have a series of hydrological and phenological feedback effects"

P2. L21-26 This should be either shortened and moved to line 15 after "The alterations of the optical properties of snow are known . . .. (. . .. Painter et al,. 2012)." Or removed.

We moved this paragraph after line 15, and we shortened it. Now it reads:

"First estimations of the impact of dust on snow date back to the beginning of the last century: Jones (1913) estimated one month of anticipated snow melting due to dust deposition in the US. Drake (1981) estimated 4 days of advancement in the snow melt. These advances in snow melt-out dates have important implications on water supply operations (Painter et al., 2012)."

P.3 L9. This sentence is then repeated a number of times in the text. Please decide where you want to mention it and remove duplications. Bearing in mind that mineralogy of particles is actually out of the scope of this study.

We removed the sentence from line 7 to line 10. This topic is then addressed in the discussion in order to link the geochemical composition of dust with its radiative effect when deposited on snow.

P.3. L.11 This is a bit strong statement (fundamental reservoir). I'd recommend it to be rephrased. Temporal and fundamental do not sound particularly good together. Of course it plays a key role in redistribution and timing of runoff and many other aspects. And then the word fundamental is repeated several times later.

We replaced "fundamental" with "important".

P.3 L11-19 This paragraph should be moved after the effects of dust ecosystems. And the last sentence (L.35-36) can be placed here "Changes in snow falls and dust depositions are likely to occur more frequently in a warming climate."

We modified accordingly.

P3 L.20-36 Please check this paragraph. Order of sentences should be changed so that you first mention what has been done and then point to the knowledge gaps in the Alps.

We modified accordingly.

P.4 Fig. 1 The map should be enlarged and zoomed, font size adjusted. Preferably the geochemistry sample site should be included as well.

We modified accordingly. We also added an aerial view of the site, and the field of view of the Phenocam. Here the new Figure 1:

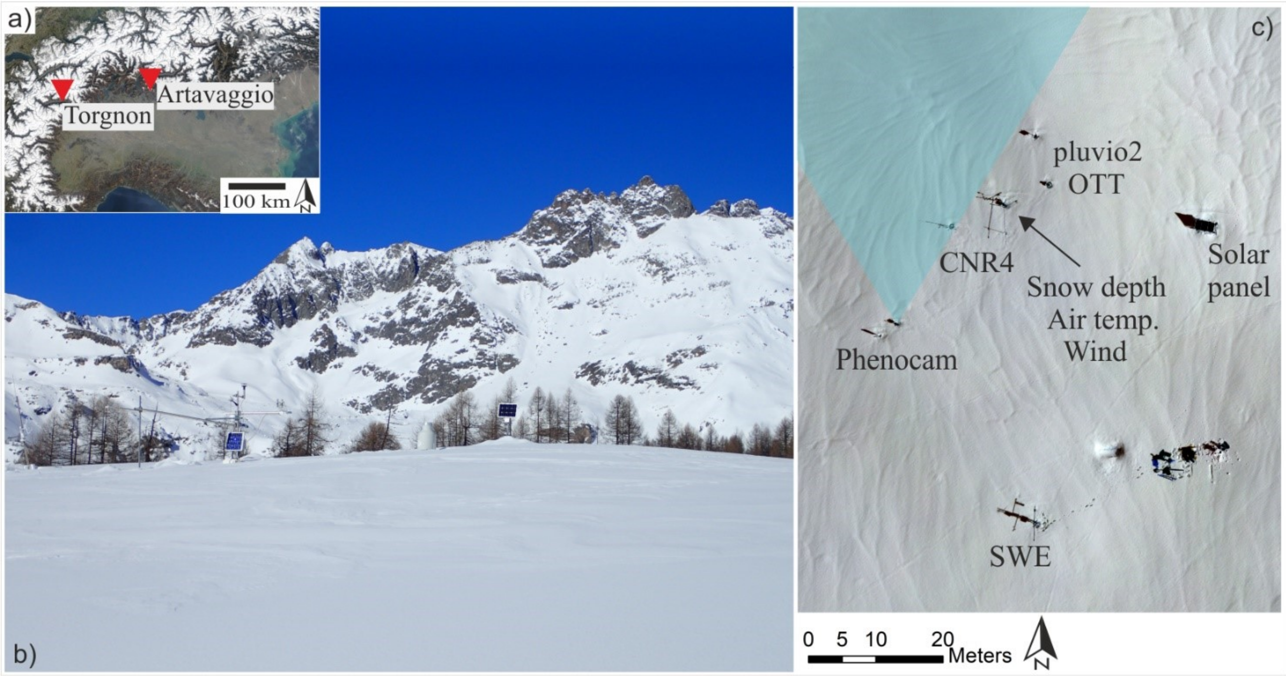


Figure 1: a) location of the experimental site of Torgnon (Aosta), and Artavaggio plains (Lecco) in the European Alps. b) a picture of the experimental site of Torgnon (2160 m a.s.l.). c) aerial view of the site in Torgnon with the location of different instruments installed. The field of view of the Phenocam is also represented with a blue shaded area.

P4 L18-P5 L2 This paragraph should be moved to the introduction.

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

"*2.2 Digital images analysis*

In recent years digital images analysis was applied to monitor 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."

P.6 L5 Which instrument was used to measure diffuse shortwave radiation?

Diffuse radiation was measured with a BF3 sensor (Delta-T Devices Ltd, Cambridge, UK). We added this information in the text.

P6 L5 These instruments should be listed in site description.

We added this information in the site description section. Now it reads:

"Solid and liquid precipitations were measured with a pluvio2 OTT instrument."

We also added:

"Wind speed and direction were measured with a CSAT3 three-dimensional sonic anemometer (Campbell Scientific, Inc.)"

P.6 L16 Can you clarify how exactly samples were collected. Was it one sample at depth 20 or one sample for the 0-20 cm layer? What was the total depth of the snow pit? Is there a description/photograph to compare the snow pit with the results of the modelling and dust layers modelling?

Samples used in this paper were collected from six different snow pits placed at few meters from the AWS station. 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. The concentrations of dust among different snow pits were very similar, so we presented just an example in Fig. 5. Unfortunately, we don't have high quality photographs of the snow pits for this comparison.

Now the sentence reads:

"On April 6th 2016, a field campaign was organized to collect snow samples at the experimental site of Torgnon. Six snow pits were dug in different locations placed at few meters from the AWS station. 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".

P.6 L.25 and further. This information is a bit confusing as the plural used for samples of dust which were used to characterize the dust events and elemental input. But at the end of the section we see that there was only one dust (presumably originated in Sahara) sample analysed. This is important issue as it's quite difficult to justify how representative results of analysis of one sample are for other dust events. It should be clearly stated how many samples were analysed for this particular study. Representativeness of this site and samples together with possible dust pathways etc. should be discussed within the results and discussion section rather than here.

For the neutron activation analysis, we used two samples: one representative for clean snow and one for the dust event of February 2014 (see line 37 in page 7). We acknowledge that only one snow sample containing dust is not enough to provide a complete overview on the composition of Saharan dust in snow in the Alps, but our analysis may pave the way for a more exhaustive characterization of dust composition in the future.

We moved this paragraph to Section 3.3, we also added this sentence (pg 17 ln 31):

"For this reason, the dataset presented in this study can be considered representative for the main composition of long-range dust deposition on snow in the Alps."

And then in pg 18 ln 11:

"We acknowledge that only one snow sample containing dust is not enough to provide a complete overview on the composition of Saharan dust in snow in the Alps, but our analysis may pave the way for a more exhaustive characterization of dust composition in the future."

P.7 L9. "only" is subjective, for some sites this would be considered quite substantial sample.

We removed "only" from the sentence.

P.7 L18. So far there was no mention about this modelling. Probably it should be mentioned somehow in introduction.

In the Introduction, we now added:

"The timing and intensity of Saharan dust depositions were simulated using two independent models (ALADIN-Climate and NMMB/BSC-Dust)."

P.7 L27 3.1 Modelled dust depositions?

We changed the title of this paragraph to: "Modelled dust deposition events"

P.7 L36-38 repetition.

We removed these two sentences.

P.8 L2 this strong dust event? (singular?)

We replaced "these" with "this".

P.9 L4 than P9. L6 Can you please explain why Crocus model shows a 100 mm SWE in Dec 2013 while this was not observed. Solid precipitation is one of the input parameters isn't it?

The GMON sensor was installed in 2013. During the first weeks, we had some problems with the power supply, so data were not recorded. In the caption of Figure 3, we added:

"SWE data are missing in December 2013 because of problems with the power supply."

P10. L.14 This is just one possible explanation though quite doubtful as particles are still quite large to be washed out that simple. It would've been great to see the description (photograph) of the snow pit in 2016 and to see how it corresponds with modelled structure. Additional samples collected from these dust layers separately could've helped. Another interesting question is how the local mineral particles (rocks, soil, vegetation. . .) affect snow melting. The mass can be substantial in the snow pack, but of course it will not be modelled by dust deposition model.

We agree with this comment. Unfortunately, we don't have high quality photographs of the snow pit. During the last two years, we've been visiting regularly the site and collecting multiple samples of snow containing dust.

In the manuscript, we added:

"This deeper layer can be probably due to the eventual scavenging of small dust particles by meltwater, or to other undetected processes".

The effect of larger particles on the snow melting is discussed in the answer to the following comment.

P.10 L18 The tail in distribution most likely is due to input from local particles. Looking at the photograph there are many rocks and vegetation around the site and Coulter Counter analysis do not distinguish between particles of different nature. This is quite an important issue. If the total mass concentration of mineral particles considered, than highest input would be from the small number of large particles.

We cannot exclude that large particles of local origin can be deposited on snow (we acknowledged it in pg 12 ln 16). Recently, we installed different deposimeters for evaluating the input of local and remote particles to the snowpack. In the future, Crocus model could be also modified to account for larger particles of local origin. In the text (pg 12 ln 16), we added:

"A contribution of large particles of local origin cannot be excluded, and it may have a strong influence on snow melting. At the moment, we don't have enough data to decouple the effect of large and small particles on snow albedo"

P.12 L4 Can you please clarify a bit more how exactly BC data were used. Was it an input to Crocus model? How large was the impact compare to dust. Isn't it the largest source of uncertainty? Can the BC signal be separated from the natural dust? Later in the text you mostly discuss the influence of the impurities without specifying.

Black carbon (soot) fluxes was one of the inputs of Crocus model (see Section 2.2). For decoupling the effect of dust and black carbon, Crocus can be run taking in account dust and black carbon separately (see Tuzet et al. 2017). In our simulations, both impurity fluxes are considered. Since we don't have direct measurements of black carbon in snow at our experimental site, we cannot exclude a possible influence on snowmelt. In the new version of the manuscript, we added:

"The role of black carbon in Alpine snow still represents a great uncertainty in snow modelling and climate prediction in the Alps. While the role of industrial black carbon on post-industrial glacier retreat has been debated (Painter et al. 2013; Sigl et al. 2018), its role on seasonal snow melting has not been studied in the European Alps."

References:

Painter, T. H., Flanner, M. G., Kaser, G., Marzeion, B., VanCuren, R. A., & Abdalati, W. (2013). End of the Little Ice Age in the Alps forced by industrial black carbon. Proceedings of the National Academy of Sciences of the United States of America, 110(38), 15216–21. https://doi.org/10.1073/pnas.1302570110

Sigl, M., Abram, N. J., Gabrieli, J., Jenk, T. M., Osmont, D., and Schwikowski, M.: 19th century glacier retreat in the Alps preceded the emergence of industrial black carbon deposition on high-alpine glaciers, The Cryosphere, 12, 3311-3331, https://doi.org/10.5194/tc-12-3311-2018, 2018.

P.12 L17 new paragraph? or maybe it's better to introduce a separate section on SDI

We added a new paragraph on SDI data and simulation.

P.14 L23 I doubt that it's a good argument to compare advancement in snow melt to distances from the deserts. You can either compare average (long-term) deposition rates or differences in snow duration reduction with similar dust concentrations.

We modified the sentence according to your comment. Now it reads:

"Despite the different deposition rates in the Alps, the advancement of the snowmelt owing to dust is comparable with published results regarding the Western US. This is true at least for one season (2015/2016), characterized by a major Saharan dust deposition."

P.14 L26 Is it possible to compare bulk concentrations (e.g. CC results) with the deposition modelling results?

A numerical comparison with Crocus prediction is provided in pg 13 ln 7. As showed in Tuzet et al. 2017, the concentration of impurities within the snowpack can be directly compared with Crocus predictions. In that case, dust concentrations were underestimated, while BC concentrations were overestimated. Our results show that observed dust concentrations were reasonably comparable with simulated ones. Also considering the large spatial mismatch between the point measurements and the ALADIN fluxes predictions.

P.14 L32-35 This is again partly repetition from the introduction. As well as in the next paragraph. Trends are not discussed in this paper at all so it can go to introduction.

We agree with this comment. But we prefer to lose this (and the following) sentence, since the introduction is already lengthy, we prefer not to add further text to it. We also removed the sentence in line 1-2 (pg 15), since it is repeated in the following paragraph.

P.15 L.8-10 This is a bit exaggerated. If the average over 82 years is late May than I believe snow disappeared in early May a number of times. Or maybe not? How many times exactly? So how rare such snow duration actually is? is it really extremely short? The next part of the paragraph is again an introduction-like and can be possibly moved up there too. The importance of the snow duration shifts is explained there. In results section it's better to discuss the exact results.

We used the expression "extremely short" because the first important snowfalls occurred in January for the 2015/2016 season. Considering this coupled with an earlier snowmelt due to dust depositions, this season is characterized by a snow cover duration of 4 months, over an average of 7 months. We acknowledge that the term is a little bit strong, so we replaced "extremely" with "very".

