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1 **Accelerated snow melt in the Russian Caucasus**
2 **mountains after the Saharan dust outbreak in March**
3 **2018**

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12 **Key Points:**

- 13 • Dust from Sahara deposited on snow in Caucasus shortened the snow cover du-
14 ration by 12 to 30 days.
- 15 • The impact of dust deposition was larger at higher elevation.
- 16 • Snow modeling uncertainties quantified by ensemble simulation strongly impact
17 the estimated snow cover duration.

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18 **Abstract**

19 Light absorbing particles, such as mineral dust, are a potent climate forcing agent. Many
20 snow-covered areas are subject to dust outbreak events originating from desert regions
21 able to significantly decrease snow albedo. Here, using a combination of Sentinel-2 im-
22 agery, in situ measurements and ensemble detailed snowpack simulations, we study the
23 impact on snow cover duration of a major dust deposition event that occurred in the Cau-
24 casus in March 2018. This is, to the best of our knowledge, the first study using ensemble
25 approach and Sentinel-2 imagery to quantify the impact of a dust event on the snow cover
26 evolution. We demonstrate that the calculation of the impact is strongly affected by the
27 snow model uncertainties but that the March 2018 dust event systematically shortened
28 the snow cover duration in Western Caucasus. The shortening is higher for location with
29 higher accumulation and higher elevation (median values of 23 ± 7 days) than for loca-
30 tion at lower elevation (median values of 15 ± 3 days). This is because for sites with higher
31 location and higher accumulation, melt occurs later in the season when more incoming
32 solar energy is available. This highlights the huge impact of a single one-day event on
33 snow cover duration, and consequently, on the hydrology of a large region.

34 **1 Introduction**

35 Light absorbing particles (LAPs) such as mineral dust or black carbon (BC) darken
36 the snow surface and trigger several snow albedo feedbacks. LAPs are acknowledged as
37 an highly efficient climate forcing [Skiles *et al.*, 2018]. Although mineral dust, hereafter
38 referred as dust, has received less attention than BC due to its lower absorption efficiency
39 and natural origin, dust in snow is also an important driver of snowpack evolution [e.g.
40 Painter *et al.*, 2012; Dumont *et al.*, 2014; Ginot *et al.*, 2014; Skiles *et al.*, 2018]. Dust
41 deposition is generally more sporadic than BC deposition [e.g. Di Mauro *et al.*, 2019] and
42 dust optical properties largely vary with the source region [e.g. Caponi *et al.*, 2017]. Pres-
43 ence of dust in snow is lowering the efficiency of darkening due to black carbon [e.g. Flan-
44 ner, 2013]. Many snow covered regions frequently undergo major dust outbreaks lead-
45 ing to deposition of a large mass of dust on the snowpack which significantly decreases
46 the snow albedo by several percent [e.g. Di Mauro *et al.*, 2015], thus largely affecting the
47 snow cover evolution until the complete melt of snow. For instance, in the Rocky Moun-
48 tains, USA, episodic springtime depositions of dust may have led to a shortening of the
49 snow cover duration by up to 51 days [Skiles and Painter, 2018]. In the European Alps,

50 *Di Mauro et al.* [2019] showed that Saharan dust deposition advanced the snow melt-
51 out date by 38 days. Such changes in duration of the snow cover in mountain areas im-
52 pact the hydrology, glacier mass balance, permafrost, as well as ecological and socioe-
53 conomic systems [*Painter et al.*, 2010; *Blankinship et al.*, 2014; *Beniston et al.*, 2018].

54 The long range transport and deposition of dust from the deserts of the Sahara and
55 Middle East to the eastern Mediterranean and the Caucasus mountains have been re-
56 ported in a number of publications [*Kokkalis et al.*, 2012; *Kutuzov et al.*, 2013; *Nastos*
57 *et al.*, 2011; *Shahgedanova et al.*, 2013]. Analysis of dust layers in ice cores showed that
58 4-7 dust deposition events occur in Caucasus every year during spring time and the strongest
59 dust deposition events in this region are associated with the dust transport from north-
60 ern Sahara [*Kutuzov et al.*, 2013]. Saharan dust deposition is thus a natural and com-
61 mon process in this region of the world, and several studies have reported increasing trends
62 in dust deposition [*Skiles et al.*, 2018; *Kutuzov et al.*, 2019]. Despite the growing corpus
63 about the climatology and history of dust deposition events so far there was no published
64 quantitative assessment of the impact of dust deposition on snow melting in this moun-
65 tainous region. The present study aims at quantifying the impact of a single dust event
66 deposition on the snow cover duration in this area.

67 A dust deposition event occurred in eastern Mediterranean, Anatolia and Cauca-
68 sus on 22 and 23 March 2018 [*Solomos et al.*, 2018; *Marmureanu et al.*, 2019]. It was se-
69 lected for our study case. The event was a record-breaking dust episode with dust con-
70 centration over Greece and Crete exceeding 6 mg m^{-3} [*Marmureanu et al.*, 2019]. A dust
71 storm started in the Libyan desert in the afternoon on 21 March uplifting a massive cloud
72 of dust to the mid troposphere that moved over the island of Crete to the eastern Mediter-
73 ranean [*Roesli and Karvelis*, 2018]. Initially dry air mass in Saharan depression was merged
74 with the atmospheric front above the Black Sea and first precipitation were recorded over
75 the Eastern Europe and Turkey (movie SI.1). A warm front reached the western Cau-
76 casus in the morning on 23 March when the dust was deposited during snowfall [*Mar-*
77 *mureanu et al.*, 2019]. The snow depth increased by 20 cm in 3 hours at the weather sta-
78 tion at 1600 m a.s.l in Krasnaya Polyana (M3 in Fig. 1b). The deposition of mineral
79 particles resulted in significant snow color change in the ski resorts, visible on standard
80 photographs. The event was widely reported in the media and social media [e.g. *Gas-*
81 *coin et al.*, 2018; *Marmureanu et al.*, 2019]. This event was then buried by subsequent

82 snowfalls. It nevertheless reappeared later due to melting, and accelerated the melt of
83 the remaining snowpack.

84 To investigate the impact of this event on snow cover duration, we uses data from
85 the Russian mountain resort Krasnaya Polyana, located in the Western Caucasus and
86 including a cluster of ski resorts (Rosa Khutor, Alpika-Service, Gornaya Carousel, and
87 Laura). The snow cover duration is usually relatively short (late December to March)
88 due to mild winter temperatures and a negative trend in snow cover has been observed
89 since the 1980's [Sokratov *et al.*, 2014]. The duration of snow directly influences the eco-
90 nomic sustainability of these low altitude ski resorts. In this study, we used the high-
91 resolution multi-spectral images from Sentinel-2 (S2) to quantify the temporal and spa-
92 tial evolution of dust content in snow after this major dust outbreak. To estimate the
93 shortening of the snow cover duration caused by this single event in this region, we com-
94 bined S2 information with in situ snow depth measurements, atmospheric reanalysis and
95 detailed ensemble snowpack simulations. We investigate the spatial variability of the short-
96 ening as a function of elevation and we quantify the uncertainty of our results.