P 16 L.20-27 repetition of the introduction

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

P.20 L. 9-11 I'd suggest to rephrase or remove this. This large topic needs much more regular analysis suitable methodology etc. It just sounds a little bit speculative.

We removed this sentence according to your comment.

Best regards,

Biagio Di Mauro and co-authors

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 Torgnon 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 (µg/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:

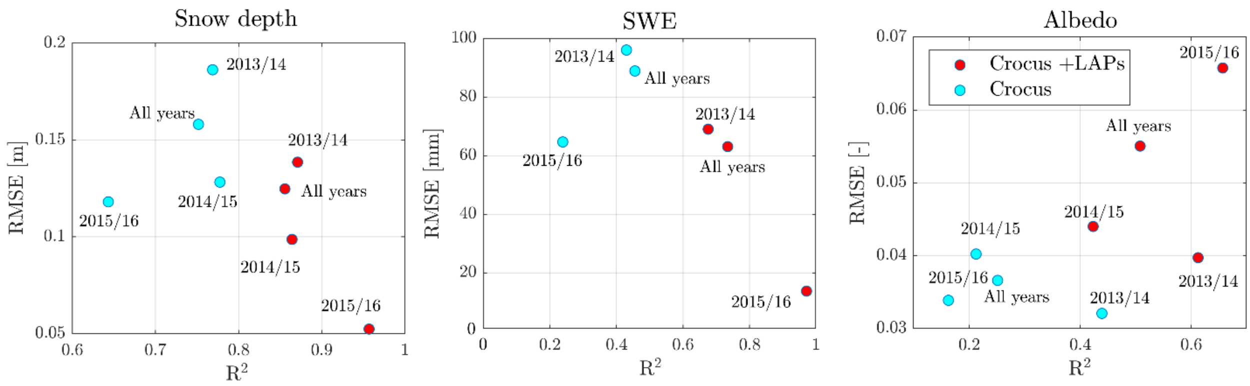


Figure 4 Comparison between snow depth (SD), snow water equivalent (SWE) and albedo observed from the AWS station in Torgnon and simulated with Crocus accounting and not accounting for the impact of LAPs on snow

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:

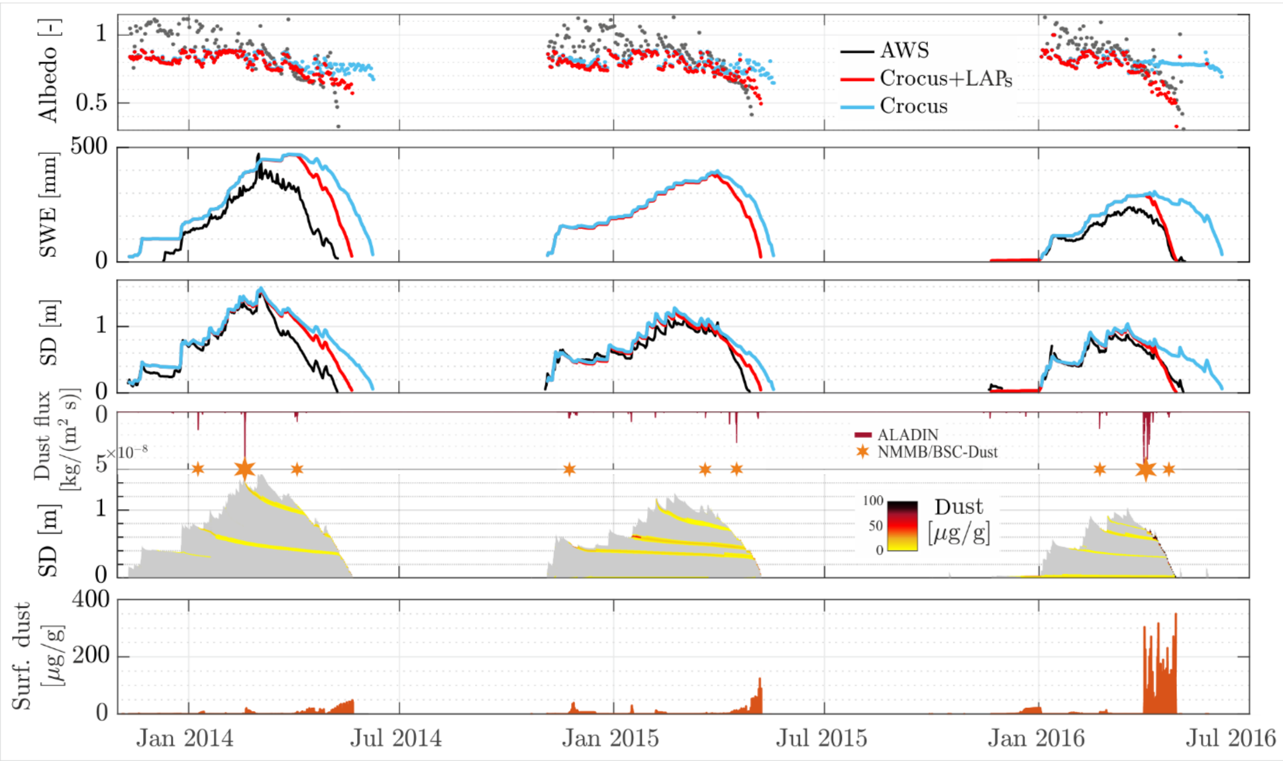


Figure 3 a)-b)-c): time series of albedo, snow water equivalent (SWE), and snow depth (SD) measured with the AWS and simulated with Crocus model including and excluding the impact of LAPs. SWE data are missing in December 2013 because of problems with the power supply. d): dust fluxes simulated with 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 (μg/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 20cmand 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 $\mu g_{dust}\ g^{-1}_{snow}$."

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 µg/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 µg/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 µg 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 µg/g for SH1, versus 180 µg/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

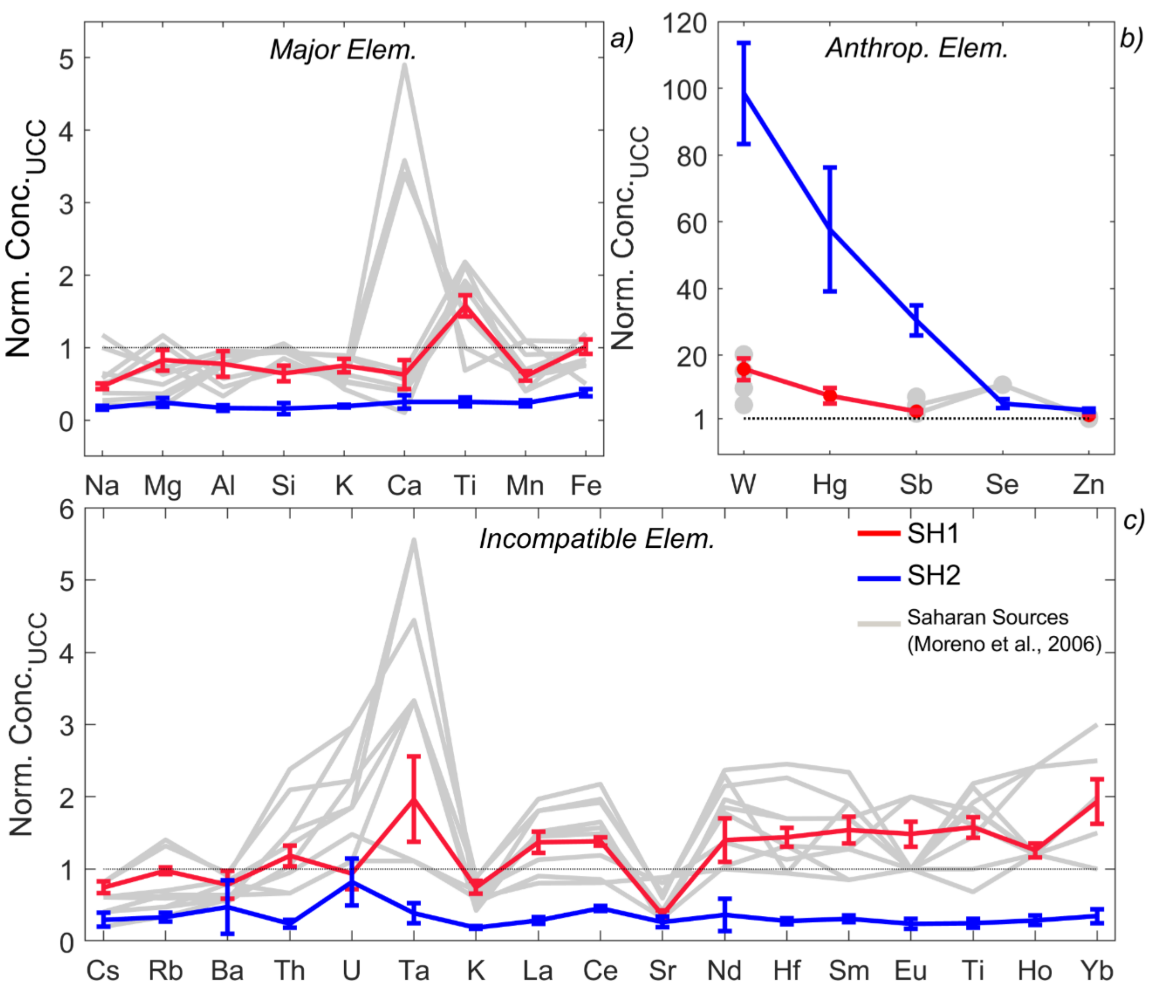
We rephrased the whole paragraph, shortening it. Now it reads:

"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

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

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Abstract. The input of mineral dust from arid regions impacts snow optical properties. The induced albedo reduction generally alters the melting dynamics of the snowpack, resulting in earlier snowmelt. In this paper, we evaluate the impact of dust depositions on the melting dynamics of snowpacks at ~~in~~ a high-altitude site (2160 m) in the European Alps (Torgnon, Aosta Valley, Italy) during three hydrological years (2013-2016). These years were characterized by several Saharan dust events that deposited significant amounts of mineral dust in the European Alps. We quantify the shortening of snow season due to dust deposition, by comparing observed snow depths and those simulated with the Crocus model accounting or not for the impact of impurities. The model was ran and tested using meteorological data from an Automated Weather Station. We propose the use of repeated digital images for tracking dust deposition and resurfacing in the snowpack. The good agreement between model prediction and digital images allowed us to propose the use of an RGB index (i.e. snow darkening index, SDI) for monitoring dust on snow using images from a digital camera. We also present a geochemical characterization of dust reaching the Alpine chain during spring in 2014. Elements found in dust were classified as a function of their origin and compared with Saharan sources. A strong enrichment in Fe was observed in snow containing Saharan dust. In our case study, the comparison between modeling results and observations 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. During the other seasons considered here (2013/2014, and 2014/2015), the advancement in snow melt-out day was 18 and 11 days respectively. We conclude that the effect of the Saharan dust is to anticipate the snow melt-out dates through the snow-albedo feedback. This process~~, that~~ is known to have a series of further hydrological and phenological feedback effects, that should be characterized in future research.~~: earlier snowmelt can propagate into altered hydrological cycle in the Alps, higher sensitivity to late summer drought, impact on vegetation phenology and carbon uptakes from the atmosphere.~~.

1 Introduction

Mineral dust (hereafter referred as dust) plays an important role in Earth's climate and in biogeochemical cycles (Mahowald et al., 2013; 2010; Thornton et al., 2009). It provides nutrients such as iron, nitrogen and phosphorous to marine and terrestrial ecosystems (Aciego et al., 2017; Jickells, 2005; Yu et al., 2015), and it influences the shortwave radiation balance of the atmosphere (Ginoux, 2017; Mahowald et al., 2013). Because of its peculiar optical properties, dust efficiently scatters incoming solar radiation, and exerts a direct climate forcing in the atmosphere (Tegen and Lacis, 1996). As a function of key variables (e.g. imaginary part of refractive index, height of the dust layer, dust particle size, and dust optical depth), the net radiative forcing of dust can be either negative or positive at the top of the atmosphere (Liao and Seinfeld, 1998; Tegen et al., 1996), representing a significant uncertainty in current climate models (Potenza et al., 2016). The main sources of dust are arid and hyper-~~–~~arid regions of the planet. Under specific atmospheric conditions, fine and coarse particles of dust can be suspended in the troposphere, generating characteristic dust storms (Francis et al., 2018; Goudie and Middleton, 2001). ~~These phenomena are not typical exclusively on Earth, but also on other planets of the solar system, as Mars for example (Smith, 2002).~~ Finer dust (< 5µm) has a prolonged atmospheric lifetime, in the order of days, allowing for its long-range transport (Mahowald et al., 2013; Tegen & Lacis, 1996). When dust is deposited on snow- and ice-covered regions its radiative impact at the surface results in a positive radiative forcing (Painter et al., 2012; Skiles et al., 2018). Snow optical properties depend largely on its microstructure and on the presence of impurities (also referred as light-absorbing particles, LAPs), such as carbonaceous or mineral particles (Warren and Wiscombe, 1980). Indeed, dust lowers the snow albedo in the visible wavelengths, enhancing the absorption of solar radiation (Di Mauro et al., 2015; Painter et al., 2007), and thus triggering the snow-albedo feedback (Hansen and Nazarenko, 2004). The alterations of the optical properties of snow are known to accelerate the melting processes (Drake 1981; Painter et al. 2012). First estimations of the impact of dust on snow date back to the beginning of the last century: Jones (1913) estimated one month of anticipated snow melting due to dust deposition in the US. Drake (1981) ~~used a model to~~ estimated ~~the advanced melting of snow next to an active mine, and estimated~~ 4 days of advancement in the snow melt.~~–~~ ~~These advances in snow melt-out dates have important implications on water supply operations, also considering that the runoff from the Colorado River supplies water to over 30 million people in seven US and Mexico (Painter et al., 2012).~~