97 2 Materials and Methods

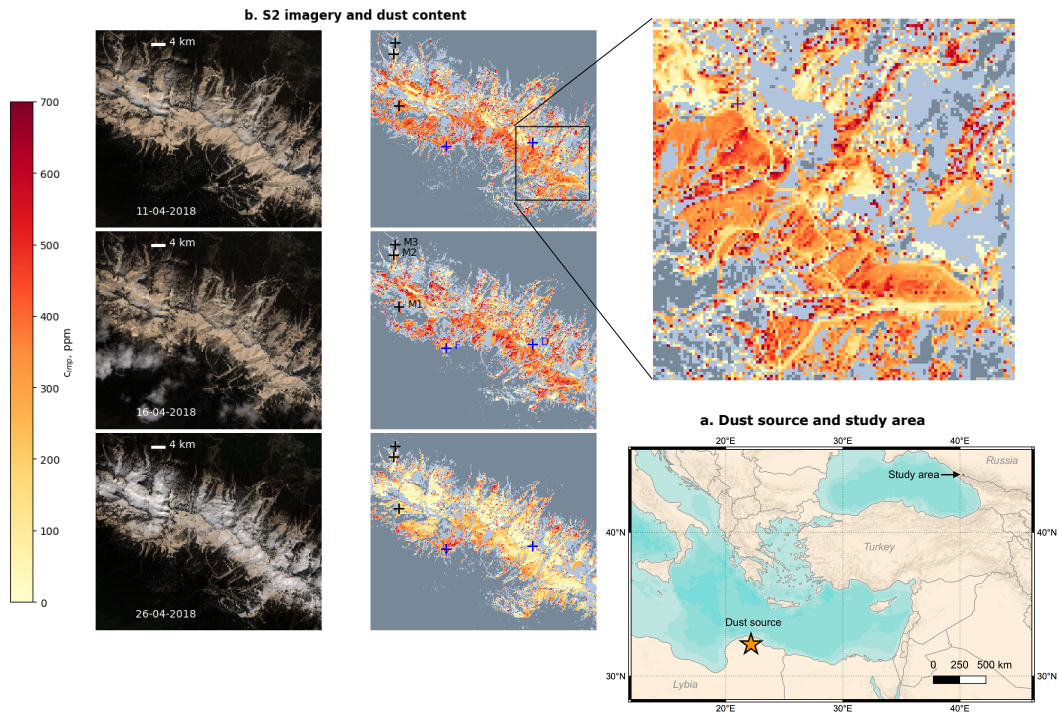
98 2.1 Study sites and in situ data

99 The study site is located close to Krasnaya Polyana mountain resort in Russia (43.68N,
100 40.20E, Fig. 1 a, b). The area covers 56 km² and the elevation ranges from 700 to 2475 m
101 a.s.l. Within the area, snow depth was measured at 3 locations (M1, 2200 m a.s.l, M2,
102 1700 m a.s.l. and M3, 1600 m a.s.l.; Fig. 1b, where M is used for measurement site). These
103 sites are located in small flat areas in the vicinity of the ski slopes at the Gornaya Karusel
104 resort. Snow depth was manually measured as a part of the snow avalanche service du-
105 ties using snow stakes at sites M1 and M2. At the M3 site, the snow depth was recorded
106 by a sonic ranger (Campbell SR50) installed on the mast of an Automatic Weather Sta-
107 tion. Note that for all the 3 sites, the area was not flat enough at the 10 meter scale to
108 properly exploit S2 data.

109 Dust content in snow was measured on 27 March 2018 at location D (Rosa Pik, 2300 m
110 a.s.l., D for dust site). Two samples were collected (300 mL each, 10 cm snow from the
111 surface), then melted and filtered using 0.2 μ m pore size filters. The dust content, cal-

112 culated from the weight of the dust particles on the filter, was 606 and 786 ppm respec-
 113 tively for the two samples. No snow depth measurement was available for site D.

114 Finally, to analyze the satellite signal avoiding uncertainties due to slopes, we se-
 115 lected a flat area far from any disturbance due to the ski resort (site F, Fig. 1b, F for
 116 flat site). The local slope, calculated from the SRTM DEM resampled at 20 m (native
 117 resolution 90 m), over 4 pixels (at 20 m resolution) is 2 ± 1 degrees. No snow depth mea-
 118 surement is available for site F.

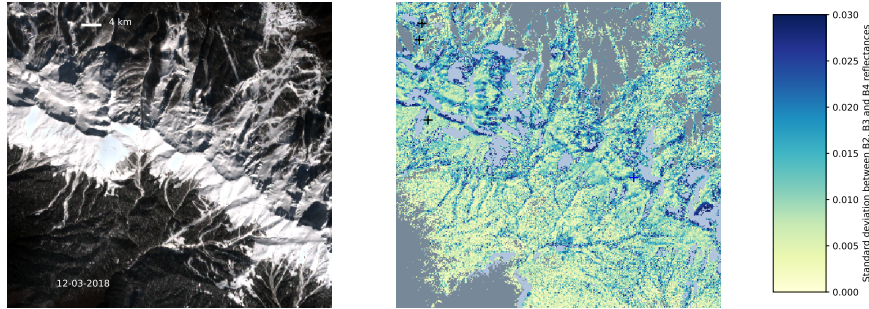


119 **Figure 1.** (a) Location of the study site and of the dust origin region, (b) S2 time series, left
 120 column RGB composite, right column, estimated dust content in ppm. Shaded areas are clouds
 121 or no snow (dark grey) or mixed, inclined or noisy pixels (light grey). The 4 locations correspond
 122 to snow depth measurement sites (M1, M2, M3), dust content measurement site (D) and a refer-
 123 ence flat area (F). On the top right, a zoom of the dust content maps is provided for the black
 124 rectangle. Cleaner ski slopes are visible on the map (see zoom).

125 2.2 Sentinel-2 data and processing

126 Sentinel-2 (S2) L2A surface reflectance images (not corrected for slope) were pro-
 127 cessed using MAJA algorithm as in *Hagolle et al.* [2017] (MACCS-ATCOR Joint Algo-

128 rithm, where MACCS stands for the Multi-Temporal Atmospheric Correction and Cloud
 129 Screening software) and the snow masks were computed with the same algorithm as the
 130 Theia snow products [Gascoïn *et al.*, 2019]. Nine scenes, almost cloud-free, were selected
 131 after the dust event covering 1 April to 27 June 2018. In addition, we used the image
 132 acquired on 12 March 2018, before dust deposition and after a dust-free snowfall (Fig.
 133 2a).