The impact of dust on snow melting has been largely investigated in the Western US ~~(Painter et al., 2012; Reynolds et al., 2013)~~, where both radiative and hydrological effects have been assessed ~~(Skiles et al., 2012)~~ using aerial, satellite and Automatic Weather Station (AWS) data (Painter et al., 2012a, 2013b, 2018; Reynolds et al., 2013; Skiles et al., 2012) ~~(Painter, et al., 2012; 2013; 2018)~~. In this area, the proximity of arid regions to the mountain ranges allows massive dust depositions on snow covered mountain ranges. The snowmelt advancement due to dust depositions ranged from 35 days (Painter et al., 2007) to a maximum of 51 days (Skiles et al., 2012), strongly impacting water supplies around the area (Painter et al. 2012; 2018). ~~First estimations of the impact of dust on snow date back to the beginning of the last century: Jones (1913) estimated one month of anticipated snow melting due to dust deposition in the US. Drake (1981) used a model to estimate the advanced melting of snow next to an active mine, and estimated 4 days of advancement in the snow melt. These advances in snow melt-out dates have important implications on water supply operations, also considering that the runoff from the Colorado River supplies water to over 30 million people in seven US and Mexico (Painter et al., 2012).~~ Increases in dust deposition has been recently observed in this area, and they were linked to human activity and climate change (Neff et al., 2008). Other studies, conducted in Iceland (Dagsson-Waldhauserova et al., 2015; Wittmann et al., 2017), in Himalaya (Gautam et al., 2013), in Norway (Matt et al., 2018) and in the European Alps (Dumont et al., 2017; Di Mauro et al., 2015; Tuzet et al., 2017; Greilinger et al., 2018) reported significant impacts of dust on snow optical properties and snowpack dynamics. Impacts on glaciers optical properties and mass balance were also reported in the literature (Gabbi et al., 2015; Di Mauro et al., 2017; Oerlemans et al., 2009).

The composition of dust varies as a function of its origin (Krueger et al., 2004) and timing (Kumar et al., 2018), with effect on its optical properties (Caponi et al., 2017). Lawrence et al. (2010) presented a comprehensive characterization of the mineralogical and geochemical properties of dust deposited from the atmosphere in the San Juan Mountains (Colorado, US). In this area, dust is dominated by silt and clay particles, indicating a regional source area. In the European Alps, a large fraction of dust reaching high mountains and glaciers is originated from the Saharan desert (Haeberli, 1977; Kandler et al., 2007; Krueger et al., 2004; Schwikowski et al., 1995; Thevenon et al., 2009), but input from local sources cannot be excluded. Even though the Alps are located at a distance of about 3000 km from the largest desert of the planet, they are frequently affected by dust depositions. ~~Thanks~~ Due to their considerable elevation, ~~they~~ the Alps act as an orographic barrier, enhancing cloud formation, precipitation and hence dust scavenging from the atmosphere to the ground (De Angelis and Gaudichet, 1991; Prodi and Fea, 1979). Dust deposition in the Alps is a well-known process, and its frequency is studied using ice cores from mountain glaciers (De Angelis and Gaudichet, 1991; Thevenon et al., 2009). Each year, Saharan desert provides up to 760 millions of tons of dust to the atmosphere (Callot et al., 2000). Dust reaching Europe is dominated by silicates and aluminium oxide (Goudie and Middleton, 2001), other contributions come from quartz, calcium-rich particles, sulfates, hematite, and soot (Kandler et al., 2007). The optical properties of particles are directly related to dust composition (Linke et al., 2006), and hence the latter is expected to modify dust radiative effect on snow (Reynolds et al., 2013). ~~Several studies characterized the optical properties of dust and iron oxides (e.g. hematite, goethite etc.) contained in it (Caponi et al., 2017; Formenti et al., 2014). The effect of iron oxides on light absorption was found to be comparable to black carbon (Alfaro et al., 2004), which is known to have important light-absorbing properties (Bond et al., 2013).~~

~~Seasonal snow represents a fundamental reservoir of fresh water in mountain ranges and polar regions. Recent climate changes showed to exert a strong impact on the duration of snow cover (Vaughan et al., 2013), in particular in the European Alps (Beniston, 2005; 2018). It has been observed that, especially in spring, snow cover extent has decreased in the Northern Hemisphere (Brown & Robinson, 2011; Brown et al., 2009). Earlier snow melt can have an impact on vegetation phenology (Steltzer et al., 2009) and water availability (Beniston et al., 2003), and it is expected to alter hydrologic regimes in the future. Accelerating snow melting due to dust can alter also surface hydrology in large mountain chains like the European Alps. In the Po plain for example, the most important renewable energy source is represented by hydropower. Meltwater from seasonal snow is a fundamental resource for agriculture during spring and summer (Huss et al., 2017). Early snow melting in spring directly impacts the water availability during summer.~~

Saharan dust can serve as a nutrient for many alpine ecosystems (Field et al., 2010; Okin et al., 2004). ~~At the moment, the impact of Saharan dust events on the biogeochemistry of ecosystems in the European Alps has been poorly analysed (Avila and Peñuelas, 1999).~~ Aciego et al. (2017) recently showed that dust transported from Asia to Western US provides nutrients to montane forest ecosystems. This aspect has never been evaluated for mountain ecosystems in the European Alps, where dust may compete with fine debris from local rocks in providing nutrients to soils. Conversely, the direct deposition of dust on plants can limit the photosynthetic capacity (Neves et al., 2009), so complex feedback may be involved in the role of dust events in alpine areas. Steltzer et al. (2009) reported results from a manipulation experiment conducted in Western US to study the dependence of vegetation phenology on snowmelt. They measured an advancement of 7 days in snow melt when dust was manually added to the snowpack. This process can simulate a dry deposition from the atmosphere. In the Alps, most of dust depositions occur via wet deposition (mainly snowfalls in high altitude mountains) (Sodemann et al., 2006), so dust is expected to be included within ice grains. Flanner et al. (2012) showed that when black carbon is internally mixed in ice grains, its radiative effect is stronger. If this holds true also for dust, wet deposition of dust may exert a stronger effect with respect to dry depositions. Shifts in vegetation phenology also impact on timing of migration, breeding, and asynchronies between interacting animal species (Cohen et al., 2018; Thackeray et al., 2016). Dust-induced snowmelt can cause an advancing in the beginning of the growing season, and this can result in an earlier start in the seasonal cycle of both animals and plants. Changes in snow falls and dust depositions are likely to occur more frequently in a warming climate. At the moment, the impact of Saharan dust events on the biogeochemistry of ecosystems in the European Alps has been poorly analysed (Avila and Peñuelas, 1999).

Seasonal snow represents an important reservoir of fresh water in mountain ranges and polar regions. Recent climate changes showed to exert a strong impact on the duration of snow cover (Vaughan et al., 2013), in particular in the European Alps (Beniston, 2005; 2018). It has been observed that, especially in spring, snow cover extent has decreased in the Northern Hemisphere (Brown & Robinson, 2011; Brown et al., 2009). Earlier snow melt can have an impact on vegetation phenology (Steltzer et al., 2009) and water availability (Beniston et al., 2003), and it is expected to alter hydrologic regimes in the future. Accelerating snow melting due to dust can alter also surface hydrology in large mountain chains like the European Alps. In the Po plain for example, the most important renewable energy source is represented by hydropower. Meltwater from seasonal snow is a fundamental resource for agriculture during spring and summer (Huss et al., 2017).

In this paper, we quantitatively estimate the impact of dust from Saharan desert on snow dynamics. As a test area we use the experimental site in Torgnon (Aosta valley, Western Italian Alps) equipped with several sensors for measuring snow properties. Snow dynamics were simulated with a multi-layer, physically based energy balance model (Crocus, Vionnet et al. 2012), which can incorporate the effect of LAPs (mineral dust and black carbon) in snow and estimate its impact on snow melting (Tuzet et al. 2017). The timing and intensity of Saharan dust depositions were simulated using two independent models (ALADIN-Climate and NMMB/BSC-Dust). Observed and simulated snow variables are compared and the role of impurities in accelerating the snow melting is discussed. We also made use of repeated images from a digital camera to track the deposition and resurfacing of impurities. ~~Furthermore~~Finally, we present a geochemical characterization of dust reaching the Alps, and thus we discuss the possible biogeochemical and hydrological role of dust in the Alps.

2 Data and Methods

2.1 Torgnon experimental site

The study area is located in the northwestern Italian Alps (Aosta Valley, IT) at an altitude of 2160 m a.s.l. (45°50'40''N, 7°34'41''E). The experimental site belongs to the Phenocam (Torgnon-nd, https://phenocam.sr.unh.edu/webcam/), ICOS (IT-Tor https://www.icos-ri.eu/) and LTER (lter_eu_it_077, https://data.lter-europe.net/deims/site/) networks. The area is a subalpine unmanaged pasture classified as intra-alpine with semi-continental climate. The site is generally covered by snow from the end of October to late May. Further information regarding the site can be found in Galvagno et al. (2013). An Automatic Weather Station (AWS) was installed in 2009 at the experimental site of Torgnon. Air temperature ~~and snow height are~~is measured by a HMP45 (Vaisala Inc.), snow depth is measured with ~~and~~ a SR50A sonic ~~snow depth~~ sensor (~~SR50A,~~ Campbell Scientific, Inc.)~~, respectively~~. Albedo is measured with a Kipp and Zonen (CNR4 net radiometer). Snow Water Equivalent (SWE) is measured with a Gamma MONitor (GMON, Campbell) sensor. Solid and liquid precipitations were measured with a pluvio2 OTT instrument. Wind speed and direction were measured with a CSAT3 three-dimensional sonic anemometer (Campbell Scientific, Inc.). Data are available at hourly time resolution.

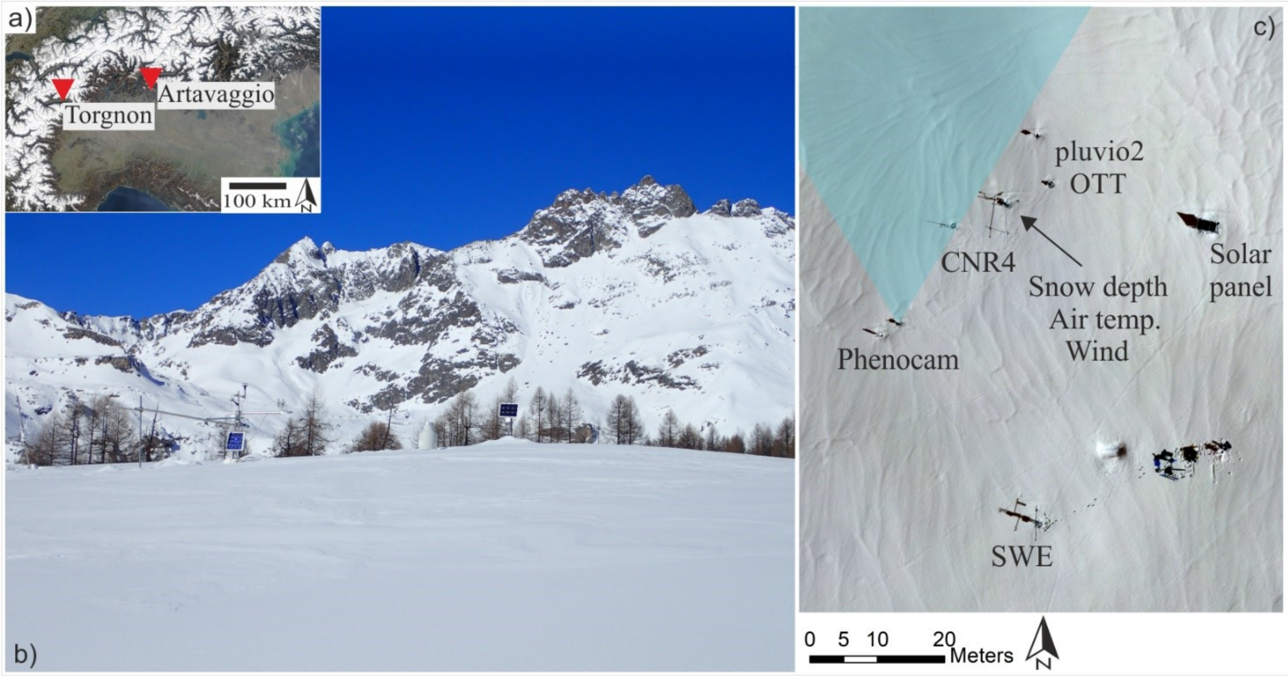

Figure 1: a) location of ~~A picture of the experimental site of~~ Torgnon (Aosta~~O~~) ~~in the Aosta valley (Western Alps),~~ and Artavaggio plains (Lecco) in the European Alps. b) a picture of the experimental site of Torgnon ~~The site is located at~~ (2160 m a.s.l.). c) aerial view of the site in Torgnon with the location of different instruments installed. The field of view of the Phenocam is represented with a blue shaded area.

~~In recent years, the application of Red Green Blue (RGB) digital images has gained a lot of interest in Earth and Environmental Sciences. The availability of low-cost digital sensors (typically compact or reflex cameras) has raised the possibility to install automatic station in impervious or remote areas, with the possibility to collect multiple images during summer and winter seasons. Common applications regard 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~~.

2.2 Digital images analysis

In recent years, digital images analysis was applied to ~~the~~ monitor~~ing 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. For this study, digital RGB images were collected using a Nikon digital camera (model d5000, also referred as ‘Phenocam’) installed at the experimental site in 2013 in the vicinity of the AWS. Following Richardson et al. (2007), the camera was pointed North and set at an angle of about 20° below horizontal. Camera focal length is 33 mm and the field of view is 79.8°. The camera was fixed at 2.5 m above the ground, and the same ~~view~~ scene was repeatedly photographed~~captured~~. Digital images were collected in Joint Photographic Experts Group (JPEG) format with ~~and they have~~ a resolution of 12 megapixels, ~~with~~ and three-color channels (namely red, green and blue) featuring~~, at~~ 8 bits of radiometric resolution. The images were collected from 10 am to 5 pm (local time: UTC+1), with an hourly temporal resolution. Exposure mode and white balance were set to automatic.

A Region Of Interest (ROI) was firstly identified in an approximately flat area to analyze snow evolution. Images were acquired during 2013/2016 hydrological years. Red, green and blue chromatic coordinates were extracted from the selected ROI using the Phenopix R package (Filippa et al., 2016). Then, the Snow Darkening Index (SDI, Di Mauro et al. 2015) was calculated from red and green digital number (DN) as follows in Eq. (1):

$$SDI = \frac{DN_{Red} - DN_{Green}}{DN_{Red} + DN_{Green}} \quad (1)$$

SDI was correlated with the concentration of dust in snow (Di Mauro et al., 2015), and was used to represent the spatial distribution of impurities from space (Ganey et al., 2017; Di Mauro et al., 2017), and from hyperspectral images~~ry~~ of ice cores (Garzonio et al., 2018). SDI calculated from RGB data collected from an Unmanned Aerial Vehicle (UAV) was found to be correlated with SDI calculated from field spectroscopy data (Di Mauro et al. 2015). This motivated the idea to monitor dust deposition and resurfacing dynamics using repeated digital images from the camera installed in Torgnon. In this work, SDI was calculated for each available image, then a daily average was calculated. Days with SDI >0 were considered as markers of the presence of dust on snow.

~~2.2~~2.3 Snowpack modeling

Snow dynamics in Torgnon were simulated using the SURFEX/ISBA-Crocus model, hereinafter referred as Crocus. Crocus is a snow model initially developed for avalanche forecasting, and used for hydrological estimation ~~and~~ as well as~~for~~ numerical prediction (Brun et al., 1989). Crocus is a one-dimensional multilayer model that simulates the evolution of the snow pack based on input meteorological driving conditions (Brun et al., 1989, 1992). 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 (Vionnet et al., 2012). In this study, we used a specific Crocus version using the Two-stream Analytical Radiative TransfEr in Snow (TARTES) radiative transfer model (Libois et al., 2013) to obtain simulations of snow spectral albedo as a function of snow properties, ~~and~~ LAPs concentrations, and LAPs optical properties. TARTES model is based on the asymptotic approximation of the radiative transfer theory (AART) (Kokhanovsky and Zege, 2004), and ~~it~~ accounts for the effect of snow microstructure and impurities such as ~~(~~dust and black carbon.~~ in the study case).~~ 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. A complete description of this specific Crocus model version can be found in Tuzet et al. (2017). Crocus is embedded in the SURFEX surface scheme and is permanently coupled with the ISBA-DIF soil model.

Variables needed for running Crocus simulations are: air temperature, direct and diffuse shortwave incoming radiation, longwave radiation, wind speed and direction, specific humidity, surface pressure, solid and liquid precipitation. The model was forced using meteorological data from the station in Torgnon for the seasons 2013/2016 at hourly time step. All variables were measured at the station of Torgnon, except for diffuse shortwave incoming radiation, that was measured (with a BF3 sensor, Delta-T Devices Ltd, Cambridge, UK) in another station located 2 km far from Torgnon. The instrument used for precipitation measurements (pluvio2 OTT) does not feature a windshield. This can be problematic since underestimations of snow fall can occur during intense wind events. For this reason, we corrected the data following the prescriptions proposed in Kochendorfer et al. (2017). Some manual adjustments to solid precipitations were needed in case of strong wind events. In addition to the above-mentioned meteorological data, the Crocus version of Tuzet et al. (2017) needs dust and black carbon deposition fluxes. In this study, these fluxes were taken from the atmospheric model ALADIN-Climat (Nabat et al., 2015). For evaluating the impact of dust depositions on the snowpack dynamics, key variables (e.g. albedo, snow depth, snow water equivalent) measured from the AWS were compared with Crocus simulations with and without impurities (dust and black carbon) in snow. In addition, soil temperature was initialized using a spin-up simulation of 4 years.

~~2.3~~2.4 Dust concentration, size distribution and geochemistry

On April 6th 2016, a field campaign was organized to collect snow samples at the experimental site of Torgnon. Six snow pits were dug in ~~at six~~ different locations placed at few meters apart from the AWS station. 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.~~For each location, four snow samples were collected from a pit respectively at a depth of 0, 20, 40 and 60 cm from the surface~~. Samples were collected using sterilized Corning tubes (50 mL) and kept frozen until ~~successive~~ measurements. Dust concentration and size distribution were measured using a Coulter Counter technique. Samples were melted in a clean room (class 1000 clean room at EuroCold laboratory facilities, University of Milano-Bicocca) and analyzed with a Multisizer™ 4e COULTER COUNTER®. The instrument was set with a 100 µm orifice, allowing for the detection of particles with a diameter (equivalent spherical) between 2 and 60 µm, divided into 400 size channels. To obtain dust mass from particle volume, a crustal density of 2.5 g/cm^3 was adopted. Total dust concentration was calculated considering the integral of the concentration between 2 and 60 µm. Details about the technique can be found in Ruth et al. (2008).

In addition, dust samples collected in the Alps at 150 km from Torgnon (Artavaggio, LC, Italy, 1650 m asl) in March 2014 are used here to characterize the bulk composition of dust events and the elemental input to Alpine ecosystems. ~~These samples are considered representative for those deposited in Torgnon because the main source area of Saharan dust events reaching the Alps is represented by North Algeria (Potential Source Area in Northern Africa 1, PSANAF-1 in Formenti et al. (2011)). Saharan dust events are regional episodes that move large quantities of mineral dust from arid region to different latitudes and longitudes. There are two main pathways for the transport of dust: it can reach Europe over the Mediterranean and also by looping back over the Atlantic (Israelevich et al., 2012; Sodemann et al., 2006). For this reason, we can assume that the bulk geochemical composition of dust events occurred on different location in the Alps and at different times is comparable. Between February 2014 18th and 20th a relevant event was observed, involving not only Southern Europe and the Alps, but also a large fraction of Europe. It was described as one of the most intense events of this kind observed in the last years. The event was associated to a particularly favorable atmospheric setting which could uplift a massive amount of Saharan dust from North Africa and transport it toward Europe in association to southwesterly winds driven by an anticyclonic structure located on the Central Mediterranean. Given the magnitude of the event, many studies reported it, spanning from microbiology (Meola et al., 2015; Weil et al., 2017), to remote and proximal sensing (Dumont et al., 2017; Di Mauro et al., 2015; Tuzet et al., 2017), and atmospheric chemistry and physics (Belosi et al., 2017; Telloli et al., 2018).~~ Snow samples were transported before melting in a cold facility, where they were stored until the preparation for the successive analyses. At first, they were melted and an aliquot (5-10 mL) was measured through Coulter Counter technique (CC) for the determination of dust size distribution. These data were already published (Di Mauro et al., 2015). A second aliquot consisting in few mL of melted snow, was dedicated to Instrumental Neutron Activation Analysis (INAA) for the analysis of elemental composition (Greenberg et al., 2011). To this aim, dust was extracted and separated using a filtration system, equipped with polycarbonate membranes (pore size 0.4 µm, well below the typical volume mode grain size of Saharan dust deposited on the Alps). Two distinct samples were prepared. One sample (SH1) was extracted from the reddish snow corresponding to the snow deposited during the Saharan event; it consisted in 7.2 ± 0.2 mg of dust. A second sample (SH2) was prepared for comparison filtering clean white snow. In this case, given the low concentration of impurities, it was possible to retrieve ~~only~~ 202 ± 11 µg of particulate matter. For both samples, in addition to absolute concentration (mass fraction), also normalized ones were calculated. The average upper continental crust composition (UCC, Rudnick and Gao 2003) was selected as normalizing reference to highlight the influence played by crustal-derived material and the possible role of non-crustal sources for specific elements. Neutron irradiation was performed at the LENA laboratories at the University of Pavia (Borio di Tigliole et al., 2010), where a TRIGA Mark II research nuclear reactor is installed (250 kW). Activated samples were successively analyzed using high purity Germanium detector available at the Radioactivity Laboratory of the Milano-Bicocca University. Two irradiations and several acquisitions of the γ-spectra were necessary to detect the largest number of radionuclides, ranging from the short-lived species to the long-lived ones. For a complete description of the method, including the estimation of errors, see Baccolo et al. (2015, 2016).

~~2.4~~2.5 Dust transport and deposition modelling

In addition to the ALADIN-Climate model, dust transport and deposition were monitored using the NMMB/BSC-Dust model. This is an online multi-scale atmospheric dust model (Pérez et al., 2011), it was used here to provide dust forecasts from the Saharan desert to the European Alps. NMMB/BSC-Dust provides both atmospheric concentration and deposition fluxes of dust with a 0.3° x 0.3° horizontal resolution. During the three seasons considered here, we classified dust events in 'strong' ~~and 'weak'. 'Strong'~~ events ~~were characterized by~~with dust deposition fluxes larger than 800 mg/m^2, and 'weak' events ~~featured~~ with lower concentrations. The timings of the events simulated with the NMMB/BSC-Dust model were qualitatively compared to those simulated with the ALADIN-Climate model during the period analysed here (2013/2016).

3 Results and Discussion

3.1 Modelled ~~D~~dust deposition events~~s~~

The period between 2013 and 2016 was characterized by two 'strong' events (dust fluxes > 800 mg/m^2), and several 'weak' events (dust fluxes < 800 mg/m^2) distributed during the seasons. The 'strong' events occurred on February 2014 and on April 2016. The event of February 2014 was already analysed in the scientific literature (Di Mauro et al. 2015; Tuzet et al. 2017; Dumont et al. 2017). The event of April 2016 lasted several days and transported a considerable dust to the Western sector of the European Alps (Fig. 2) (Greilinger et al., 2018). According to NMMB/BSC-dust model, during these two "strong" events, most of dust was deposited in the Alpine chain mainly via wet deposition. In Figure 2, we show an example (5th April 2016) of the concentration of dust deposited according to NMMB/BSC-dust, and a longitudinal and latitudinal transect. NMMB/BSC-dust predicted up to 1600 mg/m^2 of dust deposition in Western Alps. ~~The complex topography of this region probably acted as an orogenic barrier promoting the condensation of water vapor containing dust particles. This process generated the characteristic "red snow" often observed in the Alps (De Angelis & Gaudichet, 1991).~~ In the latitudinal and longitudinal profiles, it is clearly visible that the plume reached almost 6 km in altitude. The highest concentrations in the atmosphere were reached in South France and in the North-West of Italy. The experimental site of Torgnon is located in Italian Western Alps, and it represents a good candidate for analysing the effect of ~~these~~ this strong dust event~~s~~ on snow dynamics.

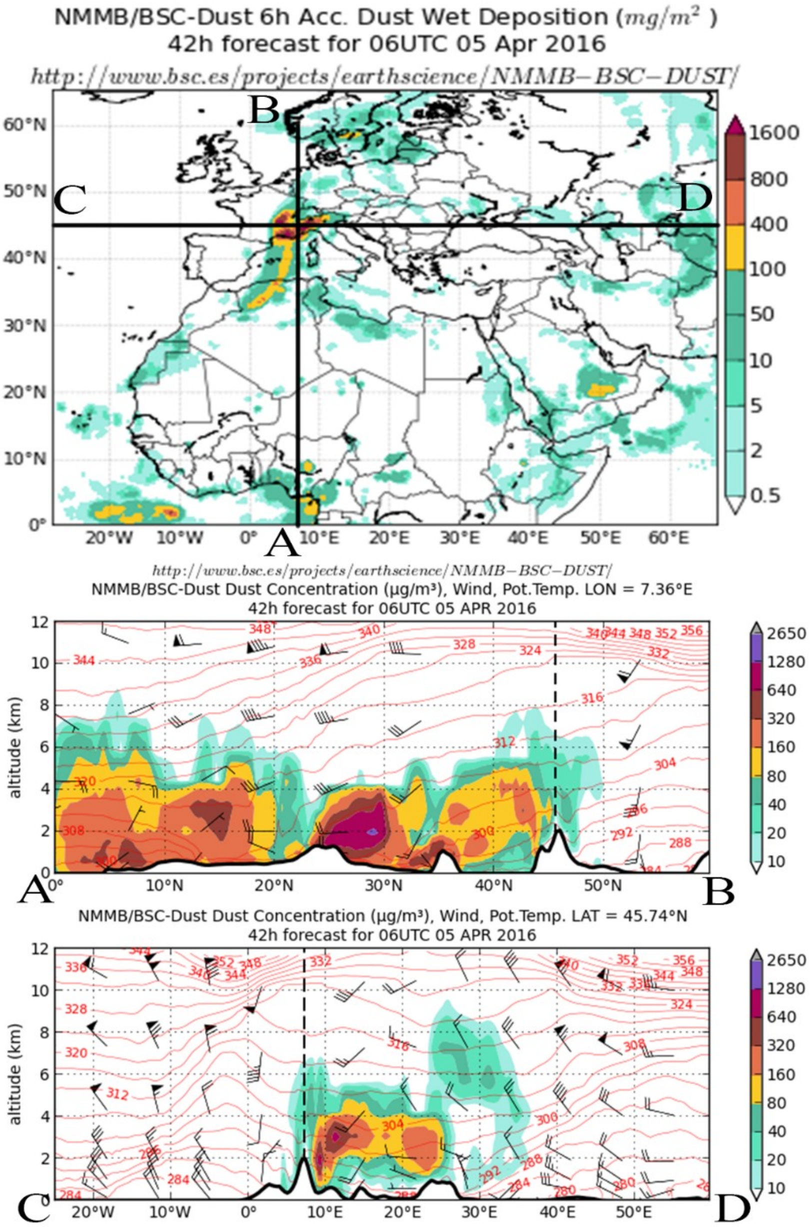

Figure 2 NMMB/BSC-Dust forecast for the event of April 2016. In the top panel, the estimated surface concentration via wet deposition. The lower panels represent respectively a latitudinal and longitudinal transect centred on the city of Aosta (45.74N; 7.36E). Images from the NMMB/BSC-Dust model, operated by the Barcelona Supercomputing Center (http://www.bsc.es/ess/bsc-dust-daily-forecast/).