134 **Figure 2.** (a) RGB image of the study area for 12 March 2018 and (b) Standard deviation
 135 between reflectance in bands 2, 3 and 4 for 12 March 2018. Slopes above 40 degrees are masked
 136 out in light grey, pixels with NDSI lower than 0.4 are masked out (dark grey).

137 First, all spectral bands were downsampled to 20 m resolution using nearest neigh-
 138 bour interpolation to match the spatial resolution of the snow masks [Gascoïn *et al.*, 2019].
 139 For every valid pixel, surface reflectance acquired at dates after the dust deposition was
 140 normalized by the surface reflectance acquired on 12 March 2018 in band 3 and band
 141 2 (central wavelengths: 492 and 560 nm) to mitigate topographic effects (local slope and
 142 aspect) on the measured reflectance in snow covered areas. For this, we assumed that
 143 the intrinsic surface reflectance on 12 March was spatially uniform for clean fresh snow
 144 and that the deviation of the recorded value was mainly due to change in local geom-
 145 etry of illumination and re-illumination and shadowing [e.g. Dumont *et al.*, 2017] and
 146 that this topographic effect was almost the same for all dates. This assumption implies
 147 that the snow surface LAP content was very low for all locations. Since the image on
 148 12 March was taken less than 24 hours after the snowfall and that the new snow amount
 149 varied between 20 and 40 cm for the measurement sites, we believe that this assump-
 150 tion is reasonable.

151 Prior to the estimation of the dust content, any pixel considered as cloud or snow-
 152 free was masked out, using the S2 snow mask from MAJA. Mixed pixels (NDSI smaller
 153 than 0.7 - approximately corresponding to the threshold for 100% snow cover in *Salomon-*
 154 *son and Appel [2004]*), steep pixels (slope greater than 40 degrees - where topographic
 155 effects require a detailed correction as explained in *Picard et al. [2020]*) and noisy pix-
 156 els on 12 March (standard deviation between reflectances in the visible bands 2, 3 and
 157 4 greater than 0.03, i.e. higher than the minimum errors in retrieved reflectance, *Kokhanovsky*
 158 *et al. [2019]*) were also discarded from the calculation (Fig. 2b).

159 The dust content, $c_{\text{dust},i}$, was estimated for date t from band i ($i = 2,3$) surface
 160 reflectance in the visible range, r_i , and surface reflectance in the near-infrared range, r_8
 161 (band 8: 842 nm), using the following equation where t_0 is 12 March 2018 :

$$\eta_i(t) = \frac{\log(r_i(t)/r_i(t_0))}{\log(r_8(t)/r_8(t_0))}, \quad c_{\text{dust},i} = f_i(\eta_i(t)) \quad (1)$$

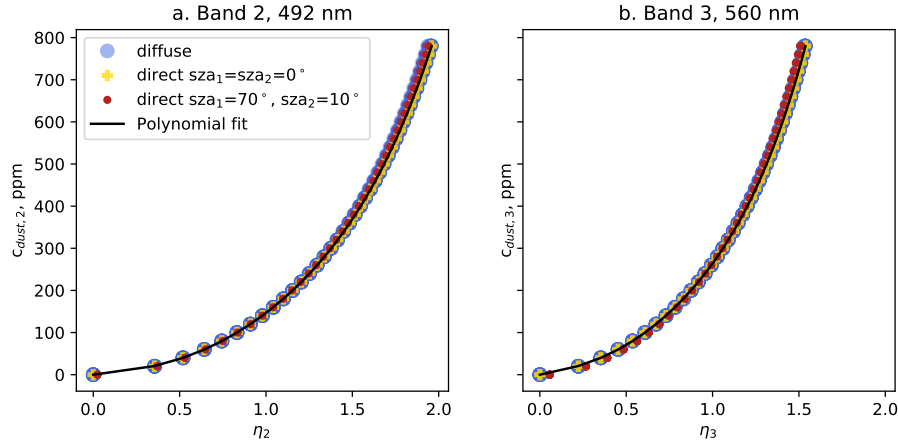
162 Such ratio is only weakly dependent on snow specific surface area (SSA) and illumina-
 163 tion geometry [e.g. *Dumont et al., 2014; Kokhanovsky et al., 2018*] (Fig. 3), enabling to
 164 separate the effect of dust and SSA on surface reflectance. Such ratio requires the use
 165 of two bands : one band sensitive to SSA and impurity content (visible range) and one
 166 band almost insensitive to impurity content (near-infrared range). The index in this study
 167 was based on 10m resolution spectral bands from Sentinel-2. Consequently, we selected
 168 band 2 and band 3 in the visible range (band 4 – 665 nm being less sensitive to impu-
 169 rity content) and band 8 in the near-infrared range. Simpler indices such as in *Dumont*
 170 *et al. [2014]; Di Mauro et al. [2017]; Huovinen et al. [2018]* are sensitive to sun illumi-
 171 nation angle and consequently to topography and dates. Such indices need to be applied
 172 to equivalent diffuse reflectance to reach high accuracy [e.g. *Di Mauro et al., 2017*]. Dif-
 173 fuse reflectance is not available from Sentinel-2. Thus the index in Eq. 1 includes a nor-
 174 malization, enabling a very weak dependence to illumination geometry (Fig. 3). The nor-
 175 malization is made possible since S2 has a constant view angle and a short revisit time.
 176 When the time span between the pre and post event images is only a few days then the
 177 sun geometry and viewing geometry can be considered identical.

178 The functions f_i are five degree polynomials. The polynomials were obtained by
 179 performing a fit on η_i values simulated with the snow radiative transfer model TARTES
 180 [*Libois et al., 2013*]. Namely, we obtained ≈ 8600 η_i values from TARTES simulations
 181 for each band with varying dust content (0-800 ppm), SSA (5 to 60 m² kg⁻¹) and illu-

182 mination geometry (diffuse, direct illumination at 0 and 70 degrees) and a five degree
 183 polynomial was fitted on these simulated τ_{a_i} values (fig. 3. For all the simulations we
 184 used the spectral mass absorption efficiency (MAE) of "PM_{2.5} Libyan dust" from *Caponi*
 185 *et al.* [2017] best corresponding to the dust origin region [*Marmureanu et al.*, 2019]. *Mar-*
 186 *mureanu et al.* [2019] performed a chemical analysis of dust sampled in Romania from
 187 the studied event and measure Fe/Ca ratio of 1.17, very close to the 1.19 for PM_{2.5} Libyan
 188 dust in *Caponi et al.* [2017]. Using the data from *Marmureanu et al.* [2019] and eq. 4 in
 189 *Caponi et al.* [2017], the estimated fractional mass element ratio of iron, MFe, was 6.9%.
 190 Note that no Mn measurement was provided in *Marmureanu et al.* [2019], which may
 191 lead to an overestimation of MFe. In *Caponi et al.* [2017], MFe is close, 5.2% for PM_{2.5}
 192 Libyan dust. Since MFe is controlling a large part of the absorption efficiency [*Caponi*
 193 *et al.*, 2017; *Moosmuller et al.*, 2012], PM_{2.5} Libyan dust from *Caponi et al.* [2017] was
 194 thus close in terms of optical properties to the dust deposited in the studied event. The
 195 simulated snow reflectance using Libyan PM_{2.5} from *Caponi et al.* [2017] was consis-
 196 tent with S2 surface reflectance spectra (Fig. 4). Note that as long as the spectral vari-
 197 ations of the mass absorption efficiency are realistic, the exact value of the MAE does
 198 not affect the computed change in snow cover since the same MAE are used for S2 re-
 199 trieval and in the snow model.