3.2 Observed and simulated snow dynamics

~~In this section, we present data from the station in Torgnon, and simulations made with Crocus model.~~ In Figure 3, a comparison of variables observed at Torgnon station and simulated with the Crocus model using using impurity fluxes is presented. We show time series of snow albedo, snow water equivalent (SWE), and snow depth (SD). In general, Crocus model well represented snow dynamics during 2013/2016 hydrological seasons. In ~~Table 1~~Figure 4, we present a quantitative comparison (coefficient of determination, R^2, and Root Mean Square Error, RMSE) between snow variables observed and simulated ~~considering~~ including and excluding the effect of ~~impurities~~LAPs. ~~Beside a general agreement between observed and simulated variables, it must be noted that some mismatches were observed.~~Crocus simulations accounting for the impact of LAPs showed a better agreement with observations than Crocus simulations that not account for the effect of LAPs. ~~For example, S~~snow albedo was underestimated from Crocus during the accumulation period (see Fig. 3a). Instead, during the melting period, the decreasing trend observed in snow albedo was well reproduced by Crocus model accounting for the role of impurities. During the accumulation period, ~~T~~the albedo ~~simulated~~ modeled by both Crocus simulations ~~without impurities~~ was always ~~higher~~ lower than the observed albedo~~the one simulated accounting for impurities~~. During the melting season, a clear divergence is observed between Crocus with LAPs and without LAPs. Instead, Crocus simulation with LAPs is more correlated with the observed snow depth. The comparisons between observed and simulated SWE and snow depth show a large interannual variability. SWE is strongly overestimated in the 2013/2014 season; while during the accumulation period snow depth is well represented in the model, the melting rate is higher in the observed snow depth. This results in a delay of snow melt-out dates in both Crocus simulations (with and without impurities). A similar pattern in snow depth is observed also in the 2014/2015 season. Unfortunately, measured SWE was not available for this season. During the 2015/2016 season, the correlation between the observed and simulated snow depth accounting for the impact of impurities was very high both for snow depth (R^2 = 0.96; RMSE = 0.04 m) and SWE (R^2 = 0.97; RMSE = 13 mm). The difference in snow melt-out dates between observed and simulated data accounting for LAPs was 12, 10 and 11 days, respectively for the 2013/2014, 2014/2015, and 2015/2016 seasons. Instead the comparison between snow melt-out dates simulated with and without impurities was 18, 11, and 38 days for the 2013/2014, 2014/2015, and 2015/2016 seasons, respectively.

In Figure 3d, we show also a qualitative comparison between the dust fluxes simulated with ALADIN-Climate and with the NMMB/BSC-dust model. ~~“Strong” and “weak” dust deposition events simulated with the NMMB/BSC-dust model are represented as large and small stars, respectively. ALADIN-Climate fluxes are reported as well.~~ In general, a good agreement between the two models was observed. The two most intense events (February 2014, and April 2016) are identified by both models. Smaller events are also reproduced, whereas sometimes small events are seen only by ALADIN-Climate.

Once dust fluxes are deposited on the snowpack, they are buried by new snowfalls. In Figure 3e, we show the multilayer concentration of dust in snow simulated with Crocus. It is clear that dust is resurfaced at the end of the season, when the snow albedo feedback intensifies, and promotes the melting. The surface concentration of dust (average of the first 10 cm of snow) in the three seasons considered in this study show an important interannual variability (Fig. 3f). In fact, whereas the first two seasons shows surface concentrations of dust lower than 150 µg/g, the last season (2015/2016) shows concentrations up to 350 µg/g at the end of the season. This can be due to the longer duration of the dust event in April 2016, and ~~This~~ may also explain~~s~~ the large change (38 days) in the snow melt-out dates observed in the data.

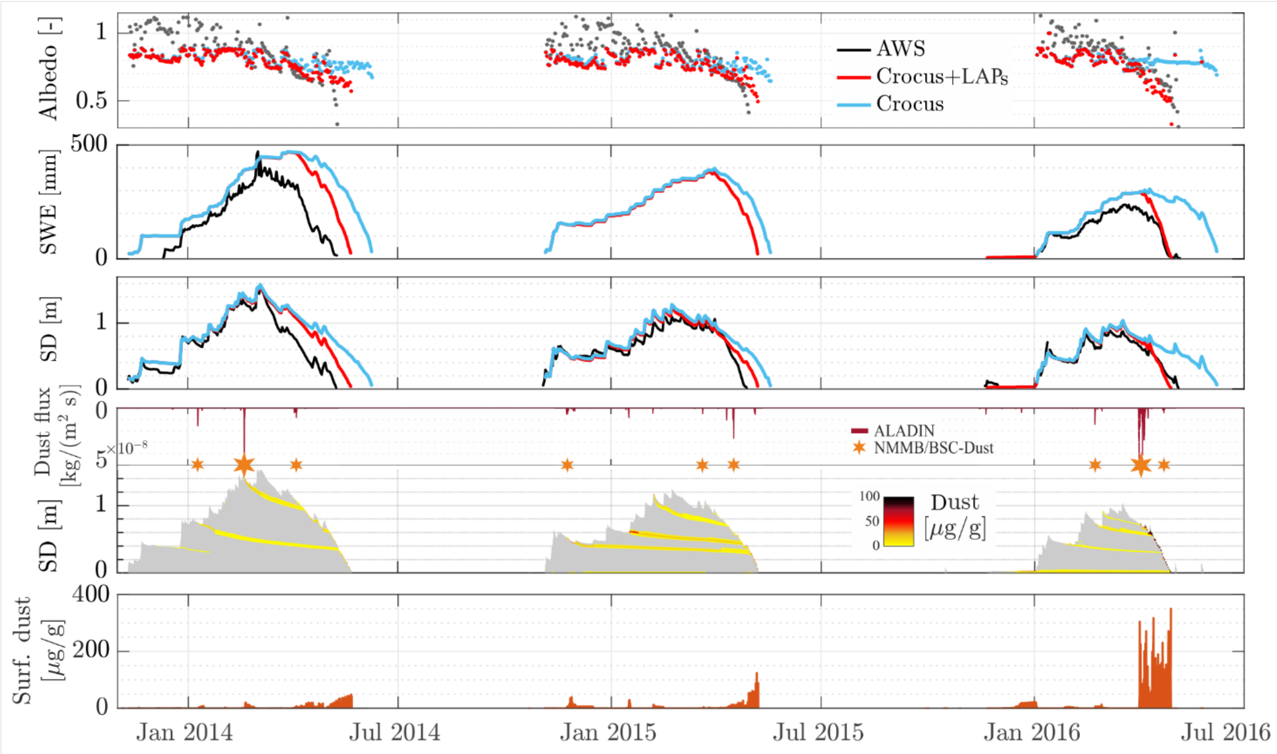

Figure 3 a)-b)-c): time series of albedo, snow water equivalent (SWE), and snow depth (SD) measured with the AWS and simulated with Crocus model including and excluding the impact of LAPs. SWE data are missing in December 2013 because of problems with the power supply. d): dust fluxes simulated with 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 (μg/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.

	~~2013/ 2014~~	~~2014/ 2015~~	~~2015/ 2016~~	~~All years~~
~~SD [m]~~	~~R^2 = 0.84 RMSE = 0.15~~	~~R^2 = 0.9 RMSE = 0.08~~	~~R^2 = 0.96 RMSE = 0.04~~	~~R^2 = 0.93 RMSE = 0.08~~
~~SWE [mm]~~	~~R^2 = 0.63 RMSE = 73.3~~	~~/ /~~	~~R^2 = 0.97 RMSE = 13~~	~~R^2 = 0.96 RMSE = 23.3~~
~~Albedo [-]~~	~~R^2 = 0.74 RMSE = 0.02~~	~~R^2 = 0.6 RMSE = 0.02~~	~~R^2 = 0.6 RMSE = 0.04~~	~~R^2 = 0.72 RMSE = 0.02~~

~~**Table 1 Comparison between snow depth (SD), snow water equivalent (SWE) and albedo observed from the AWS station in Torgnon and simulated with Crocus accounting for the impact of impurities**~~.

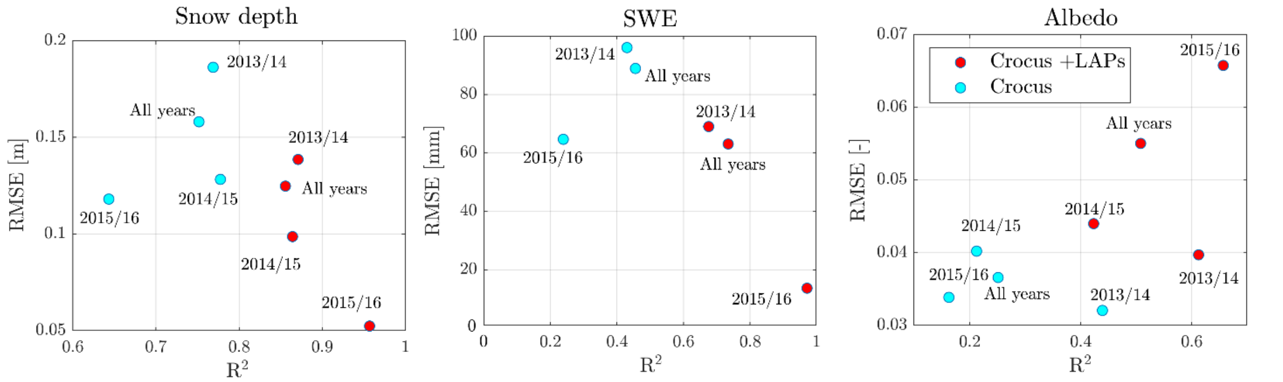

Figure 4 Comparison between snow depth (SD), snow water equivalent (SWE) and albedo observed from the AWS station in Torgnon and simulated with Crocus accounting and not accounting for the impact of LAPs on snow

Results from samples collected in Torgnon showed that significant concentrations of dust were present in the snowpack in April 2016 (Figure ~~4~~5). It is interesting to note that the mode of the dust size distribution is 7.9 µm for surface snow, 8.5 µm, and 8.5 µm for snow samples collected at 20 cm and 40 cm ~~respectively~~depth, instead snow sampled at the bottom of the snowpack (60 cm depth) features a mode of 3.2 µm. This deeper layer can be probably due to the ~~eventual~~ scavenging of small dust particles by meltwater, or to other undetected processes. The first three distributions can be due to the ‘weak’ depositions happened in February and March, and then buried by new snow. ~~At the bottom of the snowpack, finer particles were found.~~ Dust size distributions are compatible with other measurements of dust enclosed in 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. Samples ~~showed~~ shown in Figure ~~4~~ 5 feature a significant noise in the tail of the distribution. This can be ascribed to the aggregation of fine particles or to an input of local larger particles. A contribution of large particles of local origin cannot be excluded, and it may have a strong influence on snow melting. At the moment, we don’t have enough data to decouple the effect of large and small particles on snow albedo. Total concentration of dust in Torgnon was estimated by adding up different channels from the size distributions. Among the six different snow profiles measured, surface concentrations reached a maximum of 65 $\mu g_{dust}\ g^{-1}_{snow}$ with a mean of 45.6 $\mu g_{dust}\ g^{-1}_{snow}$ and a standard deviation of 15.8 $\mu g_{dust}\ g^{-1}_{snow}$.