215 The estimation of dust content was done separately with band 2 and band 3 and
 216 the average was taken to yield the final dust content shown in Fig. 1b. Bands 2 and 3
 217 have slightly different sensitivity to dust content and atmospheric and topographic cor-
 218 rections (Fig. 3). Nevertheless, the retrieved c_{dust} were only slightly different in both bands
 219 (RMSE smaller than 60 ppm) which is an indication of the robustness of our estimation
 220 metod.

221 In this study, we choose to retrieve surface dust content and instead of the dust ra-
 222 diative effect as in *Painter et al.* [2012] in order to disentangle the effects of snow phys-
 223 ical properties (surface SSA) and of dust content evolution on the radiative effect, and
 224 hence to separate the radiative effect of metamorphism versus to the radiative effect due
 225 to the enrichment in dust of the surface.

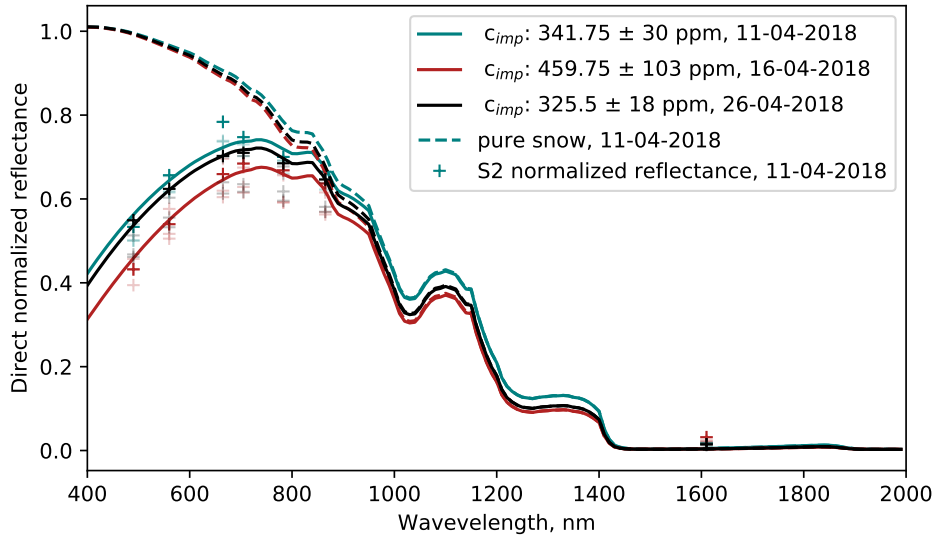


200 **Figure 3.** (a) Simulated dust content (ppm) as a function of reflectance ratio, η , in Eq. 1
 201 for band 2. The markers (circles and crosses) correspond to TARTES simulations [Libois *et al.*,
 202 2013] using every possible pairs of SSA between 5 and 60 $\text{m}^2 \text{kg}^{-1}$ by step of 5 $\text{m}^2 \text{kg}^{-1}$. Snow
 203 at t_0 is supposed to be clean (0 ppm of dust). Blue dots are for diffuse reflectance (for both t_0
 204 and t), yellow crosses are for direct nadir illumination for both t_0 and t and red circles for direct
 205 illumination at 70 degree zenith angle for date t_0 and 10 degree zenith angle for date t . The poly-
 206 nomial fit obtained from the TARTES simulations is shown by the solid black line. (b) same as
 207 (a) but for band 3.

226 2.3 Snowpack simulations

227 Snowpack simulations were performed using the detailed multilayer snowpack model
 228 SURFEX/Crocus [Vionnet *et al.*, 2012], hereinafter Crocus, including an explicit rep-
 229 resentation of LAPs [Tuzet *et al.*, 2017]. The model was used in its multiphysics ensem-
 230 ble configuration ESCROC [Lafaysse *et al.*, 2017], with 35 members ensemble. The 35
 231 members were selected to optimize the mean continuous ranked probability score on to-
 232 tal snow depth on 10 diverse sites selected for the ESM-SnowMIP project [Krinner *et al.*,
 233 2018]. This gives good confidence on the ability of this ensemble to quantify snowpack
 234 modeling uncertainties. The model was run using dust with optical properties defined
 235 above and black carbon with optical properties as in Tuzet *et al.* [2017]. In addition, two
 236 adjustments were performed with respect to Tuzet *et al.* [2017]:

- 237 • Wet snow metamorphism law: to improve the agreement between simulated and
 238 observed SSA in the melt season (as observed in Tuzet *et al.* [2017], figure 4b), we



208 **Figure 4.** S2 estimated and modeled reflectances at site F (4 pixels at 20 m resolution, mean
 209 slope of 2 degrees with 1 degree standard deviation). The crosses correspond to S2 normalized
 210 reflectance (see methods), the solid lines to TARTES simulations with impurity content pre-
 211 scribed by S2 estimated content, dashed lines to pure snow simulations. The three different colors
 212 correspond to the dates. The transparent data correspond to the pixels values while the mean
 213 is indicated in opaque. S2 and TARTES reflectances are normalized by band 3 reflectance to
 214 mitigate topographic effect.

239 accelerated the law for metamorphism of wet snow from *Brun et al.* [1992] by in-
 240 creasing the wet volumetric growth by a factor of four. Such modification allowed
 241 a better agreement between optically measured SSA and simulated SSA presented
 242 in *Tuzet et al.* [2017] (Fig. SI.1).

- 243 • Surface LAP content: in case of partial melt of the surface layer, the dust content
 244 of the first numerical layer is increasing. When the layer is too thin, the model
 245 merges it with the lower layer usually leading to a decrease in surface dust con-
 246 tent that is only a model artefact. This induces a spurious dependency of the sur-
 247 face dust content to the numerical layering. To avoid this artefact the LAP con-
 248 tent of a melting uppermost layer was homogeneously distributed over the ten up-
 249 permost mm of SWE.

250 To investigate the effect of LAPs content on snow evolution, three main simula-
 251 tion configurations were set-up : (i) pure snow simulation with no LAP ; (ii) baseline sim-
 252 ulation with a constant deposition fluxes for dust (dry : $3 \cdot 10^{-10} \text{ g m}^{-2} \text{ s}^{-1}$, wet : $3 \cdot 10^{-9}$
 253 $\text{ g m}^{-2} \text{ s}^{-1}$) and BC (dry : $1 \cdot 10^{-11} \text{ g m}^{-2} \text{ s}^{-1}$, wet : $1 \cdot 10^{-10} \text{ g m}^{-2} \text{ s}^{-1}$) ; (iii) dust_{x1}
 254 simulation, same as (ii) but with an additional wet deposition of 7.3 g m^{-2} of dust on
 255 23 March. The dust mass deposits on the snowpack were chosen in the dust_{x1} scenario
 256 in order to reconcile the simulated dust content with in the dust content measured in
 257 situ. Baseline simulations are useful to quantify the impact of the dust event since the
 258 impact of such event is varying with the amount of other light absorbing particles usu-
 259 ally present in the snowpack in the absence of a major dust outbreak event [e.g. *Flan-*
 260 *ner*, 2013]. In addition, to investigate the sensitivity of the snow cover evolution to the
 261 dust mass deposited during the event, four more simulations were performed, all iden-
 262 tical to dust_{x1} but with 0.13 (dust_{0.1}), 1.03 (dust₁), 14.6 (dust_{x2}) and 29.2 (dust_{x4}) g m^{-2}
 263 of dust on 23 March.

264 The model was forced using ERA-i meteorological reanalysis with an adaptation
 265 to the elevation of the location as in *Dumont et al.* [2014]; *Mudryk et al.* [2018]. Namely,
 266 ERA-i air temperature, specific humidity, downward longwave radiation and precipita-
 267 tion phase were adjusted using the difference in elevation between the simulation point
 268 and the ERA-i grid point. In addition, for locations M1, 2 and 3 and F, precipitation
 269 amounts were manually adjusted to fit measured snow depth before the dust event. The
 270 maximum modification performed for one precipitation event was $\pm 5.4 \text{ kg m}^2$ (20% for
 271 the total amount of this event). Shortwave radiation masking due to local topography
 272 was not taken into account in the simulations since the sites were located on open ar-
 273 eas for which the masking had little impacts. Note that we did not include the uncer-
 274 tainties linked to the SW values in the simulations. In order to initialise the ground tem-
 275 perature, the simulations were initialised with a 3 year spin-up using adjusted ERA-i me-
 276 teorological forcing and are then run from 1 June 2017 to 1 June 2018.

277 The daily surface radiative effect (SRE) due to LAP was calculated as the differ-
 278 ence between the shortwave radiation absorbed by the snowpack in the simulations with
 279 LAPs and the pure snow simulations averaged over 24 hours. The daily SRE value in-
 280 cludes the direct (snow darkening) and indirect (induced snow coarsening) radiative ef-
 281 fect of the dust particles [*Tuzet et al.*, 2017] and thus comprises feedback processes. Daily
 282 SRE was computed until t_{ground} for each location, where t_{ground} is defined as the first

283 date at which one of the members of the ensemble had less than 50 kg m^{-2} of snow mass.
284 SRE calculations were not performed later than t_{ground} to ensure that SRE was not per-
285 turbed by solar energy absorption in the ground. The ground albedo was assumed con-
286 stant over the solar spectrum and set to 0.2. Note that the surface radiative effect is not
287 radiative forcing as defined in the IPCC AR5 report [IPCC, 2013] since (i) SRE includes
288 the effect of all dust and is not a difference with respect to pre-industrial era and since
289 (ii) SRE is a difference in the energy absorbed at the surface and not a difference in the
290 downward irradiance at the tropopause.

291 3 Results

292 3.1 Temporal and spatial evolution of dust in snow

293 Fig. 1b and Movie SI.2 display the temporal and spatial evolution of the dust con-
294 tent estimated from S2. The estimated dust content varied between 0 and 700 ppm ac-
295 cording to the date and location. In Fig. 1b, the ski slopes on 11 and 16 April look cleaner
296 than natural snow, probably due to grooming and artificial snow production (see zoom
297 in Fig. 1b). The snow fall occurring between 16 and 26 April leads to cleaner snow on
298 the image from 26 April. Fig. 4 shows the evolution of S2 surface reflectance at location
299 F (4 pixels) for 3 dates in April. S2 reflectances were normalized by band 3 on 12 March
300 and compared with surface reflectance simulated with TARTES (diffuse reflectance, lines).
301 Dashed lines show pure snow simulations while solid lines show simulations with dust
302 using the S2 estimated dust content as input. It shows that the agreement between S2
303 and the simulated reflectance is within 5%. The simulated reflectance in band 11 (1614 nm)
304 is slightly lower than the observed one. This may be attributed to dust scattering, that
305 is not accounted for in TARTES and is known to increase the reflectance in this specific
306 range of wavelengths for high dust content [Warren and Wiscombe, 1980].

307 For every date, the dust content spatial distribution features a gradient with el-
308 evation (Fig. SI.2a), larger dust content being generally found at lower elevation. This
309 may be related to faster melt at lower elevation, leading to enrichment of the snow sur-
310 face in dust [Sterle et al., 2013; Skiles et al., 2018]. The distribution of dust content with
311 slope aspect displays larger dust content for south-west slopes for 16 April and 1 May
312 (Fig. SI.2b). This may also be attributed to faster melt in south-west facing slopes. An-
313 other explanation could be that these slopes were exposed to the dominant wind dur-