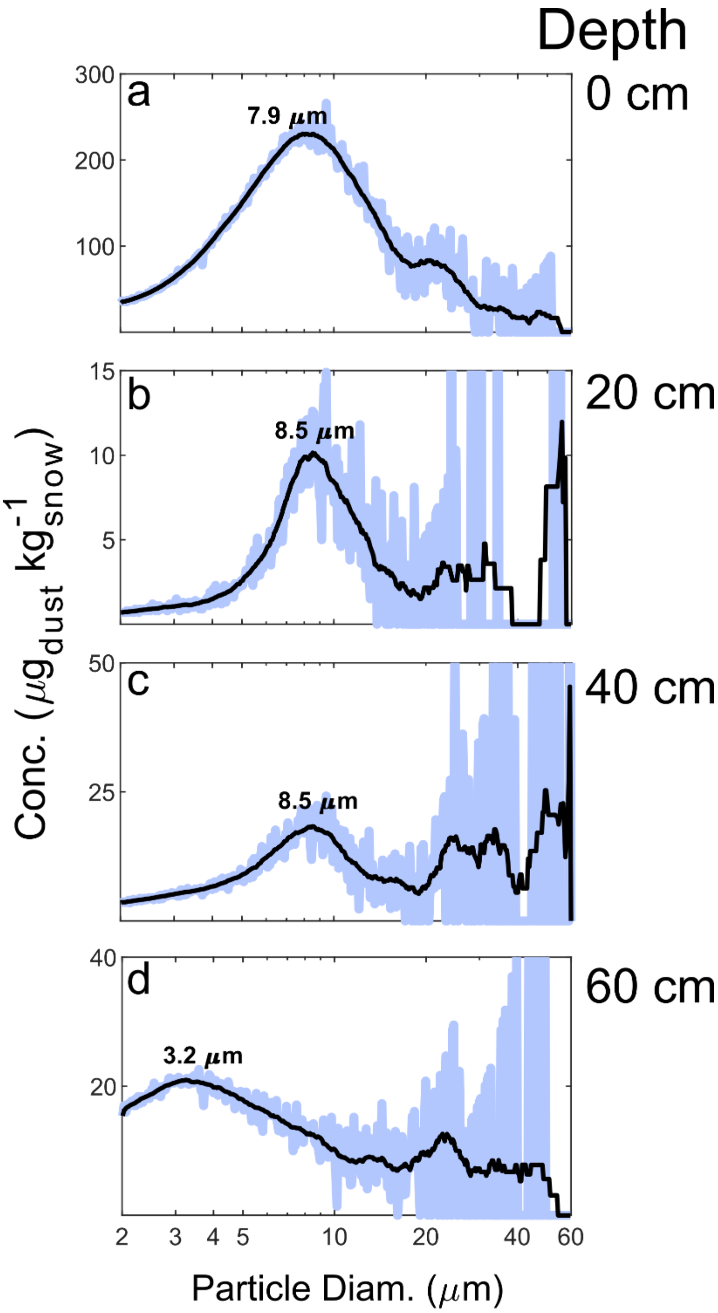

Figure ~~4~~5 Dust particles distribution (expressed in μg$_{dust}$ kg^{-1}$_{snow}$) for a snow profile sampled at Torgnon on April 6th at different depths (0 cm, 20 cm, 40 cm, and 60 cm). Blue lines are experimental data, black lines are moving averages (kernel: 25 points). Numbers in the plots represent the peak of the size distributions. Please note that the scale is changing within different plots.

Measurements of dust concentrations are available only for April 6th 2016. On this day, the dust concentration profile simulated by Crocus spans from 11 (bottom) to 108.7 (top) μg$_{dust}$ g^{-1}$_{snow}$. Modelled and measured surface concentrations of dust showed some difference: 43.7 μg$_{dust}$ g^{-1}$_{snow}$ for the most concentrated surface sample, and 65.1 μg$_{dust}$ g^{-1}$_{snow}$ for the mean of the six snow pits. This variability can be explained by the strong spatial mismatch between the spatial resolution of ALADIN-Climate model (50km) and the punctual measurement of dust concentration. Differences can also depend on snow sampling vertical resolution and Crocus layer thickness. Model improvements are needed to downscale the spatial resolution of LAPs fluxes. The installation of wet and dry sampler (e.g. deposimeter) at experimental sites may help to drive Crocus model with measured deposition fluxes. It is important to notice that ALADIN-Climate predicted also depositions of black carbon. At the moment, we do not have measurements to validate this estimation, but the presence of black carbon in snow may have amplified the snow-albedo feedback in the snowpack. The role of black carbon in Alpine snow still represents a great uncertainty in snow modelling and climate prediction in the Alps. While the role of industrial black carbon on post-industrial glacier retreat has been debated (Painter et al., 2013a; Sigl et al., 2018), its role on seasonal snow melting has not been studied in the European Alps.

Hereafter we focus on the 2015/2016 season, since Crocus simulations with impurities resulted in a 38 days advancement of the snow melt-out date compared to the corresponding simulations without impurities. This season was characterized by dust surface concentration in snow almost double with respect to the other two seasons considered in this study (see Fig. 3f). In Figure 5, we show the comparison of the snow depth simulated with Crocus including and excluding the impact of impurities. During the 2015/2016 season, about one meter of snow was on the ground in Torgnon. The model without impurities predicted a longer persistence of snow on the ground than the model with impurities. Two late snowfalls occurred in May, and this probably increased the difference between the simulations. Since air temperatures were still close to 0° (data not shown), snow was preserved at the ground in the simulations without impurities, and this further prolonged the snow season duration. ~~The presence of impurities induced an advancement of the disappearance of snow in Torgnon.~~ Considering that first significant snowfalls occurred in January, the snow season was shortened of about 20% of the total because of impurities.

~~-~~In Figure ~~5~~6, we ~~also~~ plot SDI index calculated from the radiative transfer model (TARTES) included in Crocus (SDI-Crocus hereafter), and from the RGB camera (SDI-Phenocam hereafter). Regarding the digital camera data, days with SDI >0 are represented as shaded green bands. We observed an agreement between the two data set. SDI-Crocus showed an increasing trend during April. In particular, at the beginning of April two peaks in SDI-Crocus are seen also from SDI-Phenocam. A peak then is not clearly seen by the digital camera, this could be due to the occurrence of two small snowfalls during the resurfacing of dust layers. At the end of April, the concentration of dust on the surface of snow is well represented both by Crocus and digital images. During this last period, ~~the accumulation of dust on snow further increases light absorption and decreases the albedo. A~~ a marked change in snowmelt rate is observed from the snow depth series around the 20th of April (Fig. 6). ~~This further induced an earlier snow melt-out, which was comparable with that observed from AWS data (see Fig. 3e).~~ The agreement between SDI-Crocus and SDI- Phenocam suggests that low cost digital RGB data can be used for monitoring the resurfacing of dust in snowfields, useful for satellite and model validation. In order to use quantitatively these RGB data, further comparisons with field spectroscopy and ground data are needed.

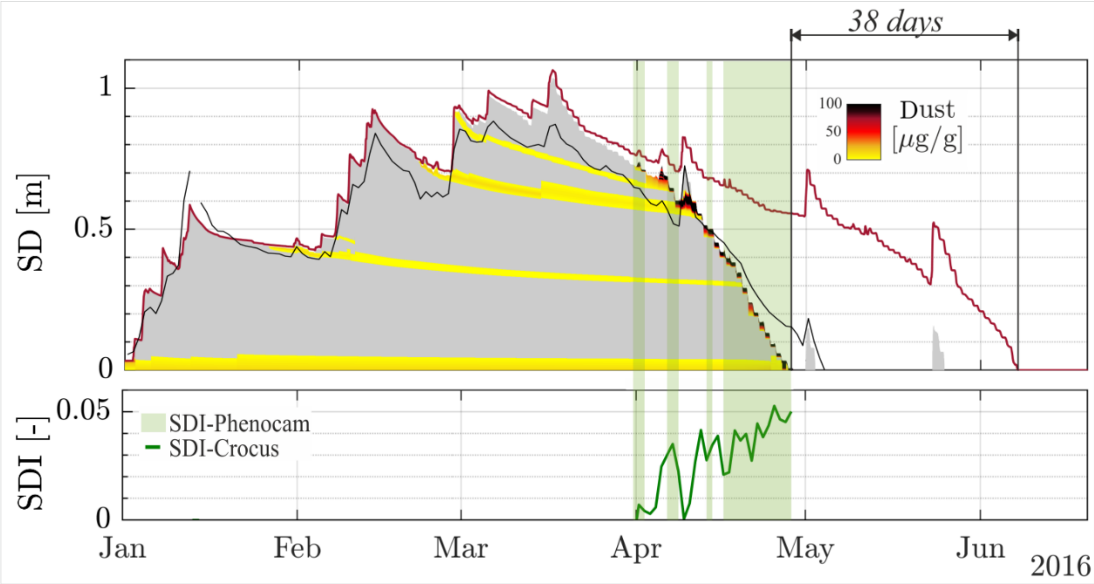

Figure ~~5~~ 6 Comparison between snow depth simulated using Crocus with impurities (grey area) and without impurities (purple line). Observed data are also ~~showed~~ shown (black line). Dust concentration in snow is represented. Shaded green bands represent days with SDI-Phenocam >0. SDI-Crocus is represented as a continuous green line.

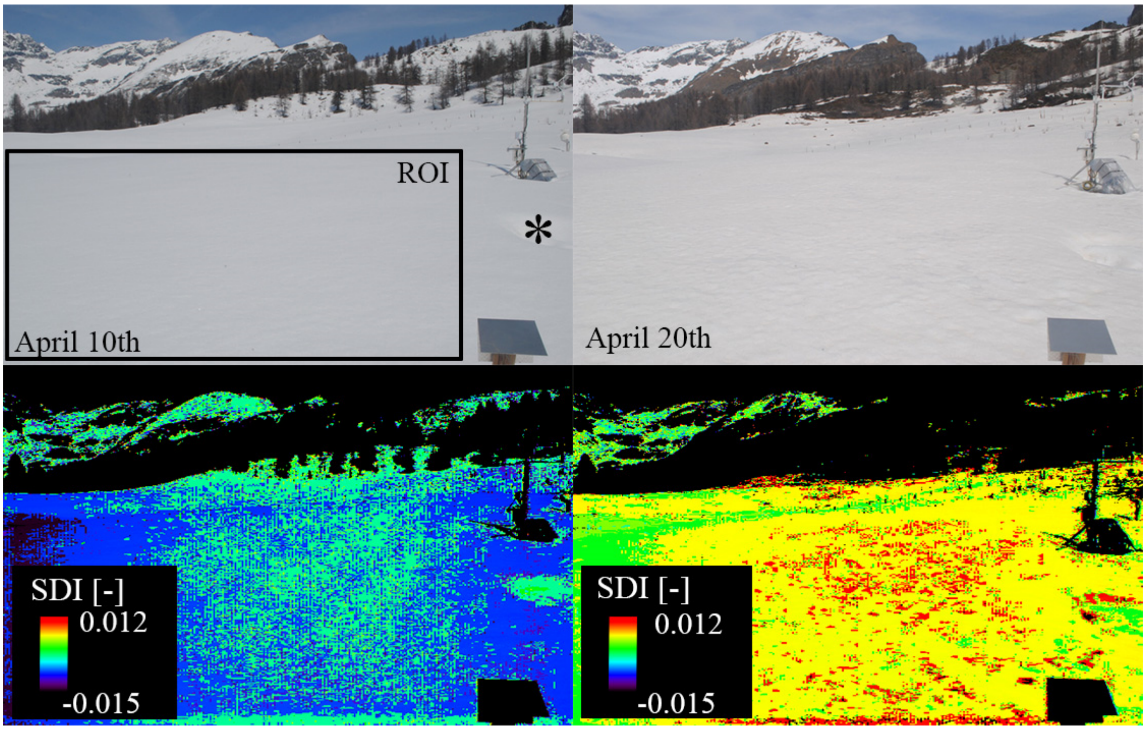

Figure ~~6~~ 7 Top panels: examples of digital images acquired from the Phenocam installed at Torgnon before and after the resurfacing of dust layers. Bottom panels: Snow Darkening Index (SDI) calculated using the Red and Green channels of the images. A region of interest (ROI, in the top left panel) was used to create SDI time series. The asterisk in the top left panel indicates the position of the snow pit.

In the upper part of Figure ~~6~~7, we show two examples of digital images collected from the digital camera. Spatial variability of SDI can be explained by local topography. The experimental site is located in a plain area, with a gentle slope (~5°). Microtopography created by snow melting and refreezing cycles can locally concentrate and dilute impurities in the snow field, also in relation to the differential sun exposure. Surface runoff may also represent an important process in shaping snow surface and in distributing dust in snow fields. This may explain the variability observed in SDI and also the differences between the measured dust concentration in snow samples and Crocus modelled concentrations. Dust redistribution on snowfields might strongly affect its radiative impact. In the lower part of Figure ~~6~~7, we present two SDI maps acquired before (April 10th) and after (April 20th) the resurfacing of dust layers. The transition from cold to warm colours reflects the increase in the values of the index. Positive values of SDI are here associated with the presence of dust on snow (Di Mauro et al. 2015). On the right of both images, a snow pit is visible. It is interesting to note that in the SDI map from April 20th, a red layer is visible in the snow pit. 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. At the end of the season, 'weak' and 'strong' depositions are concentrated by surface melting. This process amplifies the feedback mechanism of dust on snow. In fact, while the melting of snow concentrates the dust on the surface, higher concentrations of dust intensify the melting. This feedback is expected to act for each day with sufficient solar radiation during the output phase. The feedback is also expected to be enhanced until the total disappearing of the snow cover.

SDI is also sensitive to other impurities such as black carbon (Di Mauro et al., 2017) and organic material (Ganey et al., 2017). We cannot exclude that other impurities were present on snow surface, but at present we do not have enough data to evaluate these aspects. We interpret SDI variability only in relation to dust deposition and resurfacing. In the selected ROI (upper-left panel in Figure ~~6~~7), frequency distribution of SDI shows a peak at 0.005. Using this information, ~~Inverting~~ 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 ~~this SDI value is associated with~~ dust concentration equal to 56 $\mu g_{dust}\ g^{-1}_{snow}$. This value is very close to the concentrations measured with the Coulter Counter integrating particles smaller than 60 μm, that reached a maximum of 65 $\mu g_{dust}\ g^{-1}_{snow}$.