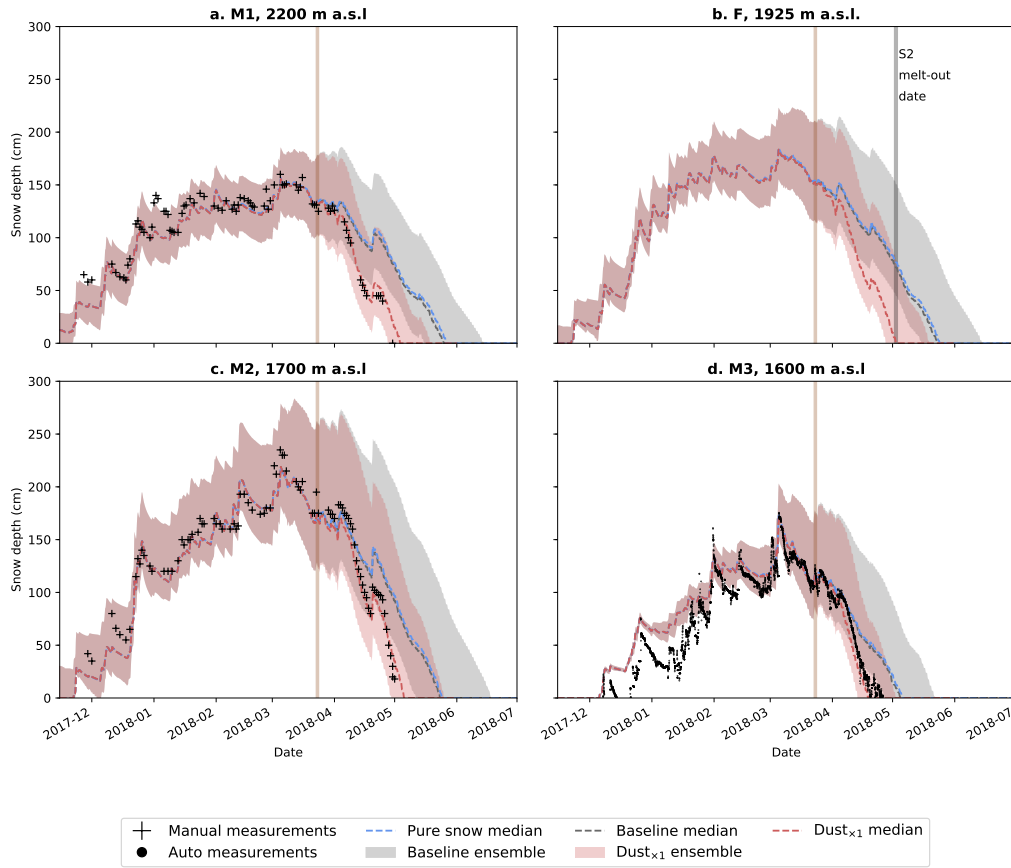
314 ing the dust outbreak thus accumulating more snow (and then more dust) than other
 315 slopes during the event.

316 **3.2 Shortening of the snow cover duration due to dust deposition**

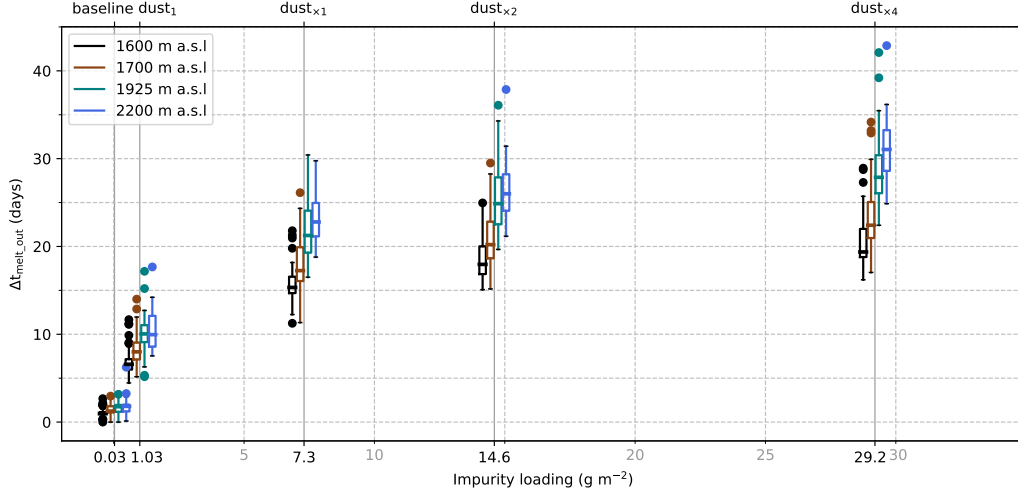
317 Fig. 5 displays the simulated and measured snow depths for locations M1, M2, M3
 318 and F (Fig. 1b). The ensemble median of three simulation set-ups (pure snow, baseline
 319 and dust_{×1}) are reported in the plots. For the sake of clarity, only two ensemble envelopes
 320 (baseline and dust_{×1}) are shown in fig. 5. For locations M1, M2 and M3, the agreement
 321 between the measured and simulated snow depths is the best for dust_{×1} and dust_{×2} sce-
 322 nari (Tab. SI.1). The simulated melt-out date (median value of the dust_{×1} simulation)
 323 fits to within 2 days for each location to the *in situ* (M1, M2 and M3) and S2 (site F)
 324 measured melt-out date. S2 estimated dust content at location F and simulated dust con-
 325 tent (dust_{×1} set-up) are in agreement for almost all dates (Fig. SI.3). The simulated dust
 326 content at site F (median ensemble value 600 ppm, ensemble values ranging between 680
 327 and 780 ppm) also agrees reasonably with the measured dust content at site D just af-
 328 ter the dust event (606 and 786 ppm from the two measurements). This is not the case
 329 for the dust_{×2} scenario in which the dust content is twice higher than S2 dust content
 330 (Fig. SI.3, not shown).

331 Fig. 6 displays the difference in melt-out dates, $\Delta t_{\text{melt_out}}$, with respect to the pure
 332 snow configuration for the different locations and configurations. The shortening of the
 333 snow cover duration in the dust_{×1} configuration by location ranges from 15 ± 3 days (lower
 334 location, M3) to 23 ± 7 days (higher location, M1). The differences in melt-out date be-
 335 tween baseline and pure snow simulations range within 1 ± 2 days, while the median dif-
 336 ferences in melt-out between the dust_{×1} and dust_{×4} simulations range between 3 and
 337 8 days. The spread in $\Delta t_{\text{melt_out}}$ increases with elevation, peak SWE value and dust con-
 338 tent. The box-plots of the baseline simulations are not overlapping with the box-plots
 339 from the three high dust scenario (dust_{×1}, dust_{×2} and dust_{×4}), indicating that the short-
 340 ening can be unambiguously attributed to the dust event regardless the uncertainty of
 341 the other parameterizations in the snowpack model. In addition, $\Delta t_{\text{melt_out}}$ sensitivity
 342 to the dust content is higher for low dust content (baseline, dust_{0.1} and dust₁) than for
 343 higher dust content (dust_{×1}, dust_{×2} and dust_{×4}) and increases with elevation.

344 Lastly, Fig. 7 shows for each configuration the dependence of $\Delta t_{\text{melt_out}}$ on the date
 345 of melt-out in the pure snow simulations. It shows that for every location and config-
 346 uration, there is a positive correlation between the two variables. In other words, the im-
 347 pact of LAP is stronger when the snowpack is melting later, most likely because solar
 348 irradiance is increasing as the days lengthen. The spread in the relationship is higher for
 349 the larger dust contents.



350 **Figure 5.** Ensemble snowpack simulations (ESCROC) for locations M1, 2, 3 and F (Fig. 1
 351 b). The grey ensemble is the baseline ensemble, the red ensemble is the ensemble with dust de-
 352 position (represented by the vertical bar in the panels). Dashed lines correspond to the ensemble
 353 medians. Snow depth measurements are shown in black: crosses for manual measurements and
 354 dots for measurements performed with a sonic ranger (see Section 2.1).

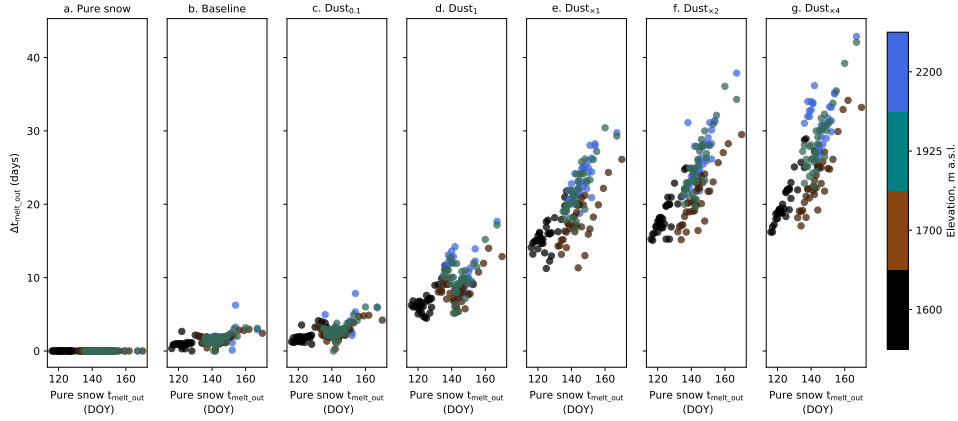


355 **Figure 6.** $\Delta t_{\text{melt_out}}$ between the different configurations (dust loading) and the pure snow
 356 scenario as a function of LAP mass in the snow pack. The color represents the elevation and the
 357 box-plots correspond to the different members of the ensemble. The dots are outliers, defined as
 358 data greater than $Q3 + 1.5IQR$ or lower than $Q1 - 1.5IQR$ where $Q1$ and $Q3$ are respectively the
 359 first and third quartile (box) and IQR is the interquartile range ($Q3 - Q1$).

364 3.3 Dust surface radiative effect

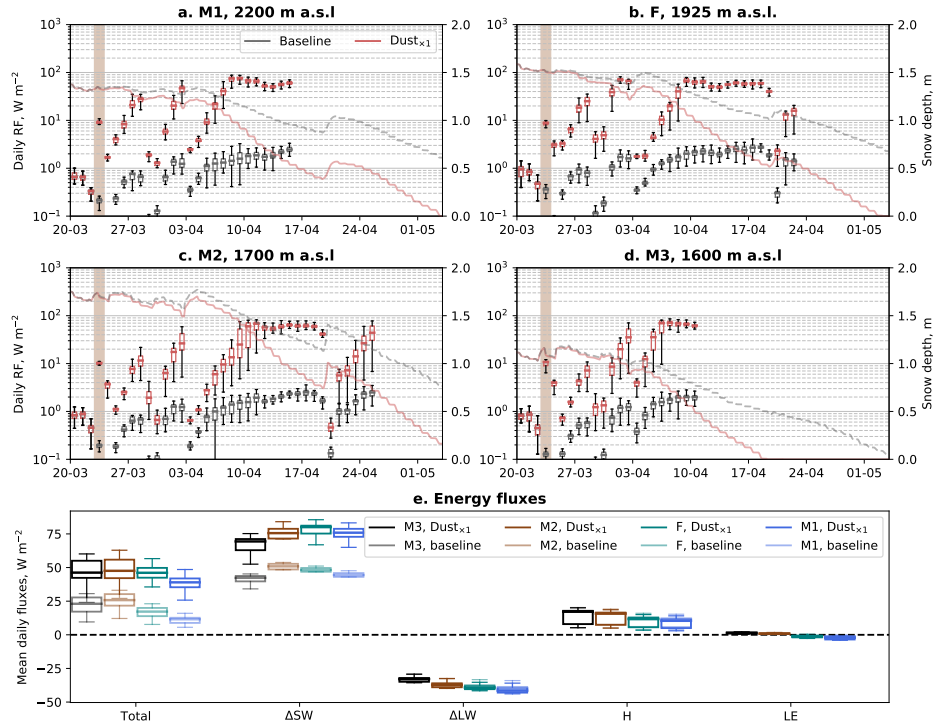
374 The daily SRE due to LAP in the baseline configuration ranges between 0.01 and
 375 4 W m^{-2} (Fig. 8). For the dust_{x1} configuration, the median daily SRE ranges between
 376 0.3 and 80 W m^{-2} (Fig. 8). The daily SRE values exhibit a strong temporal variabil-
 377 ity, smaller values being found just after the snowfalls and larger values after a long pe-
 378 riod without snowfall when the snow surface layer is progressively enriched in dust due
 379 to melting or sublimation. Some dates (e.g. 7 April for location M3, Fig. 8c) exhibit large
 380 spread ($\sigma = \pm 30 \text{ W m}^{-2}$) in SRE value. This spread corresponds to the shift of the
 381 outcropping date of the dust layer between the different members of the ensemble.

382 Fig. 8e compares the different terms of the daily surface energy balance (SEB, i.e.
 383 sum of the radiative budget and the turbulent fluxes) for the four locations on average
 384 between the date of the dust event and t_{ground} for each location. It shows that the to-
 385 tal SEB is higher for simulations including the dust event and that the difference in to-
 386 tal SEB can be mainly attributed to difference in the shortwave net radiation. Median
 387 daily SRE due to the dust event ranges between 28 and 35 W m^{-2} . Total SEB and all



360 **Figure 7.** Shortening of the snow season, with respect to the pure snow simulations as a
 361 function of the melt-out date of the pure snow simulations. The panels correspond to the model
 362 configurations: baseline, dust_{0.1}, dust₁, dust_{x1}, dust_{x2} and dust_{x4}. The different colors corre-
 363 sponds to the elevation of the locations.

388 the different fluxes vary with the elevation of the location. Total SEB is decreasing with
 389 the elevation because lower temperatures induce lower longwave net radiation and lower
 390 sensible and latent heat fluxes. On the contrary, the net shortwave radiation is increas-
 391 ing with the elevation and peak SWE. This is because snow melts later at higher eleva-
 392 tion and the incoming solar radiation is increasing with the day of year during spring
 393 months. As a consequence, the impact of dust deposition on snow melt is generally in-
 394 creasing with elevation and peak SWE values [*Painter et al.*, 2007]. This is also shown
 395 by Fig. 7 where the timing of the pure snow configuration melt-out is controlled by the
 396 peak SWE and by the elevation.