Our estimations of shifts in melt-out days are comparable with previous findings in the Western US, where it was estimated that the presence of mineral dust in snow determines a reduction of snow cover up to 51 days (Painter et al., 2007; Skiles et al., 2012). Despite the different deposition rates in the Alps, the advancement of the snowmelt owing to dust is comparable with published results regarding the Western US. This is true at least for one season (2015/2016) characterized by a major Saharan dust deposition.~~The interesting point is that, despite the distance from dust sources is larger in the Alps than in the US, the advancement of the snowmelt owing to dust is comparable, at least for a season (2015/2016) with a major Saharan dust deposition~~. Tuzet et al. (2017) estimated up to 9 days of advanced snowmelt during 2014 in a lower altitude site located in the European Alps as well. In this paper, we estimate an advance in snow melt-out days of 18, 11, and 38 days for the three seasons considered. The estimation for the season 2015/2016 is very high, considering also that snow cover normally lasts about 7 months at this altitude (2160 m~~). Our estimation may be affected by the overestimation of impurity deposition fluxes from ALADIN-climate model. This could be due mainly to the spatial mismatch between the atmospheric and snowpack models. Nevertheless, snow depth simulated considering the impact of impurities are well correlated with observations.~~ In the future, impurities concentration estimated with atmospheric model should be evaluated using ground observation. In this sense, data from in situ spectrometers (e.g. Dumont et al., 2017; Picard et al., 2016) and repeated digital images can be very helpful. In fact, the concentration of different impurities may be retrieved from spectral reflectance using both inversion scheme of radiative transfer models and spectral indices.

~~Studies like the one presented here are important since dust transports are frequent events in Europe (De Angelis and Gaudichet, 1991; Collaud Coen et al., 2004; Greilinger et al., 2018; Wagenbach and Geis, 1989). For example, dust~~

~~transport and deposition to Sierra Nevada (Spain) and Caucasus on March 2017[1] and on March 2018[2] were reported by the media.~~ Dust transport is a natural phenomenon, but it can be intensified by anthropogenic activities (Neff et al., 2008). Further research is needed to assess possible input of local dust to mountain environments. Recently, dust was found to be more important than temperature in determining snow melt in Western US (Painter et al., 2018). ~~In the future, the role of dust and air temperature should be determined also in the Alps.~~

Although no trends were found in the annual number of Saharan dust days since 1997 (Flentje et al., 2015), further research is needed to assess the role of impurities on snow dynamics in the Alps. Measurements of surface concentrations of dust and black carbon in snow are very scarce in the whole Alpine chain. At the Jungfraujoch station (3454 m.a.s.l), dust concentration in the atmosphere is measured in continuous (Collaud Coen et al., 2004). A comparison with these data will be fundamental to validate Saharan dust fluxes in the Alps and to quantify their effect on snow dynamics.

Snow duration was ~~extremely~~ very short during 2015/2016 hydrologic year. Usually, grassland in Torgnon is covered by a thick snow cover from the end of October to late May (average 1928-2010). During 2015/2016 snow arrived in January and disappeared at the beginning of May. It is known that earlier snowmelt impacts on the carbon uptake period (Galvagno et al., 2013), altering carbon exchange with the atmosphere during spring. Shifts in phenological dates, such as the beginning and end of season, may impact ecosystem functioning related to net and gross ecosystem productivity in alpine grasslands, and might lead to early depletion of soil moisture and early senescence related to summer water stress. Extreme events like heat waves have impacts on phenology of mountain grasslands (Cremonese et al., 2017). With future climate changes, these extreme events are likely to increase. With the intensification of climate changes, snow is expected to occur later in autumn and to be depleted earlier in spring (Frei et al., 2018; Verfaillie et al., 2018), with significant impact for the hydrological cycle. The effect of Saharan dust in the European Alps is to accelerate the melt via direct and indirect effect on snow albedo thus enhancing snow season shortening.

3.3 Geochemical characterization of dust in snow

Dust composition is strictly tied to its optical characteristics and hence to its radiative effect on snow (Caponi et al., 2017; Reynolds et al., 2013). Iron oxides contained in dust are particularly absorptive in the visible wavelengths (Alfaro et al., 2004; Linke et al., 2006), and this further enhances the albedo feedback when dust is deposited on snow. The composition of dust is important also for the correct representation of dust in radiative transfer models and global climate models (Albani et al., 2014). Saharan dust events provide an input of nutrients to Alpine ecosystems (Goudie and Middleton, 2001), and this has been poorly studied in the scientific literature (Arvin et al., 2017).

~~These samples are considered representative for those deposited in Torgnon because t~~The main source area of Saharan dust events reaching the Alps is represented by North Algeria (Potential Source Area in Northern Africa 1, PSANAF-1 in Formenti et al. (2011)). For this reason, the dataset presented in this study can be considered representative for the main composition of long-range dust deposition on snow in the Alps. Saharan dust events are regional episodes that move large quantities of mineral dust from arid region to different latitudes and longitudes. There are two main pathways for the transport of dust: it can reach Europe over the Mediterranean and also by looping back over the Atlantic

~~[1] https://earthobservatory.nasa.gov/images/89772/spanish-peaks-turn-tan~~

~~[2] https://www.bbc.com/news/world-europe-43533804~~

(Israelevich et al., 2012; Sodemann et al., 2006). For this reason, we can assume that the bulk geochemical composition of dust events occurred on different location in the Alps and at different times is comparable.

Between February 2014 18th and 20th a relevant event was observed, involving not only Southern Europe and the Alps, but also a large fraction of Europe. It was described as one of the most intense events of this kind observed in the last years. The event was associated to a particularly favorable atmospheric setting which could uplift a massive amount of Saharan dust from North Africa and transport it toward Europe in association to southwesterly winds driven by an anticyclonic structure located on the Central Mediterranean. Given the magnitude of the event, many studies reported it, spanning from microbiology (Meola et al., 2015; Weil et al., 2017), to remote and proximal sensing (Dumont et al., 2017; Di Mauro et al., 2015; Tuzet et al., 2017), and atmospheric chemistry and physics (Belosi et al., 2017; Telloli et al., 2018).

Hereafter, we provide results from a geochemical characterization of dust sampled in snow in the Alps (Artavaggio, LC, Italy). The analysis of the elemental composition ~~INAA~~ allowed detecting 36 elements, spanning from the so-called major elements (the ones whose oxides constitute more than 1 % of the average composition of Earth crust) to many minor and trace ones. Data of interest are showed in Figure ~~7~~8, the full list of elemental concentrations is reported in Table ~~2~~1. We acknowledge that only one snow sample containing dust is not enough to provide a complete overview on the composition of Saharan dust in snow in the Alps, but our analysis may pave the way for a more exhaustive characterization of dust composition in the future.

Element	SH1		SH2	
	Conc. (µg/g)	Conc. (UCC norm.)	Conc. (µg/g)	Conc. (UCC norm.)
Na*	~~0.56(0.05)~~5600(500)	0.47(0.04)	~~0.20(0.03)~~2000(300)	0.17(0.03)
Mg*	~~1.2(0.2)~~12000(2000)	0.8(0.1)	~~0.36(0.09)~~3600(900)	0.24(0.06)
Al*	~~6.3(1.4)~~63000(14000)	0.8(0.2)	~~1.35(0.30)~~13500(3000)	0.17(0.04)
Si*	~~20.0(3.5)~~200000(35000)	0.6(0.1)	~~4.8(2.5)~~48000(25000)	0.15(0.08)
K*	~~1.7(0.2)~~17000(2000)	0.75(0.09)	~~0.45(0.04)~~4500(400)	0.19(0.02)
Ca*	~~1.6(0.5)~~16000(5000)	0.6(0.2)	~~0.6(0.2)~~6000(2000)	0.25(0.09)
Ti*	~~0.60(0.05)~~6000(500)	1.6(0.1)	~~0.09(0.02)~~900(200)	0.25(0.06)
Mn	470(50)	0.61(0.07)	180(33)	0.23(0.04)
Fe*	~~4.0(0.4)~~40000(4000)	1.0(0.1)	~~0.018(0.003)~~180(30)	0.38(0.05)
Sc	13(1)	0.91(0.08)	3.1(0.4)	0.22(0.03)
V	100(10)	1.0(0.1)	26(5)	0.27(0.05)
Cr	123(27)	1.3(0.03)	84(22)	0.9(0.2)

Co	14(1)	0.82(0.06)	6.6(0.7)	0.38(0.05)
Ni	35(8)	0.7(0.2)	38(11)	0.8(0.2)
Zn	132(13)	2.0(0.2)	233(30)	3.5(0.4)
As	6(1)	1.3(0.2)	4(1)	0.9(0.2)
Se	<0.002	-	0.5(0.1)	5(1)
Rb	82(8)	0.98(0.09)	28(5)	0.34(0.06)
Sr	118(19)	0.37(0.06)	86(23)	0.27(0.07)
Sb	1.3(0.2)	3.1(0.4)	12(2)	30(5)
Cs	3.7(0.4)	0.75(0.08)	1.5(0.2)	0.30(0.05)
Ba	500(100)	0.8(0.2)	300(200)	0.5(0.4)
La	43(5)	1.4(0.1)	9(2)	0.29(0.05)
Ce	87(4)	1.39(0.06)	29(2)	0.46(0.04)
Nd	38(8)	1.4(0.3)	10(6)	0.4(0.2)
Sm	7.2(0.9)	1.5(0.2)	1.5(0.2)	0.32(0.05)
Eu	1.5(0.2)	1.5(0.2)	0.24(0.07)	0.24(0.07)
Tb	1.05(0.08)	1.5(0.1)	0.22(0.05)	0.31(0.06)
Ho	1.05(0.08)	1.3(0.1)	0.24(0.05)	0.29(0.07)
Yb	3.9(0.6)	1.9(0.3)	0.7(0.2)	0.3(0.1)
Hf	7.6(0.7)	1.4(0.1)	1.5(0.2)	0.28(0.04)
Ta	1.8(0.5)	2.0(0.6)	0.4(0.1)	0.4(0.1)
W	3.1(0.7)	16(3)	19(3)	100(15)
Hg	0.4(0.1)	8(2)	2.9(0.9)	60(20)
Th	12(1)	1.2(0.1)	2.6(0.6)	0.24(0.05)
U	2.5(0.6)	0.9(0.2)	2.2(0.9)	0.8(0.3)

Table 11 The elemental composition of SH1 (snow sample containing mineral dust) and SH2 (clean snow sample). Data are expressed in terms of μg g^{-1} and are referred to the mass of the extracted material, not to the considered snow volume. Values in brackets are measurement uncertainties. ~~For the elements marked by the asterisk, concentrations are expressed in terms of % mass fractions.~~ Normalized concentrations were calculated considering the Upper Continental Crust as a reference (Rudnick and Gao, 2003)**.**

Concentrations of major elements normalized to the Upper Continental Crust composition are shown~~UCC normalized concentrations of major elements are shown~~ in Figure ~~7a~~8a. It can be easily appreciated that SH1 and SH2 display a very different composition. SH1, corresponding to the dusty snow deposited during the Saharan advection episode of February 2014, presents a typical crustal signature, with UCC normalized values close to 1. On the opposite SH2 shows very low normalized concentrations, suggesting that in this case the crustal fraction is not the dominant one. Since all the considered major elements are strongly depleted (normalized concentrations span from 0.17 in the case of Na, to 0.38 for Fe), it can be inferred that probably its composition is dominated by the only major element, which is not considered here: carbon. Unfortunately INAA is not suited for its detection, but it is known that the carbonaceous fraction is an important component of snow impurities (Li et al., 2016; Wang et al., 2015). Comparing SH1 to Sahel and Saharan dust source composition a substantial correspondence can be appreciated, as it is possible to see in Figure ~~7~~8. This is not unexpected, but direct observations linking the geochemical properties of Saharan dust to the dust deposited in the Alps are quite scarce.

One of the main differences between SH1 and SH2 regards Iron (Fe). With respect to this element, SH1 presents absolute ~~and relative~~ concentrations that are more than two orders of magnitude higher than in SH2. This suggests that Saharan dust could be important for supplying this essential element to high-~~-~~altitude alpine ecosystems where other nutrient sources could be limited, as already pointed out to in relation to other species and to other environments (Avila et al., 1998; Greilinger et al., 2018; Rizzolo et al., 2017). Another issue related to Fe concentration in atmospheric dust is related to its optical properties, since iron oxide concentration and mineralogy strongly influence them (Alfaro et al., 2004; Caponi et al., 2017; Formenti et al., 2014; Linke et al., 2006). The large abundance of Fe is thus expected to affect the radiative effects of dust on snow (Reynolds et al., 2013).

Looking at Ca and Ti further information can be inferred about the most likely provenance of SH1. North African sources (grey lines in Fig. ~~7a~~8a) can be clearly distinguished in relation to the content of these two elements, indeed two groups are recognized. A first one is characterized by high Ca concentration and low Ti content, the second groups shows an opposite composition, with a larger amount of Ti and lower one of Ca (see Fig. ~~7a~~8a). ~~This is related to the carbonate content of the African samples.~~ Carbonates are rich in Ca (a constituent of these rocks) and poor in Ti, in relation to their limited content in accessory and heavy minerals. The first group (high Ca and low Ti) corresponds to the samples collected in Western Sahara, where carbonate rocks are common. On the opposite samples from North Africa display an opposed composition. Comparing SH1 to these groups it is clear that its composition is in accordance with the second group~~, not with the first one~~. Its provenance is more probably related to the mobilization of dust from the central sector of the Sahara-Sahel dust corridor, i.e. the Hoggar, Chad and Niger basins (Moreno et al., 2006).

The elemental composition of dust might have also important effect on the biogeochemical cycles of the alpine grasslands. Among the elements listed in Table ~~2~~ 1 there are elements such as K, and Ca that are known to be relevant for ecosystem functioning (Sardans and Peñuelas, 2015). For both elements, SH1 shows notably higher concentrations (see Table 1). This ~~The effect of the triplicate atmospheric inputs of K (and nearly doubled input of Ca) associated to the sample SH1 (Table 2)~~ requires more attention and further studies to understand the feedback of Saharan dust deposition on ~~deposition not only on the biophysical properties of~~ the biogeochemistry of high-altitude ecosystems.~~, but also on the biogeochemistry. K for instance is an important micronutrient regulating primarily the mechanisms that mitigate water stress (i.e. stomatal regulation, hydraulic conductivity and osmotic regulation in the plant cells), and some photosynthetic processes (i.e. enzymatic activity and synthesis of proteins) (Qiu et al., 2018; Sardans and Peñuelas, 2015). Ca, beside affecting soil pH and improving soil structure, has important effects on ecosystem physiology (Schaffner et al., 2012). There are evidences that K input in terrestrial ecosystems depends on atmospheric depositions (beside management activity and fertilization), which play an important role in regulating vegetation functioning and relief nutrients limitation (Sardans and Peñuelas, 2015). However, the impact of the input of K on ecosystem functions depends on the soil characteristics and by the leaching, and the effect of Ca might depend on the soil pH. The effect of the triplicate atmospheric inputs of K (and nearly doubled input of Ca) associated to the sample SH1 (Table 2) requires more attention and further studies to understand the feedback of Saharan dust deposition not only on the biophysical properties of the ecosystem, but also on the biogeochemistry.~~

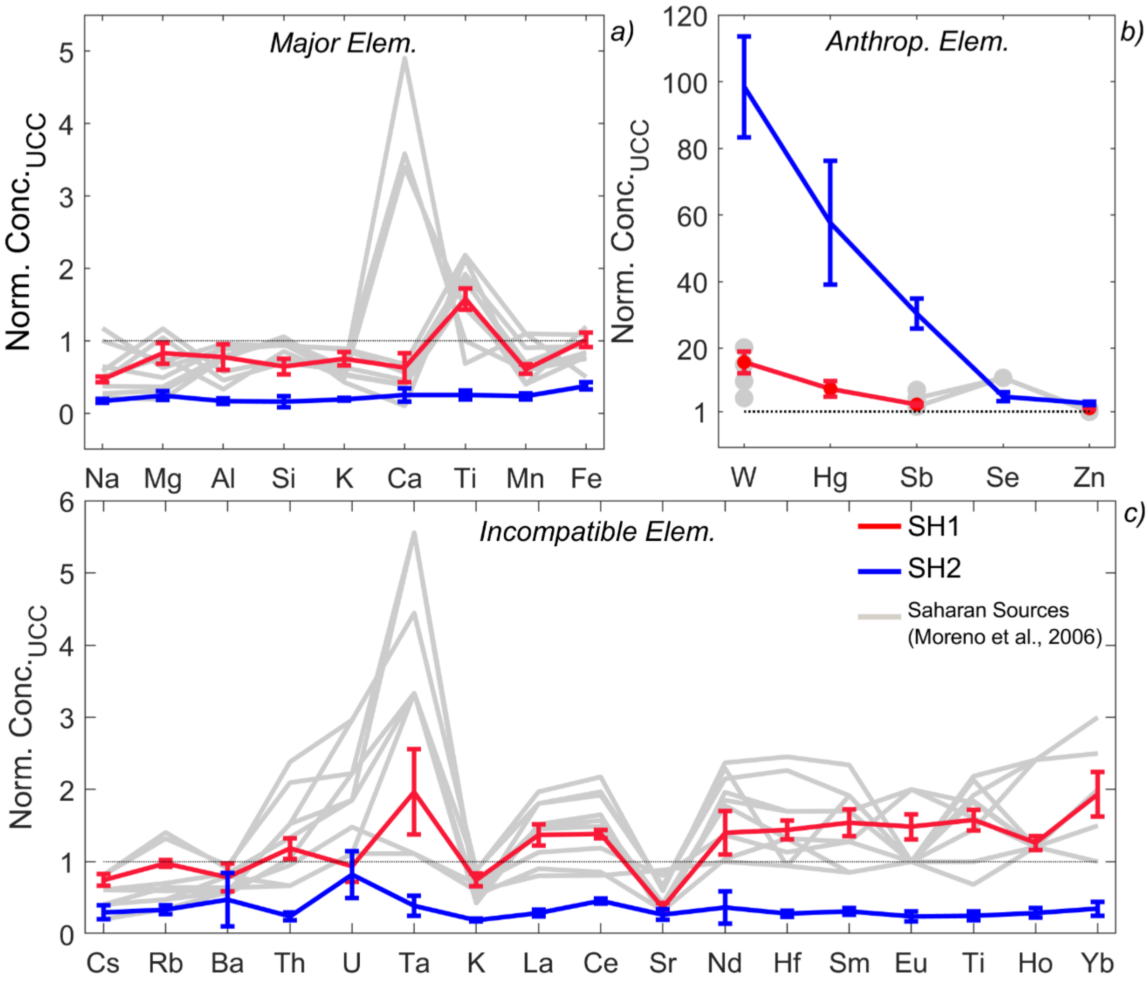

Figure ~~7~~ 8 The elemental composition of the Saharan dust extracted from the snow precipitated on the Alps in February 2014 (red line, SH1) and the composition of the particulate matter retrieved from the clean snow deposited few days later (blue line, SH2). Grey lines refer to samples collected from the Sahara-Sahel dust corridor (Moreno et al., 2006)**. ~~They are intended here as references for the potential source areas emitting the mineral dust which is usually transported from North Africa to Southern Europe.~~ Data are expressed in terms of concentration normalized to the average upper continental crust (UCC** (Rudnick and Gao, 2003)**). a- Major elements; b- anthropogenic elements~~, presenting anomalously high normalized concentrations~~; c- incompatible elements (with respect to Fe), listed following the order proposed by** (Sun and McDonough, 1989)**~~, therefore Cs and Rb display the maximum incompatibility degree, Ho and Yb the lowest one~~.**

Anthropogenic elements are presented in Figure ~~7b~~8b. They are W, Hg, Sb, Se and Zn ~~(Fig. 7b)~~.. This group of elements concerns those elements presenting important positive deviations with respect to UCC composition. They are defined "anthropogenic" to highlight that the their biogeochemical cycles have been strongly impacted by human activities in the last decades and that their mobilization in the environment related to anthropic activities exceeds the natural one (Sen and Peucker-Ehrenbrink, 2012). ~~They are W, Hg, Sb, Se and Zn (Fig. 7b).~~ Again, the signature of SH1 is completely different from the one of SH2. Unlike the case of major and incompatible elements, for anthropogenic elements the sample presenting the higher relative concentration is SH2. SH1 shows values near 1, suggesting that its composition is mainly crustal also for these elements. On the opposite, sample SH2 presents extremely high enrichments, near 100 in the case of W. Such values are not compatible with a crustal origin, contributes from other sources must be involved. Atmospheric emissions related to human activities are the best candidate to explain the enrichment of almost all of these elements. Hg, Sb, Se and Zn are all quite volatile elements, easily mobilized in the atmosphere and related to industrial processes. ~~Given the position of the Artavaggio plains it is not unexpected to detect such chemical evidences on the Alps.~~ Indeed, the sampling site is located less than 100 km far from the Po valley, one of the most industrialized and densely inhabited regions of Europe. The same interpretation is not sufficient to explain the considerably high amount of W in SH2. There is no previous available information about its occurrence in snow and in general its behaviour in the environment is quite obscure (Koutsospyros et al., 2006). It is traditionally considered a non-volatile element, given its refractory properties. The high concentration found in SH2 could be related to the anthropic activities~~ characterizing the Po valley, as in the case of the other anthropogenic elements~~, since W is used in many industrial and manufacturing activities (Koutsospyros et al., 2006). But a different transport mechanism is probably involved. Volatile elements can easily be scavenged from the atmosphere after having be adsorbed on particulate matter (Marx et al., 2008), refractory and non-volatile elements are instead more easily transported directly as airborne particles generated by industrial processes (Sheppard et al., 2007).

A suite of additional trace element composition is presented in Figure ~~7c~~8c. The elements displayed there were ordered following their incompatibility degree with respect to Fe (Sun and McDonough, 1989). This is a useful geochemical feature to understand the provenance and the geochemical signature of rock related samples. ~~As in the case of major elements an evident distinction concerns SH1 and SH2. SH1 presents a composition which is in perfect accordance with a crustal origin (normalized concentrations near one), while in SH2 the crustal contribute is definitely secondary, as revealed by the very low normalized concentrations.~~ Focusing on SH1 it can be appreciated that there is a slight enrichment of poorly incompatible elements (the ones on the right side of Fig. ~~7c~~8c). The same feature is also recognized in the African dust sources, as it was extensively discussed by Moreno et al. (2006), which related the point to the geochemical and mineralogical properties of the sources. Sr and Ta are the two elements presenting the most evident anomalies; a depletion in the first case and an enrichment in the second one. The concentration of Sr is generally related to the presence/absence of carbonates, since Sr is a well-known substituent for Ca in carbonate lattice. In Fig. ~~7c~~ 8c it is possible to appreciate that SH1 and most of the African sources are significantly depleted in Sr, confirming what already suggested by major elements. Indeed, the samples with low Sr content are the same samples presenting low Ca concentrations, pointing to a limited presence of carbonates and confirming that sources from Western Sahara were not involved in this episode.

The case of Ta is completely different, given the analytical difficulties related to its detection, its behaviour in the environment is not yet well constrained, but it seems quite common to deal with samples that present an enrichment, in particular when atmosphere-related samples are considered (Filella, 2017). Looking at Figure ~~7c~~8c, it can be seen that both the African sources and to a lesser extent SH1, present a positive anomaly for Ta. Recent studies suggested that the Ta enrichment in rocks, sediments, and atmospheric particulate matter could be attributed to the effect of chemical weathering. Being Ta extremely stable from a chemical and geochemical perspective, the loss of mobile fractions during weathering, enhanced by atmospheric transport, could explain its enrichment (Baccolo et al., 2016; Vlastelic et al., 2015).

4 Conclusions

In this paper, we investigated the role of impurity depositions on snow dynamics. In particular, we analyzed the role of Saharan dust events on snow melting in a high-altitude site of the European Alps. An overall difference of 38 days was estimated in the disappearance of snow simulated accounting for impurities with respect to snow simulated without accounting for impurities in 2015/2016. During the other seasons considered here (2013/2014, and 2014/2015), the advancement in snow melt-out day was 18 and 11 days, respectively. The season of 2015/2016 was characterized by dust depositions almost double with respect to the other years considered in this study. Snow key variables (snow water equivalent, snow albedo and snow depth) simulated with Crocus model were compared with observed variables from an AWS in the Aosta valley (Western Alps). Good agreement between observations and simulations accounting for the role of impurities was observed. The size distribution of dust found in snow confirms the Saharan origin of the event during April 2016 (Baumann-Stanzer et al., 2018). The geochemical characterization of dust and particulate matter samples distinguished the snow associated to Saharan dust from clean snow. Dusty snow showed a composition compatible with the geochemistry of the dust sources located in the central sector of the Sahara-Sahel dust corridor, i.e. the Hoggar, Chad and Niger basins North African sources. On the contrary, clean snow was characterized by strong contaminations related to anthropogenic elements. 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. ~~The elemental dataset we presented in this paper could serve as a basis for assessing the biogeochemical role of dust in snow and in high altitude alpine environments (e.g. enrichment in micronutrients such as K and Ca), and for exploring the interaction between dust composition and its radiative effect on snow.~~

In the paper, we also made use of repeated digital images for monitoring dust deposition and resurfacing in the snowpack of Torgnon. Dust deposition and resurfacing agreed well with modeling predictions. This allowed us to propose the use of an RGB index (i.e. snow darkening index, SDI) for tracking dust on snow using repeated digital images from digital cameras. The good agreement between dust deposition and SDI suggests that data from this experimental site can be used as a possible calibration/validation for satellite imagery (e.g. MODIS, Landsat, Sentinel) and for regional and global climate models (WFR-Chem, CLM) validation.

Several questions are still open regarding the role of dust in the Alps. For example, the spatial distribution of dust concentration on snow at alpine scale has never been quantitatively estimated. Possible differences between Eastern and Western Alps may arise as a function of distance from the sources. Another unresolved issue is the input from local sources: coarser dust particles can be suspended from snow-free areas and deposited on snow. Regarding the geochemical and mineralogical characteristics of dust, future research should explore in detail the relation between dust characteristics and its radiative effect on snow. In addition to the well-known snow-albedo feedback, other complex mechanisms can be involved in the impact of dust on snow. For example, the presence of dissolved carbonates may accelerate the melt of snow lowering the melting point of snow and ice crystals. The role of carbonaceous particles on snow optical properties in the Alps is also an open question. Measurements of black carbon, brown carbon, organic carbon, and elemental carbon concentration in snow are virtually absent in surface snow in the Alps. The Po plain is one of the most polluted areas of the planet. At lower altitudes, black carbon emissions from fossil fuel combustion and biomass burning may reach snow-covered areas and exert an impact on snow optical properties. Future research efforts should aim at providing spatially distributed measurements of carbonaceous particles, and this will be a fundamental contribution in the determination of the role of natural and anthropogenic activity on snow melting at regional scale.

Data availability. Data used in this paper will be made available upon request to the first author (biagio.dimauro@unimib.it)

Author contributions. BDM conceived the idea of the research, analysed the data, and wrote the manuscript with contributions from all other authors. RG analysed data from the AWS and Crocus. MG, GF, PP, UMdC, and EC established and maintained the experimental site in Torgnon, provided the data from AWS and analysed RGB data from the Phenocam. MD, FT, and ML created Crocus simulations and helped in their interpretation. GB, MC, BD, and VM measured dust

concentration and geochemical composition, and helped in their interpretation. MM helped in the interpretation of the geochemical data. MR, SM, EC, and RC supervised the research.

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