365 **Figure 8.** (a,b,c,d) Median simulated snow depth and daily surface radiative effect (SRE) in
 366 W m^{-2} for the dust_{x1} scenario (grey lines for the baseline set-up) for each location. The dust
 367 deposition event is represented by the red vertical bar. Daily SRE is computed until t_{ground} for
 368 each location and is represented by the box-plots. Median simulated snow depths are the shaded
 369 grey dotted and solid red lines. (e) Daily simulated surface energy balance fluxes in W m^{-2} av-
 370 eraged from the date of the dust event to t_{ground} for each location. The transparent box-plots
 371 are for the baseline set-up and the plain box-plots for the dust_{x1} scenario. The x-axis shows the
 372 different fluxes : total surface energy balance, Shortwave net radiation (ΔSW), longwave net
 373 radiation (ΔLW), sensible heat flux (H) and latent heat flux (LE).

4 Discussion

We used S2 imagery to retrieve the dust concentration at the snow surface after a dust deposition event. We combined these data with ensemble detailed snowpack simulations in order to calculate the shift in the snow melt-out date due to the dust event.

The daily SRE values simulated in the baseline configuration are in line with the spring SRE order of magnitude reported for Eurasia in *Skiles et al.* [2018]. The maximum daily SRE in spring in the dust configurations are also of comparable order of magnitude to the maximum daily SRE reported in *Skiles et al.* [2018] for Europe, Sierra Nevada, USA, and the Rockies, USA, and also measured in the upper Colorado river basin, USA, after several dust deposition events [*Painter et al.*, 2007; *Skiles et al.*, 2012]. For similar dust content, the simulated shortening of the snow cover duration ranges between 20 and 35 days in *Skiles et al.* [2012] in accordance with the values simulated in this study. To this aim, they used a less detailed snow model but forced by measured SRE. For a given dust amount, *Skiles et al.* [2012] found larger shortening of the snow cover duration for low elevation which is apparently in contradiction with the results presented here. These results are most probably explained by the fact that their higher elevation sites have lower peak SWE values which is not the case in the present study. We showed here that the impact of the dust event on the shortening of the snow cover duration is determined by the duration of the snow cover on the ground (without the dust event) which is mainly controlled by peak SWE values and by the elevation.

This study also demonstrates that the choice of the snow model largely impacts the computation of the surface energy balance and in turn, the shortening of the snow cover duration. *Skiles and Painter* [2019] already showed that the shortening can vary from 49 to 20 days when comparing a simple snow model with a detailed one. Here we show that the snow model set-up (depicted here by the spread of the ensemble) can lead to variations between 22 and 42 days for a given location and dust loading. The presence of LAPs, here dust, in the snowpack indeed triggers several feedbacks which are more or less powerful according to the physical laws and parameterizations chosen in the snow model. These feedbacks and the subsequent spread are increasing with the length of the snow cover duration, mainly driven by the peak SWE value and by the elevation. However, despite the uncertainties of this quantification, the multiphysics framework demon-

428 strates that the shortening due to dust is higher than the uncertainty range coming from
429 other processes.

430 Dust content retrieved from satellite data can be reconciled with simulated values
431 but it must be underlined that both are quite uncertain. First, as explained in *Warren*
432 [2013], retrieving impurity content from satellite is challenging. However the fact that
433 the dust content is particularly high here makes the retrieval more reliable. Second, the
434 surface dust content in the model is dependent on the layering due to the model struc-
435 ture which may lead to slight non-physical variations with the dynamical layering of the
436 dust surface content and SRE. Third, both are affected by the choice of the dust spec-
437 tral complex refractive index which can vary considerably with the origin region of the
438 dust [*Caponi et al.*, 2017]. However, as hypothesised in *Skiles et al.* [2012], we showed
439 that the sensitivity of the shortening to the dust mass is higher for low dust content than
440 for high dust content. This relationship between shortening and dust mass is however
441 neither linear nor logarithmic. For a given dust mass, the shortening of the snow cover
442 duration is difficult to predict without a detailed snowpack model quantifying the dif-
443 ferent feedbacks between LAP and snow cover evolution.

444 5 Conclusion

445 We have shown that S2 imagery can be used with a simple retrieval method to mon-
446 itor the evolution of the dust content at the snow surface, provided that there is a clear
447 sky/clean snow image before the event and that the dust mass deposited onto the snow
448 surface is large enough to be detected via satellite (see e.g. *Warren*, 2013 for detection
449 threshold of impurity content). Such data combined with detailed snowpack modeling
450 and atmospheric reanalysis can be used to estimate the shortening of the snow cover du-
451 ration due to dust deposition. Here, we show that the dust event from March 2018 may
452 have shortened the snow cover duration by 12 to 30 days depending on elevation and ac-
453 cumulation, with spring averaged daily SRE reaching almost 35 W m^{-2} . We also demon-
454 strated that the longer the snow cover duration, the higher the shortening due to the dust
455 event. In other words, higher elevations and locations with higher peak SWE are more
456 impacted by dust deposition events. In addition, the choice of a snow model is crucial
457 for the accuracy of the SRE and shortening calculation, leading to large uncertainties
458 in these values if computed in a deterministic framework. Last but not least, since the
459 simulations used here relies on atmospheric reanalysis and on Sentinel-2 data which are

460 both globally and freely available, such calculation could be easily extended to other lo-
461 cations and other periods provided that dust events are significant enough to be detected
462 by satellite and that the topographic effects could be corrected on the satellite data with
463 a clear sky/clean snow image. In situ measurements of impurity content are also cru-
464 cial to evaluate the accuracy of the retrieval from satellite data. The results of this study
465 are particularly important for projection of the impacts of climate change on the ski re-
466 sorts of Krasnaya Polyana as it has already been shown that the snow duration is short-
467 ening in this region and dust may have played a significant role in this process. Increas-
468 ing dust deposition trends had indeed been recorded in this part of the world, [e.g. *Ku-*
469 *tuzov et al.*, 2019], fostering the need for detailed impact studies of dust on snow depo-
470 sition in a changing climate.

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482 S2 reflectances and impurity maps and snow depth measurements are available at
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484 side the open source SURFEX project (<http://www.umr-cnrm.fr/surfex>). While it is not
485 yet implemented in an official SURFEX release, the code will be downloadable from a
486 specific tag of the git repository maintained by Centre d’Études de la Neige upon pub-
487 lication of the paper. The full procedure and documentation to access this git reposi-
488 tory can be found at : https://opensource.cnrm-game-meteo.fr/projects/snowtools_git/wiki.
489 Tartes model is available here : <http://snowtartes.pythonanywhere.com/> (web applica-
490 tion and python module downlaod).

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